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Utilisation of commercial mobile networks in the deployment of C-ITS services

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Kaupallisten matkaviestinverkkojen hyödyntäminen C-ITS-palveluissa

Tekijät
Ville Kilpiö, Ilkka Kotilainen, Risto Kulmala, Jouni Rantanen, Jani Nieminen, Simo-Ville Hönö, Niko Kynsijärvi, Mikko Mäkipää, Harri Paaso-Rantala

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Vuorovaikutteiset älykkäät liikennejärjestelmät, C-ITS, C-ITS-palvelut, matkaviestinverkko, suorituskykymittarit, palvelutasomittarit, palvelutasokriteeristö, skenaarioanalyysi

Tiivistelmä

Tämän tutkimuksen tavoitteena oli selvittää kaupallisten matkaviestinverkkojen kyvykkyyttä toteuttaa C-ITS-palveluita. Tutkimusraportti on jaettu neljään osaan: (i) C-ITS-palvelujen suorituskykymittareiden sekä palvelutasokehikon määrittäminen, (ii) mittausmenetelmäkehikon muodostaminen, (iii) nykytilan arviointi ja (iv) kehityspolkujen tunnistaminen C-ITS-palveluiden laajemman käyttöönoton edistämiseksi. Työn tutkimusmenetelminä olivat kirjallisuuskatsaus, haastattelut, työpajatyöskentely, matkaviestinverkkojen peittoennusteiden sekä kenttämittaustietojen hyödyntäminen, asiantuntijatieto ja yhteistyö projektin ohjausryhmässä.

Tutkimuksen ensimmäisen (i) osan tavoitteena oli määritellä kaupallista matkaviestinverkkoa hyödyntäville C-ITS-palveluille suorituskykymittarit sekä yhteinen palvelutasokehikko kattamaan erilaisia palvelujen käyttöskenaarioita. Tarkempaan tarkasteluun valittiin viisi C-ITS-palveluiden käyttötapausta, joiden avulla muodostettiin suorituskykymittarit kirjallisuuskatsauksen perusteella hyödyntäen sekä C-ITS-palveluissa että tietoliikenteen standardoinnissa käytettyjä mittareita. Palvelutasokehys määriteltiin matkaviestinverkossa toimivien C-ITS-palveluiden kriittisten suorituskykymittareiden arvojen perusteella. Valittujen C-ITS-palvelun avulla kehitettiin skenaarioanalyysi, jonka pohjalta simuloitiin eri C-ITS-palvelujen kokonaiskuormitusta matkaviestinverkolle Suomessa vuonna 2030.

Tutkimuksen toisen (ii) osan tavoitteena oli arvioida yleisesti matkaviestinverkkoteknologioiden kyvykkyyttä C-ITS palvelutasokriteeristöä vasten sekä kehittää mittausmenetelmäkehikko, jonka avulla olennaisia suorituskykyindikaattoreita voidaan mitata. Yleisesti käytössä olevia matkaviestinverkkojen mittausmenetelmiä käytiin läpi C-ITS-palveluihin liittyvien keskeisten mitattavien suureiden näkökulmasta hyödyntäen tutkimuksen ensimmäisen osan tuloksia. Analyysi osoitti sekä verkkoteknologioiden olevan kyvykkäitä että tutkittujen menetelmien olevan toimivia myös C-ITS-palveluiden suorituskykyindikaattoreiden mittaamiseksi. Suositeltu mittausmenetelmäkehikko muodostettiin hyödyntäen eri mittausmenetelmiä niiden soveltuvuuden mukaisesti.

Tutkimuksen kolmannen (iii) osan tavoitteena oli arvioida matkaviestinverkkojen nykytilaa C-ITS-palveluiden toteutumisen kannalta. Kaupallisten matkaviestinverkkojen kyvykkyyttä arvioitiin vertaamalla C-ITS-palveluiden kokonaiskuormitusta eri skenaarioissa (ensimmäisessä osassa kehitetyn skenaariomallin pohjalta) matkaviestinverkkojen laskennalliseen kapasiteettiin. Lisäksi kansallista nykytilaa arvioitiin tarkemmin soveltamalla toisessa osassa kehitettyä mittausmenetelmäkehikkoa, jonka mukaisesti peittokartta-aineistoja vertailtiin kenttämittausten tuottamaan tietoon. Tässä työssä ei toteutettu varsinaisia kenttämittauksia, vaan hyödynnettiin jo olemassa olevaa mittausdataa. Nykyisten matkaviestinverkkojen (pääasiassa 4G- ja 5G-teknologiat) kyvykkyys toteuttaa C-ITS palveluita todettiin hyväksi, sillä jopa haastavimmissa skenaarioissa kuormituksen odotetaan olevan alle 50 % kokonaiskapasiteetista.

Tutkimuksen neljännessä (iv) osassa esitetään ratkaisuehdotuksia C-ITS-palveluiden vaatiman kapasiteetin varmistamiseksi sekä palveluiden yleistymisen tukemiseksi.

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Användning av kommersiella mobilnät i C-ITS-tjänster

Författare
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Ämnesord
Samverkande intelligenta transportsystem, C-ITS, C-ITS-tjänster, mobilnät, prestandaindikatorer, servicenivåindikatorer, kriterier för servicenivå, scenarioanalys

Sammandrag
Målet med denna undersökning var att utreda de kommersiella mobilnätens förmåga att genomföra C-ITS-tjänster. Forskningsrapporten är indelad i fyra delar: (i) definition av prestandaindikatorer för C-ITS-tjänster samt ramen för servicenivån, (ii) utformning av ramen för mätmetoden, (iii) bedömning av nuläget och (iv) identifiering av utvecklingsriktningar för att främja ett bredare införande av C-ITS-tjänster. Forskningsmetoderna i arbetet var en litteraturöversikt, intervjuer, arbete i workshoppar, användning av täckningsprognoser för mobilnät och av fältmätningsdata, sakkunskap och samarbete i projektets styrgrupp.

Målet för den första (i) delen av undersökningen var att definiera prestandaindikatorer för C-ITS-tjänster som utnyttjar kommersiella mobilnät och en gemensam ram för servicenivån för att täcka användningsscenarion för olika tjänster. Fem användningsfall för C-ITS-tjänster valdes ut för närmare granskning, och med hjälp av dem utformades prestandaindikatorer på basis av litteraturöversikten genom användning av indikatorer som utnyttjats både inom C-ITS-tjänster och standardiseringen av telekommunikationen. Ramen för servicenivån fastställdes på basis av värdena på de kritiska prestandaindikatorer för C-ITS-tjänster som fungerar i mobilnät. Med hjälp av de utvalda C-ITS-tjänsterna utvecklades en scenarioanalys, som låg till grund för en simulering av olika C-ITS-tjänsters totalbelastning på mobilnätet i Finland år 2030.

Målet för den andra (ii) delen av undersökningen var att göra en allmän bedömning av mobilnätsteknologiernas förmåga mot kriterierna för servicenivån för C-ITS och utveckla en ram för mätmetoden, med hjälp av vilken väsentliga prestandaindikatorer ska kunna mätas. Allmänt använda mätmetoder för mobilnät gicks igenom ur perspektivet för viktiga mätbara storheter i anknytning till C-ITS-tjänster med hjälp av resultaten från den första delen av undersökningen. Analysen visade både att nätteknologierna har förmågan och att de undersökta metoderna fungerar även för att mäta prestandaindikatorer för C-ITS-tjänster. Den rekommenderade ramen för mätmetoderna utformades med hjälp av olika mätmetoder enligt deras lämplighet.

Målet för den tredje (iii) delen av undersökningen var att bedöma nuläget för mobilnäten med tanke på genomförandet av C-ITS-tjänster. De kommersiella mobilnätens förmåga bedömdes genom att jämföra C-ITS-tjänsternas totalbelastning i olika scenarion (utifrån den scenariomodell som tagits fram i den första delen) med mobilnätens beräkningsmässiga kapacitet. Dessutom bedömdes det nationella nuläget noggrannare genom att tillämpa den ram för mätmetoder som tagits fram i den andra delen och enligt vilken material med täckningskartor jämfördes med de data som fältmätningarna producerat. I detta arbete gjordes inga egentliga fältmätningar, utan redan befintliga mätdata användes. De nuvarande mobilnätens (i huvudsak 4G- och 5G-teknologiernas) förmåga att genomföra C-ITS-tjänster konstaterades vara god, eftersom belastningen till och med i de mest krävande scenariona förväntas vara under 50 procent av totalkapaciteten.

I den fjärde (iv) delen av undersökningen ges förslag på lösningar för att säkerställa den kapacitet som C-ITS-tjänsterna kräver och stödja en spridning av tjänsterna

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Cooperative Intelligent Transport Systems, C-ITS, C-ITS services, mobile network, cellular, Key Performance Indicators, Service Level Framework, Scenario Analysis

Abstract

The aim of this study was to investigate the capability of commercial mobile networks to implement Cooperative Intelligent Transport Systems (C-ITS) services. The research report is divided into four main parts: (i) defining key performance metrics and a service level framework for C-ITS services, (ii) developing a measurement method framework, (iii) assessing the current state, and (iv) recognising development paths for C-ITS deployment. The research methods included a literature review, interviews, a workshop session, utilisation of mobile network coverage predictions and field measurement data, expert knowledge, and collaboration within the project steering group.

In the first part (i) of the study, the objective was to define performance metrics for C-ITS services using commercial mobile networks and establish a common service level framework covering various service usage scenarios. Five C-ITS service use cases were selected for closer examination, and performance metrics were developed by examining literature and metrics used in C-ITS services and telecommunications standardisation. The service level framework was defined based on critical performance metric values for C-ITS services operating in mobile networks. The selected C-ITS services were used to develop a scenario analysis, based on which the overall load of various C-ITS services on the mobile networks in Finland was simulated for the year 2030.

The second part (ii) aimed to assess the overall capability of mobile network technologies against the C-ITS service level criteria and to develop a measurement method framework for measuring key performance indicators. Commonly used mobile network measurement methods were reviewed from the perspective of key measurable variables related to C-ITS services, building upon the results of the first part of the study. The analysis demonstrated both the capability of the network technologies and the effectiveness of the investigated methods for measuring the performance indicators of C-ITS services. The recommended measurement method framework was formulated by utilising various measurement methods according to their suitability.

The third part (iii) of the study aimed to assess the current state of mobile networks concerning the implementation of C-ITS services. The capability of commercial mobile networks was evaluated by comparing the total C-ITS service load in different scenarios (based on the scenario model developed in the first part) to the computational capacity of mobile networks. Additionally, the national current state was assessed by applying the measurement method framework developed in the second part, by comparing coverage map data to field measurement data. However, no actual field measurements were conducted within the scope of this work; existing measurement data was utilised. The capability of current mobile networks (mainly 4G & 5G technologies) to support the deployment of C-ITS services was found to be well suited for carrying the average expected C-ITS messaging data traffic levels, as even in the most demanding scenarios the average capacity utilisation is expected to be in the range of 50% of the total capacity.

The fourth part (iv) of the study presents proposed solutions to ensure the required mobile network capacity for C-ITS services and to support the widespread adoption of these services.

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GLOSSARY

3GPP	The 3rd Generation Partnership Project, standards organizations which develop protocols for mobile telecommunications
4G	The fourth-generation technology standard for cellular network
5G	The Fifth-generation technology standard for cellular networks
5G NSA	Non-Standalone – A solution for 5G networks where the network is supported by the existing 4G infrastructure, more specifically 4G core system.
5G SA	Standalone – a new mobile network architecture that is not dependent on existing 4G infrastructure but 5G core.
5GAA	The 5G Automotive Association
6G	The Sixth-generation technology standard for cellular networks
CA	Carrier Aggregation, technology that enables using one or more additional LTE/5G carriers from different spectrum bands in addition to the primary carrier that the user is connected to.
CAM	Cooperative Awareness Message
CINR	Carrier to Interference plus Noise Ratio
C-ITS	Cooperative Intelligent Transport Systems (C-ITS) offer secure and trusted ITS services.
C-ITS station	The set of hardware and software components needed to collect, store, process, receive and send secure and reliable messages to enable the provision of the C-ITS service. This includes the personal ITS station, ITS central station, ITS vehicle station, and ITS roadside station defined in standard EN 302 665 v 1.1.1
C-ROADS	C-Roads Platform is a joint initiative of European Member States and road operators for testing and implementing C-ITS services in light of cross-border harmonisation and interoperability.
C-V2X	3GPP standard for V2X applications, allows vehicles to interact with their surroundings, such as other vehicles, cyclists, pedestrians, road infrastructure, or mobile networks
CPM	Collective Perception Messages
CSP	Communications Service Providers
DL	Downlink, communication link from the base station to the user equipment.
DENM	Decentralized Environmental Notification Message

EDGE	Enhanced Data Rates for GSM Evolution, also called 2.75G, is a technology that provides higher data rate transmission in GSM network.
ETSI	The European Telecommunications Standards Institute
EU CCMS	EU C-ITS Credential Management System
EU CEF	European Union Connecting Europe Facility, EU funding programme
EU EIP	The European Union Intelligent Transport Systems Platform” (EU EIP), Road Authorities, Road Operators, National Ministries and partners from the private sector cooperation.
FDD	Frequency Division Duplex is a method for establishing a full-duplex communications link that uses two different radio frequencies for transmitter and receiver operation.
GPRS	General Packet Radio Service, also called 2.5G, is a packet-switched mobile data standard in GSM network.
GSM	Global System for Mobile Communication, technology used in 2nd generation (2G) mobile networks. Used interchangeably with 2G.
HLN	Hazardous Locations Notification, C-ITS service
HS(D)PA	High-Speed (Downlink) Packet Access is a packet-switched data transmission technology in UMTS network (3G). HSPA+ is a further enhancement of HSPA.
IoT	Internet of Things, common way to refer to connected devices, as compared to devices operated by humans.
ISAD	Infrastructure Support for Automated Driving
ISD	Inter-Site Distance, the distance between base stations.
ISO	The International Organization for Standardization
ITS	Intelligent Transport Systems, use of Information and Communication Technologies in transport and mobility
ITS directive	The framework directive for Intelligent Transport Systems published by the European Commission (2010/40/EU)
IVIM	Infrastructure to Vehicle Information Message
KPI	Key Performance Indicator, a performance indicator for performance measurement
LOS	Line-of-Sight, a direct and unobstructed path from the transmitter to the receiver.
LTE	Long-Term Evolution. Fourth-generation standard for mobile networks

LTE-M	LTE-Machine Type Communication is a low-power wide-area radio network communication technology standard developed by 3GPP for machine-to-machine applications.
M2M	Machine-to-Machine type of communication.
MAP	Intersection Topology
MAPEM	Intersection Topology Extended Message
MIMO	Multiple-Input and Multiple-Output, technology that enables using multiple antennas for simultaneous transmission and reception on the same spectrum.
MME	Mobility Management Entity is a key component of LTE core network, Evolved Pack Core (EPC). It provides mobility session management and supports subscriber authentication, roaming and handovers to other networks.
mMTC	massive Machine-Type Communications, a collection of 5G technologies that are tailored to support a large number of connected IoT devices.
MNO	Mobile Network Operator
NAP	National Access Point
NR	New Radio, technology used in 5th generation (5G) mobile networks. Used interchangeably with 5G.
NSA	Non-Standalone, 5G radio access network that operates on a legacy 4G LTE core.
OBU	On-Board Unit, device in a vehicle
OEM	Original equipment manufacturer, original producer of a vehicle and vehicle’s components
PKI	Public Key Infrastructure, management of digital certificates
Platoon / platooning	Linking of two or more vehicles in a convoy using connectivity technology and automated driving support systems that support automated driving (EU/2019/2144)
PVD	Probe Vehicle Data, Status data transmitted by vehicles
QCI	QoS Class Identifier
QoS	Quality of service, description or measurement of the overall performance of a service
RF	Radio Frequency
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSU	Road Side Unit

RTT	Round Trip Time
RWW	Road Works Warning, C-ITS service
S1	S1 interface, connects LTE base stations and core network element MME.
SA	Standalone, 5G radio access network architecture that is not dependent on existing 4G infrastructure to facilitate communications.
SI	Signal Phase and Timing Information
SINR	Signal-to-Interference-and-Noise-Ratio, measurement of signal strength compared to unwanted interference and noise.
SIM	Subscriber Identity Module
SNR	Signal-to-noise ratio
SPAT	Signal Phase and Timing
SPATEM	Signal Phase and Timing Extended Message
SREM	Signal Request Extended Message
SSEM	Signal request Status Extended Message
SS-RSRP	Synchronization Signal Reference Signal Received Power
TDD	Time Division Duplex is a method for duplex communication links where uplink is separated from downlink by the allocation of different time slots in the same frequency band.
TIKU-M	Definitions for communications services and networks used in Traficom's statistics and requests for information
TLC	Traffic Light Controller, controls and directs traffic to ensure traffic flow and safety.
UE	User Equipment, end-user terminal or mobile device that is used for communication.
UL	Uplink, communication link from the user equipment to the base station.
UMTS	Universal Mobile Telecommunications System, technology used in 3rd generation (3G) mobile networks. Used interchangeably with 3G.
URLLC	Ultra-Reliable Low-Latency Communications, a set of features that provide low latency and ultra-high reliability for mission critical applications such as industrial internet, remote surgery and intelligent transportation systems.

V2I	Vehicle to Infrastructure, wireless communication to exchange information
V2V	Vehicle to Vehicle, wireless communication between vehicles to exchange information
V2X	Vehicle to Everything, wireless communication between vehicles and the rest of the environment to exchange information (both V2V and V2I)
VMS	Variable Message Sign, display of programmed or predetermined messages.
VRU	Vulnerable Road User, non-motorised road users, such as pedestrians and cyclists
X2	X2 interface, is the interconnecting interface between two LTE base stations.

ALKUSANAT

Suomi yhdessä muiden Pohjoismaiden kanssa on ollut kaupallisia matkaviestinverkkoja hyödyntävien C-ITS-palveluiden käyttöönoton edelläkävijä. Suomen pitkä tieverkko, harva asutus ja erinomaiset matkaviestinverkot ovat vauhdittaneet kehitystä. Suomalaiset ja pohjoismaiset liikenneviranomaiset aloittivat yhdessä teollisuuden kanssa ensimmäiset kaupallista matkaviestinverkkoa hyödyntävien C-ITS-palveluiden pilottitestit vuonna 2015 EU:n CEF-rahoitteisessa NordicWay-hankkeessa.

Euroopan jäsenvaltiot ja tieoperaattorit, mukaan lukien Pohjoismaat ja Suomi, ovat kehittäneet yhteisiä C-ITS-spesifikaatioita ja testanneet C-ITS:n yhteentoimivuutta EU:n CEF-rahoitteisen C-Roads Platform -hankkeessa, joka perustettiin vuonna 2015. Tämä tutkimus käynnistettiin, jotta C-ITS-palvelujen suorituskykyvaatimuksia kaupallisessa matkaviestinverkossa voitaisiin arvioida entistä tarkemmin Suomessa tulevaisuudessa.

Teoksen tilasi Liikenne- ja viestintävirasto Traficom, josta Anna Schirokoff puheenjohtajana ja Pekka Pussinen asiantuntijana. Työn ohjausryhmään kuuluivat myös Matti Sihvola, Jukka Pihonen ja Mikko Räsänen Traficom, Antti Paasilehto, Atte Riihelä ja Sofia Lindbäck Liikenne- ja viestintäministeriö, Jari Myllärinen ja Peteveikko Lyly Väylävirasto, Olli Rossi Liikenteenhallintayhtiö Fintraffic Oy ja Jani Poutiainen Ilmatieteenlaitos. Työstä vastasi Sitowise Oy, sen alikonsultteina toimivat Nodeon Finland Oy, Omnitele Oy ja Traficon Oy.

Työ toteutettiin kolmessa osavaiheessa. Koko työn projektipäällikkönä toimi Ville Kilpiö Sitowise Oy:stä ja työn osavaiheista vastuussa olivat Ilkka Kotilainen Traficon Oy, Simo-Ville Hönö Omnitele Oy sekä Mikko Mäkipää Sitowise Oy. Lisäksi työhön osallistuivat asiantuntijoina Jouni Rantanen ja Harri Paaso-Rantala Sitowise Oy, Risto Kulmala Traficon Oy, Jani Nieminen Omnitele Oy sekä Niko Kynsijärvi ja Timo Majala Nodeon Oy.

Työ oli osa NordicWay 3 -projektia, joka sai taloudellista tukea Euroopan unionin Connecting Europe Facility (EU CEF) -ohjelmasta vuosina 2019–2023.

Helsinki, 4. huhtikuuta 2024

Anna Schirokoff
Johtava asiantuntija
Liikenne- ja viestintävirasto Traficom

FÖRORD

Finland har tillsammans med de övriga nordiska länderna varit en föregångare när det gäller att införa C-ITS-tjänster som utnyttjar kommersiella mobilnät. Finlands omfattande vägnät, glesa bebyggelse och utmärkta mobilnät har satt fart på utvecklingen. De finländska och nordiska transportmyndigheterna inledde tillsammans med industrin de första pilottesterna med C-ITS-tjänster som utnyttjar kommersiella mobilnät år 2015 i projektet NordicWay, som finansierades ur EU:s program Fonden för ett sammanlänkat Europa (CEF).

Europas medlemsstater och vägoperatörer, inklusive de nordiska länderna och Finland, har utvecklat gemensamma C-ITS-specifikationer och testat C-ITS-tjänsternas interoperabilitet i projektet C-Roads Platform, som finansieras ur EU:s program CEF och som startades år 2015. Denna undersökning inleddes för att prestandakraven för C-ITS-tjänster i kommersiella mobilnät ska kunna bedömas ännu noggrannare än tidigare i Finland framöver.

Verket beställdes av Transport- och kommunikationsverket Traficom, från vilket Anna Schirokoff var ordförande och Pekka Pussinen sakkunnig. I styrgruppen för arbetet ingick även Matti Sihvola, Jukka Pihonen och Mikko Räsänen från Traficom, Antti Paasilehto, Atte Riihelä och Sofia Lindbäck från kommunikationsministeriet, Jari Myllärinen och Peteveikko Lyly från Trafikledsverket, Olli Rossi från Trafikstyrningsbolaget Fintraffic Ab och Jani Poutiainen från Meteorologiska institutet. Sitowise Oy ansvarade för arbetet, med Nodeon Finland Oy, Oy Omnitele Ab och Traficon Ab som underkonsulter.

Arbetet utfördes i tre delfaser. Som projektchef för hela arbetet verkade Ville Kilpiö från Sitowise Oy, och för delfaserna ansvarade Ilkka Kotilainen från Traficon Ab, Simo-Ville Hönö från Oy Omnitele Ab och Mikko Mäkipää från Sitowise Oy. I arbetet deltog dessutom Jouni Rantanen och Harri Paaso-Rantala från Sitowise Oy, Risto Kulmala från Traficon Ab, Jani Nieminen från Oy Omnitele Ab samt Niko Kynsijärvi och Timo Majala från Nodeon Finland Oy.

Arbetet ingick i projektet NordicWay 3, som fick ekonomiskt stöd ur Europeiska unionens program Connecting Europe Facility (EU CEF) åren 2019–2023.

Helsingfors, den 4 april 2024

Anna Schirokoff
Ledande sakkunnig
Transport- och kommunikationsverket Traficom

FOREWORD

Finland and other Nordic countries have been the front-runners of C-ITS services deployment utilising commercial mobile networks. Finland's extensive road network and sparsely populated countryside with excellent mobile network communication capabilities and industry, have sped up the development. The Finnish and Nordic transport agencies together with the industry started their first C-ITS mobile network pilot tests in 2015 in the EU CEF funded NordicWay project. European Member States and road operators, Nordic countries and Finland have developed common C-ITS specifications and tested C-ITS interoperability under the umbrella of EU CEF funded C-Roads Platform which was established in 2015. This study was launched to further study C-ITS services performance requirements in commercial mobile networks in Finland.

This work was commissioned by the Finnish Transport and Communications Agency Traficom, with Anna Schirokoff as a chair of the steering group and Pekka Pussinen as a specialist. The other members of the steering group were Matti Sihvola, Jukka Pihonen and Mikko Räsänen from Traficom, Antti Paasilehto, Atte Riihelä and Sofia Lindbäck from Finnish Ministry of Transport and Communications, Jari Myllärinen and Peteveikko Lyly from Finnish Transport Infrastructure Agency, Olli Rossi from Traffic Management Company Fintraffic Ltd and Jani Poutiainen from Finnish Meteorological Institute. Sitowise Plc was responsible for the work and Nodeon Finland Ltd, Omnitele Ltd and Traficon Ltd acted as its subconsultants.

The work was carried out in three sub-phases. The project manager for the whole study was Ville Kilpiö from Sitowise Plc. Ilkka Kotilainen from Traficon Ltd, Simo-Ville Hönö from Omnitele Ltd and Mikko Mäkipää from Sitowise Plc were responsible for the sub-phases. Other members participating in the study as experts and authors were Jouni Rantanen and Harri Paaso-Rantala from Sitowise Plc, Risto Kulmala from Traficon Ltd, Jani Nieminen from Omnitele Ltd, with Niko Kynsijärvi and Timo Majala from Nodeon Ltd.

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Content

Executive summary

The executive summary serves as a concise overview of the main points, key findings, and recommendations derived from this comprehensive study. Additionally, it outlines the study's structure and provides guidance for navigating the full report to access more in-depth information.

Structure of the study

This study is reported in four parts, each building upon the discoveries of the preceding one.

Part A examines the attributes of C-ITS services and defines the needed metrics, Key Performance Indicators (KPI) and quality of service requirements. Part A introduces the service level framework, which serves as a foundation for subsequent parts of the study. Additionally, the scenario framework is developed, drawing insights from scenario analysis and projections regarding C-ITS adoption in Finland up to 2030.

Part B concentrates on mobile network technologies and measurement methodologies as well as techniques and their applicability to measure the KPIs defined in the Part A of the study. Key result of Part B is the developed measurement method framework to assess the suitability of commercial networks for the deployment of C-ITS services.

Part C concludes the findings of previous parts by estimating the capabilities of different mobile network technologies and the commercial networks in Finland. The feasibility of the defined C-ITS development scenarios (based on the scenario framework defined in Part A) and performance metrics (by applying the measurement method framework developed in Part B) are included in Part C. Key result of Part C is the estimated capability of commercial mobile networks to enable the deployment of C-ITS services.

Part D studies the network development progress for C-ITS services and suggests solutions to secure needed capacity. Additionally, recommendations are given for broader deployment of C-ITS services in national context.

Selection criteria and selected C-ITS services for the study

Cooperative Intelligent Transport Systems (C-ITS) means intelligent transport systems (ITS) that exchange real-time C-ITS messages with vehicles, other road users, infrastructure and other environment using trusted and secured communication. EU CCMS is the European Union C-ITS framework for trusted and secure C-ITS communication using Public Key Infrastructure (PKI).

The analysis is based on a restricted number of services, which were selected based on strategic, technical, and automated driving criteria in the following manner:

- Strategic criteria
    - Strategy and legislation: Day 1 and Day 1.5 messages and services, supported by the European strategy and legislation with already existing C-Roads Platform specifications.

  - Needs in Finland, expected safety impact and ongoing piloting in Finland.
- Technical criteria
  - C-ITS message type: DENM and CAM messages for comparison.
  - Infrastructure to Vehicle (I2V) (or downlink) and Vehicle to Infrastructure (V2I) (or uplink). Therefore, V2V and V2X with VRU communications are excluded.
  - Communication technology requirement in the study is mobile network.
  - Impact on the use of mobile network communication.
- Automated driving and other use case criteria
  - CAM, Collective Perception (CPM) and some IVIM services are especially relevant.

The C-ITS services and use cases selected for the analyses were:

1. Hazardous Location Notification service, Temporarily slippery road use case (HLN-TSR) (C-Roads v2.0.5 2022)
2. Road Works Warning service, Lane closure use case (and other restrictions) (RWW-LC) (C-Roads v2.0.5 2022)
3. Signalised Intersection service, Signal Phase and Timing Information use case (SI-SPTI) (C-Roads v2.0.5 2022)
4. Probe Vehicle Data service, Vehicle Data Collection use case (PVD-VDC) (C-Roads v2.0.5 2022)
5. Collective Perception Service (CPS) (ETSI TS 103 324).

For more information see *Part A. Chapter 3 C-ITS Services*.

Key performance indicators

Performance metrics are defined to measure C-ITS service performance with quantitative measurements. Key Performance Indicators (KPI) are the most important selected metrics to assess performance of the C-ITS services.

Quality-of-service (QoS) refers to overall performance of a service which is often experienced by the service user or evaluated by performance metrics. Quality requirements are set of minimum target values (or quality levels, boundaries) for the C-ITS service to meet set quality of service criteria.

The KPI categories analysis includes C-ITS services performance metrics from the literature review and 3GPP as well as ETSI standards. The analysis concludes on the three suggested Key Performance Indicator categories for C-ITS service communication utilising cellular mobile networks: 1) Availability, 2) Reliability, and 3) Integrity. The KPIs proposed are shown in Table 1.

Table 1. Key Performance Indicators (KPI) for C-ITS service communication utilising cellular mobile network.

Key Performance Indicator (KPI)	Description	Unit	Quality of service definition notes
Availability – Network coverage	Additionally, geographic coverage. Percentage of the road network and/or selection of road classes (to be case by defined) where cellular mobile network is available. (Adapted from EU EIP 2022)	%	Availability of cellular mobile network quantified with network coverage KPI. Network coverage considered here binary: 'no network coverage' or 'verified network coverage'.
Reliability - Packet loss rate	Packets not received by the destination application within the maximum tolerable end-to-end latency for that application.	%	-
Integrity – Latency: End to end latency	Time since a message is transmitted until it is received, at application layer	ms	End-to-end latency recommendation is defined as the value under which latency is 99% of cases.
Integrity - Throughput (network, capacity), communication	Instantaneous data rate/throughput as perceived at the network layer.	bps	Includes download and upload rates

For more information see *Part A. Chapter 4.5 Analysis and summary of C-ITS performance metrics and Key Performance Indicators (KPI).*

Service level framework

The service level framework is defined based on quality-of-service requirements identified for C-ITS. The threshold values of the selected Key Performance Indicators (KPI) follow the findings of the quality-of-service literature review, and expert opinion estimations. Second, service levels together with defined scenarios described here are used later in the study to further analyse and classify the service levels. This includes calculation of the scenario values in different traffic conditions and using the data collected from network coverage analysis and field measurements.

The service level framework is presented below in Table 2. The framework is divided into four levels of unreliable, basic, medium, and high.

Table 2. Service level framework for C-ITS services utilising cellular mobile network.

Key Performance Indicator (KPI)	Level 0: Unreliable operability	Level 1: Basic operability	Level 2: Medium operability	Level 3: High operability
Availability Network coverage	No or unreliable	Verified	Verified	Verified
Reliability Reliability Packet loss rate	< 90% > 10%	> 90% < 10%	> 95% < 5%	> 99% < 1%
Integrity E2E latency Throughput DL Throughput UL	> 1 s < 5 Mbit/s < 5 Mbit/s	< 1 s > 5 Mbit/s > 5 Mbit/s	< 500 ms > 20 Mbit/s > 20 Mbit/s	< 100 ms > 100 Mbit/s > 25 Mbit/s

Level 0: Unreliable operability connotes that the network does not meet the minimum requirements to operate C-ITS services. This could for example implicate that there is no MNO coverage at the geographical area in which the vehicle or field measurement was executed or that there was a network outage or a similar ongoing problem during the operation/measurement. If there is no availability, i.e., no network coverage, there cannot be reliability nor integrity. Mitigation techniques and algorithm design have an important role on how each service is dependent on availability of network coverage.

Level 1: Basic operability ensures a verified network coverage and that a single vehicle or service can always use most of the Day 1 V2I/I2V C-ITS services. Some of the services may experience intermittent slowdowns due to relatively high latency requirements but the services are available. Level 1 might hinder the real-time transmissions of C-ITS messages.

Level 2: Medium operability ensures that a single vehicle or service can use C-ITS services that require standard throughput and latency. Services should not experience intermittent slowdowns and the network should work consistently regarding the given parameters. C-ITS services that require more real-time transmission can be implemented if the specific real-time requirements are met.

Level 3: High operability ensures that a single vehicle or service can use advanced C-ITS services that require theoretical real-time transmissions and high throughput. All selected C-ITS services should work consistently and in real-time manner.

For more information see *Part A. Chapter 5 Service level framework*.

Scenario framework & analysis

Scenarios aim to describe the total load that different C-ITS services could cause to the mobile network. This takes into consideration variables related to the number of vehicles capable of receiving and sending C-ITS-messages, traffic volume, as well as to the information density factors of C-ITS-messages. To variate the number of vehicles capable of receiving and sending C-ITS-messages this study considers as a realistic scenario for the percentage of on-board units utilising cellular V2I communications in vehicles in 2030 to be 33%. Optimistic scenario for the C-ITS on-board unit adoption rate is considered to be 45% and pessimistic 20%. Traffic volume is variated by considering four different scenarios in terms of share of rush hour traffic of daily traffic volume and rush hour vehicle speed. With these variables the number of participating vehicles per road km or km^2 can be calculated.

Information density factors of C-ITS-messages are varied to comprehensively study different scenarios. Three perspectives are considered: High, medium, and low information density. The parameters to vary are update rate and density (includes factors such as number of hazards or traffic control messages, and traffic light signals in the area).

The scenario framework regarding variables and their values are shown in Table 3.

*Table 3. Scenarios with selected C-ITS services use cases and information density factors. *Extreme case with the busiest roads 366 veh./km.*

Use Case / Information density factors	**RWW: Lane closure (and other restrictions)**	**HLN: Temporarily slippery road**	**SI: Signal Phase and Timing Information**	**PVD: Vehicle Data Collection**	**Collective perception**
Participating vehicles per road km (High traffic roads) / km^2 (Main streets)*	High traffic road: 6-150	High traffic road: 6-150	Main streets: 25-127	High traffic road: 6-150	Main streets: 5-127
Update rate (or sensor update rate) (Hz)	0.1 Hz	0.1 - 1 Hz	0.5 - 4 Hz	0.1 - 1 Hz	1 - 10 Hz
Density Parameters values included in the length of relevance area (10 km or 1 km2) - Number of hazards or traffic control messages - traffic signals (n) in the area (km2) - vehicles participation percentage (%) - Number of new detections per vehicle (CPM)	1 - 5 (estimated per 10 km length of relevance)	1 - 10 (estimated per 10 km length of relevance)	5 - 19 (estimated per km^2)	100%, 50%, 10% (recom. in literature, but already included in forecast of participating vehicles)	10 - 43 (recom.)
Length of relevance (km) or area of relevance (km^2)	Length: 10 km	Length: 10 km	1 km^2	Length: 10 km (10 x 1 km)	1 km^2
ETSI C-ITS message type	DENM	DENM	SPAT (4 signals)	CAM	CPM
Size of message (bytes)	400	400	1600	100	1000 - 1600

The estimated data traffic in main streets (Mbit/s per km²) and in high traffic roads (Mbit/s/km) is illustrated in Table 4. In the realistic adoption scenario, the data traffic level in main streets is expected to be in the range of 2-6 Mbit/s when the road traffic flow is not congested. In times of congestion, the data traffic level can rise to 14 Mbit/s and up to 25 Mbit/s when traffic is badly congested. In high traffic roads with the realistic C-ITS adoption scenario, the data traffic level is expected to be in the range of 0.10 – 0.26 Mbit/s/km when traffic flow is not congested, and in times of congestion, the data traffic level is expected to be from 0.6-1 Mbit/s/km.

Additionally, an extreme scenario has been identified, which would be potentially occurring in the busiest possible roads and at times of extreme congestion, relevant only for example on the likes of Ring Road I in Helsinki.

Table 4. C-ITS scenario analysis results, main streets & high traffic roads.

	Low flow	Average flow	Congested	Badly congested
Main streets (Mbit/s/km²)				
Pessimistic (low adoption)	1.4 Mbit/s/km²	3.7 Mbit/s/km²	8.4 Mbit/s/km²	14.9 Mbit/s/km²
Realistic	2.3 Mbit/s/km²	6.1 Mbit/s/km²	13.8 Mbit/s/km²	24.6 Mbit/s/km²
Optimistic (high adoption)	3.1 Mbit/s/km²	8.4 Mbit/s/km²	18.8 Mbit/s/km²	33.5 Mbit/s/km²
Extreme				288 Mbit/s/km²
High traffic roads (Mbit/s/km)				
Pessimistic (low adoption)	0.06 Mbit/s/km	0.16 Mbit/s/km	0.35 Mbit/s/km	0.62 Mbit/s/km
Realistic	0.10 Mbit/s/km	0.26 Mbit/s/km	0.58 Mbit/s/km	1.03 Mbit/s/km
Optimistic (high adoption)	0.13 Mbit/s/km	0.35 Mbit/s/km	0.79 Mbit/s/km	1.40 Mbit/s/km
Extreme				12.6 Mbit/s/km

For more information see *Part A. Chapter 6 Scenario analysis* and *Part C. Chapter 3.5.1 C-ITS data traffic scenarios*.

Measurement method framework

The developed measurement method framework is presented in Figure 1 and it is divided into three phases:

1. Theoretical analysis (available information review)
2. Field measurements (additional information requirements)
3. Service level analysis (service level validation).

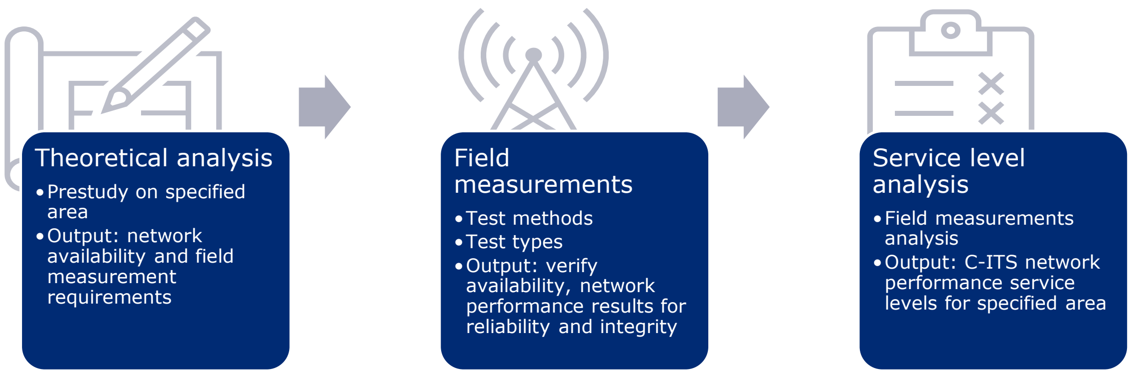


Figure 1. Measurement method framework.

Theoretical analysis includes study of network coverage predictions, which are useful tool to identify potential service availability issues, coverage holes and problematic locations with poor user experience. Coverage predictions can be then further verified with field measurements and carefully planned and conducted tests.

Field measurements conclude the principles that must be followed when conducting field measurements and the definition and description of alternative field measurement types that can be used for different needs. The main proposed addition to the current Traficom measurement methodology is the inclusion of throughput testing. The reason for this is to validate the availability of sufficient throughput to support the identified C-ITS requirements for different service levels. A stress test is preferred due to its ability to analyse available throughput and feasibility for different service levels.

Service level analysis provides guidelines how to use and refine collected data to analyse network service levels using metrics and thresholds in respect to C-ITS service requirements. An example measurement data set is analysed in the study to further illustrate the analysis facilitated by field measurements. These measurements were carried out in mostly urban and suburban areas where average available throughput is well over service level 3 target, yet there are still individual locations, where service level 3 or even service levels 1 and 2, are not available. The example measurement results indicate that although the average performance is well above the required C-ITS service levels, the variation means that the Service level 3 operability is not consistently available.

For more information see *Part B. Chapter 5 Measurement method framework* and *Part C. Chapter 3 Mobile network development metrics for C-ITS*.

Mobile network capacity assessment

The mobile network system capacity is dependent on three key factors, 1. Spectrum, 2. Technology and 3. Topology. For the assessment presented in this study, the relevant variables in different environments are the used spectrum (1.) and network topology (3.) in different areas. Abruptly, when distance to the base station increases, the signal strength decreases, resulting in lower maximum throughput capability. With lower signal strength, fewer bits can be transmitted per spectrum unit, i.e., with lower spectral efficiency. The higher spectrum bands can provide high capacity but only for a limited distance compared to the lower bands.

The total system capacity does not mean that any user would have access to the total system capacity, even if the system would be completely empty of other users. Resources are allocated to users based on demand and additionally the device capability and other limitations will impact how much capacity any single user is allocated. The total capacity is distributed to the different users in the service area at any given time. When assessing the mobile networks’ ability to carry the traffic generated by C-ITS services, the total system capacity is a good measure of the ability of the network to serve the traffic originating from and terminating to multiple individual users.

In Figure 2, an example of system capacity is presented for the different main environments, i.e., urban, suburban, rural and sparse rural, based on the typical spectrum and distance to the base station.

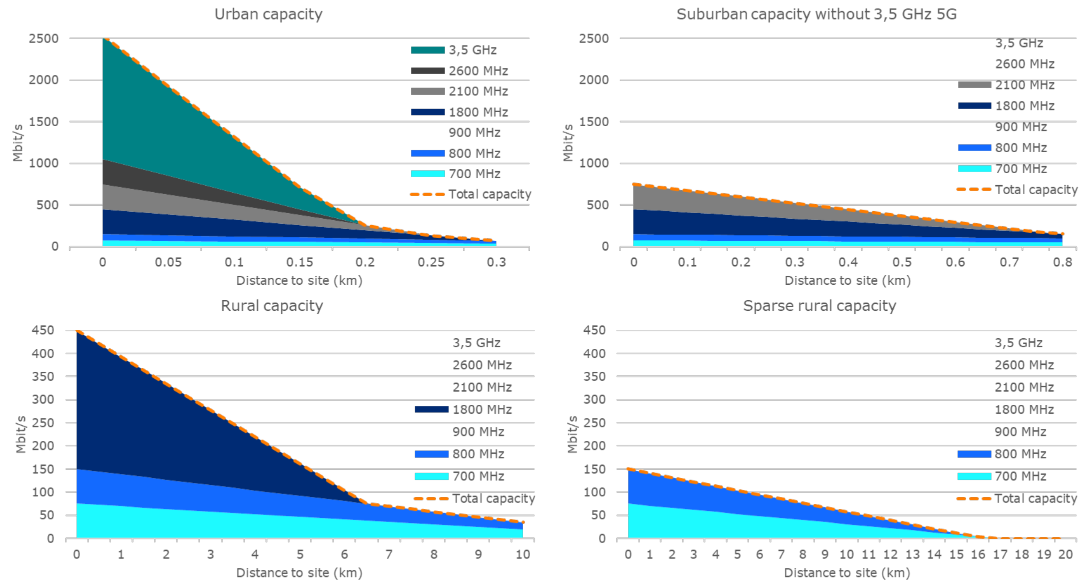


Figure 2. Total sector capacity for mobile networks in different environments.

For more information see *Part C. Chapter 2 Mobile network system capacity in different environments*.

C-ITS feasibility assessment

The analysis aims to identify the magnitude of C-ITS data traffic in the different scenarios in relation to mobile network capacity to understand how capable the networks of today are to serve estimated C-ITS data traffic of 2030. Based on the indicative mobile network capacity estimates and the scenario analysis results presented above, the sufficiency of the typical capacity and feasibility of C-ITS services can be estimated. The estimate assumes that the C-ITS data traffic is evenly distributed to the three commercial networks.

As a general observation from the capacity analysis, the C-ITS traffic scenarios are expected to generate a level of data traffic, that can be carried by urban and suburban mobile networks without issues. High-traffic roads in and near urban areas are expected to generate a C-ITS data traffic level that can be served by the urban and suburban mobile networks of today without any problems. In rural areas, using the same high-traffic road data traffic assumptions, there is potential for issues with capacity. However, even with the highest C-ITS adoption level and with high messaging frequency, in the badly congested traffic scenario, the average capacity utilisation is expected to be in the range of 50%. The probability of such road traffic and congestion on remote rural roads is likely to be low and at least anticipated. In such cases, if uplink traffic from vehicles to network would be in the same magnitude, a large share of the messages could not be delivered.

The results of the capacity utilisation in main streets and high-traffic roads are presented in Table 5. The capacity utilisation is estimated for each traffic scenario, consisting of assessment of traffic flow from low to badly congested, adoption of C-ITS services from pessimistic to optimistic, and the frequency and information density generated by the C-ITS services based on assumptions of the potential eventual implementation of the different C-ITS services. The capacity utilisation is assessed for the different environments separately.

Table 5. Mobile network capacity utilisation in different C-ITS traffic scenarios. In the table low-capacity utilisation is 0 – 10% (green colours), medium 20 – 40% (yellow colours), and high >50% (red colours).

	Main streets capacity utilisation Capacity per km² (Mbits/s/km²)				High traffic roads capacity utilisation Capacity per km (Mbit/s/km)				
Area:	**Urban**	**Suburban**	**Suburban** (no 3,5 GHz)		**Urban**	**Suburban**	**Suburban** (no 3,5 GHz)	**Rural**	**Sparse rural**
Low flow	-	-	-	-	-	-	-	-	-
Pessimistic	**0.0%**	**0.1%**	**0.1%**	**-**	**0.0%**	**0.0%**	**0.0%**	**0.4%**	**0.6%**
Realistic	**0.1%**	**0.1%**	**0.2%**	**-**	**0.0%**	**0.0%**	**0.0%**	**0.6%**	**0.9%**
Optimistic	**0.1%**	**0.1%**	**0.2%**	**-**	**0.0%**	**0.0%**	**0.0%**	**0.9%**	**1.3%**
Low: Pessimistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.0%	0.0%
Low: Realistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.0%	0.1%
Low: Optimistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.1%	0.1%
High: Pessimistic	0.2%	0.2%	0.4%	-	0.0%	0.0%	0.0%	1.4%	2.1%
High: Realistic	0.3%	0.4%	0.7%	-	0.0%	0.0%	0.1%	2.3%	3.4%
High: Optimistic	0.4%	0.5%	0.9%	-	0.0%	0.1%	0.1%	3.2%	4.7%
Average flow	-	-	-	-	-	-	-	-	-
Pessimistic	**0.1%**	**0.2%**	**0.3%**	**-**	**0.0%**	**0.0%**	**0.0%**	**1.0%**	**1.5%**
Realistic	**0.2%**	**0.3%**	**0.4%**	**-**	**0.0%**	**0.0%**	**0.1%**	**1.7%**	**2.5%**
Optimistic	**0.3%**	**0.3%**	**0.6%**	**-**	**0.0%**	**0.0%**	**0.1%**	**2.3%**	**3.4%**
Low: Pessimistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.1%	0.1%
Low: Realistic	0.0%	0.0%	0.1%	-	0.0%	0.0%	0.0%	0.1%	0.2%
Low: Optimistic	0.0%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.2%	0.3%
High: Pessimistic	0.5%	0.6%	1.1%	-	0.0%	0.1%	0.1%	3.8%	5.5%
High: Realistic	0.8%	1.1%	1.8%	-	0.0%	0.1%	0.2%	6.2%	9.1%
High: Optimistic	1.1%	1.5%	2.4%	-	0.0%	0.2%	0.3%	8.5%	12.4%
Congested	-	-	-	-	-	-	-	-	-
Pessimistic	**0.3%**	**0.3%**	**0.6%**	**-**	**0.0%**	**0.0%**	**0.1%**	**2.3%**	**3.4%**
Realistic	**0.4%**	**0.6%**	**1.0%**	**-**	**0.0%**	**0.1%**	**0.1%**	**3.8%**	**5.6%**
Optimistic	**0.6%**	**0.8%**	**1.3%**	**-**	**0.0%**	**0.1%**	**0.2%**	**5.2%**	**7.6%**
Low: Pessimistic	0.0%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.2%	0.3%
Low: Realistic	0.1%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.3%	0.4%
Low: Optimistic	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.4%	0.6%
High: Pessimistic	1.1%	1.5%	2.4%	-	0.0%	0.2%	0.3%	8.5%	12.4%
High: Realistic	1.8%	2.4%	4.0%	-	0.1%	0.3%	0.5%	14.0%	20.5%
High: Optimistic	2.4%	3.3%	5.5%	-	0.1%	0.4%	0.6%	19.2%	28.0%
Badly congested	-	-	-	-	-	-	-	-	-
Pessimistic	**0.5%**	**0.6%**	**1.0%**	**-**	**0.0%**	**0.1%**	**0.1%**	**4.1%**	**6.0%**
Realistic	**0.7%**	**1.0%**	**1.7%**	**-**	**0.0%**	**0.1%**	**0.2%**	**6.8%**	**9.9%**
Optimistic	**1.0%**	**1.4%**	**2.3%**	**-**	**0.0%**	**0.2%**	**0.3%**	**9.3%**	**13.5%**
Low: Pessimistic	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.3%	0.5%
Low: Realistic	0.1%	0.2%	0.3%	-	0.0%	0.0%	0.0%	0.5%	0.8%
Low: Optimistic	0.2%	0.2%	0.4%	-	0.0%	0.0%	0.0%	0.7%	1.0%
High: Pessimistic	1.9%	2.6%	4.3%	-	0.1%	0.3%	0.5%	15.1%	22.1%
High: Realistic	3.1%	4.3%	7.1%	-	0.1%	0.5%	0.8%	25.0%	36.5%
High: Optimistic	4.2%	5.8%	9.7%	-	0.2%	0.7%	1.2%	34.1%	49.8%
Busiest roads	-	-	-	-	-	-	-	-	-
Extreme	**8.8%**	**12.0%**	**20.1%**	**-**	**0.4%**	**1.7%**	**2.8%**	**83.0%**	**121.4%**

For more information see *Part C. Chapter 3.5.2 Mobile network capacity for C-ITS data traffic*.

Conclusions

Considering all the digital mobile network technology generations, even 4G network technologies can provide the connectivity and capacity needed, and future developments for 5G technologies can potentially even improve the ability to serve high-device-density and high-message-frequency services such as in the C-ITS framework.

In general, from coverage availability and system capacity points of view, the mobile networks of today are well suited to carry the average expected C-ITS messaging traffic levels. However, the commercial mobile networks are inherently very much environment-dependent, and spots of poor service levels will persist, individually per each national operator, depending on their local network deployments (site/technology grid) and network strategy. This is important to consider for all development and planning of C-ITS service implementation.

In terms of latency current network technologies are also capable when comparing the network latency threshold values to the service level framework defined in Part A. However, it is worth noting that overall latency is consisting of many components, for example terminal device and service itself, network latency being only one factor.

The currently collected coverage predictions are well suited for the situation overview of C-ITS feasibility. Coverage predictions enable to identify potential areas of concern for the feasibility. As a complement to coverage predictions, a measurement framework is proposed to verify the feasibility of C-ITS services through network stress tests. This measurement framework aims to complement the currently available and used information to accurately estimate the C-ITS feasibility in mobile networks.

For the potential local coverage and service availability issues five solutions are selected for closer inspection. These solutions are *network expansion, neutral host networks, network slicing, network monitoring,* and *data traffic congestion mitigation*. It was recognised that the technological capabilities would not be limiting factors with implementation of these solutions. Regulation related issues for these solutions are also quite well defined, but when considering the costs and investments related to the inspected solutions it can be noted that the business models are an aspect less established in many cases.

For more information see Part C. Chapter 4 Conclusions of Part C and Part D. Chapter 2 Solutions.

Recommendations

This study recommends the following high-level actions for C-ITS service deployment:

1. **Cooperation model for shared vision and goals.** The central part of the cooperation model would be to tackle the uncertainty regarding large-scale deployment of C-ITS services with shared view and situational awareness between actors. The different actors needed for the cooperation are mobile network operators, road operators and other national regulatory authorities, large fleet operators as well as C-ITS service providers.

Strong involvement of road operators and other national regulatory authorities would also increase the predictability and therefore make it easier for commercial operators to invest in implementation of these services. Another central task for this kind of cooperation would be influencing the European C-ITS legislation and specifications. Resiliency should also be one of the crucial themes of this proposed coordination group. Resiliency is built by increasing the awareness of risk management on C-ITS services, especially in situations such as malfunctions of mobile communication networks. In order to justify investments in the large-scale deployment of the C-ITS services it would be necessary to comprehensively evaluate the impacts of these services to the transportation system as well as individual road users.

2. **National C-ITS implementation strategy and road map.** Shared goal for the proposed cooperation model could be a national C-ITS implementation strategy and road map. Basically, the strategy would aim for a certain timeline with a minimum set of C-ITS services available in the most critical parts of the road network. A road map would help to prioritize and scale up the operations in terms of available C-ITS services and road network coverage. First steps in such a process would include selection of the services that would need to be available. The selection criteria utilized in this study is a good baseline for the selection of services in the first phase of the road map. A possible role for management and administration of C-ITS implementation could include public authority funding, e.g. road authority and municipalities, and procurement in a similar manner as it is currently the case, for example with road maintenance. This might be the initial step to start the C-ITS services in Finland, and the road map should include more detailed plan for wider emergence of commercial service providers. The road network coverage of C-ITS services could be connected to the main road network and to the larger cities. TEN-T classification (e.g., core network and comprehensive network) could be utilized when planning for the road network coverage. A suitable timeline for the road map could be aligned for example with the EU regulation regarding the ITS Directive and the timeframe that the recognized data types should be available. However, this is a minimum requirement and there’s no reason why the national implementation couldn’t be faster. As important as enabling commercial operations is enabling cross-border interoperability, and this theme should be covered in the national implementation strategy as well. Recognizing the work done in C-Roads Platform in the national implementation strategy and road map would ensure that the solutions of commercial operators would be also functional in other member states and therefore make it easier to scale up their operations in Europe.

For more information see *Part D. Chapter 4 Recommendations*.

Introduction

A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected, and automated mobility was published in 2016 by the European Commission. The strategy states that drivers expect to receive all information on traffic and safety conditions across Europe, and this can only be achieved through a hybrid communication approach which combines complementary communication technologies such as mobile networks and short-range communication. Flexibility on hybrid communication technology used eases inclusion of future technologies, e.g., 5G and beyond. (European Commission 2016)

Cooperative Intelligent Transport Systems (C-ITS) means intelligent transport systems that exchange real-time C-ITS messages with vehicles, other road users, infrastructure and other environment using European Union C-ITS security credential management system (EU CCMS). EU CCMS is the European Union C-ITS framework for trusted and secure C-ITS communication using Public Key Infrastructure (PKI).

The aim of this research was to study the performance needs of C-ITS service deployment in mobile networks, define common service level framework criterion to cover various scenarios of use of services as well as to assess the capabilities of current mobile networks to support C-ITS deployment. This report answers the following research questions:

How are the service level framework Key Performance Indicators of mobile networks required by C-ITS services defined? (Part A)

How are different mobile network technologies suited to serve the needs of different C-ITS services, based on the identified requirements from Part A? (Part B)

What kind of methods can be utilized to prove the functionality of different types of C-ITS services in the commercial mobile networks? (Part B)

How are current commercial mobile networks suited to serve C-ITS services and what are the key deficiencies/bottlenecks, if any? (Part C)

How can the network development progress for C-ITS services be assessed currently and what information is needed to assess the progress in the future? (Part C)

This study was conducted in separate work phases, and the reports of these work phases are combined into one complete report. The reports of these work phases are labelled as Parts and their content is as follows:

- **Part A. Definition of service level framework for mobile networks.** Part A examines the attributes of C-ITS services and defines the needed metrics, Key Performance Indicators (KPI) and quality of service requirements. Part A introduces the service level framework, which serves as a foundation for subsequent parts of the study. Additionally, the scenario framework is developed, drawing insights from scenario analysis and projections regarding C-ITS adoption in Finland up to 2030.
- **Part B. Measurement methodologies and techniques.** Part B concentrates on mobile network technologies and measurement methodologies as

well as techniques and their applicability to measure the KPIs defined in the Part A of the study. Key result of Part B is the developed measurement method framework to assess the suitability of commercial networks for the deployment of C-ITS services.

- **Part C. Assessing C-ITS capability of commercial mobile networks.** Part C concludes the findings of previous parts by estimating the capabilities of different mobile network technologies and the commercial networks in Finland. The feasibility of the defined C-ITS development scenarios (based on the scenario framework defined in Part A) and performance metrics (by applying the measurement method framework developed in Part B) are included in Part C. Key result of Part C is the estimated capability of commercial mobile networks to enable the deployment of C-ITS services.
- **Part D. Development paths for C-ITS deployment.** Part D studies the network development progress for C-ITS services and suggests solutions to secure needed capacity. Additionally, recommendations are given for broader deployment of C-ITS services in national context.

Scope of the study

The scope of the study limits to commercial mobile network technologies, existing C-ITS standards, European legislation, and C-Roads Platform harmonised C-ITS communication profile specifications. Following paragraphs introduce these limitations.

Mobile networks, i.e., long-range communication technologies used in C-ITS communication, that are available on a commercial basis, are in scope of this study. Ad-hoc short-range communication is out of scope of this study. C-ITS technologies and standardisation are introduced in Part A chapter 2.3.

C-ITS communication architecture includes multiple actors, servers, communication channels, links, etc. depending on the local selected implementation model. Mobile networks are one important part of this C-ITS communication chain and therefore only partly impact the overall quality of service together with other parts and actors of the communication chain. Scope of the study covers C-ITS architecture solutions and protocols relevant to mobile networks, such as the Internet Protocol. C-ITS communication architecture and different deployment models are discussed in Part A chapter 2.3.1.

Internet Protocol (IP), or IP-channel of C-ITS communication, is used in C-ITS IP based interface for C-ITS service provisioning, i.e., C-ITS message exchange between end user entity and last serving back-end entity. Scope of the study covers C-ITS services and use cases IP-channel end-to-end performance and measurements with some considerations and limitations.

It should be acknowledged, that choices made when measuring C-ITS service provision in different parts of the network, e.g., end user, radio network or network, has an impact on performance metrics such as latency and packet delivery measurements. This impact needs to be taken account when selecting KPIs and developing methods for measuring C-ITS services as well as analysis of the measurements. For example, if only mobile network service provision channel between end user and radio network entity would be considered, it could be difficult to gather data, as the data source would be the mobile network operator. Other sources can be third party measurements between end user, cellular base stations and serving back-end entity. Measurements and measurement method framework are further discussed in Part B of this report.

C-ITS messages congestion algorithms and mitigation techniques, i.e., methods to reduce and minimise any negative impact in case of C-ITS communication network issues, are partly considered and in scope of the study. Mitigation techniques include, for example, Internet Protocol build in features when C-ITS services are utilising mobile network communication. The study does not describe all different types of mitigation techniques as they can be service provider software dependent, i.e., how the algorithms have been developed. Algorithms and mitigation techniques are further introduced in Part A chapter 2.3.2.

Specifications of C-Roads Platform are followed in this study. The C-Roads specifications have been harmonised with the CAR 2 CAR Communication Consortium (C2C-CC) specifications. C-Roads specifications include such as C-ITS service and use case definitions, system specifications, mobile network service provision channel and IP-channel of C-ITS communications. C-Roads specifications are priority for the European Union Member States when preparing deployment of C-ITS. C-Roads specifications are introduced in the Part A chapter 3.2.

European legislation, at the time of this study, did not include specific C-ITS legislation, although draft C-ITS delegated act was published in 2019 (not in force). Intelligent Transport Systems (ITS) directive (2010/40/EU) priority actions b and c delegated acts do relate to C-ITS services and are therefore part of the study scope and further introduced in Part A chapter 2.4.

Methods

The research methods of this study were literature review, interviews, workshop, expert knowledge, and collaboration in the project management group. The methods are presented in more detail below.

The literature review included scientific articles, standards, legislation, conference publications and reports, e.g., of pilot projects. Literature review was conducted by using search engines and scientific publications.

Knowledge of project team and management group members as well as expert interviews were utilised (including Finnish mobile network operators). The study included multiple iterative review rounds together with the members of project’s phases (see Introduction about the structure of the report). Additionally, during the work multiple peer reviewers from Europe have been used to gather knowledge on C-ITS and mobile network performance and quality indicators.

Furthermore, combined mobile network coverage predictions and measurement information were received from Traficom to support the assessment of using currently available information as a basis for assessing the feasibility of C-ITS services in Finland.

An online workshop was also organised with stakeholders from national relevant authorities, mobile network operators and ITS service providers in order to gain insights on mobile network utilisation in C-ITS service deployment.

Part A. Definition of service level framework for mobile networks

1 Introduction

This Part of the report answers the following research question:

- *How are the service level framework Key Performance Indicators of mobile networks required by C-ITS services defined?*

This Part starts with an introduction of C-ITS and the C-ITS service, including C-ITS actors and roles as well as technologies and standards. C-ITS services are then selected for further analysis based on set criteria. Analysis of C-ITS services and mobile network performance metrics concludes to suggestion of Key Performance Indicators (KPIs) for the selected C-ITS services in mobile network communication. Service level framework for C-ITS services utilising mobile network includes suggestions for quality requirements. Finally, scenarios are suggested for selected C-ITS services communication in 2030.

Methods

The research methods of this study were literature review, interviews, expert knowledge, and collaboration in the project management group. The literature review included scientific articles, standards, legislation, conference publications and reports, e.g., of pilot projects. Literature review was conducted by using search engines and scientific publications.

The service level framework and its criteria were developed using the results of the study and previous literature. Scenario analysis was used to estimate selected C-ITS services performance requirements KPIs for commercial mobile network in future.

2 Cooperative Intelligent Transport Systems (C-ITS)

2.1 Definition of C-ITS

Intelligent Transport Systems (ITS) use Information and Communication Technologies (ICT) on mobility and road transport sector, including infrastructure, vehicles, users as well as traffic and mobility management. ITS includes computer hardware and software as well as communication technologies to offer products and services that enhance transport safety and flow as well reduce emissions. Examples of ITS services are traffic signals and navigation. (EU 2010/40/EU)

Automated vehicle (AV), being part of ITS, can at least partially perform a driving task without human driver input. **Connected vehicle** can communicate with infrastructure (Vehicle to Infrastructure (V2I) or Infrastructure to Vehicle (I2V)), with other environment (Vehicle to Everything, V2X) or with other vehicles (Vehicle to Vehicle, V2V) using wireless communication technologies. **Autonomous vehicle** does not use communication technology, therefore is not a connected vehicle, but is able to perform a driving task without a human driver.

Cooperative Intelligent Transport Systems (C-ITS) means intelligent transport systems (ITS) that exchange real-time C-ITS messages with vehicles, other road users, infrastructure and other environment using trusted and secured communication. EU CCMS is the European Union C-ITS framework for trusted and secure C-ITS communication using Public Key Infrastructure (PKI).

C-ITS services mean ITS services provided using C-ITS. Examples of C-ITS services are road safety-related events or conditions such as temporary slippery road, unprotected accident area, short-term road works or exceptional weather conditions. C-Roads Platform defines C-ITS service as "a clustering of use cases based on a common denominator, for example, an objective such as awareness or a context like road works. Services are also known as ‛applications." (C-Roads WG2 TF2)

Difference between ITS and C-ITS: both offer similar services and features, for example safety related messages as mentioned in the previous paragraph. While Intelligent Transport Systems (ITS) focus on digital technologies providing intelligence placed at the roadside or in vehicles, C-ITS focuses on the communication between those systems – whether it is a vehicle communicating with another vehicle, with the infrastructure, or with other C-ITS systems. ITS services use different protocols such as RDS-TMC or DAB-TPEG.

In addition, C-ITS uses trusted and secured communication (using PKI) as well as V2V and V2X ad-hoc communication. Additionally, C-ITS station, hardware and software components to provision ITS service through C-ITS using wireless communication (see following chapters), also separates the usage of C-ITS and ITS. For example, a mobile device would require a (personal) C-ITS station to provision C-ITS services.

2.2 C-ITS actors and roles

C-ITS service operations require collaboration of several actors with different roles and responsibilities. Four top-level roles in the context of C-ITS have been defined in the ISO TS 17427-1 as presented in Figure 3 below.

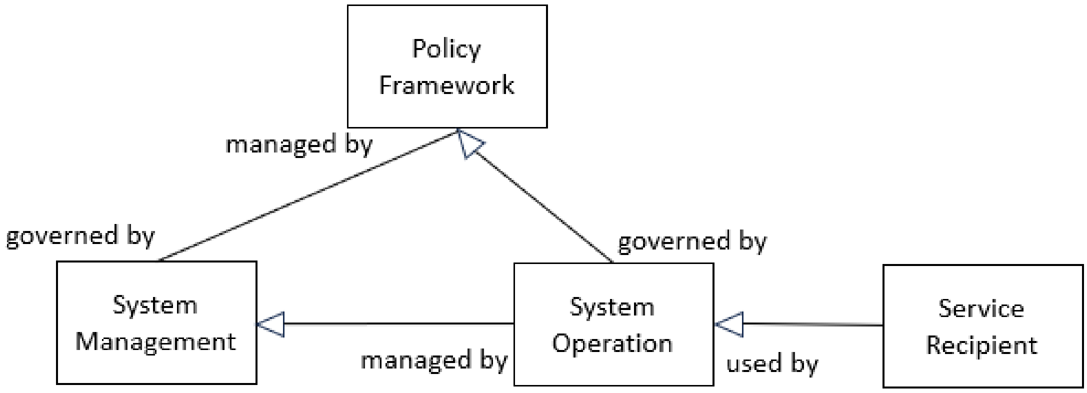


Figure 3. C-ITS roles and responsibilities adapted from ISO TS 17427-1.

C-ITS actors and roles are described in an unpublished C-Roads Platform WG1 C-ITS Organisation draft report titled as "Ecosystem for fully operational C-ITS service delivery – The infrastructure perspective" (2022) and C-Roads Platform 'Report on legal structures' (2018). Following roles are adapted from an unpublished report "Authorities' roles in implementation and operational use of C-ITS services in Finland" (Traficom, 2023).

Public Authorities roles includes government or other public administration operator, such as national, regional, local (e.g., municipality) or other person performing their legal duties. Tasks include policy decisions, funding, rules and legislation. Likely role in organizing and maintaining the C-ITS security infrastructure.

European Commission is the politically independent executive body of the European Union. Helps for example in C-ITS related research, implementation, investments, legislation and coordination. One of the most important is the delivery of security certificates for C-ITS services. Adoption of the European C-ITS strategy.

Infrastructure operators' roles are road operator, rail network operator, public transport rail network operator or a third party as a concessionaire on behalf of a public authority.

Component and equipment suppliers are companies that for example are manufacturing of equipment, materials, spare parts and components for C-ITS services.

Automotive actor's role includes Original Equipment Manufacturers (OEMs), i.e. mainly vehicle manufacturers. Tasks include manufacture vehicles that are equipped with the necessary communication and On-Board Unit (OBU) devices required by C-ITS services.

Mobile Network Operators are companies that own a mobile communications network (e.g., 4G and 5G), that provides a communication between vehicles and infrastructure, and a license to operate the network as an operator.

Service provider are third-party service providers, such as map producers and companies that provide telecommunications services as a service, offering access to for example road operators and equipment manufacturers to the data and geomessaging technologies needed to produce C-ITS services.

C-ITS service operators are organizations such as a road operator, an original equipment manufacturer or a third party such as a map manufacturer or an information traffic service provider that provides C-ITS services to an end user or another organization. Additionally, supporting and planning the platforms required by the services (e.g. cloud services).

National Access Point (NAP) and nominated body is a mechanism for accessing, exchanging and re-using traffic-related data, the requirements of which are part of the ITS directive for intelligent transport systems its delegated regulations. Possibly support and implement some C-ITS functions. Conformity is assessed by nominated bodies.

2.3 C-ITS technologies and standardisation

Cooperative Intelligent Transport Systems (C-ITS) are ITS that enable ITS users to exchange trusted and secured C-ITS messages. In Europe, C-ITS security and trust is ensured with EU C-ITS security credential management system.

C-ITS communication technologies include wireless communication of short-range direct communication, i.e., ad-hoc network, and long-range communication, such as existing mobile cellular network.

Short-range communication uses 5.9 GHz spectrum range, where for example following two technologies can be used: IEEE WLAN (802.11p), also known as ITS-G5 or DSRC (Dedicated Short-Range Communications), and 5G C-V2X Direct communication, using direct communications (PC5 and NR) and network communications (Uu) using 3GPP standards. (Garcia et al. 2021, 5GAA)

Long-range communication mainly uses cellular mobile network technologies (e.g., 4G/LTE and 5G). Long-range communication of C-ITS messages may utilise Internet Protocol (IP) and protocols used by cloud technologies.

C-ITS station is a set of hardware and software components used to provision of an ITS service through C-ITS using wireless communication. C-ITS station reference architecture, also known as ITS station in standardisation, is defined in the ETSI EN 302 665 and ISO 21217:2020 standards. Following four C-ITS station types, i.e., ITS sub-systems are defined (European Commission C/2019/1789, ETSI EN 302 665):

- vehicle C-ITS station (mobile), for example in cars and trucks,
- personal C-ITS station (mobile), for example in hand-held devices,
- central C-ITS station (fixed), which is part of a C-ITS central system,
- roadside C-ITS station (fixed), for example on poles.

Harmonised communication profile is required for the C-ITS service and message exchange. Communication profiles are based on the respective C-ITS standards. In Europe, C-Roads Platform has published harmonised C-ITS specifications. In addition, CAR 2 CAR Communication Consortium (C2C-CC) defines services for vehicles. (C-Roads News)

C-ITS messages are signed messages that are exchanged between C-ITS stations. They are defined by ETSI and ISO and profiled in the C-Roads. In C-Roads the following C-ITS messages are profiled: CAM, DENM, MAPEM, SPATEM, SREM, SSEM and IVIM. The data and format of these messages have been standardised to insure the interoperability across borders and different manufacturers. The messages enable data flow between C-ITS stations to implement C-ITS Services. MAPEM- and SPATEM –messages are originating from the roadside infrastructure and are used in Signalized Intersections -service. SREM- and SSEM –messages are used for vehicles to ask for priority in signalized intersection and to communicate the signal request status back to the vehicle. DENM-messages function is to communicate information about an event that has potential impact road safety or traffic condition. The purpose of the CAM-messages is to achieve cooperative awareness between road users. IVIM messages are Infrastructure to Vehicle Information Message that support road signage (static, variable, or virtual signs) such as contextual speeds and road works warnings. (C-Roads WG TF2 2022, ETSI TS 103 301 2018)

2.3.1 C-ITS architecture and deployment models

Setting up C-ITS services offer multiple implementation possibilities, e.g., communication technologies, and therefore different architectures have been proposed depending on pilots and implementations local requirements. EU EIP (2022) notes that the information chains of C-ITS data-ecosystems are complex as several different actors such as ITS roadside, vehicle, or central stations as well as Traffic Control Centre and National Access Point exists. Additionally, choice of system architecture and communication flows, e.g., NAP, cellular, ETSI ITS G5, have an impact.

C-ITS station reference architecture, as defined in the previous chapter, following ISO model principles of layered architecture is defined in the ETSI EN 302 665 standard. (ETSI EN 302 665)

Architecture and technology definitions for C-ITS implementation in Europe are supported by the C-Roads Platform harmonised communication profile. The C-Roads C-ITS deployment technical documentation and requirements includes reference architectures for ITS-G5 (IEEE WLAN, 802.11p) and IP-based technology (utilising mobile network). The latter including Central C-ITS station architecture for Basic Interface and evolved architecture for country/region information sharing. (C-Roads WG2 TF4, C-Roads Platform 2021)

Vehicle to Infrastructure (V2I) and Infrastructure to Vehicle (I2V) C-ITS communication covers communication channels from first, end user to (A) serving back-end or ITS-G5 roadside infrastructure and secondly, the final communication channel from there forward to another (B) serving back-end. The first service provisioning channel between end user and (A) serving back-end entity has a free choice of communication strategy, for example mobile network. The latter C-ITS communication as described in C-Roads specification is presented below in Figure 4. (C-Roads Platform TF4 version 2.0.5 2022).

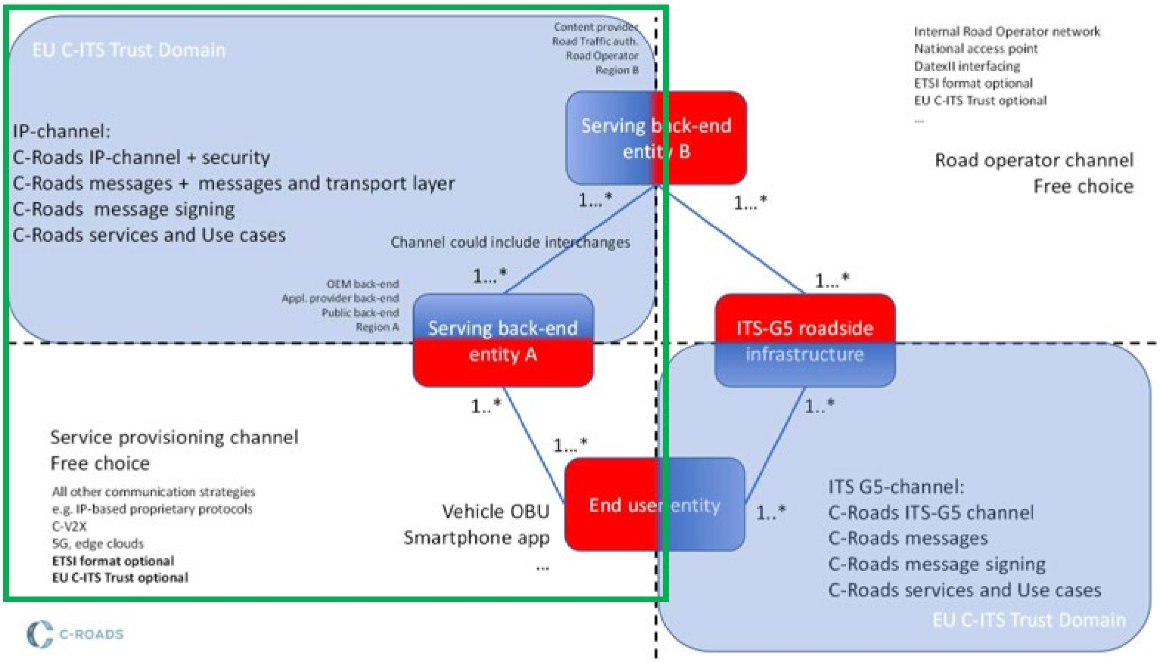


Figure 4. Overview of C-ITS communication where the added green rectangle shows scope of the study. The red colour indicates free choice of communication strategy and blue colour communication in the EU C-ITS Trust Domain. (C-Roads TF4 version 2.0.5 2022)

C-Roads Platform's European Union Member States C-ITS deployments and pilots each have different implementations depending on national requirements, though, following the C-Roads specifications. These different Member States and C-ITS actors deployment models, where communication is established through centralized (model B) or decentralized approach (model A) backend communication, are presented in the below Figure 5 according to C-Roads WG2 TF4 C-ITS Based Interface Profile (2022).

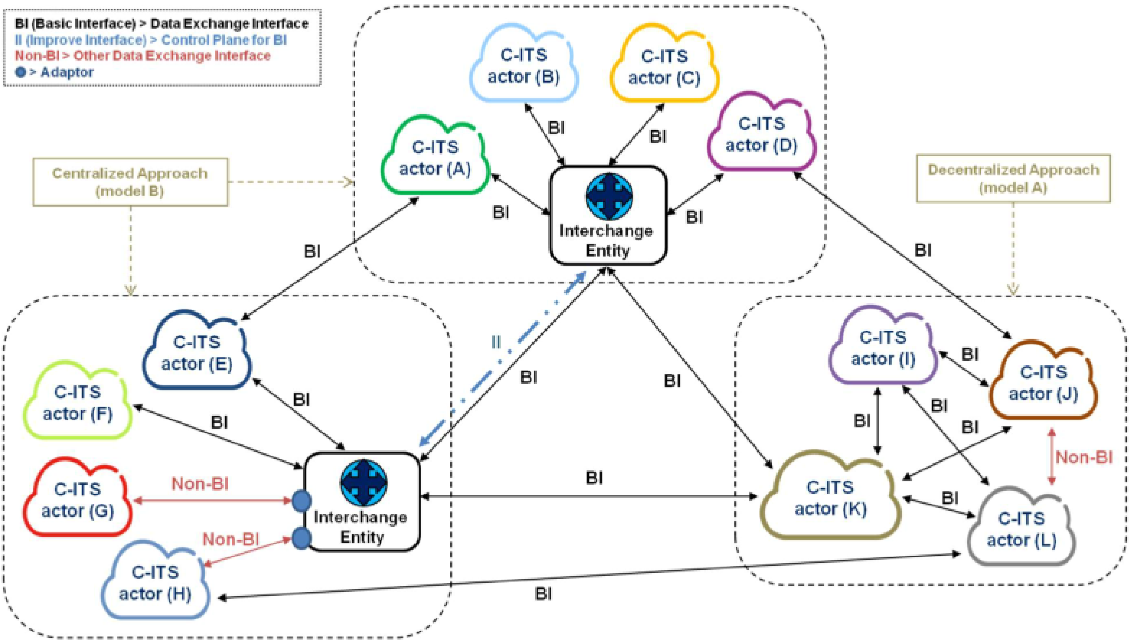


Figure 5. C-ITS deployment models (C-Roads TF4 2022)

2.3.2 C-ITS messages congestion control algorithms and mitigation techniques

Each C-ITS service is a unique service and each situation where the service is delivered to or from end user is unique in kind. Situational decisions of C-ITS service message provision may depend for example on service's message deliver frequency (Hz), message size (bytes or bits) known network coverage and road conditions.

C-ITS service provider may implement mitigation techniques and algorithms depending on service to ensure efficient delivery of service. Mitigation techniques are methods to reduce and minimise any negative impact in case of C-ITS communication network issues. For example, Road Works Warning messages might be downloaded and cached or stored to the system based on driving route or geographic area of the vehicle. In another example, Prove Vehicle Data (PVD) could be sent (upload) from vehicle in patches, or when change of speed.

Internet protocol (IPv4/IPv6) and Transmission Control Protocol (TCP), provide the end-to-end data communication between the C-ITS actors and interchange entities. Transmission Control Protocol (TCP) offers multiple mitigation techniques to correct errors and deal with duplicate or lost packets. For example, the protocol uses retransmission (after a timeout) to ensure delivery of every segment. Additionally, congestion control can be applied. These TCP mitigation techniques supports performance of the C-ITS service. (C-Roads TF4 2022, IETF 1981)

Upload data from vehicle to serving back-end can be reduce with different techniques, for example Collective Perception Message' (CPM) can aim to minimize the number of messages and number of objects in the messages, because not all vehicles are required to be involved in the creation of a comprehensive landscape picture. The aim is to have only one observation to reduce the amount of data transfer without additional benefits. The use of these techniques has been presented, e.g., in ETSI standards.

Download data from serving back-ends to vehicle can be reduced, e.g., static data, which has a long validity period, is download only when data is updated or only updated parts – not the entire material. Dynamic data, which has a short validity period, means that the data requires higher frequency of updates and thus downloaded more often, but also this regional limitation affects the amount of data sent. Location or area of location (geofence) and route information of the vehicle can influence the mitigation techniques selected.

V2X message distribution over mobile network has two different approaches according to 5GAA (2023): 'Digital Twin' and 'Geofenced':

- *Digital Twin* approach assumes V2X service provider to have real-time knowledge of each vehicle's location, after which targeted data for the vehicle and end user can be provided.
- *Geofenced* approach assumes V2X service provider to have knowledge of the vehicle position of a vehicle in defined fixed area. Therefore, all information in the area of relevance is send to the vehicle. This leads mostly likely to a larger

amount of data sent. Area of relevance can be generated through geofencing model 'geohashing'.

There are other methods available for C-ITS services message distribution, which all depend on service, service provider software and made decisions to use mitigation techniques. All actors, or at least most in C-ITS benefit reduction of data transfer.

2.4 Regulation of C-ITS

ITS directive (2010/40/EU) is a framework directive that supports coordinated and coherent deployment and use of Intelligent Transport Systems (ITS) in the European Union across Member States borders. ITS directive enables European Commission possibility to adopt delegated acts for the directive's priority actions. The ITS directive applies to road transport ITS applications and services as well as their interfaces with other modes of transport. One of the four ITS directive priority areas IV Linking the vehicle with the transport infrastructure relates to C-ITS services. European Commission has proposed in 2021 to renew the 2010/40/EU ITS directive.

European Commission adopted delegated act for C-ITS in 2019, but the Council of the European Union objected to the regulation, and it did not enter in force. Possible preparation of a C-ITS delegated act has not been announced by the date of this report. (European Commission C/2019/1789)

ITS directive (2010/40/EU) defines following priority actions (a-f), which of European Commission has adopted delegated acts for actions a-e:

a) the provision of EU-wide multimodal travel information services;

b) the provision of EU-wide real-time traffic information services;

c) data and procedures for the provision, where possible, of road safety related minimum universal traffic information free of charge to users;

d) the harmonised provision for an interoperable EU-wide eCall;

e) the provision of information services for safe and secure parking places for trucks and commercial vehicles;

f) the provision of reservation services for safe and secure parking places for trucks and commercial vehicles.

Delegated acts

According to the Finnish Transport and Communication Authority Traficom funded study of "Authorities' roles in implementation and operational use of C-ITS services in Finland", where ITS directive and its delegated acts legislation was analysed, the following ITS directive priority actions b and c delegated acts would have implication to C-ITS services as they are mentioned in the draft C-ITS delegated act of 2019 (Kotilainen et al. 2024, European Commission C/2019/1789):

- Priority action b delegated acts: Provision of EU-wide real-time traffic information services (EU 2015/962, EU 2022/670)

- Priority action c delegated act: Data and procedures for the provision, where possible, of road safety-related minimum universal traffic information free of charge to users (EU No 886/2013)

The three above mentioned delegated acts (EU 2015/962, EU 2022/670 and EU No 886/2013) include regulation related to C-ITS such as how to share data through National Access Points (NAP), data formats and standards. Many of the ITS services mentioned in the delegated acts are also found among the C-ITS services defined in Europe (see Part A chapter 3.3).

Other legislation

Furthermore, according to the Traficom (2023) study, for example, following European and national legislation areas relate to C-ITS services: radio equipment, market surveillance and information security and protection, motor vehicles type approval, cyber security, road, and street network as well as land use.

3 C-ITS services

The aim of this chapter is to study available and developed C-ITS services. The main focus is on services available in Europe. Following subchapters review C-ITS services from the perspective of:

1. European strategies and studies,
2. specifications,
3. legislation,
4. road transport automation,
5. status in Finland (and Nordic Region) and
6. other mobile network use cases.

The final subchapter will summarise the findings of the above subchapters and give recommendations for the selection of C-ITS services for further analysis in the study when evaluating utilisation of mobile networks.

3.1 European strategy and studies on C-ITS services

European Commission supported deployment of connected driving by setting up a C-ITS Deployment Platform from 2014 to 2016. The aim of the platform was to develop a shared vision on the interoperable deployment of C-ITS in Europe. Platform members included national authorities, C-ITS stakeholders and the Commission. The platform's results report included a common technical framework and a list of Day 1 (C-ITS) services. Second phase of the platform further developed a shared vision of C-ITS between 2016 and 2017. (European Commission CCAM, C-ITS Platform, C-ITS Platform phase II)

The European Commission published in 2016 a European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility. The C-ITS strategy proposes specific action based on the C-ITS Platform recommendations. One of the actions was "Priorities for deployment of C-ITS Services". Continuity of service was highlighted as the most important factor, i.e., to have interoperable C-ITS services widely available across Member State borders. (European Commission COM(2016) 766)

The European C-ITS strategy refers to C-ITS Platform cost benefits analysis and a list of technologically mature and highly beneficial C-ITS services, defined as Day 1 C-ITS services, that should be prioritised for the deployment and fully supported by Member States, authorities and private industry. Additionally, during public consultation of the strategy, respondents also agreed to include in a second phase Day 1.5 C-ITS services list, which were considered to be generally mature for deployment. (European Commission COM(2016) 766)

Table 6 and Table 7 below present the European C-ITS strategy Day 1 and 1.5 C-ITS services list originally defined in the C-ITS Platform (2016). The list is included with vehicle communication (V2V, V2I and V2X) and primary purpose of the service / geographic coverage criteria as defined in the C-ITS Platform (2016) cost benefit analysis.

Table 6. Day 1 C-ITS services list (European Commission COM(2016) 766, C-ITS Platform 2016).

Day 1 C-ITS services list	Com-muni-cation	Primary purpose of the service / geographic di-mension
Hazardous location notifications:		
Slow or stationary vehicle(s) & traffic ahead warn-ing	V2V	Safety
Road works warning	V2I	Motorway
Weather conditions	V2I	Motorway
Emergency brake light	V2V	Safety
Emergency vehicle approaching	V2V	Safety
Other hazards	V2I	Motorway
Signage applications:		
In-vehicle signage	V2I	Motorway
In-vehicle speed limits	V2I	Motorway
Signal violation / intersection safety	V2I	Urban
Traffic signal priority request by designated vehicles	V2I	Urban
Green light optimal speed advisory	V2I	Urban
Probe vehicle data	V2I	Motorway
Shockwave damping (falls under European Tele-communication Standards Institute (ETSI) category 'local hazard warning').	V2I	Motorway

Table 7. Day 1.5 C-ITS services list (European Commission COM(2016) 766, C-ITS Plat-form 2016).

Day 1.5 C-ITS services list	Com-muni-cation	Primary purpose of the service / geographic di-mension
Information on fuelling & charging stations for al-ternative fuel vehicles	V2I	Smart Routing
Vulnerable road user protection	V2X	VRU
On street parking management & information	V2I	Parking
Off street parking information	V2I	Parking
Park & ride information	V2I	Parking
Connected & cooperative navigation into and out of the city (first and last mile, parking, route advice, coordinated traffic lights)		–
Traffic information & smart routing	V2I	Smart Routing

3.2 C-Roads Platform and C2C-CC – European specifications for C-ITS service

C-Roads Platform was established in 2015 and co-funded by the European Union Connecting Europe Facility (EU CEF). The platform is a joint initiative of European Member States and road operators for testing and implementing interoperable C-ITS services for European road users. C-Roads Steering Committee, which approves the C-Roads specifications, consist of Member State representatives. C-Roads Platform core and associate members agree to follow C-Roads Platform specifications. Finland is a core member of C-Roads.

CAR 2 CAR Communication Consortium (C2C-CC) does research and development of C-ITS solutions. The consortium members include European and international vehicle manufacturers, equipment suppliers, engineering companies, road operators and research institutions. The objective of the consortium is to "contribute to European and International standardisation and harmonisation activities for development of technical specifications, required for Cooperative Intelligent Transport System (C-ITS) including V2X communication." C2C-CC developed Basic System Profile has been harmonised with the complementing C-Roads specification for road infrastructure.

C-Roads Platform activities on specifications and definitions of C-ITS is performed by the working groups. All C-Roads specifications follow C-ITS standards (see Part A chapter 2.3). Working Group 2 Technical Aspects and its Task Force 2 Service Harmonisation is responsible for understanding the C-ITS Day 1 services functionality. C-ITS services defined by the C-Roads WG2 TF2 specifications of services and use cases is presented in Table 8. C-Roads Platform specifications are used in the European C-ITS deployment and pilot projects.

Table 8. C-ITS services defined in the C-Roads specifications version 2.0.5 (C-Roads WG2). C-ITS message type and Communication type columns abbreviations have been introduced in chapter 2. Verv2V = Emergency or Rescue/Recovery vehicle to vehicle, Vpr2V = Public Transport Vehicle to Vehicle communication; information exchange between public transport vehicles and other vehicles, Vro2V = Road operator vehicle to vehicle; information exchange between road operator vehicles and other vehicles. (C-Roads WG2 TF2)

Day 1.5 C-ITS services list	C-ITS message	Communication type
In-Vehicle Signage (IVS)		
Traffic Signs (IVS-TS)	IVIM	I2V
Free Text (IVS-FT)	IVIM	I2V
Hazardous Locations Notification (HLN)		
Accident Zone (HLN-AZ)	DENM	I2V
Traffic Jam Ahead (HLN-TJA)	DENM	I2V
Stationary vehicle (HLN - SV)	DENM	I2V
Weather Condition Warning (HLN-WCW)	DENM	I2V
Temporarily slippery road (HLN-TSR)	DENM	I2V
Animal or person on the road (HLN-APR)	DENM	I2V
Obstacle on the road (HLN-OR)	DENM	I2V
Emergency or Rescue/Recovery Vehicle in Intervention (HLN-ERVI)	DENM	Verv2V
Emergency or Prioritized Vehicle Approaching (HLN-EPVA)	DENM	Verv2V
Railway Level Crossing (HLN-RLX)	DENM	I2V
Unsecured Blockage of a Road (HLN-UBR)	DENM	I2V
Alert Wrong Way Driving (HLN-AWWD)	DENM	I2V
Public Transport Vehicle Crossing (HLN-PTVC)	DENM	Vpt2V
Public Transport Vehicle at a Stop (HLN-PTVS)	DENM	Vpt2V
Road Works Warning (RWW)		
Lane closure (and other restrictions) (RWW-LC)	DENM	I2V
Road Closure (RWW – RC)	DENM	I2V
Road Works Mobile (RWW-RM)	DENM	I2V

Winter Maintenance (RWW-WM)	DENM	Vro2V
Signalized Intersections (SI)		
Signal Phase and Timing Information (SI-SPTI)	SPATEM, MAPEM	I2V
Green Light Optimal Speed Advisory (SI-GLOSA)	SPATEM, MAPEM	I2V
Imminent Signal Violation Warning (SI-ISVW)	SPATEM, MAPEM	I2V
Traffic Light Prioritisation (SI-TLP)	SSEM, SREM	I2V, V2I
Emergency Vehicle Priority (SI-EVP)	SSEM, SREM	I2V, V2I
Automated Vehicle Guidance (AVG)		
SAE Level Guidance (AVG-SAELG)	IVIM	I2V
Platoon Support Information (AVG-PSI)	IVIM	I2V
Probe Vehicle Data (PVD)		
Vehicle Data Collection (PVD-VDC)	CAM	V2I
Event Data Collection (PVD-EDC)	DENM	V2I

3.3 Legislation related to C-ITS services

As mentioned in the previous Part A chapter 2.4 “Regulation of C-ITS”, at the time of writing this report there was no direct regulation for C-ITS and therefore no regulation that would mandate C-ITS services. The draft C-ITS delegated act (not in force) states that the Member State would choose independently part of road infrastructure where to implement C-ITS stations, while no obligation to implement specific C-ITS services is given (European Commission C/2019/1789).

Following delegated acts on road safety-related traffic information and real-time traffic information services were identified in the Part A chapter 2.4 “Regulation of C-ITS” relevant for C-ITS. Therefore, the delegated acts are analysed below for any relevance to C-ITS services.

Delegated act (EU) No 886/2013 on road safety-related minimum universal traffic information concerns “road safety-related traffic data, offered by public and/or private road operators and/or service providers to end users through any delivery channels.” As C-ITS services aim to enhance road safety, C-ITS can be one of the delivery channels for safety-related traffic information. Following safety-related traffic information event and condition categories are found in the delegated act EU No 886/2013 article 3:

a) temporary slippery road;

b) animal, people, obstacles, debris on the road;

c) unprotected accident area;

d) short-term road works;

e) reduced visibility;

f) wrong-way driver;

g) unmanaged blockage of a road;

h) exceptional weather conditions.

Delegated act EU 2015/962 and the renewed EU 2022/670 of real-time traffic information services have similarities in their data categories, although new data categories have been introduced in the latter. Following Figure 6 introduces one comparison of the RTTI delegated acts data types according to NAPCORE (2023).

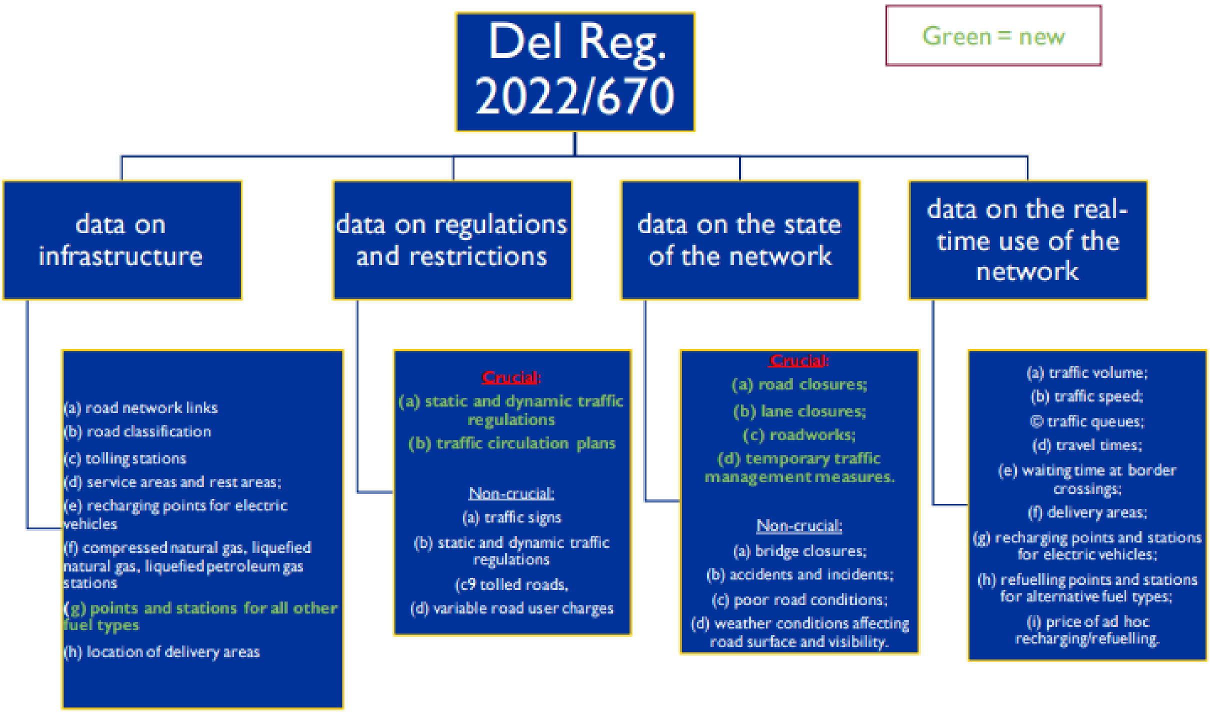


Figure 6. Comparison of the real-time traffic information services delegated acts (EU 2015/962 and EU 2022/670) data categories. Green colour marks new data categories introduced in the 2022 act. (NAPCORE Veenendaal 2023)

3.4 Road transport automation C-ITS services

C-ITS services can extend the vehicle electronic horizon for automated vehicles by providing important source of information beyond the range of the vehicle's own sensors and support the making of highly automated decisions. C-Roads has specified in their service and use case definitions Automated Vehicle Guidance (AVG) C-ITS service and clustered road transport automation related use cases under this service. At the moment of writing there are two AVG use cases defined in C-Roads. These are SAE Level Guidance and Platoon support for automated vehicles.

In Automated Vehicle Guidance (AVG) service, the guidance can be for certain types of traffic conditions of road networks, but also for specific vehicle types. The guidance can range from simple guidance for a specific road segment or lane to recommendations for high level automated vehicles. This supports the introduction of automated vehicles into the traffic and helps the vehicles to operate in traffic conditions where most of the traffic is not yet automated.

The SAE Level Guidance use case allows road operators to provide information on what SAE automation levels they consider unfit for partly automated vehicles on certain road or lane segments. This guidance is based on overall road conditions and traffic situation. The vehicle will process the guidance information as additional information, and this can result in an increase or decrease of functionalities required from the vehicle and increase or decrease what is required from the driver. This guidance is expected to improve efficiency of traffic flows as well as road safety. C-Roads has defined IVIM-message as the C-ITS message to be used in this use case.

The platoon support information use case is aimed for C-ITS capable automated vehicles that want to drive in platoon. The road operator provides information on the unsuitability for platoon driving on a specific road or lane segment. This information can be based on different vehicle types, road conditions and the traffic situation. The platoon itself can consist of trucks as well as cars and it can be type specific or of mixed vehicle type. Information is provided as additional information for vehicles entering platooning situations. The use case might differ in national implementations due to differences in legal framework in individual member states. Some might limit platooning to certain vehicle types or environments only.

3.4.1 Remote operation

Remote operation, or remote management and teleoperation, of highly automated vehicles is a possible solution for dealing with situations where the SAE Level 4 automated driving system is losing or has lost its Operational Design Domain (ODD). According to UNECE (2023) remote management "refers to the activities that aim to manage one or more automated vehicles which do not have a responsible human inside… it is possible that any humans in the vehicle will be passengers only." The key issues are safety and liability for the safe operation of vehicles. In recent congresses, remote operation or rather supervision capabilities have been discussed looking at how, together with automated driving systems, they could accelerate the deployment of highly automated vehicles (SAE 4) on public roads for smart mobility and ITS services. Experts had already developed smart procedures on handling the remote assistance in selected ODD departure cases.

A new role of "technical supervisor" has been proposed to deal with such remote assistance situations in practice. The technical supervisor provides assistance to the automated driving system, which then decides on how to proceed with the automated driving task based on the information at its disposal including the assistance from the technical supervisor. (Sampson, et al. 2023)

In any case, much regulatory work needed to be done to ensure efficient remote assistance of highly automated driving systems. The concepts of remote assistance used in aviation have been found usable and some companies have been providing remote operation as a service. (Sampson, et al. 2023)

3.4.2 Cooperative awareness and collective perception

One of the main challenges for large-scale deployment of automated driving is the insufficient environmental and situational awareness of the vehicles. Environmental and situational awareness are needed for the vehicles to operate safely and comfortably. V2X (Vehicle-to-everything) communication enables vehicles to share information about their state and surroundings and this way improve their environmental perception and decision-making capabilities. **Cooperative awareness** and **collective perception** are examples of V2X applications that are considered some of the main enabling technologies for automated vehicles (Schiegg et al., 2021).

Cooperative awareness allows vehicles to transmit data about their state and this service is standardized in Europe by ETSI (2019a). Data is transmitted via Cooperative Awareness Messages (CAMs) and vehicles transmit these messages continuously with a variable frequency between 1 and 10 Hz, depending on the variation of their dynamic state (i.e., current heading, position, and speed) and the measured channel load. CAMs can also include attribute information about the vehicle specific data, such as dimensions, vehicle type and role in the road traffic.

CAM generation and message size
According to rules defined in ETSI standard CAMs should be generated every 100ms to 1s, which means that CAM messages are transmitted between one to ten times per second. In addition to the time constraint, there are also triggering conditions related to the changes with the vehicles' dynamic state. A change in position by more than 4m, change of speed equal to or larger than 0,5m/sec and change of direction of equal or more than +/- 4° will all lead to the CAM generation (CAR 2 CAR Communication Consortium, 2018).

CAR 2 CAR Communication Consortium (2018) has conducted a study collecting real test-drive data to estimate the size and time-interval of CAM message generation. Their study concludes that CAM size is not static but rather depends on the attributes included to the message as well as on the inclusion of the security content like signatures and certificates. Therefore, CAM size typically varies between around 200 Bytes and up to 800 Bytes depending on the message content, the average size of CAM being around 350 Bytes.

Collective perception allows vehicles to transmit data detected by their object tracking sensors (such as object distance, speed, and acceleration) and this data is exchanged via Collective Perception Messages (CPMs). This service is standardized in Europe by ETSI TS 103 324 (ETSI 2023). Similarly, to the CAMs, CPMs are to be generated with a frequency between 1 – 10 Hz, and the maximum number of objects, which could be included into one message, is 128. The content of a CPM may vary depending on the situation and the detection capabilities of a vehicle, but it consists of a set of perceived objects and regions, along with their observed status and attributes. The availability of CPMs offers multiple sources of information about objects and unoccupied regions that leads to lower uncertainty about surrounding objects and their properties. The CPMs can also be transmitted by infrastructure sensor systems, for instance to provide warnings/information about approaching vulnerable road users or non-C-ITS vehicles to vehicles approaching urban junctions with restricted visibility. The CPMs will likely be event triggered in most cases. CPMs can be utilised in production of HD maps when aggregated together with other data sources and map layers (5GAA 2023).

Evaluation of the size of the CPM
Klöppel-Gersdorf & Otto (2021) evaluated the required message size for CPMs in test setup by implementing two scenarios. In the first scenario, all optional fields for a CPM message were filled with data leading to a storage requirement of

61.25 Byte or 490 Bits in total per object. In the second scenario, only data currently available in the given test vehicle was considered, leading in total to a storage requirement of 30.125 Byte or 241 Bits per object (which is less than half of the requirements for the first scenario). The second scenario represents the expected near to mid future development regarding CPMs better. In their test setup Klöppel-Gersdorf & Otto were able to detect a maximum of 29 objects in urban arterial roads (leading to a message size of 1777 bytes in scenario 1 and 874 bytes in scenario 2) and 14 objects in residential area roads (leading to a message size of 858 bytes in scenario 1 and 422 bytes in scenario 2).

While both articles by Schiegg et al. (2021) as well as Klöppel-Gersdorf & Otto (2021) recognize the benefits of utilizing CPMs they also bring up the additional resources that CPMs demand, hence increasing the channel load for the communication network. Schiegg et al. (2021) proposes to use *message size*, *channel busy ratio (CBR)*, and *packet delivery ratio (PDR)* as network-related evaluation metrics. *Message size and frequency* are two of most straightforward metrics to describe the load for the communication network. *Channel busy ratio (CBR)* is also a common metric to evaluate the load caused by communicating V2X stations and it represents the fraction of time the channel is perceived as busy (which in turn depends on the message sizes and frequencies). *Packet delivery ratio (PDR)* in turn represents the probability of receiving a certain packet, typically in dependence of the CBR and the distance between the transmitting and receiving station (also packet error rate can be utilized to measure same case).

The dynamic selection of the objects that are included in each CPM reduces the message size while performing similarly to static rules in terms of inter-object update times. The dynamic generation rules take into account the vehicles' dynamics and is more scalable than the periodic approaches that include all the perceived objects in all CPMs. As a result, the dynamic generation rules reduce the channel load generated compared to a periodic solution operating at 10 Hz, especially when considering the mechanism to reduce the CPM frequency (this mechanism can both reduce the channel load generated and improve the awareness). Although the periodic approach is able to outperform the dynamic generation rules proposed in terms of awareness, it comes at the cost of significantly higher channel load. The results obtained have also demonstrated a high impact of the range and field of view of the local sensors on the channel load generated and awareness levels observed. (ETSI 2019b) It is evident that in cases involving high accident risks (such as C-ITS-unequipped vehicle not visible to C-ITS vehicle sensors approaching a junction at high speed) the infrastructure sensor should send the CPM at 10 Hz.

3.5 Road operators and industry priorities

C-Roads Day 1 and 1.5 services also contain road authority and operator as well as industry priority services as these have been selected in a pan-European process.

In 5GAA reports, C-ITS use cases are mapped according to communication/V2X service provider network strategies. Selected four use cases represented good overall representation of the Road Operators’ expectations according to research interviews. The use cases were selected according to data demand on the radio cell/sector (uplink and downlink). (5GAA 2023)

- Local hazard and traffic information (LHTI)
- Green light optimal speed advisory (GLOSA)
- HD maps data collection and sharing (HD Maps)
- Probe vehicle data (PVD)

Probe vehicle data (PVD) collection as well as local hazard and traffic information (LHTI) services are already provided as non-C-ITS services. HD maps data collection and sharing is also being carried out today by digital map providers. GLOSA is also provided as a very C-ITS like service. In total, three of the four services have been specified as C-ITS services, i.e., LHTI, GLOSA and PVD.

The HD maps will provide huge amounts of data communication, and often only safety relevant anomalies included in HD maps will require quick transmission to road users as C-ITS messages, which means that HD maps service will likely be provided as a non-C-ITS service. HD map object information is collected via data communication on multiple 'layers' depending on type of information, while sources of information include probes, satellite imagery, road operator data, sensor data (5GAA 2023). The safety relevant objects or anomalies in HD maps detected by the vehicles via their sensors can be provided by the collective perception service as CPMs, i.e., CPM information can be part of the creation of HD map, depending on service provider map creation process.

3.6 C-ITS services status and results in Finland

This chapter outlines the European Union (EU) co-funded C-ITS pilots in Finland where Finland as a Member State, Finnish road authorities and operators have taken part together with the industry. Other smaller C-ITS testing, trials and pilots conducted by the cities or industry, are not reviewed here.

Finland has been a part of the EU CEF co-funded NordicWay (2015–2017), NordicWay 2 (2017–2020) and NordicWay 3 (2019–2023) C-ITS pilot projects. The NordicWay projects are a collaboration between public and private partners in Finland, Norway, Sweden and Denmark. The most recent NordicWay 3 project and Nordic countries mentioned are also part of C-Roads Platform, therefore, using C-Roads specifications. The NordicWay projects' results include e.g. demonstration of C-ITS services interoperability across Nordic countries borders and technical evaluation of the quality of services. (NordicWay)

NordicWay pilot project's Finnish evaluation study found direct safety impact, i.e., reduction in traffic accidents, travel efficiency and benefits to the traffic management, especially from warnings of slipperiness and animals or people on the road services. (NordicWay Evaluation Outcome Report)

The piloted NordicWay 2 C-ITS services use cases (2017–2020) and their corresponding C-Roads Platform services in Finland, Norway and Sweden are presented in Table 9 below.

Table 9. Piloted NordicWay 2 C-ITS services use cases and corresponding C-Roads services in Finland, Norway and Sweden. (Innamaa, et al. 2020).

	C-ROADS SERVICES	NORDICWAY 2 USE CASES	FI	NO	SE
Day-1 services	IVS	In-vehicle speed limit	x	x	-
	Hazardous location notifications (HLN)	Weather and road condition	x	x	-
		Slow or stationary vehicle	x	x	-
		Emergency vehicle approaching	-	-	x
		Traffic ahead warning	x	x	-
		Emergency brake light	-	x	-
		Cooperative collision warning	-	x	-
	Road works warning (RWW)	Road and lane closure	x	x	-
		Mobile roadworks	-	x	x
	Signalised intersections (SI)	Signal violation / intersection safety	-	x	-
		Time to green	-	-	x
		Green light optimal speed advisory (GLOSA)	-	x	x
		Traffic signal priority request	-	-	x
	PVD	Single vehicle data	x	x	-
Day-1.5 services	Traffic management	Traffic information & smart routing	x	x	-
		On-street parking information and management	-	x	-
		Information on alternative fuel vehicle fuelling & charging stations	-	x	-
	CAD	Data collection for mapping of infrastructure readiness	-	x	-
	CCN in and out of the city	Dynamic access control of designated infrastructure	-	-	x
	Dynamically controlled zones	Dynamic environmental zone	-	-	x

The NordicWay 2 Evaluation results (Innamaa et al. 2020) indicate largest direct safety effects for in-vehicle speed limits, emergency brake lights, and slow/stationary vehicle and traffic ahead warnings. Indirect safety impacts magnitude was hard to estimate.

In the NordicWay 3 pilot project, the Nordic countries have common flagship pilots that are coordinated C-ITS pilots with mature technology and with full cross-border functionality. The four flagship pilots are

1. Traffic Signals,
2. Dynamic Zones,
3. Emergency Vehicle Warnings and
4. Road Works Warning. (NordicWay 2023)

At the time of this study in 2023 there were multiple NordicWay 3 C-ITS pilots ongoing in Finland, mainly in the Tampere city region. Objective in these pilots was to have pilot deployments to develop interoperable and harmonized C-ITS services in Finland (C-Roads, 2023). These pilots mostly focus on C-ITS services in urban scenarios and are closely linked together.

The data exchanged in the Finnish C-ITS pilots in city of Tampere was mostly Signalised Intersections C-ITS service with SPAT and MAP -messages. Already in Tampere there were around 780 000 C-ITS messages exchanged daily. These messages were originating from C-ITS capable traffic light controllers in the city's street network.

Communication in the pilots was done utilising existing mobile networks all the way from the roadside infrastructure to the backend systems and the vehicle. However, in one of the pilots there was also work done to evaluate direct communication trough LTE-V2X (C-V2X) as communication was done using a roadside unit installed in city of Tampere and an onboard unit retrofitted to a vehicle.

One of the ongoing C-ITS pilot activities in Finland was focusing on EU CCMS and the goal was to implement and test fully C-Roads compliant C-ITS service that also incorporates the cyber security aspects of the C-ITS.

To connect Finnish C-ITS ecosystem to other Nordic countries there was also a project to set up a Finnish Interchange node as a part of the federated Nordic interchange network. The interchange node operator was connected to the National Access Point (NAP) as well as to the already existing node of the city of Tampere.

3.7 Other use cases utilising mobile network in road transport

As transport related use cases will become more common and rely more on mobile network, there are also other use cases utilizing the same network. Especially entertainment and remote work-related applications are considerable use case when considering the data requirements for the mobile network.

As Table 10 indicates, video streaming, online gaming and video calls require big amounts of data to be transmitted. Streaming services can utilize a buffering feature to mitigate the load for the network, but for example, video calls and remote supervision of vehicles require data to be transmitted in real-time. Entertainment and remote work-related use cases can be expected to become more common when the autopilot features of vehicles develop and release more time for the human driver from the dynamic driving tasks.

Additionally, public transportation vehicles, such as busses and trains, can cause a heavy load locally when multiple passengers are video streaming, and the load is directed to a single cell of mobile network. Less data demanding but still very common use cases are also music streaming, internet browsing and usage of social media services (Eloranta et. al, 2020).

Table 10. Typical entertainment use cases and their average demand for data transfer.

Use case	**Download speed**	**Upload speed**	**Recommended latency**
High-resolution audio	320 kbit/s	160 kbit/s	< 150 ms
Internet browsing	3 Mbit/s	0,5 Mbit/s	< 150 ms
Social media	1,5 Mbit/s	0,5 Mbit/s	< 150 ms
HD-video (60 fps)	5 Mbit/s	0,5 Mbit/s	< 150 ms
FHD-video (60 fps)	10 Mbit/s	0,5 Mbit/s	< 150 ms
4K-video (60 fps)	25 Mbit/s	0,5 Mbit/s	< 150 ms
8K-video (60 fps)	>80 Mbit/s	0,5 Mbit/s	< 150 ms
Online gaming	>5 Mbit/s	1 Mbit/s	< 30 ms
Audio call (Teams, Zoom)	0,5 Mbit/s	0,5 Mbit/s	< 50 ms
Video call (Teams, Zoom)	1,2 Mbit/s	1,2 Mbit/s	< 50 ms
Group video call (more than 7 persons, Teams, Zoom)	8 Mbit/s	512 kbit/s	< 50 ms
VR & AR (low resolution)	20-50 Mbit/s	20-50 Mbit/s	< 40 ms
VR & AR (high resolution)	200-1000 Mbit/s	200-1000 Mbit/s	< 10 ms

3.8 Summary and recommendations of the C-ITS services for analysis

Based on the literature review, European and Finnish national/local strategies as well as cost-benefit requirements, the following summary and recommendations are given.

European Commission strategy and study results of C-ITS services: according to the European Commission strategy and evaluation study, Day 1 and Day 1.5 C-ITS services should be prioritised for the deployment and fully supported by Member States.

C-ITS services European pilot projects, deployments and specifications: C-Roads Platform, an umbrella for the European C-ITS pilot projects and deployment, specifications include C-ITS Day 1 and Day 1.5 messages supported in the European Commission strategy.

Legislation of C-ITS services: there is no mandating legislation about C-ITS services implementation at the time of study. ITS directive (EU 2010/40/EU) delegated act (EU) No 886/2013 on safety-related traffic information include event and condition categories which are similar to the Day 1 services list in the European C-ITS strategy.

Road Transport automation C-ITS services include several advanced use cases, such as Cooperative Perception Messages (CPM) and remote operation, that are more future-oriented C-ITS services; services maturity and adaptation was still low at the time of this study.

Services piloted in Finland: Finnish authorities and industry have piloted C-ITS services in the NordicWay projects between 2015–2023. Several Day 1 messages have been included in the pilots and evaluation results indicating direct safety impacts for selected messages. At the time of the report, Signalised Intersections were piloted in the city of Tampere, Finland.

Other use cases utilising mobile network are not related to C-ITS services but offer a possibility for comparison with C-ITS services performance.

Strategic criteria

The strategic criteria include current European legislation, European C-ITS strategy, European C-ITS services harmonisation by C-Roads, and pilot results by Finland and other Nordic countries.

1. *Strategy and legislation*: Day 1 and Day 1.5 messages, supported by the European strategy and legislation. Day 1 and 1.5 services are the most mature piloted services in Europe including Finland and the other Nordic countries (NordicWay projects, e.g., NordicWay 3 flagship pilots) with already existing C-Roads Platform specifications.

2. *Needs in Finland*: Selection of services depending on the expected safety impact and ongoing piloting in Finland (e.g., Signalised Intersections).

Technical criteria

The technical criteria include the analysis of the C-ITS message type, the mobile network transmission type, and the C-ITS service use case impact on mobile network.

3. *C-ITS message type*: DENM and CAM messages for comparison.

4. *Logic of transmission*: Infrastructure to Vehicle (I2V) (or downlink) and Vehicle to Infrastructure (V2I) (or uplink). Therefore, V2V and V2X with VRU communications are excluded. Communication technology requirement in the study is mobile network, for example 4G/LTE or 5G technology.

5. C-ITS service use case impact on the use of mobile network communication, e.g., additional latency and update frequency requirements, analysed together with metrics and KPIs.

Automated driving and other use case criteria

6. Automated vehicles can receive safety benefits from C-ITS services similarly as the human driver. Automated driving related ITS services, such as HD maps, are mostly not realised by C-ITS services. The notable exceptions include CAM and Collective Perception (CPM) as well as some IVIM services, which utilise C-ITS messages.

Table 11 below presents a list of C-Roads Platform C-ITS services and use cases, as defined in the respective specifications, and analysis based on the above selection criteria.

Table 11. C-ITS services list based on C-Roads Platform TF2 specifications (v2.0.5 2022) and additional Collective Perception Service (CPS, not part of C-Roads). Colour coding according to selection criteria presented in the chapter: red colours indicate services excluded from the study as out of scope, green colour services selected for further analysis, and black colour as not selected, but similarities with the selected (green colour) services.

C-ITS service selection criteria / Day 1 and 1.5 C-ITS services list	(1) Strategy: Day 1/1.5	(2) Strategy: Needs in Finland	(3) Tech: C-ITS message type	(4) Tech: Logic of transmission	Analysis summary with (5) tech and (6) automated driving criteria
In-Vehicle Signage (IVS)					
Traffic Signs (IVS-TS)	Day 1	Pilots	IVIM	I2V	Separate planning and studies in Finland (Kulmala et al. 2020, Kilpiö et al. 2022)
Free Text (IVS-FT)	Day 1	not incl.	IVIM	I2V	Not piloted in Finland
Hazardous Locations Notification (HLN)					
Accident Zone (HLN-AZ)	Day 1	Pilots	DENM	I2V	–
Traffic Jam Ahead (HLN-TJA)	Day 1	Pilots	DENM	I2V	–
Stationary vehicle (HLN - SV)	Day 1	Pilots	DENM	I2V	–
Weather Condition Warning (HLN-WCW)	Day 1	Pilots	DENM	I2V	–
Temporarily slippery road (HLN-TSR)	Day 1	Eval.	DENM	I2V	Safety benefits in Finland. More dynamic event than other HLN (technical criteria).
Animal or person on the road (HLN-APR)	Day 1	Eval.	DENM	I2V	–
Obstacle on the road (HLN-OR)	Day 1	not incl.	DENM	I2V	–
Emergency or Rescue/Recovery Vehicle in Intervention (HLN-ERVI)	Day 1	not incl.	DENM	Verv2V	V2V service
Emergency or Prioritized Vehicle Approaching (HLN-EPVA)	Day 1	not incl.	DENM	Verv2V	V2V service
Railway Level Crossing (HLN-RLX)	Day 1	not incl.	DENM	I2V	–
Unsecured Blockage of a Road (HLN-UBR)	Day 1	not incl.	DENM	I2V	–
Alert Wrong Way Driving (HLN-AWWD)	Day 1	not incl.	DENM	I2V	–
Public Transport Vehicle Crossing (HLN-PTVC)	Day 1	not incl.	DENM	Vpt2V	V2V service
Public Transport Vehicle at a Stop (HLN-PTVS)	Day 1	not incl.	DENM	Vpt2V	V2V service
Road Works Warning (RWW)					
Lane closure (and other restrictions) (RWW-LC)	Day 1	Pilots	DENM	I2V	Use case piloted in Finland.
Road Closure (RWW – RC)	Day 1	Pilots	DENM	I2V	Not piloted in Finland. Similar as Lane closure.
Road Works Mobile (RWW-RM)	Day 1	not incl.	DENM	I2V	Not piloted in Finland. PVD use case for higher frequency of messages.
Winter Maintenance (RWW-WM)	Day 1	not incl.	DENM	Vro2V	Not piloted in Finland.
Signalized Intersections (SI)					

Signal Phase and Timing Information (SI-SPTI)	Day 1	Pilots	SPATEM, MAPEM	I2V	Use case piloted in Finland.
Green Light Optimal Speed Advisory (SI-GLOSA)	Day 1	not incl.	SPATEM, MAPEM	I2V	Not piloted in Finland. Similar as SPTI.
Imminent Signal Violation Warning (SI-ISVW)	Day 1	not incl.	SPATEM, MAPEM	I2V	Not piloted in Finland. Similar as SPTI.
Traffic Light Prioritisation (SI-TLP)	Day 1	not incl.	SSEM, SREM	I2V, V2I	Not piloted in Finland.
Emergency Vehicle Priority (SI-EVP)	Day 1	not incl.	SSEM, SREM	I2V, V2I	Not piloted in Finland.
Automated Vehicle Guidance (AVG)					
SAE Level Guidance (AVG-SAELG)	unknown	not incl.	IVIM	I2V	Excluded based on technical criteria
Platoon Support Information (AVG-PSI)	unknown	not incl.	IVIM	I2V	Excluded based on technical criteria
Probe Vehicle Data (PVD)					
Vehicle Data Collection (PVD-VDC)	Day 1	Pilots	CAM	V2I	Mobile network (V2I) technical capabilities when using high frequency CAMs.
Event Data Collection (PVD-EDC)	Day 1	not incl.	DENM	V2I	Other vehicle sensor information or user detected events excluded.
Collective Perception Service (CPS)					Non-C-Roads service. Likely important for road safety

Note that in practice, all use cases marked with logic of transmission type Vxx2V in the table will also include communication with the road operator and/or fleet operator via V2I/I2V. This will likely provide considerable benefits to these operators.

Summary of the analysis is based on the criteria presented above and analysis in Table 6. Following selected C-ITS services and use cases are considered being relevant in the future according to the selection criteria:

1. Hazardous Location Notification service, Temporarily slippery road use case (HLN-TSR) (C-Roads v2.0.5 2022)
2. Road Works Warning service, Lane closure use case (and other restrictions) (RWW-LC) (C-Roads v2.0.5 2022)
3. Signalised Intersection service, Signal Phase and Timing Information use case (SI-SPTI) (C-Roads v2.0.5 2022)
4. Probe Vehicle Data service, Vehicle Data Collection use case (PVD-VDC) (C-Roads v2.0.5 2022)
5. Collective Perception Service (CPS) (ETSI TS 103 324)

The following paragraphs introduce each of the selected C-ITS service and use case.

Hazardous locations notification (HLN) service informs and warns road users of hazardous locations on their route. This is done by providing in-vehicle information about the hazard. The information includes the location and type of the hazard but also possibly the duration of events and lane and speed advice. This in-vehicle information leads to more attentive driving near a hazardous location.

C-Roads has specified fourteen different use cases under HLN service. These are accident zone (HLN – AZ), traffic jam ahead (HLN – TJA), stationary vehicle (HLN – SV), weather condition waning (HLN – WCW), temporary slippery road (HLN – TSR), animal or person on the road (HLN – APR), obstacle on the road (HLN – OR), emergency or rescue/recovery vehicle in intervention (HLN – ERVI), emergency or prioritized vehicle approaching (HLN – EPVA), railway level crossing (HLN – RLX), unsecured blockage of a road (HLN – UBR), alert wrong way driving (HLN – AWWD), public transport vehicle crossing (HLN – PTVC) and public transport vehicle at a stop (HLN – PTVS).

The message type used in the service is DENM. The logic of transmission for most of the use cases is I2V, but some use cases utilize V2V communication. V2V communication use cases are HLN – ERVI, HLN – EVPA, HLN – PTVC and HLN – PTVS.

Temporarily slippery road (HLN – TSR) use case alerts road user of dangerous slippery sections of the road. Objective is to have road users to adapt their speed and driving to the situation. With C-ITS it is possible to have improved coverage and information quality compared to having information only on VMS. The logic of transmission is I2V, but there is possibility in future to have V2V broadcast also. The information could come from the road operator or the vehicle itself detects slipping and broadcast alert message.

Road Works Warning (RWW) service provides warnings from different types of road works, mobile or static, short-term or long-term, to the road users. The road user will be provided in-car information to increase attentive driving near work zones or road operator vehicles. The service and the use cases clustered in it support and increase the safety of road operators and road users.

C-Roads has clustered four use cases under the RWW service. These are lane closure (RWW – LC), road closure (RWW – RC), road works – mobile (RWW – RM) and winter maintenance (RWW – WM).

The expected benefits of the service are of improved safety. More attentive driving around a work zone or road operator vehicle helps to avoid sudden manoeuvres or breaking. This leads to less accidents but also to better flow of traffic.

The logic of communication for a majority of RWW use cases is I2V and is done using DENM-messages. However, for winter maintenance the communication can be V2V, meaning directly from the winter maintenance vehicle to other vehicles nearby.

The Lane closure (and other restrictions) (RWW – LC) use case informs road users about a partial closure of the lane, or closure of the whole lane or multiple lanes. In this specific use case, the closure is due to a static road work. The desired behaviour of the road user includes increased vigilance and adaption of speed. In this use case the road operator is the origin of information, this mean that the information originates from Traffic Operations Center or from a road operator vehicle. The actors involved in this use case are the road operator, the road user and the service provider.

Signalized intersections (SI) service clusters together five use cases that work in the context of a signalized intersection. This service providers information to road users but also vehicle data to traffic light controllers. This will enable more safe and efficient driving at a signalized intersection.

C-Roads has specified five different use cases under SI service. These use cases are signal phase and timing information (SI – SPTI), green light optimal speed advisory (SI – GLOSA), imminent signal violation warning (SI – ISVW), traffic light priorisation (SI – TLP) and emergency vehicle priority (SI – EVP).

The expected benefits of SI service are enhanced safety, increased traffic flow efficiency and minimized environmental pollution at a signalized intersection. These benefits are realized by providing in-car information, speed advice and priority to designated vehicles.

The communication logic is I2V and V2I. The infrastructure part of the communication is a C-ITS capable traffic light controller that communicates with the vehicles nearby. C-ITS messages exchanged in the service are SPATEM, MAPEM, SREM and SSEM. SREM and SSEM are used for asking and communicating status of a priority in priority use cases. SPATEM and MAPEM are used to describe the topology of the intersection and communicate the status of the traffic light signal.

Signal phase and timing information (SI – SPTI) use case informs road users approaching a signalized intersection of the current and upcoming phases of the traffic light. The desired behaviour is for road user to be able to adapt their speed while approaching the intersection. The information of the phases is transmitted periodically and in real time as SPATEM messages. The topology of the intersections is transmitted as MAPEM message. The communication logic in the use case is I2V.

Probe vehicle data (PVD) is a service that provides vehicle information to other vehicles and traffic management infrastructure. The objective of the service is to collect data from road users to increase safety and improve traffic management. This data can be utilized for improving knowledge of traffic conditions, traffic flow, incidents, weather conditions, etc. In addition, the data can be used for statistical and modelling purposes.

C-Roads has specified two different use cases under PVD service. These are vehicle data collection (PVD – VDC) and event data collection (PVD – EDC).

In C-Roads, the description of the PVD services scope only includes V2I PVD services from the perspective of the road operators and the service providers active in C-Roads. This means that V2V service requirements are out of the scope in the current C-Roads service requirements description.

In the current C-Roads scope, the logic of communication is V2I, and the messages transmitted are CAM-messages. This message holds information of vehicles operation and can be position, speed, direction, vehicle type, length, etc.

Vehicle data collection (PVD – VDC) use case operates sending automatically vehicle data out for road operator to collect it. The road operator processes the collected vehicle data to improve traffic management and safety operations on the public road network. Important factor when collecting and processing vehicle data is to make sure that the road operator and service provider operations shall be compliant with the GDPR and local legislation. The vehicle data is sent out as

CAM-messages and the data could be enriched by connecting to the vehicle CAN bus.

Collective Perception service (CPS) aims at improving the awareness of the human driver of the vehicle or the automated driving system about the objects and other road users surrounding and approaching the expected trajectory of the vehicle. The Collective Perception Messages (CPMs), that are event triggered, can be transmitted by both vehicles and road infrastructure systems. CPMs are important to ensure safe operation of automated driving systems especially in operating environments with restricted detection capabilities for vehicle sensors, for instance at urban junctions surrounded by buildings and other sight obstacles.

4 Literature review of C-ITS services metrics, Key Performance Indicators (KPI) and quality of service requirements

4.1 Metrics conceptual definitions

C-ITS performance metrics, Key Performance Indicators (KPI) and Quality-of-Service concepts are used widely in the scientific literature and in work of C-ITS pilots and deployment. Following summarises the conceptual definitions used in this study.

Performance metrics are here defined as operational and tactical level parameters to measure C-ITS service performance. Performance metrics provide quantitative measurements.

Key Performance Indicators (KPI) are strategic metrics, i.e., highly important selected metrics to assess performance of the C-ITS services. KPI parameters can be used to assess and further enhance the C-ITS service quality.

Quality-of-service (QoS) refers to overall performance of a service which is often experienced by the service user or evaluated by performance metrics. Quality requirements are set minimum target values (or quality levels, boundaries) for the C-ITS service to meet set quality of service criteria (EU EIP 2022).

4.2 Mobile telecommunications system performance indicators

The 3rd Generation Partnership Project (3GPP) unites telecommunications standard development organisations, for example ETSI, and covers cellular communications technologies.

3GPP specification 32.450 (Definitions) and 32.451 (Requirements) define "Telecommunication management; Key Performance Indicators (KPI) for Evolved Universal Terrestrial Radio Access Network (E-UTRAN)". Respective release 17 has been published in ETSI TS 132 450 (2022) and ETSI TS 132 451 (2022) technical specifications. KPIs defined in the ETSI specifications are introduced in Table 12 below.

Table 12. ETSI TS 132 450 (v17, 2022) and ETSI TS 132 451 (v17, 2022) specifications definitions and requirements of Telecommunication management; Key Performance Indicators (KPI) for Evolved Universal Terrestrial Radio Access Network (E-UTRAN).

KPI Category (ETSI TS 132 450)	**Description of the KPI (network or user view)**	**Unit**
Accessibility	Probability for an end-user to be provided with an E-RAB (E-UTRAN Radio Access Bearer) at request.	Percentage
Retainability	How often an end-user abnormally loses an E-RAB during the time the E-RAB is used.	Active release / second
Integrity: Throughput	How E-UTRAN impacts the service quality provided to an end-user.	kbit/s
Integrity: Latency	How E-UTRAN impacts on the delay experienced by an end-user.	Milliseconds

Availability	Availability of E-UTRAN Cell. Percentage of time that the cell is considered available.	Percentage
Mobility	How E-UTRAN Mobility functionality is working.	Percentage
Energy Efficiency	Data energy efficiency in operational E-UTRAN.	bit/J

The 3GPP/ETSI 132 451 (2022) specification provides business and specification level requirements for each of the KPI categories. The business level requirements reason that any problems encountered in the use of the radio communication network would make it harder to charge for the service - "why should I pay for the service if I cannot use it". Similarly, end-user might change wireless subscription provider, which would mean loss of income for the operator. The energy efficiency KPI corresponds to the energy consumption related costs in the mobile network operators' operational expenditure (OPEX).

The 3GPP/ETSI 132 451 (2022) also lists specification level requirements, which include the limitation of the KPIs to the E-UTRAN contribution to the end user impact, i.e., only the mobile communication related aspects are considered instead of those for the whole end-to-end part of service provision.

3GPP TS 28.554 (2022) Technical Specification Group Services and System Aspects; Management and orchestration; 5G end to end Key Performance Indicators (KPI) (Release 18) lists the following KPIs for 5G in Table 13.

Table 13. Technical Specification Group Services and System Aspects; Management and orchestration; 5G end to end Key Performance Indicators (KPI) (Release 18). (3GPP TS 28.554 2022)

End to end KPI (3GPP TS 28.554 2022)	**Definitions examples**
Accessibility	Registered subscribers, accessibility for services, connected subscribers, session established success rate
Integrity	Downlink latency in base station, downlink delay, uplink delay, upstream and downstream throughput for network, RAN UE throughput
Utilization	Mean number of Packet Data Unit (PDU) sessions (between UE and 5G core network), virtualised resource utilization, session establishment, mean number of successful periodic registration updates, max. number of sessions
Retainability	QoS flow retainability, i.e., how often an end-user abnormally loses a QoS flow, and DRB retainability
Mobility	Handover success rate, successful rate of mobility registration updates
Energy Efficiency (EE)	Data energy efficiency, network slice energy efficiency, energy consumption
Reliability	Network layer packet transmissions, as the percentage value of the packets successfully delivered to a given system entity within the time constraint required by the targeted service out of all the packets transmitted. For example, packet transmission reliability KPI in DL and UL Uu, DL and UL N3.

4.3 C-ITS metrics and Key Performance Indicators (KPI)

The scientific papers on C-ITS communication performance have often focused on some specific aspects of communication but a few have produced a list of indicators describing the Quality of Service (QoS) for the communications. The indicator list compiled by Damaj et al (2021) is the following:

- accessibility
- channel busy ratio
- number of transmitted packets
- packet delivery ratio
- routing control overhead
- transmission delay
- dropped data packets ratio
- bit error rate
- communication throughput
- latency
- received signal strength indicator
- responsiveness
- reliability
- scalability

Specific indicators are specifically supported by Amador et al. (2022), Fitah et al. (2018), MacCarthy et al. (2021) and Triwinarko at al. (2021).

Santa et al (2022) approaches the issue from the mobile phone network aspect and proposes another set of indicators as shown in Table 14. Gallego-Madrid et al. (2023) provide another network layer performance metrics list for future 6G vehicle applications as shown in Table 15.

Table 14. Mobile phone network Key Performance Indicators (KPI). (Santa et al 2022).

KPI	Description	Unit
User data rate	Data rate as perceived at the application layer	bps (bits per second)
Throughput	Instantaneous data rate/throughput as perceived at the network layer	bps
End to end latency	Time since a message is transmitted until it is received, at application layer	ms
Network latency	Time since a data packet is transmitted until it is received, at network layer	ms
RAN (Radio Access Network) latency	Time since a data packet is transmitted until it is received, at RAN layer	ms
Control plane latency	Control plane latency to move from idle state to active state	ms
Network reliability	Amount of application/network layer packets successfully delivered	%

Position accuracy	Deviation of measured position using UE (User Equipment) 5G positioning service	m
Network capacity	Maximum data volume transferred over a dedicated area	bps (bits per second)
RAN handover reliability	Ratio of successfully completed handover events within the RAN	%
Application hando-ver reliability	Ratio of successfully completed application-level handovers for maintaining a session	%
Mobile interruption time	Time a user terminal loses connectivity dur-ing handovers	ms

Santa et al. (2022) also propose to use the average number of LTE Resource Blocks (RBs) per LTE cell required by vehicles for communicating over the LTE system as an indicator.

Table 15. Mobile phone network Key Performance Indicators (KPI) for future 6G vehicle applications. (Gallego-Madrid et al. 2023)

KPI	Description	Unit
Network capacity	Maximum data volume transferred on a particular geographical area per time slot	b
Network latency	Time since a data packet is transmitted until it is received	μs
Network jitter	Fluctuation in the network latency	μs
Network manage-ment response time	Time from event detection to effective re-action in the management of the network, taking into account analysis and decision making	μs
Network reliability	Amount of application/network layer packet successfully delivered	%
Network throughput	Instantaneous data rate/throughput as perceived at the network layer	bps
Position accuracy	Deviation radius of measured position us-ing terminal's 6G positioning service	cm
UE (User Equip-ment) connection delay	Control plane latency in the terminal con-nection status to move from idle state to active state	μs
Slicing creation de-lay	Time needed to make effective an E2E net-work slice	μs

Slicing QoS compliance	Level of compliance with slicing QoS requirements indicated	%
System components' trustworthiness	Trust between elements within the disaggregated 6G architecture	%

Concerning latency, the maximum tolerable elapsed time calculated from the instant a data packet is generated at the source application to the instant it is received by the destination application. Low Latency values are provided to support services in the case of mutual awareness of vehicle or to send warning messages. (3GPP 2022)

Concerning reliability, the maximum tolerable packet loss rate at the application layer, meaning a packet is considered lost if it is not received by the destination application within the maximum tolerable end-to-end latency for that application. (3GPP 2022, also Damaj et al 2021)

Messages sizes are important when multicast or broadcast messages are being sent to vehicles within range to either warn them for collision prevention or when an event occurs to inform other vehicle about an accident. (3GPP 2022)

With regard to frequency requirements, the minimum required bit rate is needed for the application to function correctly. The sending rates i.e. frequency of messages is relatively important especially for critical vehicular safety application. (3GPP 2022)

The range requirements specify the maximum distance between the source and destination(s) of the radio transmission. Within this maximum range the application should still achieve the specified reliability. (3GPP 2022)

The speed requirements give the maximum relative and absolute user speed under which the specified reliability should be achieved. (3GPP 2022)

Mugahl et al. (2021) propose the use of outage probability where outage relates to a specific vehicle not receiving a message.

Giluka et al. (2018) pay specific attention to:

- packet drop percentage/probability
- expected queue length (number of packets)
- expected packet waiting time i.e. average delay
- throughput of a particular class.

Amador et al. (2022) define packet delivery ratio as the ratio of vehicles that received a given message to the number of vehicles within the area at the moment the message was generated (i.e. the vehicles that should have received the message).

Jalooli et al. (2019) uses message coverage as the performance indicator.

Charitos & Kalivas (2017) apply packet delivery ratio (PDR), computed as the ratio between the number of received packets and the transmitted packets during the simulation time, and end-to-end delay, computed as the sum of all mean delays for each vehicle, normalized over the total number of flows in the network, where mean delay is defined as the ratio between the sums of all delays and the total number of received packets. They define throughput as the sum of received data frame bytes at the destinations, averaged over the total number flows in the network. Furthermore, they use SNIR Lost packets indicating the lost packets per number of vehicles, i.e., packet collisions and packets not received due to bit errors.

The maximum time between message generation and its reception on the server is an important indicator. This time is proportional to the safety message generation period and the network latency between the transmission of safety message and its reception at the server. During this time, the server does not have updated information about a vehicle while it moves, as location information is changing. Thus, it is crucial to minimize this time to increase the freshness of vehicles' information on the server. (Soleimani & Boukerche 2018)

The maximum distance between the actual position of a vehicle and the location information of the vehicle on the server. This distance is the maximum distance that the vehicle travels while the server has not received updated information. This distance, which can be inferred as the location accuracy of the vehicle on the server, is proportional to the vehicle speed and the maximum time between message generation and its reception on the server. Ideally, it is better to have similar location accuracy for all vehicles instead of having a high accuracy for some vehicles while other vehicles suffer from low accuracy. (Soleimani & Boukerche 2018)

Another important metric for performance evaluation is the number of PRBs resources used for transmission of C-ITS messages (PRB or Physical Resource Block is made up of 12 consecutive subcarriers for a duration of one slot). It is desirable to lower the resource usage in order to save resources for other applications. (Soleimani & Boukerche 2018)

Shehzad et al. (2021) use unbiased and biased UE (User Equipment) association probability as well as network coverage probability as metrics for C-ITS communication performance.

Islam & Kwon (2022) propose the use of six indicators:

- access rate
- sum rate
- fairness
- reliability
- latency
- energy efficiency.

Access rate refers to the number of D2D (Device to Device) pairs that can be admitted to a given sub-channel/resource block. The access rate varies based on the algorithm design. (Islam & Kwon 2022)

Sum rate refers to the aggregate achievable data rate of all D2D and cellular users. It depends on the achievable Signal to Interference and Noise Ratio (SINR) levels of the individual receivers. The SINR levels in turn depend on the overall interference levels. Efficient interference management and resource allocation lead to significant improvement in achievable sum rates. (Islam & Kwon 2022)

Fairness, in the context of resource allocation, refers to the provision of equal resource allocation opportunity to all users irrespective of their position and required rates. Generally, access rate and sum rates can be improved by prioritizing D2D pairs with relatively low target SINRs. However, this results in an unfair system where D2D pairs with higher SINR requirements have lesser probability of being served. (Islam & Kwon 2022)

Reliability refers to guaranteed and uninterrupted service to all the users. It is a crucial performance metric specially in applications such as Vehicle-to-Vehicle (V2V) communication, industrial automation etc. where unreliable connections may lead to fatal situations. (Islam & Kwon 2022)

Latency refers to the delay between the transmission and reception of a signal at its intended destination. It is a critical performance metric for time sensitive applications such as vehicular communication and industrial automation. Resource allocation schemes for such applications are typically bounded by some threshold on latency. (Islam & Kwon 2022)

Although energy efficiency is important in general, its importance increases in Sensor-to-Sensor (S2S) and D2D communication scenarios where miniature devices with low energy capacity are deployed on long term basis. (Islam & Kwon 2022)

The 5G Automotive Association (5GAA), cross industry organisation of companies from the automotive, technology and telecommunications industries (ICT) developing mobility and transportation services, has published several technical reports that were reviewed in this the study for relevance of C-ITS performance metrics.

5GAA has investigated Communications Service Providers (CSP) Supporting Road Operator Priorities and Expectations as well as Road Operator use case modelling and analysis. The resulting 5GAA report lists the following selected metrics, i.e., network requirements, when comparing different C-ITS services use cases. (5GAA 2023)

- Network coverage
- Communications latency
- Data throughput capacity

5GAA reports have often been used as a basis for Finnish C-ITS studies on C-ITS services utilising hybrid communications. The Finnish Transport Agency report on 5G operations (Jokinen et al. 2019) referred to the 5GAA study on C-V2X use case examples and requirements (5GAA 2019), where metrics such as latency and reliability are mentioned. The cost analysis study of communication networks (2020) referred to the 5GAA (2020) study on Day 1 and advanced use cases requirements which include data transfer and latency metrics. The Finnish Transport Infrastructure Agency’s research on service level framework for automated road transport, part of AUTOMOTO project, and its task 1.2. Communications utilised 5GAA studies on C-V2X use cases and service level requirements (Volumes I and II, 2020) which include performance metrics of reliability, download, upload and latency.

4.4 C-ITS Quality-of-Service requirements

The literature on quality-of-service requirements has so far been dominated by latency requirements. Obviously, the latency requirements for C-ITS messaging depend on the use case – for a warning of an imminent collision a short latency is a must and for a warning of a road works site some km ahead a latency of a few seconds would mostly be enough.

In 2009, ETSI classified the C-ITS use cases according to the latency and message frequency in the following manner: (ETSI 2009)

Latency <50ms, Minimum frequency of messages 10 Hz

- Pre-crash sensing warning

Latency <100ms, Minimum frequency of messages 10 Hz

- Emergency electronic brake lights
- Emergency vehicle warning
- Wrong way driving warning
- Stationary vehicle warning
- Signal violation warning
- Overtaking vehicle warning
- Lane change assistance
- Across traffic turn collision risk warning
- Merging traffic turn collision risk warning
- Co-operative merging assistance
- Intersection collision warning
- Co-operative forward collision warning
- Collision Risk Warning from RSU

Latency <100ms, Minimum frequency of the periodic message 2 Hz

- Slow vehicle warning
- Motorcycle warning
- Road work warning
- Co-operative glare reduction
- Traffic light optimal speed advisory
- Co-operative adaptative cruise control
- Platoon

Latency <100ms, Minimum frequency of the periodic message 1 Hz

- Safety function out of normal condition warning
- Vulnerable road user warning

Latency <200ms, Minimum frequency of the periodic message 1 Hz

- Electronic toll collection

Latency <500ms, Minimum frequency of the periodic message 1 Hz

- Traffic information and recommended itinerary
- Enhanced route guidance and navigation
- Intersection management

- Co-operative flexible lane change use
- Limited access warning, detour notification
- In vehicle signage
- Point of interest notification
- Automatic access control/parking access
- Local electronic commerce
- Car rental/sharing assignment/reporting
- Media downloading
- Map download and update
- Instant messaging
- Personal data synchronization
- SOS service application
- Stolen vehicle alert
- Remote diagnosis and just in time repair notification
- Vehicle relation management
- Vehicle data collection
- Insurance and financial services
- Fleet management
- Vehicle software/data provisioning and update
- Loading zone management
- Vehicle and RSU data calibration

Singh at al. (2019) classified selected V2I/I2V warnings in two latency categories according to the C-ITS service:

1. latency less than about 100 ms
   - pedestrian in signalized crosswalk warning
   - stop sign violation warning
   - stop sign gap assistance
   - traffic signal violation warning
2. latency less than about 1 s
   - reduced speed / work zone warning
   - curve speed warning

Some papers also include recommendations for other quality of service indicators. Ahmadi (2019) compiled latency, reliability, data rates and communication range for types of user cases as indicated in Table 16.

Table 16. Performance requirements of different V2X use cases (Ahmadi 2019)

Use case	V2X mode	End2end latency (ms)	Reliability (%)	Data rate per vehicle (kbps)	Communi-cation range
Cooperative awareness	V2V/V2I	100 – 1000	90 – 95%	5 – 96	Short to medium
Cooperative sensing	V2V/V2I	3 – 1000	> 95%	5 – 25 000	Short
Cooperative manoeuvre	V2V/V2I	<3 – 100	> 99%	10 – 5 000	Short to medium
Vulnerable road user	V2P	100 – 1000	95%	5 – 10	Short
Traffic efficiency	V2N/V2I	> 1000	> 90%	10 – 2 000	Long
Tele-operated driving	V2N	5 - 20	> 99%	> 25 000	Long

The requirements compiled by Garcia et al (2021) for 5G NR requirements are presented in Table 17. They define Payload as the amount of data required by a specific service and generated by the application, and Tx rate as the number of messages per unit time that the transmitter generates and the receiver is expected to receive subject to other relevant requirements (e.g., payload size, latency, communication range, etc.). Maximum end-to-end latency is the maximum allowed time between the generation of a message at the transmitter's application and the reception of the message at the receiver's application. Reliability is defined as the probability that a transmitted message is correctly received within a specified maximum end-to-end latency subject to other relevant requirements (e.g., payload size, communication range, etc.). Finally, Data rate represents the total amount of data that needs to be received by the receiver per unit time. It is related directly to the payload and the Tx rate and is measured in bits per second (bps). It is also subject to other requirements (e.g., latency, reliability, etc.)

Table 17. Requirement ranges for V2X use case groups (Garcia et al. 2021)

Use case group	Payload (bytes)	Tx rate (message/s)	Max end2end latency	Reliability (%)	Data rate (Mbps)
Vehicle platooning	50 - 6000	2 – 50	10 – 25	90 – 99.99	<= 65
Advanced driving	SL 300 – 12 000 UL 450	SL 10 – 100 UL 50	10 – 100	90 – 99.999	SL 10 – 50 UL 0.25 – 10 DL 50
Extended sensors	1 600	10	3 – 100	90 – 99.999	10 – 1 000
Remote driving	16 000 – 41 700	33 – 200	5	99.999	UL 25 DL 1

Note: If not specified otherwise the requirement applies to all link types i.e. Downlink (DL), Uplink (UL) and Sidelink (SL).

The actual requirements depend a lot on the context of use, specific use case, vehicle speed and other factors. For example, Bodell and Gulliksson (2016) found that an end-to-end latency of 300 ms worked for teleoperated driving at 30 km/h in a safe manner.

In the C-ITS context, numbers given for an "end-to-end latency" might look at application-to-application delivery from the sender to the receiver, which includes any kind of "in-station latency" like data collection, message creation and processing through the layers of the communication stack – on both ends, including security checks. So, the latency on the communication link might only be a minor contribution to the overall latency. In any case, a higher communication latency will always introduce unfavourable effects at some point.

The average latency might not be the only/most relevant aspect of latency. Another important metric is the jitter or the variance of the latency. Making up an example: An average latency of 12 ms sounds better than 15 ms, but for a use case with a strictly required communication latency of max. 20 ms, a stable link with a guaranteed latency of 15 ms +/- 2 ms might be preferable compared to a more shaky link with 12 ms +/- 10 ms – or even a longer tail of few data packages with higher latency The importance of the jitter is also dependent on the use case and protocols used, i.e. if the packages need to be received "in order" (e.g. certain data streams) or if late delivery of (outdated) packages might create other issues. (Berndt-Tolzman 2023)

The size of the messages is not so much an issue for most C-ITS messages, since they're designed to be small. When looking at "collective perception", long lists of detected objects might cause message size to increase – but it's still very different from the data consumed by infotainment videos, for instance. (Berndt-Tolzman 2023)

Another challenging metric is the overall quality of service (QOS) – and how it changes in time and space (predictive QOS). With teleoperation as an example: If we know that the current 4k-video stream cannot be provided/guaranteed on the next five kilometres of road going through the woods, it might be better to reduce the video resolution and/or the vehicle speed in advance (which helps the teleoperator to stay in control) or not offer the service at all. This would probably be a lot better than being surprised by a sudden QOS reduction or even a complete loss of communication.

QOS is tricky, since the radio characteristics are usually rather static or at least within certain limits (density of base stations, antenna power, number of devices – things that can be predicted with some confidence), but it might also change dynamically due to e.g. snow/rain/thunderstorms or issues like high loads in the core network since redundant links have been destroyed by an excavator – which happens quite often. Network slicing might become an interesting concept to cover certain QOS needs – but someone always has to pay for that. (Berndt-Tolzman 2023)

LTE service requirements for V2X services has been supported by 3GPP in the ETSI TS 122 185 technical specification. The specification includes overall specific service and security requirements. Specific service requirements include latency, message size, frequency, range and speed. (Appendix 2, 3GPP 2022)

EU EIP C-ITS Quality package

The European ITS Platform (EU EIP) sub-activity 4.1 "Determining Quality of European ITS Services" develops road operator's view on quality requirements and quality assessment practices for ITS Directive priority services. Part of this task includes C-ITS data and information quality. The document elaborates three elements of quality assessment: 1. quality criteria basic parameters, 2. quality requirements minimum quality levels for C-ITS services (target values) and 3. quality assessment methods.

The preceding EIP+ project proposed RTTI/SRTI services quality requirements, and EU EIP (2022) proposed following quality criteria for C-ITS Services and data, summarised in Figure 7.

Quality Criterion		
Based on	**Name**	**Definition**
EU EIP Definitions	**Availability**	Average availability for all operating connected data senders, including the communication chain up to the data receiver.
	Latency	Total time for communicating messages between a timestamp at a C-ITS sender and a timestamp at a C-ITS receiver.
	Refreshment Rate	Time interval for refreshing / updating the status reports coming from a data sender.
	Location accuracy	Deviation of the reported horizontal location of an event information with respect to the actual location.
	Error Rate	Percentage of messages with erroneous information, as reported by a data sender, out of the total number of messages.
ETSI Standardisation	**Transmission Interval** (DENM data element)	Time interval for DENM transmission as defined by the originating ITS station. Informs the receiving ITS stations about the intended transmission interval of two consecutive DENM transmissions. *Correlates with "Refreshment Rate": "Transmission Interval" is embedded into the message content, whereas "Refreshment Rate" allows external quality assessments.*
	Event Position / Position Confidence Ellipse (DENM data frame)	The horizontal position accuracy in a shape of ellipse with a predefined confidence level (e.g. 95 %). The centre of the ellipse shape corresponds to the reference position point for which the position accuracy is evaluated. *Correlates with "Location Accuracy": "Position Confidence Ellipse" is embedded into the message content, whereas "Location Accuracy" allows external quality assessments. Nevertheless, the way how the accuracy is calculated for "eventPosition" is also applied for "Location Accuracy".*
	Information Quality (DENM data element)	Quality level of the information provided by the ITS-S application of the originating ITS-S. It indicates the probability of the detected event being truly existent at the event position. *Correlates with "Error Rate": "informationQuality" relates to the confidence of a reported event, i.e. a level of likelihood that a reported event is really happening in reality, based on the applied detection and verification technique. "Error Rate", on the other hand, quantifies the adherence to reality in terms of erroneous messages.*

Figure 7. EU EIP proposed quality criteria for C-ITS Services and Data (EU EIP, 2022).

The proposed quality criteria do not give detailed suggestions for definitions of C-ITS-quality, but generic implications. Additionally, the Quality Package value chain of traffic information scope only covers event and traffic situation content, i.e., content detection and content processing. Service side and therefore end user (or vehicle) side service provision and service presentation were left to Service Providers as outside of road authorities' responsibility.

The following quality criterion were considered relevant in context of this work: availability, latency, refreshment rate and error rate, which are considered having possible impact for the vehicle when receiving and sending messages using commercial mobile network. Location accuracy does not relate to mobile network usage. ETSI standardisation will be evaluated separately in this chapter.

4.5 Analysis and summary of C-ITS performance metrics and Key Performance Indicators (KPI)

The aim of Part A was to study service level indicators of mobile networks required by C-ITS services and how those are defined. Following analysis process was conducted to review the C-ITS services performance metrics for relevant Key Performance Indicators (KPI):

1. A literature review and interviews were conducted to list C-ITS services performance metrics.
2. First selection round of metrics and exclusion of metrics that
    a. concern architecture layer and communication that is not or less relevant for analysis of C-ITS communication utilising cellular mobile network, such as an application layer and ad-hoc short-range communication.
    b. More future oriented metrics, such as 6G network. Although these might be relevant for future C-ITS services use cases, this study mainly concentrates on Day 1 and 1.5 services.
3. Analysis of the listed C-ITS performance metrics together with telecommunication standardisation metrics and definition of KPI categories.
4. Second selection round of KPIs for C-ITS services communication utilising cellular mobile network based on
    a. performance metrics relevance and frequency in the literature as well as
    b. expert opinion of the project team members, interviews and management group.

The analysis step 1. literature review was presented in the Part A chapter 4 previous subchapters. The next chapter presents list and selection of the metrics.

4.5.1 Analysis of C-ITS services metrics for Key Performance Indicators (KPI)

The analysis steps are 1. a list of performance metrics and 2. selection of metrics. Table 18 below presents a summary of the results of the literature review of the C-ITS services performance metrics according to the analysis process (steps 1.–4.) described above. A green colour of a performance metric in the table indicates the selection of the metric for further study.

Table 18. C-ITS services communication performance metrics. 'N' indicates number of times the metric was mentioned in the literature. Row 'Analysis of KPI categories' was evaluated according to literature and standard and includes 'Metric's evaluation based on study scope'. Green colour indicates a performance metric that was selected as a KPI. Red colour indicates a performance metric that was excluded being out of scope for the study (see analysis steps in the beginning of the chapter).

Performance metrics	N	Description	Unit	Analysis of KPI categories – Metric's evaluation based on study scope
Accessibility		Accessibility of the communication service, probability of radio access, successful attempts compared with total number of attempts.	%	(Reliability)
Access rate		Number of D2D pairs that can be admitted to a given sub-channel/resource block (algorithm design dependent)	–	Device-to-device (or V2V) communication not incl.
Application handover reliability		Ratio of successfully completed application-level handovers for maintaining a session	%	(Reliability)
Availability (avg.)	2	Avg. availability for connected data senders and receivers (EU EIP)	–	(Availability)
Bit error rate		Bits received in error by the total number of bits transmitted (time period)	%	(Reliability) Relevant, but mostly measured by the network operator. Error rate can cause packet loss
Channel busy ratio		Percentage of time the channel is busy, which is a metric of the channel occupation	%	(Availability, Reliability)
Download speed	2	Rate of data transferred from I2V (downlink)	Kbit/s or Mbit/s	(Integrity)
Energy efficiency		Energy efficiency within the network	–	Sensor-to-Sensor (S2S) and D2D communication scenarios or network infrastructure energy efficient dependent on network design and development
Error rate	2	Percentage of messages with erroneous information out of total messages (EU EIP)	–	(Reliability)
Expected packet waiting time		Average delay of packet	–	(Reliability) Similar as 'latency', see below
Expected queue length		Number of packets	–	(Reliability)
Fairness		Provision of equal resource allocation opportunity to all users irrespective of their position and required rates	–	(Reliability) Depends on network infrastructure design and development, i.e., resource allocation algorithms.
Frequency (messages)		Sending rates, minimum required bit rate, i.e., frequency of messages	Hz	C-ITS service use case dependent
Latency: Network latency	7	Time since a data packet is transmitted until it is received, at network layer	ms	(Integrity)
Latency: End to end latency	7	Time since a message is transmitted until it is received, at application layer	ms	(Integrity)
Latency: Control plane latency		Control plane latency to move from idle state to active state	ms	One smaller part of communication latency
Message coverage		Message coverage in 2D environments, i.e., urban areas.	–	(Availability) 2D area, or 1D as a highway section

Message Size	2	Size of a message	–	Not much of an issue (Day 1 and 1.5 messages size is small)
Mobile interruption time		Time a user terminal loses connectivity during handovers	ms	(Reliability)
Network capacity	2	Maximum data volume transferred over a dedicated area (also: per time slot)	bps	(Integrity) Dedicated area
Network coverage	2	Additionally, geographic coverage. Percentage of the road network and/or selection of road classes (to be case by defined) where cellular mobile network is available. (Adapted from EU EIP 2022)	%	(Availability), also reference of message coverage. See also range.
Network jitter	2	Fluctuation in the network latency, i.e., variance of the latency	µs	(Integrity)
Network management response time		Time from event detection to effective reaction in the management of the network, taking into account analysis and decision making	µs	(Integrity)
Number of transmitted packets		Number of transmitted packets	–	(Integrity)
Outage probability		Specific vehicle not receiving a message	–	(Reliability)
Packet delivery ratio (PDR)	3	Ratio of vehicles that received a given message to the number of vehicles within the area at the moment the message was generated (i.e. the vehicles that should have received the message)	–	(Reliability)
Packet drop percentage/probability		Total number of packets dropped compared to packets generated	–	(Reliability)
Packet loss rate	3	Packets not received by the destination application within the maximum tolerable end-to-end latency for that application.	%	(Reliability)
Position accuracy	2	Deviation of measured position using UE (User Equipment) 5G positioning service. Location accuracy (EU EIP) Event position (ETSI)	m / cm	(Reliability) If e.g., 5G positioning service is used, relates to mobile networks. Message level out of scope.
RAN (Radio Access Network) latency		Time since a data packet is transmitted until it is received, at RAN layer	ms	(Integrity)
RAN handover reliability		Ratio of successfully completed handover events within the RAN	%	(Reliability)
Range		Max. distance between source and destination(s) of a radio transmission with-in which the application should achieve the specified reliability	–	(Availability, Reliability)
Received signal strength indicator		Amount of power, strength of a received signal measured at the receiver’s antenna.	–	(Integrity) Part of network coverage analysis, see work phase 1.2 report
Resource Blocks (RBs)		Average number of LTE Resource Blocks (RBs) per LTE cell required by vehicles for communicating over the LTE system	–	(Integrity)
(Physical) Resource Block (PRB)		Number of PRBs resources used for transmission of C-ITS messages	–	(Integrity)
Refreshment rate	2	Time interval for refreshing / updating the status reports coming from a data sender (EU EIP)		C-ITS service use case dependent, see also Frequency (messages)

Reliability	5	Guaranteed and uninterrupted service to all the users	–	(Reliability) Critical for well-functioning C-ITS services.
Reliability of network	2	Amount of application/network layer packets successfully delivered	%	(Reliability) Critical for well-functioning C-ITS services. Same as "Reliability" above.
Responsiveness		Communication network and system responsiveness	–	(Integrity) Relates to latency, congestion management, etc.
Routing control overhead		Number of control message associated with the total amount of message that has been transmitted.	–	–
Scalability		Network and connectivity scalability	–	(Integrity)
Slicing creation delay		Time needed to make effective an E2E network slice	μs	Future-oriented, e.g., 6G
Slicing QoS compliance		Level of compliance with slicing QoS requirements indicated	%	Future-oriented, e.g., 6G
Speed (user)		Max. relative and absolute user speed under which the specified reliability should be achieved.	–	Possible C-ITS service and use case dependent.
Sum rate		Aggregate achievable data rate of all D2D and cellular users		(Integrity) V2V not in scope of the study
System components' trustworthiness		Trust between elements within the disaggregated 6G architecture	%	Future-oriented, e.g., 6G
Transmission delay		Delay of data packet transmitted from sender to receiver	–	(Integrity) Similar as latency, see above
Throughput (network, capacity), communication	4	Instantaneous data rate/throughput as perceived at the network layer	bps	(Integrity)
Upload speed		Rate of data transferred from V2I (uplink)	Kbit/s or Mbit/s	(Integrity)
UE (User Equipment) connection delay (also unbiased and biased)		Control plane latency in the terminal connection status to move from idle state to active state	μs	Future-oriented, e.g., 6G KPIs, see also 'control plane latency'
User data rate	2	Data rate as perceived at the application layer	bps	(Integrity)

4.5.2 *Analysis of Key Performance Indicator (KPI) categories for C-ITS service communication in cellular mobile networks*

The third step of the analysis was to analyse the listed C-ITS performance metrics together with telecommunication standardisation metrics to review and define Key Performance Indicator (KPI) categories. The following Table 19 summarises the KPI categories that were selected among the performance metric parameters.

Table 19. Suggested KPI categories for C-ITS services utilising mobile network. Suggestion based on analysis of telecommunication standardisation metrics and C-ITS services KPIs.

KPI category (ETSI TS 132 450 (2022) and 3GPP TS 28.554 (2022)	**Analysis of the ETSI/3GPP technical specification KPI relevance for C-ITS services and C-ITS KPI category**	**Suggested KPI category for C-ITS services mobile network KPIs**
Accessibility	C-ITS service KPI: Accessibility Successful radio access is the necessity of C-ITS service communication and part of reliability of the communication.	Reliability
Retainability	C-ITS service KPI: Packet loss rate Loss of quality-of-service flow, or abnormally released data connection hinders the communication reliability. Packet loss rate suggested as a simple metric. Part of reliability of the service. Possible use of mitigation techniques to prevent or recover of packet loss. Impact depends on individual C-ITS service requirements.	Reliability
Integrity	C-ITS service KPIs: Latency, Jitter, Capacity, and Throughput Latency and throughput have an impact on the C-ITS service delay and quality for the end user.	Integrity
Availability	C-ITS service KPI: Network coverage Availability of the cellular mobile network, or cell, enables the C-ITS service provision, and was therefore selected as one of the KPI categories.	Availability
Mobility	C-ITS service KPI: handover metrics Vehicles maintain mobile network connection while moving between different locations on street and road networks by performing handover between cells and access networks.	Reliability
Energy Efficiency	C-ITS service KPI: Energy efficiency Data energy efficiency and energy consumption relate mostly to network design and development therefore it was excluded. Different C-ITS services algorithms and mitigation techniques might have an impact.	Energy Efficiency
Reliability	C-ITS service KPI: Accessibility, Packet loss rate, Reliability of network Reliability was selected as one of the KPI categories as reliable packet transmission is critical for well-functioning C-ITS services.	Reliability
Utilisation	C-ITS service KPI: – (not identified) Utilisation of sessions and data path between User Equipment and network, i.e., connection stays available. Impact on service reliability.	Reliability

The KPI categories analysis included C-ITS services performance metrics from the literature review and 3GPP as well as ETSI standards. The following KPI categories were excluded:

- Accessibility: successful radio access metrics available through other metrics, such as coverage and packet loss rate.

- Mobility: Handover reliability is also visible in the packet loss rate. Additionally, C-ITS Day 1 and 1.5 messages are estimated having low requirement for handover performance.
- Energy Efficiency: not in scope of this study. The metric mainly concerns mobile network development. Data transfer rates of C-ITS services might have an impact on energy efficiency.
- Utilisation: C-ITS performance metrics were not identified. Part of reliability metrics such as data loss rate.

The analysis concluded to following three suggested Key Performance Indicator categories for C-ITS service communication utilising cellular mobile networks:

1. Availability
2. Reliability
3. Integrity

4.5.3 KPIs quality of service requirements for the C-ITS services

The selected KPIs were next analysed for their quality-of-service requirements for the C-ITS service performance in cellular mobile network. It should be noted that mitigation techniques and algorithms used by the C-ITS services have an impact on the service operation and quality of service, i.e., mitigation techniques enable resilience when communicating the service. Table 20 below presents KPI quality of service values for those attributes that were found in the literature (Part A Chapter 4.3, 5GAA 2023, FTIA publications 21/2021 and Part A Chapter 5.1).

Table 20. Quality-of-service KPI requirements for C-ITS services utilising cellular mobile network.

Key Performance Indicator (KPI)	RWW: Lane closure (and other restrictions)	HLN: Temporarily slippery road	SI: Signal Phase and Timing Information	PVD: Vehicle Data Collection	Collective perception
Network coverage (Availability)	100%	100%	100%	100%	100%
Signal-to-noise ratio (SNR) (Availability)	-	-	-	-	-
Accessibility (Reliability)	-	-	-	-	-
Bit Error Rate (Reliability)	-	-	-	-	-
Packet loss rate (Reliability)	< 5–10%	< 5%	< 5%	< 5%	< 5%
Reliability of network (Reliability)	-	-	-	-	-
Latency: End to end latency (Integrity)	< 1 s	< 100ms	< 100ms	< 500ms	< 100ms
Network jitter (Integrity)	-	-	-	-	-
Network capacity (Integrity)	-	-	-	-	-
Throughput (network, capacity), communication (Integrity)	> 5 Mbit/s (download and upload)	> 5 Mbit/s (download and upload)	> 20 Mbit/s (download and upload)	> 20 Mbit/s (download and upload)	> 100 Mbit/s download, > 25 Mbit/s upload

Since not all quality of service values of KPIs are available from the literature, and the threshold values are C-ITS service specific, another analysis was conducted where the aim was to estimate the KPI direction of effect for the quality of C-ITS service (Table 21). In this assessment it should be noted that the quality of C-ITS services is only assessed through the selected KPIs, and therefore EU EIP C-ITS quality criteria or human factors are not considered in the evaluation. The values merge the above Table 20 quality-of-service values. Values used in the estimation of the KPI direction of effect: +++ High, ++ Medium, + Low, - None or very little.

Table 21. Estimation of KPI direction of effect for C-ITS services utilising cellular mobile network. "Mitigation" text in the cells indicates techniques and algorithms that provide solutions for the C-ITS service to operate in conditions where the KPI would otherwise hinder (see Part A Chapter 2.3.2).

Key Performance Indicator (KPI)	RWW: Lane closure (and other restrictions)	HLN: Temporarily slippery road	SI: Signal Phase and Timing Information	PVD: Vehicle Data Collection	Collective perception
Network coverage (Availability)	+ Mitigation	+++	+++	++ Mitigation	+++
Signal-to-noise ratio (SNR) (Availability)	+ Mitigation	++	+++	++ Mitigation	+++
Accessibility (Reliability)	+	++	++	++	+++
Bit Error Rate (Reliability)	+	++	++	++	+++
Packet loss rate (Reliability)	+	++	++	++	+++
Reliability of network (Reliability)	+	++	++	++	+++
Latency: End to end latency (Integrity)	+	+++	+++	++ Mitigation	+++
Network jitter (Integrity)	-	++	++	++	+++
Network capacity (Integrity)	- Mitigation	++	++	++ Mitigation	+++
Throughput (network, capacity), communication (Integrity)	- Mitigation	++	++	++ Mitigation	+++

General insights from the table above: trend from low direction of effect to high direction of effect when moving from static traffic information (RWW) to dynamic traffic information (Collective perception), i.e., the more advanced, e.g., Day 2 services and automated driving services, the more effective the KPIs for measurement. Vice versa for the Day 1 and 1.5 services. The more dynamic, i.e., real-time the C-ITS service is the higher the KPI effectiveness when measured. Evaluation of the KPIs per category and reasoning for selection and exclusion of metrics for further analysis (Availability, Reliability and Integrity):

Availability

Network coverage (Availability) KPI has high direction of effect for all services evaluated as network coverage (geographic coverage) has been evaluated as a necessity to have the service message delivered. Although, a momentary loss of service coverage can be mitigated by using techniques and algorithms in the software, e.g., cache.

Signal-to-noise ratio (SNR) would help to measure availability of connectivity in addition to network coverage as being part of the measurement of signal strength and noise level.

Reliability
Accessibility, Bit error rate and Reliability of network KPIs can be measured through packet loss rate. These metrics present similar effect through the field.

Integrity
Latency: End to end latency (Integrity) KPI requirement higher with dynamic services. Network Jitter (Integrity) KPI has greater impact on dynamic services. Network capacity (Integrity) is similar to throughput, only the latter has higher estimated effectiveness. Throughput (network, capacity), communication (Integrity) KPI higher for dynamic and large size services

4.5.4 Suggested KPIs for further analysis

This chapter summarises the previous chapters analysis of performance metrics and provides a summary and recommendations of the Key Performance Indicators (KPIs) per KPI category. The KPIs presented in here are further analysed in Part B of the report.

Availability, as referred in the ETSI TS 132 450 (2022), the KPI indicates if the C-ITS services is available for all the end user and therefore, the cellular mobile network (or cell) is available. Availability in the literature was also referred as availability for connected data senders and receivers (EU EIP 2022). Availability KPI is presented in Table 22 below.

Table 22. Availability, Key Performance Indicator (KPI) for C-ITS service communication utilising cellular mobile network.

Availability – Key Performance Indicator (KPI)	Description	Unit	Quality of service definition notes
Network coverage	Additionally, geographic coverage. Percentage of the road network and/or selection of road classes (to be case by defined) where cellular mobile network is available. (Adapted from EU EIP 2022)	%	Availability of cellular mobile network quantified with network coverage KPI. Network coverage considered here binary: 'no network coverage' or 'verified network coverage'. See more in the work packet report 1.2.

Reliability of the service, as in 3GPP TS 28.554 (2022), refers to guaranteed and uninterrupted service to all the users, i.e., continuous packet transmissions within time constraint required by the service without failures or performance issues. Reliability KPI is presented in Table 23 below.

Table 23. Reliability, Key Performance Indicator (KPI) for C-ITS service communication utilising cellular mobile network.

Reliability – Key Performance Indicator (KPI)	Description	Unit	Quality of service definition notes
Packet loss rate	Packets not received by the destination application within the maximum tolerable end-to-end latency for that application.	%	-

Integrity of the service, as in ETSI TS 132 450 (2022) and 3GPP TS 28.554 (2022), includes metrics throughput and latency, i.e., how the radio access network impacts the service quality to all end-users. Integrity KPIs are presented in Table 24 below.

C-ITS communication includes many actors between end user and Traffic Management Centre (TMC). For example, connection between vehicle C-ITS station (OBU) and Traffic Management Centre includes several radio access network servers, links and clouds which all impact the measurement of end-to-end latency (see Part A Chapter 2.3). Nevertheless, impact of the cellular mobile network communication, radio access network, is considered having only a minimal impact on the overall latency of the C-ITS communications. Therefore, it is seen here feasible to use end-to-end latency KPI to measure message transfer time.

Table 24. Integrity, Key Performance Indicator (KPI) for C-ITS service communication utilising cellular mobile network.

Integrity – Key Performance Indicator (KPI)	Description	Unit	Quality of service definition notes
Latency: End to end latency	Time since a message is transmitted until it is received, at application layer	ms	End-to-end latency recommendation is defined as the value under which latency is 99% of cases.
Throughput (network, capacity), communication	Instantaneous data rate/throughput as perceived at the network layer.	bps	Includes download and upload rates

4.5.5 Recommendation for selection of KPIs for C-ITS service use case utilising mobile networks

Since each C-ITS service and use case are different and unique for their purpose of usage, also KPIs vary between the services. Therefore, the previously presented list of metrics and selected KPIs should not be considered final and to be used for each C-ITS service and use case by itself.

The following steps are recommended when analysing C-ITS services communication utilising cellular mobile network performance.

1. Analysis of C-ITS service use case with the KPI categories, i.e., availability, reliability, and integrity.
2. Analysis of C-ITS service use case by using the suggested KPIs under each KPI categories.
3. Analysis of possible other KPIs such as the C-ITS services communication performance metrics as presented in Table 18.

5 Service level framework

5.1 Service level frameworks in literature

The service level framework for automated road transport was studied in the AUTOMOTO project task 1.2. Communications. The AUTOMOTO project report studies the feasibility of selected motorway section for the operation of automated vehicles (SAE level 3 & 4) and proposes a framework for service level classification for automated vehicles. The service level classification builds on the ISAD (Infrastructure Support for Automated Driving) levels but has been extended to other relevant attribute areas of physical infrastructure, environmental conditions, and dynamic elements. (FTIA publications 21/2021)

The AUTOMOTO report recognises following C-ITS services, that all support road transport automation:

- Immediate collision warning
- Event, incident, and other hazardous location information
- Road works information
- In-vehicle signage
- Information on weather conditions

The Key Performance Indicators in the AUTOMOTO service level framework for automated transport are following (FTIA publications 21/2021):

- Communication performance is defined with:
    - download and upload speed (Mbit / s)
    - latency (s)
    - reliability
    - Performance describes the overall capability and reliability of communication.
- Classification for digital infrastructure
    - includes connectivity, positioning, HD map, C-ITS or similar services, traffic management and framework.
    - High requirements on connectivity performance (see pic. below), especially on higher ISAD-levels (B & A)
    - capacity requirement is not continuous and the capacity demand per vehicle varies heavily during the drive.

Based on the KPIs the following service level framework was defined in the AUTOMOTO report (Table 25).

Table 25. Service level framework for automated road transport was studied in the AUTO-MOTO project task 1.2. Communications. (FTIA publications 21/2021)

	ATTRIBUTE	E: CONVEN-TIONAL (PHYSICAL) INFRA-STRUCTURE ONLY, NO AV SUPPORT	D: STATIC DIGITAL INFORMATION / MAP SUPPORT	C: DYNAMIC DIGITAL INFOR-MATION	B: COOPERATIVE PERCEPTION	A: COOPERATIVE DRIVING
CONNEC-TIVITY	Cellular communication	None required	Available	Available	Available	Available
	Short-range communication (ITS-G5, C-V2X, etc.)	None required	None required	Available at selected hot spots	Available at all hot spots	Available at all hot spots and critical road sections
	Communication performance	None required	Download and upload speed min 5 Mbit/s, latency <5 s, reliability min 90%	Download and upload speed min 15 Mbit/s, latency <500 ms, reliability min 95%	Download speed min 100 Mbit/s and upload speed min 25 Mbit/s, latency <20 ms, reliability min 99%	Download speed min 100 Mbit/s and upload speed min 100 Mbit/s, latency <10 ms, reliability min 99.99%

The AUTOMOTO project's service level framework refers to Infrastructure Support Levels for Automated Driving (ISAD) framework, which is a categorization of infrastructure information provided to Automated Vehicles (AV). For comparison, Table 26 below presents the five ISAD levels (A–E).

Table 26. Categorization: Infrastructure Support Levels for Automated Driving (ISAD) (Inframix).

	Level	Name	Description	Digital information provided to AVs: Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Digital infrastructure	A	Cooperative driving	Based on the real-time information on vehicles movements, he infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow	X	X	X	X
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time	X	X	X	
	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs	X	X		
Conventional infrastructure	D	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs	X			
	E	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs				

5.2 Service level framework

The aim of the service level framework is to provide guidance or criteria for the quality of C-ITS services in the mobile network. The KPIs selected and recommended in this study are used to assess the performance and quality of C-ITS services. The service level framework can support measurements related to the C-ITS services, which are further analysed in Part B of the report.

Service level framework was developed in this study through the following iterative process, during which the service levels and quality-of-service threshold values were verified.

First, service level framework was defined and based on the C-ITS quality-of-service requirements introduced in the previous chapters (Part A Chapter 4.5.3). The quality-of-service requirements were analysed using the five selected C-ITS services. The threshold values follow the findings of the quality-of-service literature review, Key Performance Indicators (KPI) selected (Part A Chapter 4.5.4) and expert opinion estimations.

Second, service levels together with defined scenarios (Part A Chapter 6) were used in the following parts of the study to further analyse and classify the service levels. This included calculation of the scenario values in different traffic conditions and using the data collected from network coverage analysis and field measurements.

Service level framework defined in this study is presented below in Table 27. The framework includes the most critical KPI for C-ITS services to operate on mobile networks. The framework is divided into four levels of unreliable, basic, medium, and high.

Table 27. Service Level Framework for C-ITS services utilising cellular mobile network.

Key Performance Indicator (KPI)	Level 0: Unreliable operability	Level 1: Basic operability	Level 2: Medium operability	Level 3: High operability
Availability	No or unreliable network coverage	Verified network coverage	Verified network coverage	Verified network coverage
Reliability	Reliability < 90%, Packet loss rate > 10%	Reliability > 90%, Packet loss rate < 10%	Reliability > 95%, Packet loss rate < 5%	Reliability > 99%, Packet loss rate < 1%
Integrity	End-to-end Latency > 1 s Throughput < 5 Mbps (download and upload)	End-to-end Latency < 1 s Throughput > 5 Mbps (download and upload)	End-to-end Latency < 500ms Throughput > 20 Mbps (download and upload)	End-to-end Latency < 100ms Throughput > 100 Mbps download, > 25 Mbit/s upload

Level 0 Unreliable operability connotes that the network does not meet the minimum requirements to operate C-ITS services. This could for example implicate that there is no MNO coverage at the geographical area in which the vehicle or field measurement was executed or that there was a network outage or a similar ongoing problem during the operation/measurement. If there is no availability, i.e., no network coverage, there cannot be reliability nor integrity. Mitigation techniques and algorithm design, as introduced in the Part A chapter 2.3.2, per C-ITS service have an important role on how each service is dependent on availability of network coverage. More about the dynamics of the level 0 unreliable operations, i.e., characteristics of the KPIs, and KPIs measurements are discussed in Part B of the report.

Level 1: Basic operability ensures a verified network coverage and that a single vehicle or service can always use most of the Day 1 V2I/I2V C-ITS services. Some of the services may experience intermittent slowdowns due to relatively high latency requirements but the services are available. Level 1 might hinder the real-time transmissions of C-ITS messages.

Level 2: Medium operability ensures that a single vehicle or service can use C-ITS services that require standard throughput and latency. Services should not experience intermittent slowdowns and the network should work consistently regarding the given parameters. C-ITS services that require more real-time transmission could be implemented if the specific real-time requirements are met.

Level 3: High operability ensures that a single vehicle or service can use advanced C-ITS services that require theoretical real-time transmissions and high throughput. All selected C-ITS services should work consistently and in real-time manner.

As mentioned in the above analysis of the service levels, each selected C-ITS service is available in real-time manner in the highest level 3. Similarly, none or unreliable operability of the services is at level 0. Between levels 1–2 each service availability may vary, i.e., the performance of the service may hinder, or the service may not be available. The service availability depends on operational conditions, i.e., network availability, reliability and integrity at a given time. Table 28 below presents each of the selected five C-ITS services quality-of-service requirements (Part A Chapter 4.5.3) compared to an expert estimation of the services availability in each of the service levels 0–3.

Table 28. Service Level Framework and C-ITS services utilising cellular mobile network availability. Definitions: '–' indicates not available or unreliable operation, '(+)' indicates available but service operation may hinder, and '+' indicates available with full functionality.

C-ITS service selected for analysis (Part A Chapter 3.8)	Level 0: Unreliable operability	Level 1: Basic operability	Level 2: Medium operability	Level 3: High operability
WW: Lane closure (and other restrictions) (RWW-LC)	(+)	+	+	+
HLN: Temporarily slippery road (HLN-TSR)	–	(+)	+	+
SI: Signal Phase and Timing Information (SI-SPTI)	–	(+)	+	+
PVD: Vehicle Data Collection (PVD-VDC)	–	(+)	+	+
Collective perception	–	–	–	+

6 Scenario analysis

6.1 Literature review and methodology of scenario analysis

The scenario analysis in this study aims to simulate the total load that different C-ITS services could cause on the mobile network. It is important to notice that in this report the main aim is not to study the development and adaptation of the C-ITS services from the market perspective but rather to assess the total data needs required from the mobile network.

Therefore, the term *'scenario'* in this study refers to the analysis of each of the selected C-ITS services use cases and their mobile network data communication requirements. The analyses and conclusions are based on the literature review.

The **literature review** of this study utilised the 5GAA technical report on use case modelling and analysis (5GAA 2023), which included modelling of mobile networks data capacity requirements. When analysing data capacity, the 5GAA report uses the following model parameters, for most parts also used in the 5GAA technical report on spectrum needs (5GAA 2021):

- Environment, vehicle density and mobile sector coverage
- Information (or message) density parameters
- Connectivity architecture models
- C-ITS-message model parameters.

The environment analysis included use cases for urban, dense urban and highway. Rural environment was left out due to low requirements for network capacity. Furthermore, mobile network coverage model and sector dimension, vehicle density (per km^2) and vehicles per sector coverage was defined. (5GAA 2023)

The information (message) density parameters include analysis of each 5GAA selected use case for elements that impact on information density, such as participating vehicles (%), message update rate (Hz), detections per vehicle and number of messages. The analysis has been further divided into "Participation and detectable objects in PVD and HD maps" and "Local hazard and Traffic Information as well as GLOSA density model parameters". (5GAA 2023)

The connectivity architecture models, which were presented in more detail in chapter 2.3.2 of Part A, were divided into two: Digital Twin and Geofenced connectivity approaches. Digital Twin area of relevance parameters had three environment settings of urban (0.008 km^2), dense urban (0.008 km^2) and highway area of length (10 km). For geofenced approaches three options scale from smaller (0.023 km^2 and 0.744 km^2) to larger size of relevant areas (23.834 km2). (5GAA 2023)

C-ITS-message model includes following parameters for each of the use case (5GAA 2023):
- ETSI C-ITS message types: CAM, CPM, DENM/IVIM and SPAT
- Size (of messages, bytes)
- Update Rate (Hz).

Methodology and approach of scenario analysis

This study uses similar modelling techniques and parameters as the 5GAA study (5GAA 2023). The following paragraphs describe selections of parameters for this study. The selected analysis methods and parameters reflect the local environment in Finland, and partly in the Nordic countries when the results of the NordicWay project are used.

Environment assumptions presented below were considered in this study:

- All services selected in the study are available for the users, i.e., there is an OEM or service provider offering the selected services.
- A commercial mobile network is available at the area, i.e., the geographic coverage exists (service level framework level 1 requirement).

Environmental vehicle and C-ITS stations adaption rate variables presented below were used to forecast C-ITS use for 2030 in Finland and originate from the NordicWay 2 evaluation report (Innamaa, et al 2020):

- The percentage of C-ITS station on-board units available in vehicles.
- Traffic volume on the specific road network: high volume road, main highway, other highway, and main streets in bigger cities.
- Daily traffic volume.

Regarding the *information (or message) density parameters*, the values of 5GAA (2023) were used but complemented with the values related to the collective perception service obtained from other literature.

The connectivity architecture model chosen was the geofenced approach since the fixed area position has mostly likely larger amount of data send. This goes together within the aim of this study to analysis possible maximum data rates, i.e., highest level of data exchange in mobile networks. Additionally, geofencing approach has benefits when data privacy is considered as position of vehicle is only known within a (larger) fixed area, i.e., not the accurate real-time position as in the Digital Twin connectivity approach. Vehicle location data can be considered as personal information as it is revealing of the life habits of data subjects (EDPB 2021).

Regarding *C-ITS-message model parameters,* the values utilised were by 5GAA (2023) complemented with the values related to the collective perception service obtained from other literature.

6.2 Forecasts of C-ITS use for 2030 in Finland

European forecasts for the penetration of C-ITS on-board units in vehicles have been presented by Asselin-Miller, et al., 2016), but this report uses the more recent Nordic forecasts provided by NordicWay 2 (Innamaa, et al., 2020) as these differentiate between different road networks in Finland.

The NordicWay 2 forecasts for the percentage of on-board units utilising cellular V2I communications in vehicles in 2030 were the following:

- high traffic volume roads 39%
- other main highways 34%
- other highways 29%
- main streets in bigger cities 33%.

The average daily traffic volumes on Finnish roads using the same classfication as above in 2030 are predicted as:

- high traffic volume roads 25 000 veh/day
- other main highways 7 100 veh/day
- other highways 2 500 veh/day
- main streets in bigger cities 10 600 veh/day.

NordicWay 2 assumed that the services will also be used at all times in all vehicles equipped with an on-board unit.

If we assume that on a typical afternoon rush hour the hourly volume is 15% of the average daily volume, the average number of cellular C-ITS users in a typical afternoon rush hour in 2030 would be:

- high traffic volume roads 25 000 x 0,15 x 0,39 = 1462 veh/h
- other main highways 7 100 x 0,15 x 0,34 = 362 veh/h
- other highways 2 500 x 0,15 x 0,29 = 109 veh/h
- main streets in bigger cities 10 600 x 0,15 x 0,33 = 525 veh/h

The basic traffic flow equation states that q = vd, where q is traffic volume, v is speed and d the density of the flow. If the rush hour speed is very low, e.g. 20 km/h on an average high traffic volume road, this could mean 73 (1462/20) cellular C-ITS users per km.

In order to assess the needs in the worst-case scenario, all of the figures above are to be multiplied by five (5) as then the estimates would cover the traffic demand on the busiest roads also in the case of major events and incidents.

The density of C-ITS users on the road will be highest during severe incidents blocking at least some parts of the road and resulting in a stop and go traffic. Assuming a 2+2 lane highway with traffic stopped in both directions this could mean 800 vehicles/km and 312 cellular C-ITS users/km (assuming 4 m car length and 1 m distance between stopped vehicles).

6.3 Scenario framework

The scenario framework builds on assumptions presented in the previous chapters and it studies the selected C-ITS services separately with common parameters, as shown in Table 29.

Table 29. Scenarios with selected C-ITS services use cases and information density factors.

Use Case / Information density factors	RWW: Lane closure (and other re-strictions)	HLN: Temporarily slippery road	SI: Signal Phase and Timing Information	PVD: Vehicle Data Collection	Collective perception
Participating vehicles per road km	High traffic road: 73 vehicles x 5 = 365	High traffic road: 73 vehicles x 5 = 365	Main streets: 26 vehicles x 5 = 130	High traffic road: 73 vehicles x 5 = 365	Main streets: 26 vehicles x 5 = 130
Update rate (or sensor update rate) (Hz)	2 Hz (ETSI short range), 0.1 Hz (LHTI 5GAA)	1 Hz (ETSI short range), 0.1 Hz (LHTI 5GAA)	2 Hz (ETSI short range), 1 Hz (GLOSA 5GAA), 0.5 - 4 Hz (field experience)	1 Hz (ETSI short range), 1 Hz (GLOSA 5GAA)	10 Hz (mitigation, event triggered) (Garcia et al.)
Density Parameters values included in the length of relevance area (10 km or 1 km2) - Number of hazards or traffic control messages - traffic signals (n) in the area (km2) - vehicles participation percentage (%)	1 (estimated per 10 km length of relevance)	10 (estimated per 10 km length of relevance)	19 (estimated per km^2) (5GAA urban)	100%, 50%, 10% (recom. in literature, but already included in forecast of participating vehicles)	–
Length of relevance (km) or area of relevance (km^2)	Length: 10 km	Length: 10 km	1 km^2	Length: 10 km (10 x 1 km)	1 km^2
ETSI C-ITS message type	DENM	DENM	SPAT (4 signals)	CAM	CPM
Size of message (bytes)	400	400	1600	100	1000 (5GAA), 1600 (Garcia et al.)
Number of new detections per vehicle (CPM)	–	–	–	–	43, 25, 10 (recom.) (5GAA)

Regarding **participating vehicles**, the number for high volume roads was used to obtain the maximum data requirements. However, the number for main streets in bigger cities was used in the case of signal phase and timing information and collective perception as these services are expected to be used especially in urban environments.

Update rate values are mainly from ETSI and 5GAA sources presented in this report's literature review of C-ITS metrics. *SPAT messages* frequency is based on C-ITS Signalised Intersection field experience from city of Tampere, Finland. Value fluctuates due to multiple factors. These factors include the number of lanes in the intersection, possible pre-emptions for different types of traffic, traffic amounts and the logic of the controller controlling the signalized intersection. In addition, it has been noticed that the frequency of SPAT messages in the signalized intersection varies during the day.

Density factors were divided into following categories:

- number of hazards or traffic control messages,
- traffic signals (n) in the area (km2) or

- vehicles participation percentage (%)

The traffic signal density of 19 per km2 was based on 5GAA urban estimation 5GAA (2023), which was considered applicable to urban conditions in Finland. Similarly, SPAT message size of 1600 bytes approximation was used. Field experience in Finland indicate on average below 500 bytes SPAT message size, which include four individual phased signals per junction (or per Traffic Light Controller, TLC). Therefore, 1600 bytes SPAT message size can be considered worst case scenario.

In the case of Probe Vehicle Data, Vehicle Data Collection, vehicles participation percentages of 100%, 50% and 10% were found in the literature. In this study, the forecasts for the percentage of on-board units utilising cellular V2I communications in vehicles in 2030 were used from the NordicWay 2 study (Part A Chapter 6.2, Innamaa, et al., 2020). The assumption was made that all the vehicles capable to C-ITS-communication would participate, hence 100% participation was considered, as the total amount of vehicles capable to C-ITS-communication was already taken into consideration in traffic volume calculations.

Length of relevance (km) or area of relevance (km2) definitions depend on the nature of the service and area or location of the service usage. Scenario services RWW, HLN and PVD are used in high traffic roads, which are linear in nature (km). On the other hand, SI and CP services are used in urban areas streets where area of relevance is more suitable (km2).

Size of message (bytes) were mainly based on the 5GAA (2023) estimations, but also literature review references and field experience from the Finnish C-ITS pilot studies were applied.

6.4 Scenarios for the study

The scenarios aim to simulate the total load that different C-ITS services could cause to the mobile network. This study takes into consideration variables related to the number of vehicles capable of receiving and sending C-ITS-messages, traffic volume, as well as to the information density factors of C-ITS-messages.

In order to variate the number of vehicles capable of receiving and sending C-ITS-messages this study considers as a realistic scenario for the percentage of on-board units utilising cellular V2I communications in vehicles in 2030 to be 33%. Optimistic scenario for the C-ITS on-board unit adoption rate is considered to be 45% and pessimistic 20%.

Traffic volume is variated by considering four different scenarios:

- **Low traffic flow**, share of rush hour traffic 5% of daily traffic volume and rush hour vehicle speed of 40 km/h.
- **Average traffic flow**, share of rush hour traffic 10% of daily traffic volume and rush hour vehicle speed of 30 km/h.
- **Congested traffic**, share of rush hour traffic 15% of daily traffic volume and rush hour vehicle speed of 20 km/h.

- **Badly congested traffic**, share of rush hour traffic 20% of daily traffic volume and rush hour vehicle speed of 15 km/h.

Share of C-ITS-capable vehicles combined to the traffic flow results to the number of vehicles per kilometre in each four scenarios, as presented in Table 30. In addition, also the extreme scenario is considered, which represents the worst-case scenario as presented in more detail in Part A chapter 6.3 Scenario framework. With regards to main streets, the area of square kilometre is considered to include two roads crossing, therefore the number of vehicles is multiplied by two.

Table 30. Scenarios for the study. R = realistic, O = optimistic, and P = pessimistic adoption rate for the C-ITS on-board units.

		Low traffic flow				Average traffic flow				Congested traffic				Badly congested traffic			Extreme
		R	O	P		R	O	P		R	O	P		R	O	P	
Rush hour traffic (% of daily traffic volume)	5%				10%				15 %				20%				15%
Rush hour vehicle speed (km/h)	40 km/h				30 km/h				20 km/h				15 km/h				20 km/h
Vehicles per kilometre																	
High traffic volume roads		10	14	6		28	38	17		62	84	38		110	150	67	366
Main streets (traffic per km2)		9	12	5		23	32	14		52	72	32		93	127	57	262

Additionally, information density factors of C-ITS-messages were varied in order to comprehensively study different scenarios. Three perspectives were considered: *High, medium, and low* information density. The parameters to vary were update rate and density (includes factors such as number of hazards or traffic control messages, and traffic light signals in the area), as presented in Table 31.

Table 31. Information density factors of C-ITS-messages. H = high, M = medium, and L = low information density.

Use case / Information density factors	RWW: Lane closure (and other restrictions)			HLN: Temporarily slippery road			SI: Signal Phase and Timing Information			PVD: Vehicle Data Collection			Collective perception		
Road type	High traffic road			High traffic road			Main streets			High traffic road			Main streets		
	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L
Update rate (or sensor update rate) (Hz)	0,1	0,1	0,1	1	0,5	0,1	4	1,5	0,5	1	0,5	0,1	10	5	1
	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L
Density Parameters values included in the length of relevance area (10 km or 1 km2) - Number of hazards or traffic control messages - traffic signals (n) in the area (km2) - vehicles participation percentage (%) - number of detections per vehicle (CPM)	5	3	1	10	5	1	19	11	5	100 %	100 %	100 %	43	25	10
Length of relevance unit	km			km			km2			km			km2		

In the case of PVD (Vehicle data collection) service participation percentage of 100% is considered, since the share of vehicles capable of sending and receiving C-ITS-messages is already taken into consideration in vehicles per kilometre parameter. The density parameters of Collective Perception service are not considered as multipliers directly, but they are taken into consideration by the size of message (1600/1300/1000 bytes, more detections per vehicle results to larger size of the message).

7 Conclusions of Part A.

The aim of this first part of the research was to define Key Performance Indicators for C-ITS services utilising commercial mobile network as well as a common service level framework criterion to cover various scenarios of use of services. The research methods of this study were literature review, interviews, expert knowledge, and collaboration in the project management group.

Cooperative Intelligent Transport Systems (C-ITS) means intelligent transport systems that exchange real-time C-ITS messages with vehicles, other road users, infrastructure and other environment using European Union C-ITS security credential management system (EU CCMS). EU CCMS is the European Union C-ITS framework for trusted and secure C-ITS communication using Public Key Infrastructure (PKI).

The criteria were defined to select C-ITS services for analysis: 1) strategic: European strategy and legislation and needs in Finland, 2) technical: C-ITS message type, logic of transmission and C-ITS service use case impact on mobile network and 3) impact of automated driving and other services. Five C-ITS service use cases were selected for further analysis: 1) Road Works Warning, Lane closure, 2) Hazardous Location Notification, Temporarily slippery road, 3) Signalised Intersection, Signal Phase and Timing Information, 4) Probe Vehicle Data, Vehicle Data Collection and 5) Collective Perception Service.

C-ITS services performance metrics and telecommunication standardisation metrics were listed to study Key Performance Indicators (KPI). Three KPI categories were identified: Availability, Reliability, and Integrity. For the KPI categories, four KPIs were identified: network coverage, packet loss rate, throughput, and latency.

The Service Level Framework was defined based on the identified critical KPIs for C-ITS services to operate on mobile networks. The framework was divided into four levels of operability: level 0 unreliable, level 1 basic, level 2 medium, and level 3 high. The minimum requirements for quality were also recommended for each service level.

Scenarios were developed for each of the selected C-ITS services use cases to simulate the total load that different C-ITS services could cause to the mobile network in 2030. The scenarios included estimation of information density factors.

The KPIs presented in the study should not be considered as final indicators for C-ITS service use cases utilising a mobile network. Instead, the KPIs are heavily C-ITS service dependent, and individual analysis is needed each time when evaluating the performance or quality of the services. Therefore, the limitations of this study only cover KPIs for the selected C-ITS services. Mitigation techniques and congestion management algorithms used by the service providers have an impact on the quality of the service and were only partly covered in this study.

The selected KPI values, service level framework and scenarios were further developed in the research project’s other parts. Further study of the C-ITS services utilising commercial mobile networks is recommended in the future, where KPIs such as identified in this study are further developed.

Part B. Measurement methodologies and techniques

1 Introduction

In order to define whether the performance of mobile networks in Finland is adequate for C-ITS services, measurement methods must be developed to cover the specific need of C-ITS services.

This Part answers the following research questions:

- *How are different mobile network technologies suited to serve the needs of different C-ITS services, based on the identified requirements from Part A?*
- *What kind of methods can be utilised to prove the functionality of different types of C-ITS services in the commercial mobile networks?*

This Part starts with an introduction of different mobile network technologies and measurement methods used to measure mobile networks of the various Finnish mobile network operators. C-ITS specific requirements for the mobile network measurements are taken into consideration based on the definition of C-ITS related KPIs from the Part A.

Chapter 2.1 provides a high-level overview of mobile networks technologies, their capabilities and functionality. Chapter 2.2 discusses the characteristics of wireless networks and the challenges in guaranteeing service level to different use cases. Chapter 2.3 presents future development of mobile network technologies, including some key features and functionality that are expected to be introduced and potentially affecting the ability of mobile networks to provide the required service level for C-ITS services. Chapter 2.4 provides insights into mobile network spectrum options and highlights the characteristics of different frequency bands, their advantages and disadvantages. Chapter 2.5 discusses the current commercial mobile networks and technology deployments in Finland. Chapter 3 provides an overview of mobile network measurement and analysis methods and chapter 4 analyses and summarizes the applicability of current measurement methods from the perspective of C-ITS specific requirements. Finally, a measurement methodology is developed in chapter 5 to assess the suitability of commercial networks for the introduction of C-ITS services and for future development needs.

Methods

The research methods of this study were literature review, expert assessment, and collaboration in the project management group. The methods are presented in more detail below.

The literature review included scientific articles, standards, legislation, conference publications and reports, e.g. of pilot projects. The literature review was conducted by online research and scientific publications. The applicability of current measurement technologies was determined by comparing the C-ITS specific requirements for the measurements to the capabilities of current technologies. A measurement methodology framework was developed using the results of this study and previous literature in an iterative process within the project team.

2 Mobile networks

2.1 Overview of mobile network technologies

This chapter provides an overview of the technologies used in commercial mobile networks. The overview includes a high-level comparison of the typical deployments, performance capabilities and functionality of the different technologies, and discusses the differences between technologies ability to support mobility and increase in number of connected devices.

Digital mobile networks have been part of the Finnish communications infrastructure since the early 1990s. Different mobile network technologies use different access techniques and specific spectrum bands, but technologies coexist in some spectrum bands. Spectrum bands and their characteristics are further discussed in the following chapters.

GSM (Global System for Mobile Communications) technology, also known as the 2nd generation technology of mobile networks, or 2G, made mobile communication accessible to the public during the 1990s. 2G technology was originally aimed at providing circuit-switched voice call communication, but packet-switched data communication was also available through GPRS (General Packet Radio Service) and EDGE (Enhanced Data Rates for GSM Evolution) technologies for 2G. The EDGE technology was able to provide close to 0,4 Mbit/s theoretical maximum data rate.

UMTS (Universal Mobile Telecommunications System), or 3G technology networks were built in Finland in the early 2000s, providing an improved voice and data communications network. The first UMTS networks enhanced with HSDPA (High-Speed Downlink Packet Access) technology were able to provide data communications with over 2 Mbit/s data rate. Later evolution of High-Speed Packet Access (HSPA) advancements in UMTS networks, like higher order modulation and dual-cell, improved the data service and were able to provide up to 42 Mbit/s maximum downlink data rates and over 10 Mbit/s in the uplink.

LTE (Long Term Evolution) technology and its later advancement LTE-A (LTE-Advanced) are the technologies used in 4th generation, 4G, mobile networks. LTE technology was deployed in Finland in the early 2010s, offering up to 150 Mbit/s download data rates and up to 50 Mbit/s in the uplink. LTE-A enabled for example the simultaneous use of different frequency spectrum carrier and more efficient modulation, increasing the achievable downlink data rates to over 300 Mbit/s.

NR (New Radio) technology has enabled the deployment of the 5th generation, 5G, mobile networks. Although technically very similar to LTE technology, NR advancements enable the use of higher frequencies and wider spectrum bands, as well as more extensive antenna configurations (massive-MIMO). These advancements can provide over 1 Gbit/s downlink data rates with the widely available 3,5 GHz spectrum band (C-band, 3,4-3,8 GHz), and in the future over 10 Gbit/s with the already assigned spectrum in the 26 GHz range.

Although previously all technologies operated fully independently and separately from each other, LTE and NR technologies are designed for interoperability, enabling Non-Standalone (NSA) 5G network use with LTE networks (using LTE signalling leg and LTE core network), before the required 5G centralized functionality in the core networks is deployed. Standalone (SA) 5G networks will enable further development in especially machine-type and low-latency communications.

Table 32 below presents an overview and comparison regarding key properties and functionality of the existing mobile network technologies.

Table 32. High-level mobile network technology comparison.

	2G	3G	4G	5G
Overview				
Original functionality	Circuit-Switched voice calls	Circuit-Switched voice calls + Packet-Switched data service	Packet-Switched data service	Packet-Switched data service
Age	30+ years	20+ years	10+ years	<5 years
Network and device land-scape	Mature	Mature	Mature	Developing
Future outlook	Limited life-time left	Limited life-time left	10+ years lifetime left	20+ years lifetime left
Common frequency bands (2024)	900 / 1800 MHz	900 / 2100 MHz	700 / 800 / 900 / 1800 / 2100 / 2600 MHz	700 / 2100 / 3500 MHz
Duplexing method	Frequency Division Duplex	Frequency Division Duplex	Frequency Division Duplex (Time Division Duplex only on 2600 MHz)	Frequency Division Duplex (<3 GHz) / Time Division Duplex (>3 GHz)
Data service				
DL throughput magnitude	~100 kbit/s	~1-10 Mbit/s	<1 GHz: 50 Mbit/s 1-3 GHz: 100 Mbit/s	<1 GHz: 50 Mbit/s 1-3 GHz: 100 Mbit/s >3 GHz ~500 Mbit/s
UL throughput magnitude	50 kbit/s	~1 Mbit/s	~20 Mbit/s	<3 GHz: ~20 Mbit/s >3 GHz: ~100 Mbit/s
Latency level	~1000 ms	~100 ms	~20 ms	<3 GHz: ~20 ms >3 GHz: ~10 ms (SA)
Jitter	high	high	low	low
Features and functionality				
Mobility	Hard Handover	Soft & Hard Handover	Hard Handover	Coordinate Multi-Point
Carrier Aggregation	No	Intra-band (dual-cell)	Yes	Yes
MIMO deployments	No	No (support specified)	4x4	massive-MIMO (TDD) like 64x64

	2G	3G	4G	5G
MIMO: spatial multiplexing	-	-	<1 GHz: 2x2 1-3 GHz: 4x4	<1 GHz: 2x2 1-3 GHz: 4x4 >3 GHz: 8x8
MIMO: transmit diversity	-	-	Yes (e.g., 2x1, 4x2, 4x1)	Beamforming (e.g., 64x8)
Max vehicle speed	250 or 130 km/h	500 km/h	500 km/h	500 km/h
Number of connected users per cell	Max ~6 (1 TRX config, and 10 kbps)	Max ~40 (With 1 carrier and 10 kbps)	~100-300	~1000+

2G networks have been used for over 30 years but are expected to be gradually shut down in the future. No specific date for 2G shutdown is publicly communicated by any of the Finnish operators, but the regulator has extended the requirement to keep 2G networks still live until the end of 2029. There are still several machine-to-machine (M2M) deployments connected in the 2G networks like energy meters, sensors, card payment machines etc. that affect operators' capability to close the network. The shutdown timeline of 3G networks has been publicly communicated in Finland by end of 2023, therefore freeing the valuable spectrum resources like 2100 MHz band from legacy technology to be used for next generation technologies. There is no indication or plans for phasing out 4G technology, as that remains the primary mobile data communication technology. 5G adoption will decrease the 4G significance in the future, but both are expected to maintain relevance and can coexist and interoperate well into the future.

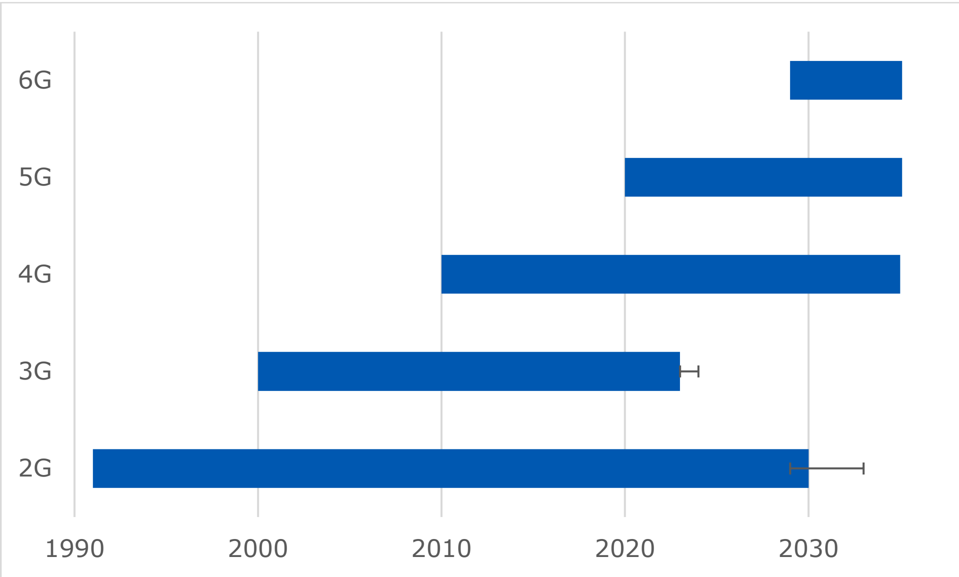


Figure 8. Expected lifecycles of mobile network technologies in Finland.

Concerning mobility features, originally 2G network was specified to support vehicle speeds up to 250 km/h on 900 MHz and 130 km/h on 1800 MHz band. Later generations 3G, 4G and 5G all support vehicle speeds up to 500 km/h. The main difference between 2G network mobility and 3G is hard vs. soft handover i.e.

multi-cell connectivity. In GSM network all cell changes are performed as hard handovers, where the user terminal is always connected to only one cell at the time and when moving away from the service area of one cell the link is broken, and another is established. In 3G technology the user is typically served by multiple cells even from different base stations at the same time. 3G soft handovers between cells of the same frequency are performed "softly", meaning that connection to a new cell is established before the old one is released. Hard handovers are also executed in 4G networks, used in mobility between the same (intra-band) and different carrier layers (inter-band). X2 interface -based handover is used when an X2 interface exists between two LTE base stations, i.e., the base stations communicate directly with each other in managing the handover from one base station to the other. S1 interface -based handover is used when no X2 interface is available between the source and the target LTE base station. In that case, the handover process is managed by the MME (Mobility Management Entity), an element in the mobile core network. In 5G technology there are two types of handovers: network controlled, and UE (User Equipment) controlled handovers.

2.2 Mobile network characteristics

This chapter discusses the characteristics of wireless networks and the challenges that wireless connectivity inherently presents for guaranteeing service level to different use cases and applications.

A key difference between the capabilities of the mobile network base station and the (end-user) device is that the mobile network base station transmit power is in the range of tens to hundreds of watts (W) and the transmit power of the (end-user) devices is limited to two watts. Therefore, the signal from the base station can be stronger by a magnitude of several ten-fold compared to the signal from the (end-user) device. This enables larger coverage in downlink, as the Signal-to-Interference-and-Noise-Ratio (SINR) at the receiver side can be increased with higher transmit power at the transmitter side. The receiver sensitivity in the mobile network base station is much higher than in the (end-user) devices, which alleviates the asymmetricity to some extent, but the mobile networks are still inherently uplink-coverage limited.

Mobile network capacity and service level can be increased through different means. The three main development paths are:

- Spectrum – add additional spectrum to increase the spectrum bandwidth: different spectrum bands are best suited for different purposes. Due to smaller attenuation of radio signal propagation, low bands below 1 GHz serve best on rural areas and provide best (indoor) coverage benefit, but only moderate capacity due to narrow bandwidth. Mid and high bands with wider bandwidth provide the best capacity option with small cell deployments in dense-grid environment like urban/cities.
- Technology – improve the spectrum utilisation efficiency through the use of improved technologies, including repurposing/refarming spectrum for legacy technologies (e.g., 2G and 3G) to future-proof technologies (e.g., 4G and 5G), and further improve with advanced features that improve the spectrum utilisation efficiency.

- Topology – introduce new network nodes for better coverage, capacity and serving the local special demand, like traffic hotspots and events.

The key challenge with mobile networks is that the network deployment is rather static in nature, whereas the users are mobile. In most cases, the patterns of behaviour remain rather constant, e.g., for road sections utilised for daily traffic and extreme overnight shifts in traffic flow are rare. However, introducing new services utilising the mobile networks can change the data traffic demand in mobile networks even drastically if the adoption is quick. The service level in mobile networks cannot therefore be expected to remain constant, or even predictable in many cases.

Because new spectrum and technology deployment and especially topology changes require installation of new equipment and sometimes civil works, there needs to be sufficient lead time for network changes until the time when such additional capacity or deployment is needed. Therefore, the more predictive the measurements and assessments are, the better the network operators can prepare for the changes in traffic patterns by deploying additional equipment to their networks.

The call for effective measurement and even prediction capabilities are ever more pressing with the introduction of additional services relying on mobile networks. And if the services using the mobile networks are safety critical, the requirements for such capabilities are emphasised.

Referring to the first question set in the beginning of this Part "*How are different mobile network technologies suited to serve the needs of different C-ITS services, based on the identified requirements from Part A of this report.*", it can be first concluded that 2G networks are clearly not serving the packet-switched date service needs that C-ITS services would require, not even on the very lowest service level (level 1). What comes to 3G networks, their capabilities are much better and would be partly suitable for supporting such data service needs on level 1. However, as all national 3G networks are about to be shut down until the end of 2023, any further analysis becomes irrelevant. The most futureproof mobile networks, 4G and 5G, are the key technologies in supporting C-ITS services in the long-term, in general providing required capabilities and functionality. Network capacity is then the next question, and how much C-ITS traffic can be accommodated in 4G/5G networks besides all the other data traffic generated by other mobile users.

2.3 Future development of mobile network technologies

This chapter presents some key features and functionality that are expected to be introduced to mobile networks and could have an impact on the ability of mobile networks to provide the required service level for C-ITS services. The mobile network development is subject to the continuous development of the equipment on both the network and the end-user devices. New features and functionality are introduced to mobile networks through every release.

Main features and functionality of mobile 4G and 5G networks are:

- Carrier aggregation: technology that enables higher throughputs by using multiple spectrum bands simultaneously, available in 4G and 5G, as well as between the technologies in both NSA and SA. Limited support for aggregation on sub-GHz due to physical end-user device limitations (requiring larger device size for efficient antenna element separation between different spectrum bands). Carrier aggregation is used to boost the throughput of a single user by allocating capacity from multiple spectrum bands simultaneously, when the coverage is available from the network and the traffic to the device requires additional capacity. The C-ITS applications under investigation in this report do not require such throughput capacity that carrier aggregation would be needed. Therefore, the analysis focuses more on the mobile network total capacity, and the availability of adequate coverage, e.g., from sub-GHz bands in rural areas.

- Antenna systems: MIMO (multiple-input, multiple-output) technology allows using different antennas to either boost the signal strength to users by transmitting the same signal from multiple antennas to amplify the signal at the receiving end – transmit diversity. Alternatively, using different antennas to transmit different signal on the same spectrum to effectively multiply the capacity of the spectrum band – spatial multiplexing. Traditional MIMO systems typically enable up to 4 antenna streams for mid-bands (1-3 GHz) and 2 antenna streams in low bands (< 1 GHz). Massive MIMO, available with higher frequency spectrum and Time Division Duplex (TDD) deployments, effectively allows using several antennas to provide both spatial multiplexing for multiplying the available capacity and transmit diversity to boost the signal strength.

- Improved modulation: higher order modulation allows the signal to carry more bits per signal symbol. High-order modulation is already widely available, and further improvements are likely only on higher frequency spectrum bands and 5G. High-order modulation (like 256QAM, Quadrature Amplitude Modulation) usage is a compromise between needing more re-transmissions to deliver data correctly, the overall aim is to maximise system capacity (15% retransmission ratio is typically accepted, aiming to maximise use of higher order modulation). Higher order modulation is generally available only in very good signal conditions.

- 5G network slicing: defining virtual instances with different QoS (Quality of Service) targets for different services, further priorities to enable "almost" guaranteed 100% reliability end-to-end service experience, low bit rate service through slicing. Slicing will not increase the overall capacity, therefore still requiring investment to additional capacity, where capacity is limited. Proper slicing can only be implemented in 5G SA deployments including 5G core network, so that both radio and core elements are able to track the unidirectional performance of application flows and take dynamic enforcement actions where needed.

- IoT (Internet of Things) solutions:
    - NB-IoT (Narrow-Band IoT): using 200 kHz bandwidth – limited capacity.
    - Cat-M / LTE-M: using 1.4 MHz bandwidth – higher capacity.

- 5G mMTC (massive Machine-Type Communications): enabling very high density of connected devices. Development still on-going but could potentially have elements suitable for high-device-density and high-message-frequency services such as in the C-ITS framework.

- 5G URLLC (Ultra-Reliable, Low-Latency Communications): very low latency and high reliability services
  - Low latency through use of higher spectrum carriers: short transmission time interval from increased sub-carrier spacing.
  - Earlier "mini-slot" development for lower sub-carrier spacing not continued, air-interface 5G latency on sub-GHz and mid-bands is comparable to 4G.
  - Reliability: different network slices for different QoS services, e.g., offering low data rate service, with near guaranteed delivery: lower order modulation to ensure sufficient Signal-to-interference/noise-ratio (SINR).

2.4 Mobile network spectrum options

Mobile networks today are based on a combination of different spectrum bands, with different amount of total spectrum bandwidth and different signal propagation characteristics. With 4G and 5G technologies, different spectrum bands can be combined, i.e., used together, for mobile network users to increase the available capacity when needed.

A further difference between the different spectrum bands, is the method of allocating resources between downlink and uplink communication. Uplink communication is the communication from (end-user) devices towards the mobile network base station, and downlink communication is the communication from the mobile network base station towards the (end-user) device.

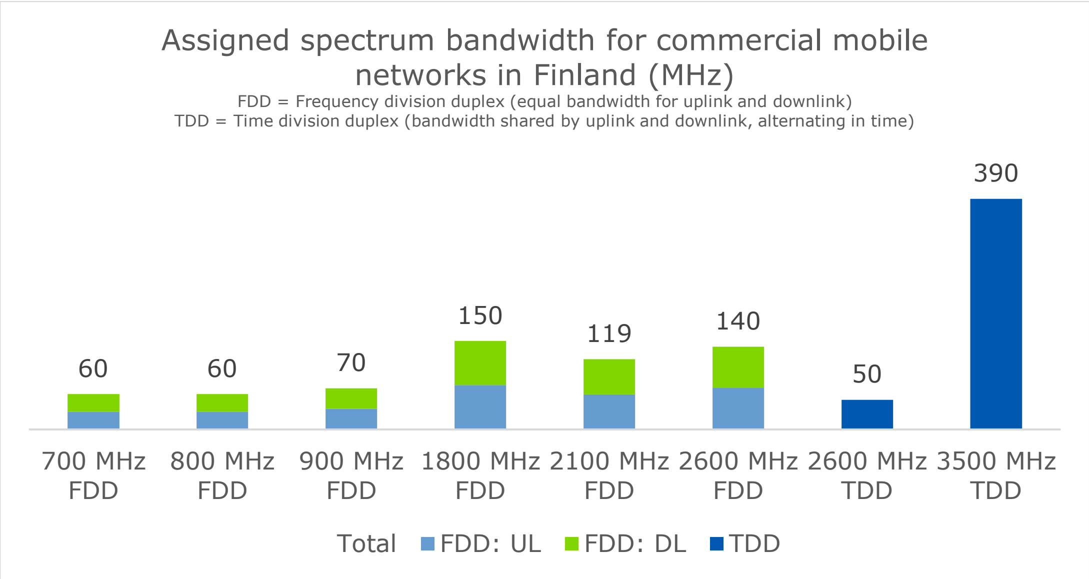


Figure 9. Mobile network spectrum in Finland as per November 2023.

The mobile network spectrum bands assigned to commercial mobile networks in Finland are illustrated in Figure 9. The different spectrum bands are either using Frequency or Time Division Duplexing method, FDD or TDD, as standardised across different regions globally, and the spectrum is assigned to the operators with designated duplexing method. Except for the 2600 MHz TDD spectrum, the other spectrum bands are roughly evenly distributed between the three national commercial mobile network operators, with 1/3 of the total spectrum assigned to each.

Different spectrum bands provide the opportunity to match the service level to the user needs. Sub-GHz bands provide excellent coverage characteristics and can cover large geographical areas and reach deep indoor users. However, due to limited spectrum bandwidth available on the sub-GHz bands, the deployment cannot provide high-capacity services. Mid bands, i.e., frequency spectrum between 1-3 GHz can provide higher capacity services due to availability of more spectrum bandwidth and the ability to effectively aggregate the different spectrum bands in both 4G and 5G technologies. The higher bands, i.e., bands between 3-6 GHz, can offer even higher capacity services due to much more bandwidth and the ability to use wider contiguous bandwidth in 5G technology, but require denser site grid due to higher radio path attenuation.

Due to the different propagation characteristics of the different spectrum ranges, all spectrum bands are not suitable for nationwide coverage. The lower spectrum bands can provide much more extensive coverage compared to higher spectrum bands.

In urban city environments, the coverage area is limited mainly by buildings. Because mobile networks are also providing coverage indoors, the placement of the base station antennas is designed to cover a specific area and the buildings in the specific area. To avoid interference between the different base stations and to ensure sufficient capacity in the service area, the mobile network operators design small service areas for each base station. In typical urban city environments, the coverage of sub-GHz bands (700-900 MHz) is in the range of ~500 meters, while the coverage of mid-bands (1800-3500 MHz) is in the range of 200-300 meters. On city road sections, the outdoor coverage of mid-bands can be close to equal to sub-GHz bands.

In suburban environments, the buildings are typically not as high and are further apart, allowing the coverage to extend further. Furthermore, with users spread out less densely over the area, the mobile network operators can design larger coverage areas while still providing sufficient capacity to the coverage area. Often mobile network base station antennas are deployed in 30-50 m towers, enabling larger coverage area than in urban areas, where antennas are most typically deployed on building rooftops or the sidewalls of buildings. Typically, the coverage range of sub-GHz bands in suburban areas can reach over 1.5 km and mid bands can reach over 500 m.

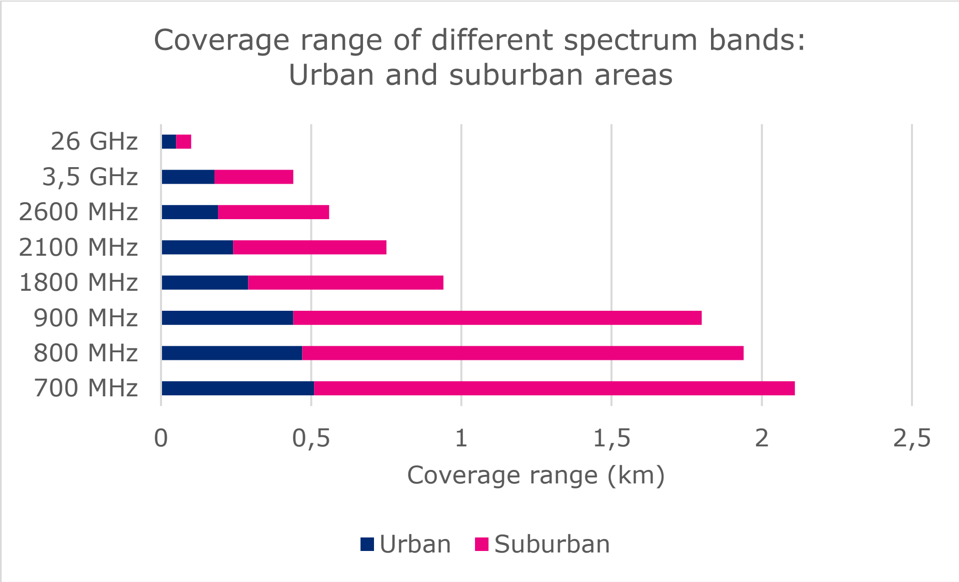


Figure 10. Indicative coverage range of typical spectrum bands in urban and suburban environments.

In rural areas, base station antennas are typically deployed in higher towers (over 60 meter), enabling a much larger coverage area. Typical coverage range for sub-GHz bands can be in the range of 10 km, and 5 km for mid bands.

On remote road sections, a high mobile network tower can in theory provide coverage from very long distance (over 20 km) if there are no attenuating obstacles along the line of sight. In practice, at such distances from the mobile network base station, the signal strength and quality will vary significantly based on the location of the end-user terminal.

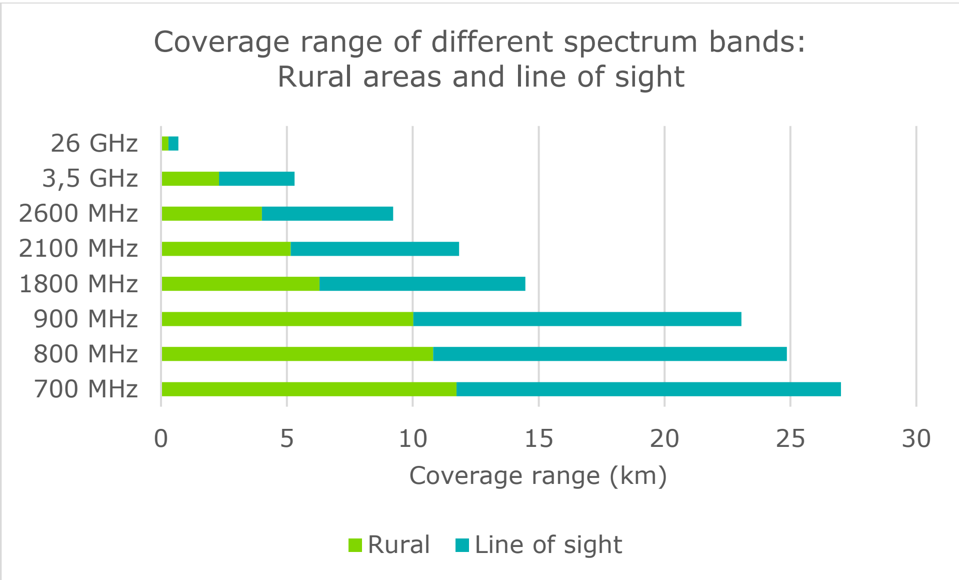


Figure 11. Indicative coverage range of typical spectrum bands in rural environment and when there is a direct line of sight.

In the following chapters, a set of typical coverage range and site density values are used for estimating the ability of mobile networks in different environments to serve the C-ITS traffic. The key values are presented in Table 33. The values for coverage range are based on mobile network link budget calculations and represent typical averages for the different environments.

Table 33. Typical figures for mobile networks in different environments.

Environment	Antenna height	Primary LTE band	Primary band range	Coverage area (max)	Inter-site distance
Urban	20 m	1800 MHz	300 m	0.2 km²	200 - 300 m
Suburban	35 m	1800 MHz	1 km	2 km²	0.5 - 1 km
Rural	60-80 m	800 MHz	10 km	200 km²	5 - 10 km
Sparse rural	80+ m	800 MHz	15 km	400+ km²	10 - 15 km

Typical mobile network base station sites in Finland are three-sector sites, meaning that there are three antenna directions from any given tower or rooftop location. In an ideal a 3-sector configuration, the sector service range is 2/3 of the Inter-Site Distance (ISD). Some roadside base station sites may only have two sectors, to cover the road in both directions. In these scenarios, the sector service range is 1/2 of the inter-site distance.

2.5 Commercial mobile networks

Commercial mobile network development is still heavily driven by data traffic demand development. Networks are being developed continuously to serve the increasing data traffic demand. Figure 12 illustrates the extent of 100 Mbit/s availability with 4G (Traficom, 2023) and 5G (Traficom, The coverage of mobile network 5G 100Mbit/s 250 x 250 m grid (30.6.2023), 2023) in Finland with a focus area separately highlighted from a predominantly rural area. With 4G, the 100 Mbit/s coverage requires at least mid-band (1-3 GHz) deployment, and the focus area shows that smaller villages are covered with 100 Mbit/s. With 5G, the 100 Mbit/s coverage is currently available in practice with the 3,5 GHz band, and the focus area shows, that most smaller villages do not have 5G 100 Mbit/s available. Typical small villages are rural areas, while some larger towns could be considered suburban areas.

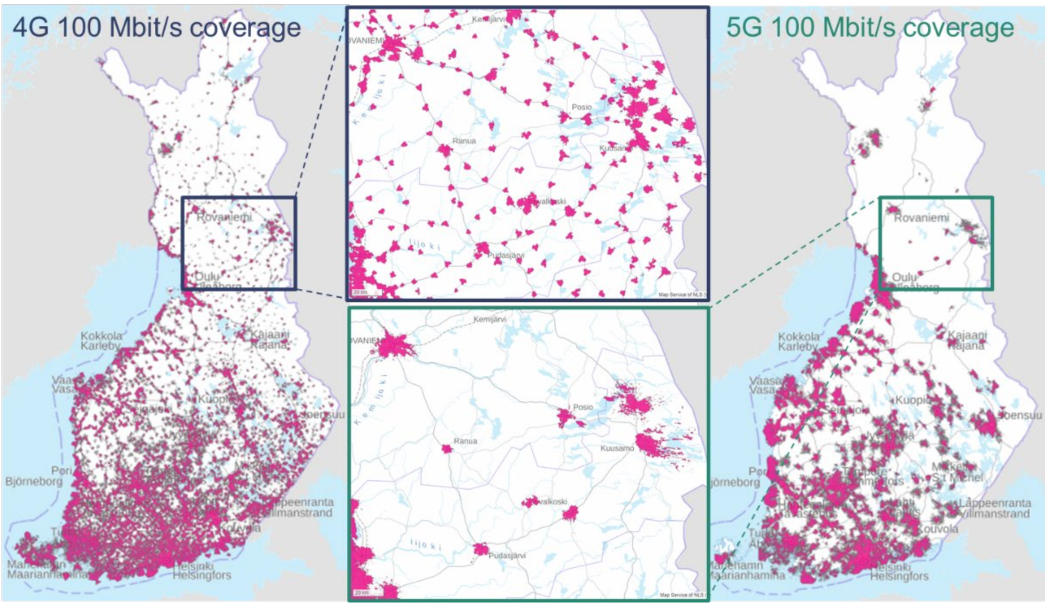


Figure 12. Rural 4G (on 31.3.2023) and 5G (on 30.6.2023) 100 Mbit/s coverage.

Based on the best assessment of the commercial network developments in Finland, Table 34 indicates the typical use of the different spectrum bands in different environments.

Table 34. Estimated share of base stations sites where spectrum band is used in different environments.

Spectrum band	Technology	Bandwidth in 4G/5G	Urban	Sub-urban	Rural
3,5 GHz	5G	100 MHz (UL/DL)	>75%	>50%	
2600 MHz	4G	2x20 MHz (UL+DL)	<50%	<50%	
2100 MHz	4G/5G	2x20 MHz (UL+DL)	>75%	>75%	<50%
1800 MHz	2G/4G	2x20 MHz (UL+DL)	100%	100%	>50%
900 MHz	2G/4G/5G	2x5-10 MHz (UL+DL)	<50%	<50%	<50%
800 MHz	4G	2x10 MHz (UL+DL)	100%	100%	100%
700 MHz	5G	2x10 MHz (UL+DL)	>50%	>50%	>75%

Legend for 4G/5G usage of spectrum bands	
Typical in most sites	>75%
Common for additional capacity or coverage	>50%
Sometimes for additional capacity or coverage	<50%
Not used in the environment	

In the Finnish 4G networks, 800 MHz band is deployed nearly networkwide. This provides the baseline 4G coverage in rural areas and improves the indoor coverage in urban and suburban areas.

A 1800 MHz band has been used as the baseline 4G layer in urban and suburban areas, and it is typically complemented with higher bands for additional capacity where needed and lower bands for improved indoor coverage. 1800 MHz is used also quite often for additional capacity in smaller villages in rural areas, where the 800 MHz provides larger area coverage around the village and 1800 MHz provides additional capacity to the more densely populated villages.

A part of the 900 MHz spectrum band continues to be used for 2G network coverage, complemented locally with a small part of the 1800 MHz spectrum. 2G deployment does not require the whole available band and can therefore accommodate also other technologies in the same bands.

Until quite recently, the 900 and 2100 MHz spectrum bands have been extensively used for 3G networks. With the shutdown of the 3G networks, the spectrum is released for 4G/5G usage. 2100 MHz has already gradually been freed for 4G/5G usage and is already quite extensively used for 4G networks in urban and suburban areas. 900 MHz use for 4G/5G is still relatively limited but can be expected to increase in the near future. Especially close to eastern country border LTE900 has been deployed due to limitations with 800 MHz band usage. As new technologies provide better spectral efficiency and better coverage with low data rates using the same site locations, it's also a driver for refarming the legacy bands (like 900 MHz) and repurposing them for LTE/5G.

The 2600 MHz band was the first 4G-dedicated band available in Finland. The use of the band is limited to high-traffic locations in urban and suburban areas. Smaller towns often have a few individual areas of higher population density with mobile network base station site(s) equipped with low and mid bands, also including 2600 MHz.

The 3,5 GHz spectrum band has been quite actively deployed in cities and suburban areas. In cities, the deployment is becoming quite commonplace, while in suburban areas, the deployment is more opportunistic. It can be expected that deployment will continue in the coming years.

3 Current mobile network measurement and analysis methods

Mobile network measurement and analysis methods used in Finland can be roughly divided into three main categories: coverage predictions, field measurements and crowdsourced data. The measurements and analyses of results within these categories must be conducted in a category specific manner, and even if different actors conducting these measurements might have different procedures for the measurements, the results within the same category are usually in line in terms of reliability and usability, regardless of their producer.

There are three competing mobile network operators operating in mainland Finland, for which frequency bands have been allocated evenly from each available frequency range. These operators publish commercially produced network performance measurements, in which the priorities can be slightly optimized in the direction desired by each subscriber, but the larger the sample, the more likely the benefit from optimization will be lost due to the diversity of mobile networks. In addition, the authorities require the operators to deliver data about their network coverage, produced with a certain set of parameters. The authorities publish the combined field measurement results from various operators, so that the differences between different operators are not available.

3.1 General information about measurements and analysis

Every measurement method has its own strengths and weaknesses and are therefore applicable differently to selected use cases and assessing the network information. Table 35 presents high-level comparison of main measurement methods with their pros and cons as well as usability.

Table 35. High-level comparison of main measurement methods and their usability.

MEASURE	Coverage predictions	Field measurements	"Crowdsourced" user measurements
WHAT	Estimate signal strength or quality level in any given location.	Measure the actual coverage and service performance.	Measurement from actual user devices.
HOW	Radio network planning tool with digital map data using signal propagation models.	Use cases empirically tested with professional measurement equipment.	Embedded SW to collect usage statistics or dedicated applications for connection testing.
CURRENT USE	Used to assess the availability of different data performance (like throughput) levels based on predefined signal strength thresholds.	Measure the network performance and Quality of Service level, a reliable comparison.	Used for commercial benchmarks.
PROS	Efficient assessments of overall development and rough indication of service availability.	Accurate snapshots depending on collected sample counts. Real network performance and maximum capability testing (stress test). Ability to plan and test new use cases.	View of a set of users using the selected services / applications.
CONS	Low reliability for localized assessment. Is based on estimative conversion between signal strength and data performance but does not include capacity and traffic load related aspects at all.	Extensive measurements required to gather samples (results) covering the overall deployment area. Service quality results present network performance of only a certain short timeslot.	Limited to current use cases. No control of used terminals, subscriptions and their capabilities or restrictions. Hence, does not provide reliable view of full network performance potential.

Measurement methods can be differentiated based on measurement accuracy (approximation or actual) and measurement scale/coverage (snapshot or extensive) as Figure 13 illustrates. Because of these different characteristics it is not possible to place these methods in a ranked order, but rather the suitable method depends on the use case, and it can even be a combination of different methods.

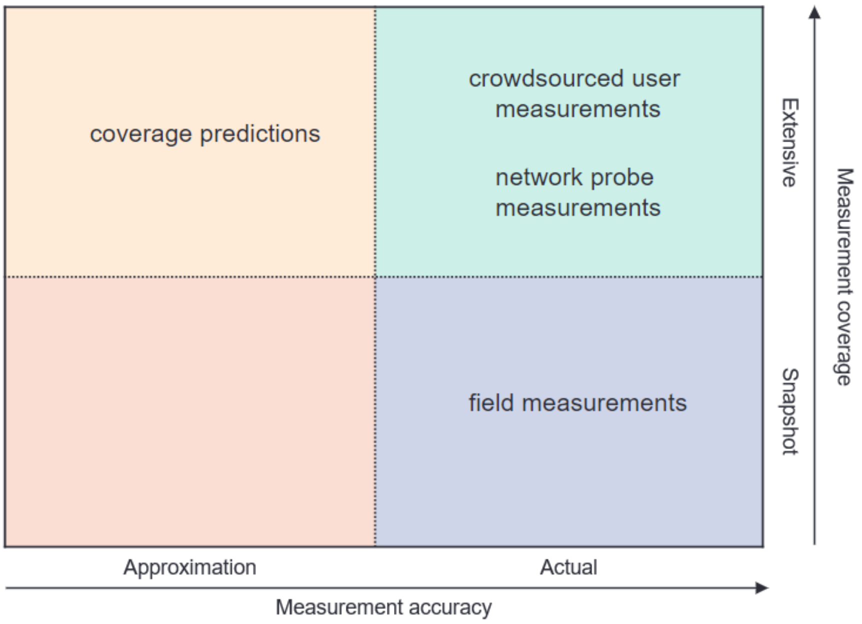


Figure 13. Measurement accuracy/coverage matrix (Omnitele 2023).

3.2 Coverage predictions

Coverage predictions require up-to-date digital map data which provides information about attributes such as environment, typical causes of signal processing clutter and ground height. In a densely built environment, such as in cities, buildings create covered areas, obstacles, and cause signal reflection and degradation. Typically, this can be done by combining maps with different vector data like topology, buildings (especially height information) and population. In order to simulate signal strength with proper accuracy, antenna type specific radiation patterns are required and signal propagation models need to be finetuned for different environments and frequency bands using empirical field tests. Finally, to be able to apply coverage predictions on desired service deployment, service level requirements and signal thresholds need to be defined by link budget calculations.

Currently, coverage predictions are widely used to estimate the availability of different throughput levels based on predefined signal strength thresholds. The availability of different throughput levels in Finland is based on the coverage predictions provided by mobile network operators to competent authority (Traficom). The predictions are based on the coverage thresholds and parameters defined by Traficom in TIKU-M definition document. (Traficom 2023)

However, the thresholds i.e., minimum service level requirements are only estimating what level of coverage would theoretically be needed to enable desired data performance. Pure mapping between pilot/reference signal strength and data performance does not include any network capacity or traffic load related considerations. In addition, the output of coverage simulation depends on propagation models and deployed antenna configurations. Therefore, as every operator uses its own models, each will also end up generating different predictions, despite of the same applied thresholds. In addition, the deployed network architecture, multiple frequency bands and layers (with Carrier Aggregation) and vendor configurations make it very challenging to create guidelines on how to generate accurate service level predictions in entire network scale.

Coverage predictions can provide rough estimates of overall development and indication of service availability on certain area. However, the reliability of any localized assessments is low and requires complementary inputs from other measurement methods.

3.3 Field measurements

Empirical tests in a live mobile network carried out with professional measurement equipment provide actual data on coverage and service performance. Test cases are selected according to deployed services, used applications and end-user behaviour. Carefully planned and executed field tests give reliable and accurate snapshots on Quality of Service (QoS), especially on focus-areas and predefined locations.

Nonetheless, extensive scale of measurements involving comprehensive data collection (samples gathered) are required to cover the overall deployment area and to enable feasible benchmarking or other comparison in means of statistical reliability. Depending on the nature of field measurements (signal coverage/quality scanning vs. voice/data service tests) the applicability of results varies as the service quality test results present network performance of just a certain short time period. Hence, repeating the tests would most likely result in slightly different outcomes. With scanning measurements, the variation is much smaller, and the validity of test results remains typically longer as the network configuration stays unchanged.

The test terminal measures the performance of the network and its cells as well as parts of the network to which it is connected. Scanners can be used at the RF level to study the frequency bands for which the scanner is configured. The GPS receiver is used to record the exact location and time (Expresa 2023). Combined this field test equipment setup collects adequate results for an analysis of a mobile network performance. Example of such test equipment setup is presented in Figure 14.

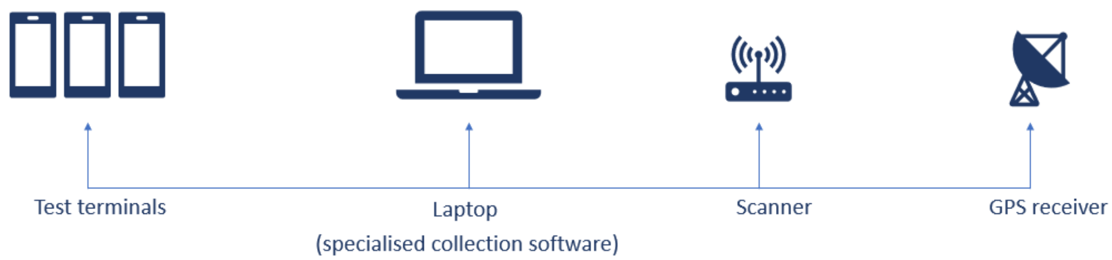


Figure 14. Example of a basic field test equipment setup.

Figure 15 presents an example of available RF scanner measurements conducted from the assignment of Finnish Transport and Communications Agency Traficom. In the figure the best RSRP plot of LTE network, including Finnish Shared Network and Elisa's carriers, are presented. In the figure, the RSRP levels are expressed in different colours at 10 dBm intervals. The lower right corner shows the sample counts (incidence of each level in seconds) and percentages in the measured area.

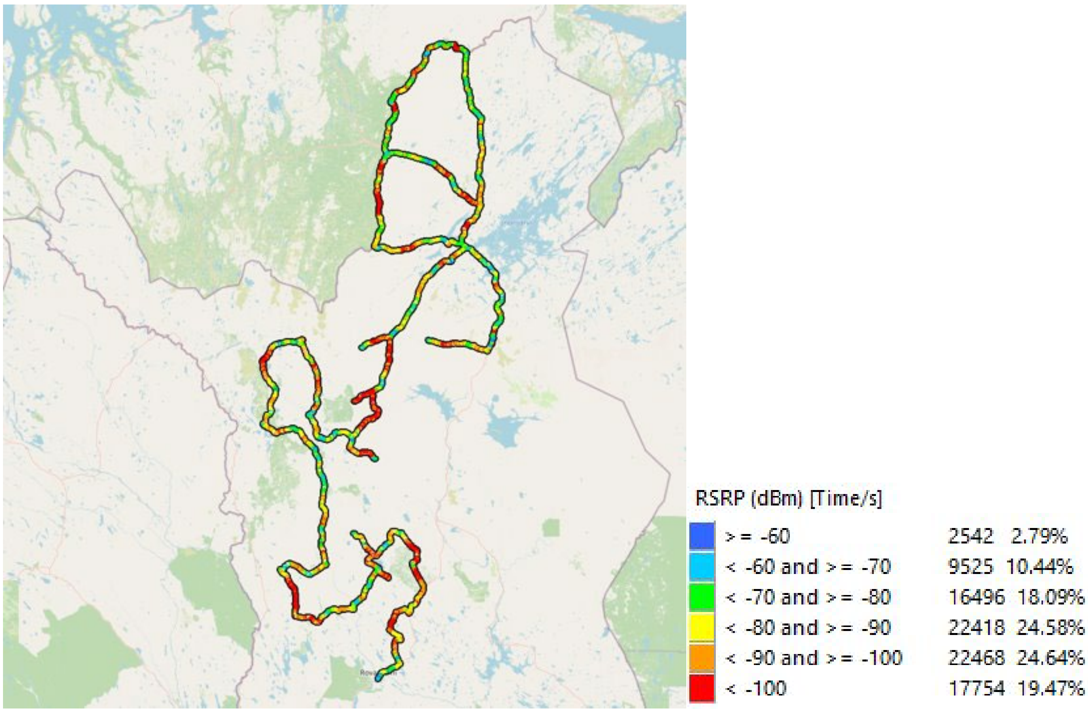


Figure 15. Field measurements in northern Finland.

Field measurements can provide vast amounts of information, typically service/application performance simultaneously with the radio technology related KPIs. Radio interface KPIs are typically utilized in performance analysis and when investigating the root-causes behind any performance gaps. Measurement scripts, which are lines of commands that define for example in which intervals ping is sent and when to start downloading test files, are designed specifically for use case testing to measure the relevant success rates and QoS metrics. The most common set of data service KPIs obtained from the field measurements are presented in Table 36 with the typical subset of technical radio interface KPIs related to data performance presented in Table 37.

Table 36. Most common set of data service KPIs.

KPI	Unit
Application layer downlink throughput	Mbit/s
Application layer uplink throughput	Mbit/s
Median Round Trip Time (ping RTT)	ms
PDP Context drops	Count

Table 37. Typical subset of technical radio interface KPIs related to data performance.

KPI	Unit
Downlink signal strength i.e. mean RS RSRP / CPICH RSCP	dBm
Downlink signal quality i.e. mean RS RSRQ or CINR / CPICH Ec/N0	dB / Value
Channel Quality Indicator (CQI)	Value
Serving system and band distribution	%
Packet technology distribution	%
Carrier Aggregation distribution	%
DL/UL bandwidth distribution	MHz
MIMO usage / Rank distribution	%
PDSCH/PUSCH modulation distribution	%

Mobile operators provide field measurement data, which is mainly based on commercial comparisons of throughput. Throughput measurement alone however is not a sufficient review basis for delay-critical services. No conclusions can be directly drawn about the wider functionality of the networks or the functionality on certain network traffic routes from these measurements made for commercial purposes. Raw data or measured areas are not available and may have been optimized for the technology used by a certain operator or geographical location.

Operators execute small-scale field measurements mainly for the needs of their customers and during the implementation phase of new technology. In general, the measurements executed by the operators are quite local and, especially when introducing new technology, the situation is often not established, so the results themselves are not comparable. Another reason for conducting field tests is for example a situation when there is a doubt that some area is lacking coverage and consequently suffering from insufficient end-user experience, and the competent authority requires verification for this. Field measurements are conducted with tools and software intended for professional use and, in the case of at least one MNO, with a specially tailored application that makes use of a normal smartphone and a typically commercially available subscription.

It should be noted that while field measurements can be used to test service capability even before service adoption, they are not an efficient way of achieving high measurement coverage. Field measurements are by nature time consuming and workforce heavy and should thus be used to test and validate on a regional (or pilot/test case) rather than nationwide scale.

3.4 Crowdsourced data

By definition, crowdsourced data collection is a method where a large number of people are participating to the data collection. Depending on these data sources there is large amount of variety in how well they cover the customer base. Some crowdsourcing solutions may not support e.g. different device operating systems, and most require customers to install an application and initiate test measurements. Some crowdsourced data collection is directly embedded in popular applications to collect network quality information automatically. Figure 16 presents different solutions in terms of coverage. There are multiple commercial companies in the market offering crowdsourced data collection and the variety of data types available and measurement principles are wide.

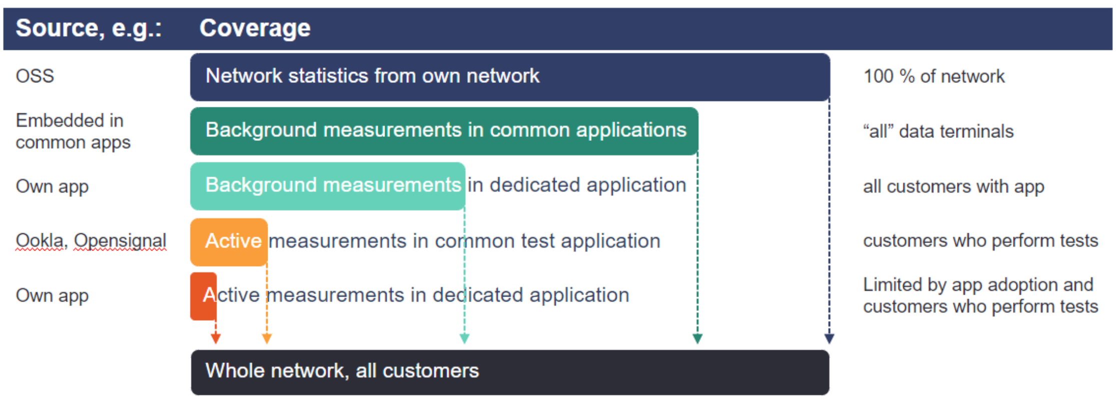


Figure 16. Crowdsourced data collection.

The advantage of utilizing crowdsourced data is to obtain measurements and perceive end-user experience from actual user devices using the selected services and applications network wide. Crowdsourcing is applied widely in commercial network benchmarks and other performance reports. However, crowdsourcing does not have any control of used terminals, subscriptions and their capabilities or possible restrictions like service quality classes (QCI) or SIM's data rate limitations. Consequently, it can't be used as such to measure absolute network performance capabilities.

4 C-ITS services' special requirements for measurements

This chapter examines the special needs for mobile network measurements from the point of view of C-ITS services. These C-ITS service specific perspectives are defined in the Part A of this report and elaborated in this chapter by comparing to the methods currently in use. Analysis of the mobile network measurement methods is divided into three categories considering availability, reliability, and integrity. Measurable quantities (network coverage, packet loss, throughput, and latency) are placed under these categories. Some of the common KPIs used in mobile network measurements which were not considered to provide much added value in terms of evaluating the C-ITS service's operation have been omitted from the quantities.

When implementing large-scale field measurements or collecting crowdsourced data, it is reasonable to collect data much broader than the metrics defined in this study in order to utilize the results better, for example on a more comprehensive analysis of network performance. Methods should be at least parallel to the methods that are traditionally used to measure and analyse the operation of the mobile network. This kind of approach makes it possible to identify problems more widely in terms of the operation of the mobile network. The metrics presented in this chapter have been considered from C-ITS service’s point of view and are insufficient in discovering root causes to analyse larger-scale issues or inoperability of the network.

4.1 Availability

One of the most important KPIs recognized in this study in terms of C-ITS services is the service availability, which can be quantified with mobile network coverage area. Inside the coverage area multiple other quantities can be measured and different results can be obtained from them, and as contrary outside the coverage area, all other measured quantities indicate extremely poor results. In addition to the coverage area, availability is affected by the functionality of base stations in general. Operators need to make changes to the network, base stations might turn off due to power outages, cells need to be closed or changed during property maintenance, and in addition, vandalism, excavation works, and equipment failures cause malfunctions. In most cases, the functionality of base stations has a small contribution to the overall availability of the network, but locally it can produce a significant effect in the area of a network with few base stations. In the future, cyber-attacks and radio interference may also be a growing threat to mobile communication networks.

MNOs’ perspective on availability

MNOs constantly measure the availability of their networks in production use by various means. As a rule, the indicators compare the up and down times of cells or telecommunications equipment (ETSI 2022). Good availability of the radio network is important from a business perspective; hence operators react quickly to changes in these metrics, in order to keep the percentage of downtime small. Extending availability (coverage) to areas where customers move less often, or data transfer needs are generally small, does not have very high investment potential to commercially operating mobile operators.

Mobile network operators must also take into consideration network coverage obligations that are applicable in Finland. Licenses for certain frequency bands of mobile networks include coverage obligations for highways, main roads, regional roads and collector roads. The coverage obligation requires the functionality of the service on the mentioned parts of the road network and the railway network as a whole. The license does not, however, specify any numerical value for signal strength or interference.

The scope of this study is to consider availability in the terms of network coverage and other functionality aspects of base stations are excluded from the analysis. However, such information would be useful in order to understand the reasons behind weak measurement results especially locally.

4.1.1 Network coverage

Availability of mobile networks can be quantified with network coverage measurement or analysis and has therefore been recognized as an important KPI in Part A of this report. Network coverage analysis is an efficient way to distinguish the lack of network and to verify its effect on other quantities. However, network coverage is not the only affecting attribute and other factors like network congestion, incorrect arrangements/configurations or temporary failure situations may have significant impact on network availability. From the mobile network development perspective, it is essential whether the problems of other quantities are due to the lack of a network coverage or something else. In order to quantify the network coverage, the coverage can be predicted with coverage maps or actual field measurements can be utilized as presented earlier in the chapter 3 of Part B.

Network coverage measurements utilizing received signal power

Network coverage can be also measured with field measurements utilizing received signal power levels, like Reference Signals Received Power (RSRP) measurements in LTE network. Due to radio propagation characteristics (higher frequency experiences higher attenuation), the measured RSRP is dependent on the used frequency band(s) (Figure 17) and the total available bandwidth (Table 38).

From this, reasonable coverage requirement thresholds can be estimated for different minimum throughput requirements. Generally, it could be assumed that on more remote road sections on rural areas a Sub-GHz band is available but without carrier aggregation with higher bands while in urban and suburban areas a mid-band carrier is available with additional carriers for aggregation (CA). Furthermore, it could be assumed that at locations where any traffic lights are deployed (due to pedestrians) also mid-bands are available. Due to the dynamic nature of mobile networks, the devices will be directed to the most suitable available serving carrier based on network configuration by the operator.

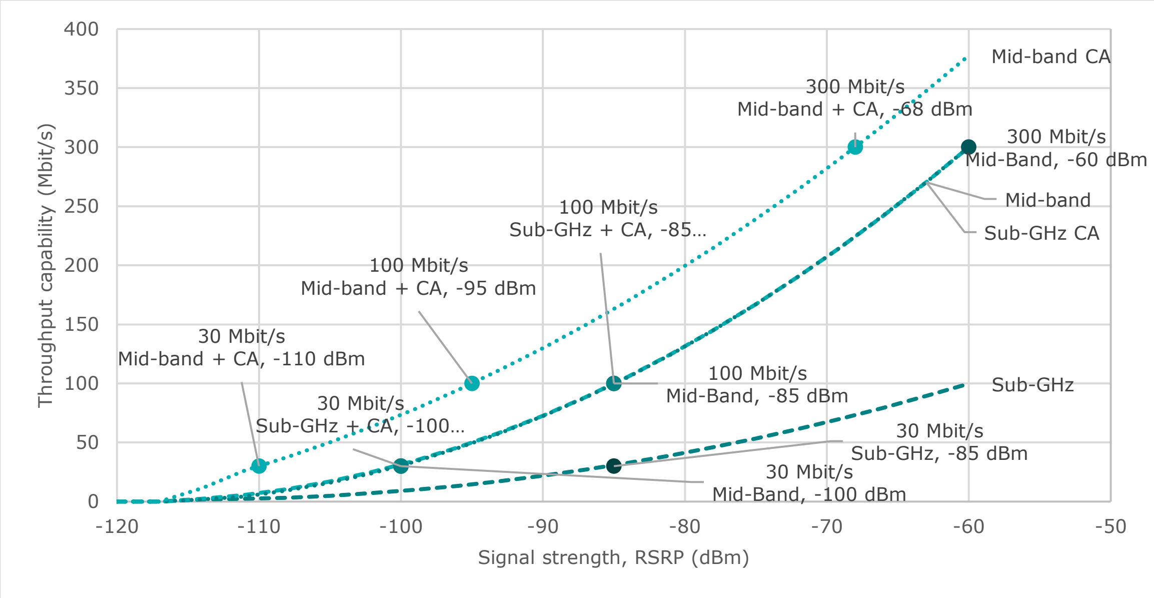


Figure 17. Sub-GHz and mid-band 4G throughput capability (Pre-existing field measurement data analysed by Omnitele).

Table 38. Coverage requirement (LTE RSRP and 5G SS-RSRP) thresholds estimated for different minimum throughput requirements (Pre-existing field measurement data analysed by Omnitele), values in dBm.

Mbit/s DL	Sub-GHz (bandwidth 10 MHz) (RSRP)	Mid-band (bandwidth 20 MHz) (RSRP)	Sub-GHz with CA (RSRP)	Mid-band with CA (RSRP)	5G@3500 MHz (bandwidth 100 MHz) (SS-RSRP)
5	-105	-111	-110	-117	
10	-99	-108	-107	-115	
15	-95	-106	-105	-113	
20	-91	-104	-103	-112	-114
25	-88	-102	-101	-111	
30	-85	-100	-100	-110	
40	-80	-97	-97	-107	-113
50	-76	-95	-95	-105	
100		-85	-85	-95	-110
200		-70		-80	-105
300		-60		-68	-100
500					-90
1000					-65

Coverage thresholds for different throughput levels

The coverage threshold estimates for different downlink (DL) throughput levels are presented above, which are a combination of the definitions by Traficom for coverage predictions and field measurements, where the correlation of signal strength and achievable throughput has been compared in real environments. For a more precise estimate, extensive correlation measurements are recommended to represent the networks more accurately in Finland. Furthermore, assessing uplink (UL) throughput capabilities based on coverage thresholds is not as straightforward as for DL throughput, as there are further factors impacting the capability. However, in typical field measurements, the achievable UL throughput with similar signal conditions is on average ~10% of the DL throughput with notable variation (most of the time between ~5...30%). Targeting high UL throughput would therefore typically be the limiting factor instead of DL throughput capability, as the base stations have in comparison much higher output power compared to mobile devices, which need to also limit the maximum output power to not interfere with other mobile network users.

For 5 Mbps, in rural areas or remote road sections, at least -105 dBm is required (Sub-GHz without carrier aggregation to higher bands), or in more urban areas, even less than -115 dBm signal strength could suffice. However, with very poor signal level (under -110 dBm), errors are more likely, and i such a low signal level the mobile device would move to a lower band as the main serving carrier. On a sub-GHz carrier with CA, a level of -110 dBm would suffice. Typically, the sub-GHz bands are widely deployed in both rural and urban areas, and therefore serve as the best estimate for edge of coverage estimates for throughput availability. With lower throughput requirements, the Sub-GHz carrier signal strength requirements can be used to estimate the availability of the throughput on road sections: on remote road sections, using Sub-GHz requirements without carrier aggregation and on main roads, as well as in and near cities, using Sub-GHz with carrier aggregation requirements.

For 20 Mbps, the signal strength requirements would therefore be -91 dBm and -103 dBm on remote roads and main roads respectively.

The presented signal strength requirements represent the minimum requirements where such throughput levels would likely be achieved. Due to the dynamic nature of mobile networks, the achievable throughput varies based on multiple factors, such as other usage, vehicle speed and position, and interference. Based on measurements comparing the measured signal strength on the main carrier and the achievable throughput, much higher throughputs can be achieved on average.

The below graph (Figure 18) represents measurements in urban and sub-urban areas, where a mid-band LTE carrier serves as the primary carrier, i.e., the signal strength is measured on the mid-band carrier. For example, the measured results with -110 dBm signal strength on the mid-band carrier vary from 30 Mbit/s (5th percentile) to 215 Mbit/s (95th percentile).

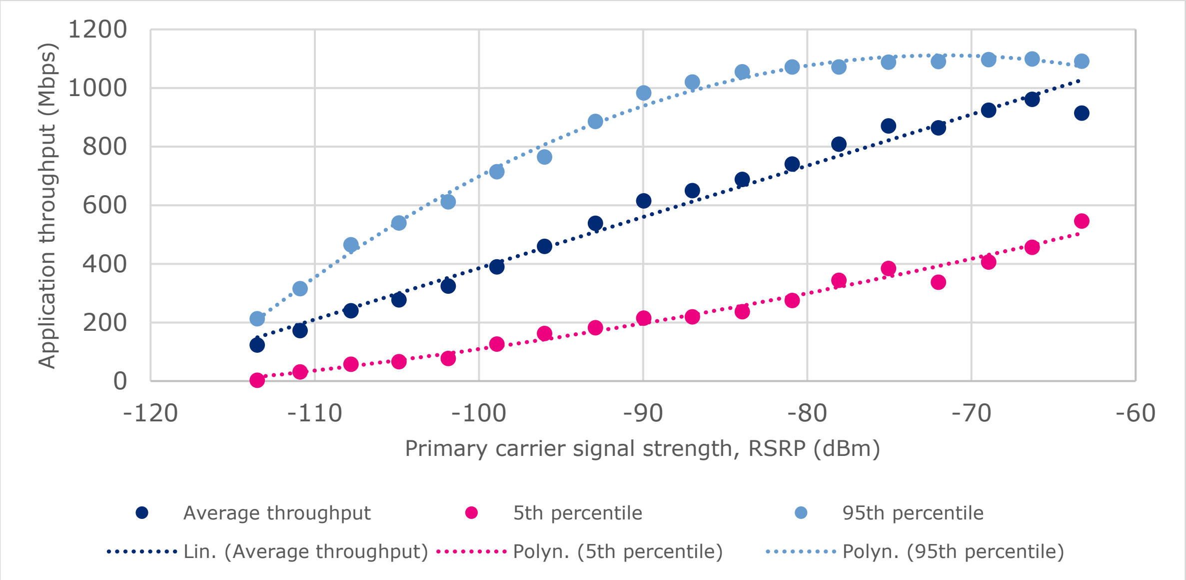


Figure 18. Achievable throughput as a function of signal strength from field measurements in urban and suburban areas (Pre-existing field measurement data analysed by Omnitele).

Received signal power in respect to service level

As presented, received signal power is a commonly used as a LTE network performance indicator that is used to determine the signal strength/attenuation in the exact location. The received signal power can be measured by field measurements to verify the network coverage that is estimated through MNO's network coverage maps. For this work, received signal power threshold values in respect to throughput requirements are defined in Part A of this report and shown in the table below (Table 39). It can be concluded that the received signal power measurements are a practical method to quantify availability from the perspective of this study.

Table 39. Network coverage and received signal power thresholds to classify network performance for C-ITS services.

KPI metric	Level 0	Level 1	Level 2	Level 3
Network coverage	No or unreliable coverage	Verified coverage	Verified coverage	Verified coverage
RSRP SS-RSRP	LTE < -110 dBm 5G < -110 dBm	LTE > -110 dBm 5G > -110 dBm	LTE > -100 dBm 5G > -100 dBm	LTE > -90 dBm 5G > -90 dBm

4.2 Reliability

In terms of C-ITS services, the reliability of mobile communication networks is another important KPI recognized in this study. Reliability is a complex entity and can be viewed using many different metrics. Most commonly, the reliability of mobile communication networks is examined in terms of the establishment of connections, interruptions, and transitions.

Reliability based on connections and interruptions

In earlier mobile communication networks, a fixed separate time slot was reserved for calls, within which the data was transported end-to-end, regardless of the content. The data transfer of the data connection could take place based on the same time slots or data packets. With 4G technology, the mobile communication networks have switched to using data packets and data transmission based on a fully IP network. The data packets are sent to the network and assembled in the correct order at the receiving end. Connections are established whenever data needs to be sent or received. Before data is transferred the terminal must establish a connection. A failed attempt lowers the reliability of mobile network, and a successful attempt improves it. If the connection is already ongoing, it can also be disconnected. The same type of definition applies here, i.e., an uncontrollably broken connection weakens reliability of the mobile network, and an unbroken connection improves it.

Reliability based on transitions

There can be several different types of transitions: from one cell or technology to another within the mobile network, from one network to another at the border of different operators, and the transition can also take place in a controlled manner between the WLAN network and the mobile communication network. Likewise, to the connections and interruptions analogy, a successful transition improves the reliability of mobile network and failed attempts to transition decrease it. Traditionally, these events are measured in mobile communication networks under the terms of accessibility, retainability and mobility. These terms can be combined into one entity under the term reliability, which also appears in connection with C-ITS services (ETSI 2022).

Network reliability in C-ITS services

Decreases in reliability in any form weakens the movement of data packets in some way. Therefore, a suitable measure of reliability recognized in this study is the timely delivery of data packets. A data packet that has been traveling for too long can be considered a loss of reliability from the point of view of a certain type of service. From a purely C-ITS service point of view, the reliable operation is also the transmission of C-ITS messages consisting of data packets in sufficient time from the vehicles C-ITS units via the network to the central C-ITS station or other vehicles C-ITS units. For these reasons, packet loss was chosen as the measure to quantify reliability in this study.

4.2.1 Packet loss

Packet loss or bit error ratio is measured or analysed continuously in mobile communication networks even at short connection intervals. Bit errors are also one of the reasons behind packet losses. When the amount of bit errors exceeds the error correction mechanism’s ability to process them, it appears as a packet loss. This cause effect is the reason why this study focuses on packet loss instead of bit errors. Physical device assemblies are often equipped with built-in technical implementation ready to measure these quantities. However, built-in measurements cannot be used only when measuring packet losses of C-ITS services, because network equipment meters typically calculate losses for all traffic. Additionally, the mobile terminal of the C-ITS service limits the use of fixed measurements when the connection sometimes moves quickly from one base station or technology to another. Packet loss can be measured from the terminal to the server, and it can also be used as one of the performance metrics in terms of C-ITS services. Of course, packet loss measurement carried out alongside the service or with separate equipment does not show the absolute number of errors that occurred in the data transmission of the service, but it can be used to measure packet losses caused by the network in a relatively reliable way.

Applicability from C-ITS services’ perspective

When measuring packet losses, a longer measurement time gives a more reliable picture of the network's operation. In the traditional coverage map data, packet losses cannot be distinguished except, of course, in the case when the network fails completely, in which case the packets do not travel, and the loss is considered to be 100%. In field measurements, information about lost packets is still collected between the terminal and the server. This result can be used directly when evaluating the packet losses of the mobile communication network. Due to the nature of the measurement, information is typically obtained only momentarily from each geographical location. On the other hand, drive test measurement, which progresses and constantly changes places in the network, gives the most realistic picture of the operation of the mobile terminal and the mobile communication network from the end-user perspective. Measurements over a longer period would provide a better picture of the effect of congestion peaks on packet losses. Crowdsourced data could also be used to measure packet losses. On a large-scale, this is not used by current service providers, or it has not been made freely available like other results. When packet loss is used as a measurement, it would be good to relate the packet size and other quantities to the needs of C-ITS services and monitor the results together with the amount of traffic required by the services.

Due to nature of C-ITS services, which typically perform through application layer, packet loss was considered to be a valid reliability performance metric for this study. The service level framework defined in Part A sets some threshold values for the packet loss rate as presented in Table 40 below. Packet loss is measured as a percentage of packets lost with respect to packets sent. It can be concluded that these measurements are also functional from the perspective of this study. In wireless networks packet loss is typically caused by errors in data transmission or network congestion.

Table 40. Packet loss thresholds to classify network performance for C-ITS services.

KPI metric	Level 0	Level 1	Level 2	Level 3
Packet loss	> 10%	< 10%	< 5%	< 1%

4.3 Integrity

Integrity is a group of quantities that is perceived as a "normal" variation of service quality, unlike in the availability and reliability categories, where weak result of the quantities is often due to some fault or deficiency. Especially in mobile communication networks, the value range can vary a lot, without the cause being an actual problem. However, the variation of results from one extreme of the permitted limits to the opposite extreme weakens integrity. When the network is working well, the values are usually closer to the better extreme. In some situations, the values might not be able to reach the better extreme, for example, if the availability is only implemented with a certain technology, in which case the values cannot rise to the better side of the limits, set by this technical implementation. In case of problems or in the absence of a network, these values also appear as results that are worse than the "normal" range. In order to quantify integrity throughput and latency were chosen for relevant measurements in this study.

4.3.1 Throughput

Data transmission capacity is unambiguous in terms of C-ITS services. The service needs capacity for normal communication between different units and for transmitting information from different services. A range or a possible maximum data rate can be defined for the data transfer capacity from the point of view of one terminal using the service. The terminal device's data transfer is divided into sending and receiving data transfer.

Traditional data rate meters can be used in the data transfer between the terminal device and the network, which can be used to measure the theoretical and practical data transfer of the network. The throughput measurement performed in the field can be done utilizing directly the server located in the backbone network of the commercial mobile network, in which case the data rate achieved in that network can be measured.

Concerning the base station (network), the data transmission capacity is more multidimensional. The data transmission of C-ITS services alone does not create a realistic picture of the network's operational requirements. In addition to network load caused by the C-ITS services, the measurement method framework should take into account the overall network load and the possible network congestion from other sources by conducting a field measurement.

The service level framework defined in Part A sets threshold values for the throughput as presented in the table below (Table 41). It can be concluded that methods currently utilized to measure throughput values as presented in this chapter are also functional from the perspective of this study.

Table 41. Throughput thresholds to classify network performance for C-ITS services.

KPI metric	Level 0	Level 1	Level 2	Level 3
Throughput	< 5 Mbit/s	> 5 Mbit/s	> 20 Mbit/s	> 100 Mbit/s download > 25 Mbit/s upload

4.3.2 Latency

Latency and its formation when using the C-ITS service is an entity consisting of many components. Latency is at minimum the sum of its components when communication is successful, and the message travels the shortest physical route with the fastest available technology. Latency is measured and processed in thousandths of a second, i.e., the unit is ms (millisecond).

Latency in C-ITS services, i.e., end-to-end consists of the following parts:

- Terminal (UE, OBU, RSU) latency: Latency generated by the terminal device's software and processor and the systems connected to the terminal device.
- Radio network latency: Latency generated by the air-interface between the mobile terminal and the base station and the equipment of the 4G or 5G radio network.
- Fixed network latency: Latency generated by the devices of the fixed network connecting the different parts of the radio network. Additionally, latency generated by the backbone network and the server access network.
- Server/application latency: Latency generated by server equipment and server software.

Figure 19 presents how end-to-end latency is generated by different parts of the network.

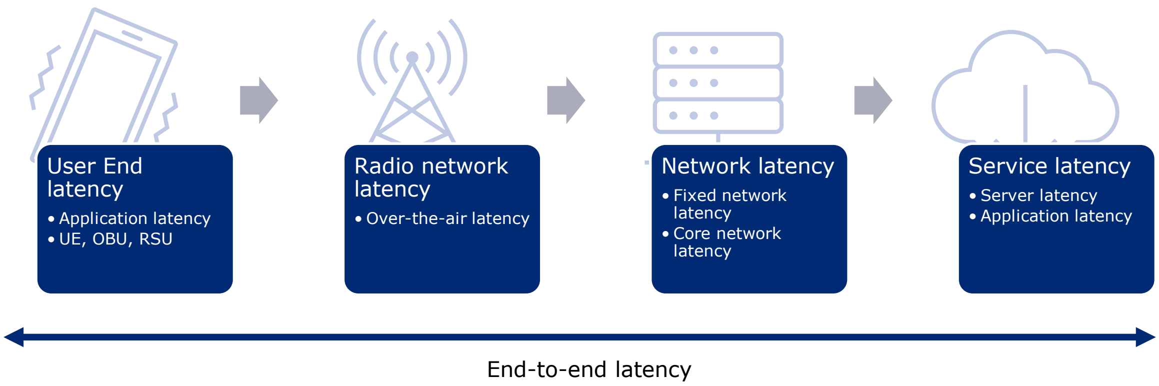


Figure 19. End-to-end latency.

Latency considerations in C-ITS services

Considering a C-ITS service that requires fast communication, it is important to comprehend the possible variations in latency due to the network. In respect to the network, the terminal placed in the vehicle is always at the network edge when processing data traffic from the terminal to another network via the mobile communication network. The sent messages traverse through the network via different devices. For example, when the fixed network is almost fully utilised, there is a possibility for the data transfer to be reserved for other use or the connections may overload the network. These are often intermittent problems, but they need to be recognized as they may result in variation in latency critical C-ITS services. In addition, latency can also be the product of the components instead of the sum of some of the components.

These factors inevitably introduce variation in latency, even if the location remains the same. Typically, the load in the mobile communications network varies, but the load variation can often be predicted on the basis of the diurnal cycle. Figure 20 presents how data traffic typically varies during one week. The same cycle often also applies to backbone networks and access networks, but the capacity of the backbone network is generally not considered to cause more than minor exceptions in latency.

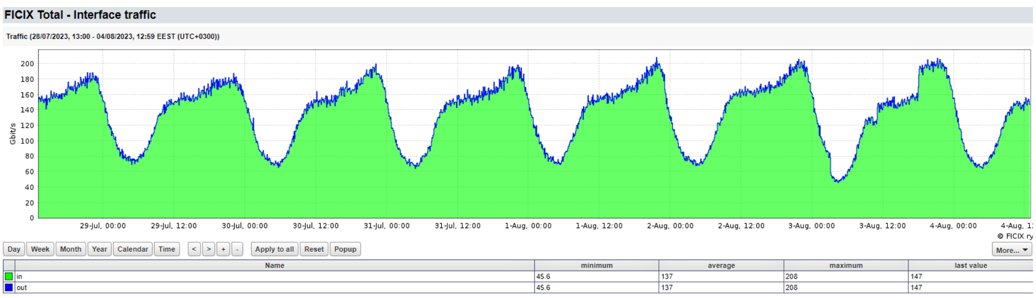


Figure 20. The amount of data traffic varies during the week at Finland's largest internet exchange point. (Ficix 2023)

In current 4G and 5G mobile networks, the delay caused by equipment and radio path is considered a significant part of the overall latency (Ludwig 2023). The future development of 5G SA (Standalone i.e. with 5G Core Network) technology with high-band (> 6 GHz) deployments utilising wide sub-carrier spacing options allow for lower latency (Ultra-Reliable Low Latency Communications, URLLC). In commercial mobile networks, the difference in latency between 4G and 5G technologies is not yet that that significant due to 5G NSA (Non-Standalone) deployments and existing LTE signalling leg. However, both technologies have higher latency compared to fixed optical network connections. Apart from RAN (Radio Access Network), significant part of end-to-end latency is also contributed by Core and Transport networks as well as service and application layers.

Latency field measurement considerations

Organized field measurements give the best picture of the latency at a certain moment. The measurement is most often carried out in the so-called drive test measurements, which is why the actual measurement is conducted in a relatively fast paced manner. Therefore, latency measurement is not necessarily very reliable when performed with traditional field measurement methods. On the other hand, drive test measurement produces a better situational picture comparable to a moving vehicle terminal.

Crowdsourced data typically involves latency measurement and collection. However, it should be considered that other simultaneous ongoing processes of the terminal device which may affect the results are not typically stopped during the measurement and may cause variation between the results of the users. In many cases, the latency is measured in the idle state of the program, in some cases also when the program is performing the maximum performance of data transfer.

Typically, latency measurement is a short-term event, and the load on the terminal does not correspond to the data transfer of the C-ITS terminal. Additionally, in the measurement of latency, some limitations can arise from the type of connection and terminal device, and often this information is not reliably available. When measuring the latency requirement of C-ITS services, data transfer should therefore be related to the level of data transfer needs of C-ITS services, and the terminal device should also be loaded in proportion to the corresponding service needs.

The service level framework defined in Part A sets threshold values for the latency as presented in Table 42. It can be concluded that methods currently utilized to measure latency as presented in this chapter are also functional from the perspective of this study.

Table 42. Latency thresholds to classify network performance for C-ITS services.

KPI metric	Level 0	Level 1	Level 2	Level 3
Latency (average)	> 1000 ms	< 1000 ms	< 500 ms	< 100 ms

4.4 Applicability of current measurement methods

Chapter 4 examines the special requirements for mobile network measurements in respect to C-ITS services specific requirements defined in the Part A and elaborated in this chapter. These selected key performance indicators are availability, reliability, and integrity and in order to measure these network coverage, packet loss, throughput and latency were considered relevant quantities.

Based on the analysis of this chapter, it can be concluded that the current commonly known and utilized measurement technologies, presented in the chapter 3 of Part B, are suitable for measuring the KPI indicators identified in relation to C-ITS services. Furthermore, it can be concluded that the current network performance measurement methods are applicable, meet the identified requirement levels of accuracy in measurements, and can be applied with specified thresholds to determine the service level of mobile networks for C-ITS specific use cases.

5 Measurement method framework

Although the earlier chapters of this study state current measurement methods to be sufficient and functional for measuring the necessary network attributes, guidelines are needed for analysing the results and creating a measurement process specifically targeted at C-ITS services. By utilising current measurement techniques and by analysing the results against C-ITS service level criteria, the capabilities of mobile networks to support C-ITS services can be determined in the most cost-effective way. In this work, a process-like model is defined for analysing service levels, and it will be reviewed step by step in Part C. The process is divided into three parts: theoretical analysis, field measurements, and service level analysis, according to Figure 21.

The first part of the process is theoretical analysis which is a prestudy approach for specified geographical location. Theoretical analysis is based on pre-existing network coverage data from MNO's and Traficom and it is conducted to estimate the network services availability on the specified area. Prestudy can also be used to determine if a field measurement is needed to verify the network performance.

The second part of the process is the field measurements. Because of the variating demand for the mobile networks, based on concentration of traffic, there are two different methods suggested for field measurements: a drive test and fixed-point test.

- A drive test is to measure the network performance for a real traffic situation in a specified geographical location and it represents well the experienced service level for the end user.
- A fixed-point test is to measure the network performance in a fixed geographical location to show network stability and performance variation and possible intermittent issues for example on a heavy traffic cross-section or city centres.

The third part of the process is the service level analysis, which makes conclusions from refining and analysis of the field measurement data.

It is essential to comprehend that field measurements are not mandatory in all cases, and a theoretical analysis together with service level analysis may be adequate, if there is enough data from previous field measurements with correct attributes. In some cases, even the theoretical analysis might suffice, depending on the area to be studied.

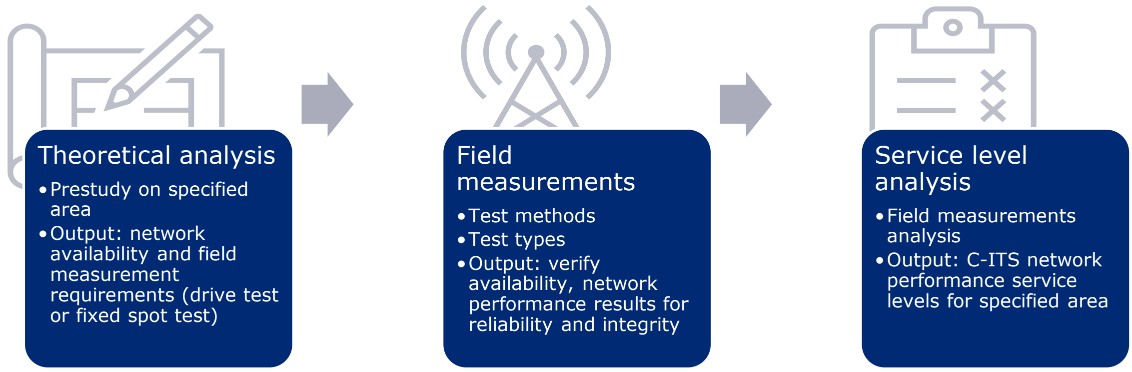


Figure 21. Measurement method framework.

5.1 Theoretical analysis

The purpose of theoretical analysis is to determine the network availability for the C-ITS services in a specified geographical location. Theoretical analysis (also a prestudy) can be conducted based on pre-existing network coverage data from MNO's and Traficom. The most important result of a theoretical analysis is to determine if a field measurement is needed to verify the adequate network performance on a specified area. Theoretical analysis should at least include analysis of network coverage maps and areas of high-density road traffic.

The theoretical analysis should consider the aspects of the area and base stations available. Location of area for the service needed can be rural, suburban, or urban and the service level required for the area should be considered as well. Regarding the base stations, MNO's that have service on studied area, and the density of the base stations should be recognized. Additionally, current technologies that MNO's have in the studied area (4G/5G), and the simulated capacity of the MNO's coverage areas should be included in the theoretical analysis. Another factor to include is the distance of the nearest MNO's base station (approximation of the attenuation of the signal based on network coverage maps and used frequency bands).

Exemplary notes for a theoretical analysis are shown in Table 43 below.

Table 43. Exemplary notes for a theoretical analysis.

Location of area	Traffic density	Base station study	Pre-existing field measurements	Service level needed	Field measurement needed
Rural	Low	Only few base stations, outer edge of the network coverage, intermittent blind spots found, only one MNO network coverage	Not available	Level 1	Recommended
				Level 2	Highly recommended
				Level 3	Highly recommended
Urban	High	High number of base stations, multiple MNO's, studied area inside network coverage	Yes, partial	Level 1	Not needed
				Level 2	Not needed
				Level 3	Recommended

In conclusion, the theoretical analysis must take multiple aspects into consideration and should be done by a person that has knowledge to understand the behaviour of radio signals in different areas. If the study concerns a safety critical C-ITS service, it is highly recommended to conduct a new field measurement as theoretical analysis are mainly based on simulated data examination which may be inaccurate.

Pre-existing field measurements can also be used as a data source for a service level analysis as described later in chapter 5.3 of Part B.

It is important to consider that often the pre-existing data may be inadequate or outdated to show the realistic view of the network performance and thus field measurements should be conducted with a low threshold if there is any consideration of the networks performance especially if evaluating the network performance for critical C-ITS services.

5.1.1 Network coverage maps

Network coverage maps are used in theoretical analysis as a starting point to examine the network availability on specific geographical location. Traficom collects network coverage information from commercial mobile network operators periodically according to a specific set of definitions (Traficom 2023). The collected information aims to identify the availability area of different minimum throughput levels, based on predefined coverage thresholds. Network coverage maps are usually divided into 250 x 250 m squares. This is due to the availability of population data on a 250 x 250 m square grid, which is correlated with the mobile network coverage information to produce population coverage statistics. Calculating coverage is reasonably efficient on the 250 x 250 m granularity for large areas and calculating nationwide coverage with higher resolution requires significant additional processing capabilities. The resolution may not be accurate enough for a very detailed theoretical analysis for example in high density population areas such as city centres.

Network coverage maps should be examined across the study area and possible weak spots should be highlighted for a detailed examination and to determine if field measurements are necessary to verify the availability, reliability, and integrity of the mobile network. A detailed examination may also include a higher resolution coverage analysis, e.g., from 250 m square grid to 50 m square grid on the area of interest. It is to be noted that calculation of coverage requires detailed network data and is also limited by the available resolution of the maps from different areas.

The results from examining the network coverage maps indicate if field measurements are required, which areas the field measurement should focus on, and which type of field measurement should be conducted to verify the network performance in the most suitable way concerning the C-ITS services to be implemented.

5.1.2 Pre-existing field measurements

Pre-existing field measurement data can be used as a data source for theoretical analysis and for service level analysis. For adequate results, the collected KPI’s must correlate to metrics defined in chapter 5.3 of Part B.

As development of mobile networks is fast paced and 5G networks are being deployed constantly the time of pre-existing field measurements should be taken into consideration as outdated field measurements may not be accurate.

Analysis of pre-existing measurement data will result in service level definition of specified area or show the need for a new field measurement. The type of field measurement can also be defined by examining the pre-existing data. As a simplified example if the results show that the network performance is degraded in a heavy traffic cross-section but all the other areas on route show great performance, a fixed spot test could be conducted on the cross-section area to examine if the service levels show degradation only at a certain time.

5.2 Field measurements

5.2.1 Principles of field measurements

Traditional network performance field measurements involve collecting a lot of different metrics that must also be collected in C-ITS service-related measurements defined in this study. These include metrics such as RSRP, RSRQ/SINR, BER, jitter, channel, and frequency information. Measuring these metrics do not cause interference or produce unreliable results with the performance metrics chosen in this study. Various collected metrics can be beneficiary and used to understand the root causes behind poor network performance.

For example, reliability in the scope of this study focuses solely on packet loss, however it is highly recommended to collect data about multiple reliability measurement metrics during a field measurement such as bit error rate (BER). Bit error rate can point out the causes for the packet loss which then can be forwarded to the MNO’s knowledge to fix possible network issues. Similarly, analysis of Signal-to-Interference-Ratio (SINR) can reveal interference issues, causing either packet losses, dropped connections or degraded data transmission experience (throughput).

Based on the data from measurements, analyses of the network's operation in relation to new services can later be carried out, as well as the market-based development of commercial networks as traffic volumes or the number of users of the services increase, or in the event of changes in the areas covered by the services.

Field measurements should be carried out with a certain similarity each time to produce comparable results. Minor changes between measurements are tolerable but need to be addressed.

The field measurement results may vary heavily depending on the chosen time period of the test. By default, the time period should be chosen to verify the network performance in a normal traffic situation. Typically, suitable hours to conduct measurements would be during morning/afternoon commuting.

5.2.2 Preparations for field measurements

Prior to the field measurements, it must be ensured that the equipment and connections (data communication) correspond to the service level to be measured in terms of performance. The correct operation of the equipment must be verified before the measurements. Professional mobile network measuring equipment with special data collection software must be used.

The measuring devices are equipped with subscriptions of the mobile network operator being measured, which exceed the thresholds of the measured service level, so that the connection does not limit the capacity in any respect. Antennas and devices that analyse radio frequency must cover all frequency ranges used by the operator to a sufficient extent. If several terminals are used in the measurement at the same time, the number of terminals must always be used as the capacity factor.

For field measurements to be adequate in defining the network service level for C-ITS services, the configuration and the script of the test should correlate with the service level framework metrics and thresholds. Below are detailed definitions that need to be specified before field measurements.

1. Device selection and placement

    - **Device**. A C-ITS service can be simulated even before the adoption of C-ITS services or C-ITS-specific vehicle units, with typical measurement equipment (smartphone) and planning a measurement that generates traffic according to the C-ITS service traffic profile, with transmission of messages of appropriate size at the appropriate interval.
    - **Placement**. When modelling typical C-ITS device in the car, an external antenna for the measurement device is needed to model the likely setup for C-ITS devices in the future. A C-ITS unit is likely to have an externally mounted antenna for optimal transmission and reception, in practice a vehicle antenna will be utilized.
    - **Network frequency scanner**. Network frequency scanner measurements do not impact other measurements as these do not generate any load to the network and can therefore always be carried out in parallel to validate coverage predictions and for further correlation analyses. Frequency scanning should be conducted in parallel to obtain measurements on network coverage i.e., signal strength (RSRP/SS-RSRP) and quality (RSRQ/CINR). Scanner should be configured on selected bands and carrier frequencies that are relevant to the desired area. Signal strength should be used as primary indicator of service availability and quality measurements as supporting KPIs (potential root-causes) when analysing the gaps in service performance.
    - **Server requirements**. The measurement service provider must use a dedicated test server located in the same country in which the test is conducted. The operation of the server must be ensured by successful measurements with a wide enough sample, considering the variation of data network capacities, for example at different times of the day. When testing the functionality of the server and the communication network, a fixed network subscription must be used. The server must be able to respond in all situations with sufficient capacity in relation to the measured level. The server must be connected to the internet with a high-speed fibre connection that will be sufficient for testing and will not produce a bottleneck.

2. Subscription (SIM) selection

   - **Subscription**. For testing purposes and simulation of C-ITS services, a typical off-the-shelf subscription is considered suitable, potentially even with a low-tier data rate limitation. With different subscriptions typical future C-ITS subscription profile, including QCI priority class and potential data rate limitation can be modelled.

   - **Multi-operator testing**. Possibility to test different subscription profiles or all commercial networks simultaneously. Because a typical C-ITS implementation in normal private vehicles is likely to rely on a single mobile network subscription, the different operators' networks should be tested separately. Because simultaneous measurements can be carried out in different networks without impacting the measurement of other networks, the tests can be carried out for all three national (continental Finland) networks at the same time. This will require three separate devices, one for each network. In addition, multichannel router system can also be applied to be used in measurements, although a multi-SIM equipment usage in vehicles applying C-ITS services is seen improbable.

3. Sample rate for field measurements

   - To ensure adequate number of measurement points for service level analysis, the sample rate should be set to measure network performance for a maximum distance of 25 meters. In high-speed environments e.g., highway, this implies that the sample rate should be set at minimum 1 per 0.7 s to achieve the desired maximum distance between the measurement points. As an example:

     - Highway drive test: 120 km/h (~33 m/s) with a sample rate of 1 per 0,7 seconds equals roughly to one measurement point per 25 m.

     - Urban drive test: 50 km/h (~14 m/s) with a sample rate of 1 per 1 second equals (maximum sample rate) roughly to one measurement point for every 14 m distance travelled.

5.2.3 Service level test methods

Different service levels or services can be tested by network stress test or planning a measurement script that generates the service-level or service-specific equivalent network traffic profile in the main test devices.

Network stress test method (primary)

The main option to measure and analyse mobile network capability to support different services and service levels (combination of services) and fulfilment of their requirements is to conduct a stress test to assess the full capability of the network at the given place and time. A stress test is done by downloading a large size file from a test server continuously during the measurement. Results of such test will reveal the areas/locations where data performance is or is not sufficient to support different data rate requirements like 5 Mbit/s, 20 Mbit/s or 100 Mbit/s.

Thus, stress test results can be mapped directly to corresponding service levels or a specific service.

Service-specific test method (secondary)

The network traffic profile can be made to simulate a single service, by producing the network traffic equivalent to the specific service, i.e., transmission of messages of appropriate size at the appropriate interval. Depending on the selected measurement software, the sending and receiving of messages with short cycles may require selecting an equivalent method of message testing, depending on the capability of the software to measure, send and receive of direct messages using a suitable messaging protocol as opposed to typical upload and download using, e.g., HTTP or FTP protocols. By combining the service-level specific services into an equivalent total-network traffic-based test, e.g., Service level 3 based throughput test in main test device: dimensioned data transfer (download/upload) and latency testing (ping RTT). Latency testing via ping RTT should be included, especially to measure latency variations and the share of long round trip times. The primary device would measure the availability of the service from end-user perspective.

A service specific test method should primarily be used to verify network performance thresholds for critical use cases that have special requirements for example concerning safety. It can be based on specific C-ITS service and use case, for example, Hazardous Location Notification service's Temporary Slippery Road use case notifying about slippery conditions in a specific road network area. The setup for service-specific tests is presented in Table 44.

Table 44. Service-specific test method testing procedure.

Test case	Main device 1	Device 2 – n	Frequency scanner
C-ITS service level or a specific service	C-ITS service level or service specific traffic in DL and UL, latency.	Background traffic generation to model service adoption in given time and area.	Pilot scanning for LTE/5G network coverage and quality (selected bands/frequencies).
Example: CPM	10 times 1,6 kB transmissions per second in DL/UL, ping RTT	Background traffic according to area (main streets, urban, etc.), and level of C-ITS adoption.	Scanner optional for additional verification.
Example: Lane closure	2 times 400 B transmissions per second in DL, ping RTT.		

The presented method is aimed at providing more accurate assessments of the networks' ability to serve C-ITS data traffic before widespread adoption by introducing simulated background C-ITS load to the network while testing the functionality of specific services. This simulation can also provide better understanding of the underlying network requirements for C-ITS services and allow further fine-tuning of thresholds for service capability assessment.

The secondary device(s) could be applied to generate background data traffic and simulate other users, a combination of different C-ITS services used in the same area. Depending on the environment and area type (dense city / urban / suburban / rural) the applied background traffic (load) would be different. Additional devices will therefore simulate C-ITS service adoption. Background network traffic should be planned based on the selected C-ITS services and scenarios as presented in Part A of the report.

5.2.4 Applicable test types

The service level test methods can be applied to drive tests or fixed-point tests. The test type should be chosen based on an estimate of the amount of traffic and network load variation at the measurement location.

Drive tests

Drive tests can be carried out without separate arrangements, taking traffic and work safety into account. The supplier of the measurement service must take the traffic volumes and possible peak times of the road sections into consideration. On road sections with less traffic (< 5000/day), the measurements can be performed at all times of the day, but it is recommended to perform the measurements at a time when other road users are assumed to be most active. On other road sections, the measurements should be performed at a time when the traffic volume on the road is above the hourly average.

If, during the measurements, events deviating from the typical traffic flow of the road section are observed, the events must always be considered when recording and analysing the measurement data.

In drive tests, data is recorded over the entire length of the road section being measured. If the measurement is done in parts, the start and end points of the different measurements must be limited to each other by at least the size of the serving cell observed in the area.

Fixed point tests

As drive test measurements represent a snapshot of the mobile network load in certain time, it might be difficult for this type of measurements to define the volume of absolute peak traffic and take into consideration other natural traffic volume fluctuations. With fixed point tests it is possible to include the effects of the variating traffic volume on the network capacity.

The principle of fixed-point tests is to define an exact fixed location or multiple locations in the area to be measured, in which measurements are made at fixed or regularly changing appropriate intervals.

Reasons for the choice of a fixed-point test can be, for example:

- An area of weak coverage or weak capacity located on the base of coverage map analysis.
- An area which has repetitive network performance problems based on previous drive test field measurements.
- A traffic node point where large momentary traffic flows can be shown to accumulate.
- Based on driving speed, the slowest or fastest section on the measured road section.

- An area that can be concluded to have a particularly high need for C-ITS services.
- A section with a particularly large population or other permanent mobile network users.
- From the MNO's point of view, the most challenging section of road to be measured. The challenge may be related to capacity, geographical and structural barriers, profitability of commercial activities, etc.

A sufficient number of special measurement points must be selected in order to be able to ensure the operation of the mobile communications network in various situations.

The antenna equipment used in fixed point tests must be placed approximately at the same height as they would be in a vehicle.

5.2.5 Summary of field measurements

There are numerous details that need to be addressed before conducting a suitable field measurement to achieve the best possible results for analysing the service level of the network. The diagram presented in Figure 22 summarizes the process for defining a field measurement.

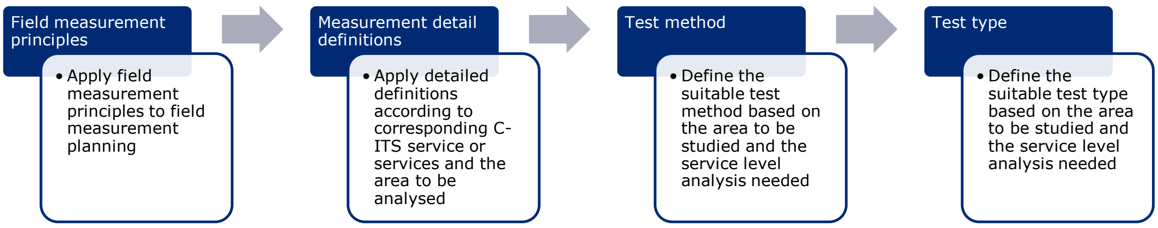


Figure 22. The process of planning a suitable field measurement.

In Table 11 below is a compiled summary of the two different test methods including the explanation of each methods function, results, and the applicable test types in which these test methods can be used.

Table 45. A compiled summary of test methods and corresponding details.

Test method	Function	Results	Applicable test types
Network stress test	To measure the total performance of the network in specified route or fixed location	Service level can be calculated from measurement data in analysis with different user scenarios	Drive test, fixed point test
Service-specific test	To determine the network performance of specific C-ITS service in specific route or fixed location	Verifies if the network performance is adequate for certain C-ITS service	Drive test, (fixed point test)

As can be concluded, field measurements require detailed planning to achieve the desired results. Field measurements can be carried out to determine the service level in general or to determine the adequacy of network performance on a service-specific basis. Both test methods have their own purpose in determining network service levels in the implementation of C-ITS services. In general, network stress test method is more effective to determine the network performance service level on larger areas and the collected data can be used for a more comprehensive analysis. On the contrary service-specific tests can be more agile to determine if the specific C-ITS service or combination of services will be available in the desired location.

5.3 Service level analysis

The main goal of service level analysis is to determine the service level of a studied area in respect to service level framework defined in this study. In addition, service level analysis results can be used to present visualisation and relay information and requests to MNOs of possible needed enhancements for the mobile networks.

5.3.1 Data collection and refining

The raw data obtained through field measurements is always stored in its entirety. Typical measurement software store information from the measurements with a sample rate from 1 per 0.1-1 second, whereby the average, and potentially minimum and maximum values are stored with each sample timestamped and with location coordinates from GPS. Typical professional measurement software can also collect several radio-access-network related KPIs in addition to the measured service or application level KPIs, which allow further post processing and root-cause analyses.

All collected and stored measurement data must contain accurate time stamps of measurement events. The quantities defined in the service levels of this work must be easily distinguishable from the measurement data.

In fixed point test measurements, the location must be recorded with the coordinates where the measurement was performed, but in storing data it is not necessary to store it in connection with each event. In drive test measurements and semi-fixed measurements, the coordinates must be connectable to the event and time stamp.

The recordings must also be in a format where it can be processed and sorted in other ways than with the tools of the software or equipment supplier used for the measurement. Typical measurement software allows exporting the data in non-exclusive formats, such as text files, for later post processing.

The recordings must be made in a format where they can be used to create a geographic representation with commonly used tools, for example GIS.

5.3.2 Service level analysis intervals

Based on the measurement data, the area to be measured is divided into the service levels defined in this study.

There are two different approaches for dividing the studied area to analyse and to visualise the service level. The chosen approach must be considered carefully for an appropriate and functional visualisation of service levels.

Using the most accurate data, service level can be analysed for each measurement point by each coordinate (maximum 25 m distance between measurement points). However, as the measurement data might show intermittent variation, analysis is recommended to be performed with a calculated average value of each KPI in intervals that correspond to the environment.

1. Dividing the studied area for an analysis based on the location of the study area (rural, suburban, urban)
    - For rural (high-speed) environments the service level is recommended to be calculated and analysed in 100 m intervals.
    - For suburban (medium speed) environments the service level is recommended to be calculated and analysed in 75 m intervals.
    - For urban (low-speed) environments the service level is recommended to be calculated and analysed in 50 m intervals.
2. Utilizing 250 m x 250 m square grid to model service level in each square
    - Already utilized by Traficom for example in visualising and defining the availability of different throughput levels in mobile networks.
    - Applicable to show service levels of Finland in entirety.
    - Accuracy of the service-level may not be adequate for detailed service-level analysis for example in urban cross-sections.

When using pre-existing field measurement data, the collected data will affect the accuracy of the service level definition.

The results must be analysed separately between MNOs as combined results may result in overly positive service levels and will not reveal MNO specific weak spots.

The results should be visualised by using analysis tools used by field measurement service providers or a separate GIS-software to have an overall view of the studied area.

5.3.3 Comparing measurement results to the service level metrics and thresholds

In each approach, the service level should be determined based on the weakest service level analysed in the area. However, especially when using custom intervals for analysis, it should be noted that the collected data should be analysed considering a tolerance in respect to exact thresholds, as for example minor decreases in throughput or received signal power are tolerable regarding the functionality of the specific C-ITS service.

For practical reasons there might also be exemptions from the service level thresholds which are defined by Traficom or a road authority.

Table 46 summarizes the different metrics and threshold values to classify network performance for C-ITS services based on the service level criteria defined in

Part A of this report. Using the thresholds presented in the table, corresponding network service level for C-ITS services can be evaluated.

For availability there are two metrics to analyse: network coverage from simulation models and received signal power data from field measurements. As RSRP indicates LTE network signal strength at exact location, it is recommended to be analysed within a certain route or in a perimeter around a fixed spot. Intermittent signal attenuation is shown in received signal power measurement data and the possible effects on C-ITS services should be addressed during the analysis based on the longevity and/or duration of the attenuation period. In these cases, latency and throughput measurement data must also be examined to verify if the signal attenuation has an effect on these attributes as received signal power variation in certain levels is considered normal.

Reliability is analysed with packet loss and integrity with throughput measurement data. Reliability and integrity determine the service level according to the lowest threshold. Similarly, as received signal power, packet loss and throughput must be examined for a certain area or route rather than a single exact location as the measurement may show intermittent packet losses which still are in the tolerable range for the C-ITS services.

Table 46. Summary of KPI metrics and thresholds to classify network performance for C-ITS services.

KPI	Metrics	Level 0	Level 1	Level 2	Level 3
Availability	Network coverage (prestudy)	No or unreliable network coverage	Verified network coverage	Verified network coverage	Verified network coverage
	RSRP SS-RSRP	LTE < -110 dBm 5G < -110 dBm	LTE > -110 dBm 5G > -110 dBm	LTE > -100 dBm 5G > -100 dBm	LTE > -90 dBm 5G > -90 dBm
Reliability	Packet loss	> 10%	< 10%	< 5%	< 1%
Integrity	Throughput	< 5 Mbit/s	> 5 Mbit/s	> 20 Mbit/s	> 100 Mbit/s dl > 25 Mbit/s ul
	Latency	> 1 s	< 1000 ms	< 500 ms	< 100 ms

For field measurements, a lower service level result may be accepted for availability if the service is at a higher level for all other KPIs. In theoretical reviews, availability works like other KPIs, and the level of service is determined by the weakest threshold.

5.4 Applicability to the increase in the number of users

Overall, it can be concluded that no changes are needed to be made to the measurement and analysis of availability even with increasing numbers of available C-ITS services or users. In Finland, the regulations governing the operation of the mobile network provide a good basis for the availability of the mobile network. MNO's effort to maintain networks from commercial aspects also supports the preservation of availability in areas where the network has been invested in line with users' needs. Of course, severe network congestion can lead to situations where network availability suffers from this, but authentication can still be performed in the ways discussed above.

The field measurements for reliability and integrity made from the perspective of one user give a sense of the network's operation even when data traffic volumes and the number of terminal devices increase, when a normal non-prioritized connection and terminal equipment is used. The mission of the mobile network is to share data capacity among all users. Users with similar radio conditions experience problems with the data capacity of the base station in a relatively similar way. For example, when the network is congested, the targeted throughput cannot be reached in field measurements, in which case it can be concluded that the situation is the same for a group of users in a certain area. However, connectivity problems caused by service availability/coverage are perceived rather differently between the users depending on the location of a single user in a serving cell. The closer to the base station the users are, the higher the signal quality and consequently the better user experience typically is. The problems may occur only at the cell edge.

The "natural" development of mobile networks progresses at the same time as new services become available or more service users become active. The current situation of mobile communication networks is assessed in Part C of this study. Based on the data of the measurements made today, a comparison can be made regarding the theoretical and realized network capacity at each moment. With the help of these measurement data and the theoretical development of networks and capacity growth, it is possible to identify future bottlenecks for C-ITS services.

With the expansion of services and the emergence or generalization of new services, there may be some other important measurable quantities that should be added to the measurement methods. Additionally, the development of the mobile communication network may bring the need to change measurement methods, for example, due to the slicing of the network or the development of side link traffic. Changes to the now defined limit values or service levels may be needed even with current services if they are found to be too imprecise in practice.

6 Conclusions of Part B.

One of the central research questions of this part was "How are different mobile network technologies (2G,3G,4G,5G) suited to serve the needs of different C-ITS services?"

Considering all the digital mobile network technology generations, 4G and 5G network technologies can provide the connectivity and capacity needed, and future developments for 5G technologies can potentially even improve the ability to serve high-device-density and high-message-frequency services such as in the C-ITS framework. In terms of latency these network technologies are also capable when comparing the network latency threshold values to the service level framework defined in Part A. However, it is worth noting that overall latency is consisting of many components, for example terminal device and service itself, network latency being only one factor.

Another central research questions to answer in this part of the study was "*What kind of methods can be utilised to prove the functionality of different types of C-ITS services in the commercial mobile networks?"*

In this part of the study, the current and professionally used mobile network performance measurement methods and the applicability of these methods were studied and discussed as the basis for the selection of measurement methods. It was concluded that these measurement methods are adequate to be utilized and to collect data for service level definition of mobile networks in respect to C-ITS services. Thresholds for different service levels were also applied for KPIs chosen in Part A of this report as a basis for measurement method framework.

As a part of this work phase, a measurement method framework was developed as a process-like model. This model can be used to cost-effectively analyse large areas and carry out measurements where necessary. The studied area can be chosen based on e.g., traffic volumes and the development of mobile communication networks.

The developed measurement method framework was divided in to three phases:

1. Theoretical analysis
2. Field measurements
3. Service level analysis.

The theoretical analysis consists of network coverage maps study which concludes if a field measurement is needed to verify the network performance, and which type of field measurement should be used.

The section concentrating on field measurements concludes the principles that must be followed when conducting field measurements and the definition and description of different field measurement types that can be used for different needs and to collect the required network performance data for service level analysis in the area of interest.

The service level analysis part consists of guidelines how to use and refine collected data to analyse network service levels using metrics and thresholds in respect to C-ITS service requirements. Service level analysis also presents two alternative approaches for dividing the studied area to achieve location specific and comparable results for various service level analysis, and to act as a basis for the presentation of the service levels in a comprehensible way.

Part C. Assessing C-ITS capability of commercial mobile networks

1 Introduction

This Part analyses the feasibility of Cooperative Intelligent Transport Systems (C-ITS) services over commercial networks and estimates the different options for assessing the network development from the C-ITS perspective.

The aim of this Part was to establish the current status of the commercial networks in Finland, estimate the feasibility of the defined C-ITS development scenarios and performance metrics (based on Part A. "Definition of service level framework for mobile networks" and Part B. "Measurement methodologies and techniques"), and to identify the required development of measurements and methodologies to assess the progress of network development and feasibility of C-ITS scenarios.

This Part answers the following research questions:

- *How are current commercial mobile networks suited to serve C-ITS services and what are the key deficiencies/bottlenecks, if any?*
- *How can the network development progress for C-ITS services be assessed currently and what information is needed to assess the progress in the future?*

The contents of this Part are as follows. In chapter 2 system capacity is analysed and it provides examples regarding typical system capacity for different main environments, i.e., urban, suburban, rural and sparse rural. Chapters 3.2 and 3.3 present more detailed review of the currently collected information (coverage predictions and field measurements) on commercial mobile network development, and how to use this information to assess the feasibility of the service level framework. Chapter 3.4 covers the suitability of the currently used development metrics to assess the C-ITS feasibility potential. Furthermore, additional measurements and assessment metrics are compared and proposed for future use. Chapter 3.5 assesses the feasibility of providing the required capacity of serving 2030 C-ITS services. This is carried out by providing an overview of the assessed traffic scenarios in 2030 and comparing them to current (2023) estimated mobile network capacity in Finland in the different environments. In the capacity sufficiency assessment, the potential gaps from today to 2030 are also discussed. Chapter 4 considers the key findings and conclusion related to the content inputs for Part C.

Methods and background material

This Part was carried out as expert work based on the professional knowledge and experience of the project team, gathered from various projects and assignments worldwide, as well as utilising publicly available resources like articles and technical reports. Furthermore, combined mobile network coverage predictions and measurement information were received from Traficom to support the assessment of using currently available information as a basis for assessing the feasibility of C-ITS services in Finland.

2 Mobile networks system capacity in different environments

The mobile network system capacity is dependent on three key factors, 1. Spectrum, 2. Technology and 3. Topology. For the assessment presented in this chapter, the relevant variables in different environments are the used spectrum (1.) and network topology (3.) in different areas. From the technology point of view, similar deployments are assumed to be in use in for the specific spectrum bands in the different environments. In practice, as the mobile networks have different equipment generations in use in different parts of the networks, there are variations in the technology used in different areas. The more advanced equipment generations can support higher order modulation and more advanced MIMO solutions, enabling more bits per spectrum. For this analysis, a capacity overview is provided assuming the use of the latest technical advancements that are widely deployed already in the current commercial networks.

Figure 23 illustrates how the distance to the base station affects the available capacity from the mobile network user point of view. The distance is presented as a relative share of the maximum coverage of the band with the best coverage (700 MHz). When distance to the base station increases, the signal strength decreases, resulting in lower maximum throughput capability. With lower signal strength, fewer bits can be transmitted per spectrum unit, i.e., with lower spectral efficiency.

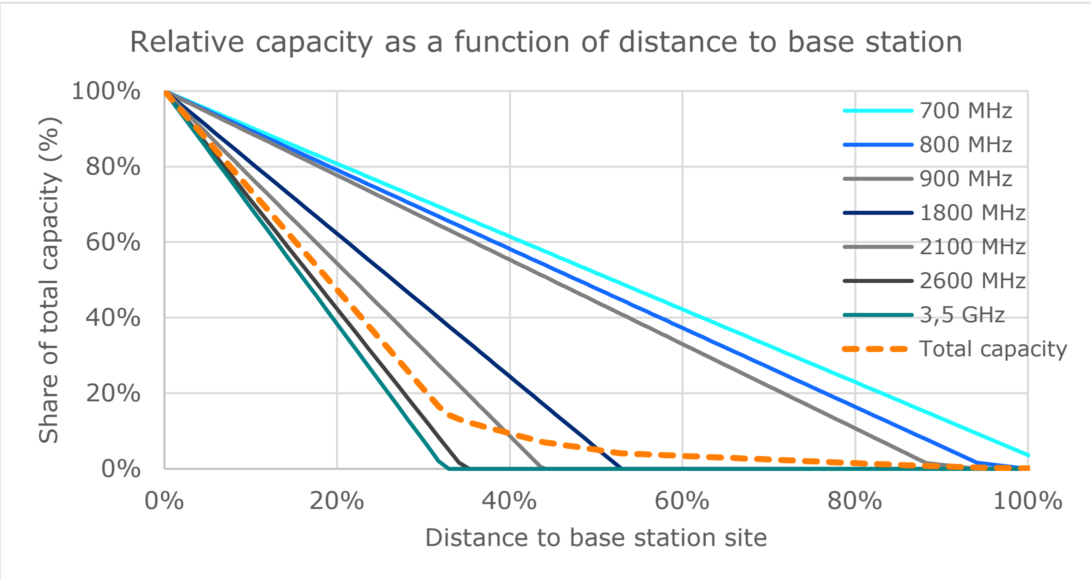


Figure 23. Relative capacity of different spectrum layers as a function of distance interpreted here as the relative share of the maximum coverage of the band with the best coverage (700 MHz).

The capacity levels from different spectrum bands available at different distances from the base station site are visualised separately, and the total capacity at any given distance from the base station is the sum of the different spectrum bands. The relative capacity of different spectrum layers illustrates the different coverage capability of each layer. Depending on the environment, the lower bands can typically provide service to twice as far compared to higher bands. However, as there is notably less spectrum bandwidth available on the lower bands (< 1 GHz), the absolute capacity of lower bands is lower. In the mid-bands (1-3 GHz) there is generally twice as much bandwidth per band, typically 2x20 MHz compared to lower bands with 2x10 MHz. In the 3,5 GHz band, the operators typically use 100 MHz bandwidth.

Figure 24 illustrates the absolute mobile system capacity with all the previously presented spectrum bands, assuming the typically deployed spectrum bandwidth for 4G and 5G. This highlights the challenge with mobile networks, that the higher bands can provide high capacity but only for a limited distance compared to the lower bands. The capacity of different spectrum bands is assumed to decrease roughly linearly when the distance to the base station increases outdoors. Indoors, the available capacity is impacted more by the building and how much the structures obstruct and attenuate the signal. The average effective capacity in a mobile network sector is largely dictated by the user distribution within the service area. If majority of the users are either farther away from the base station, or in challenging indoor locations, the effective average capacity of the sector decreases compared to the situation where majority of users would be near the base station in good signal conditions.

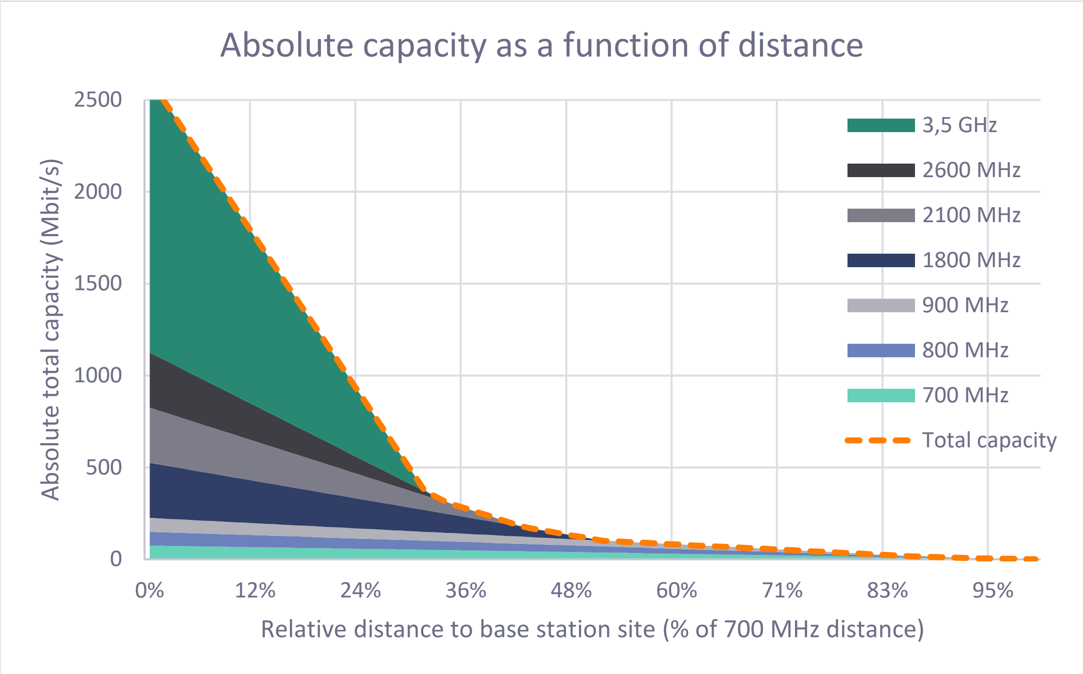


Figure 24. Absolute system capacity as a function of distance interpreted here as the relative share of the maximum coverage of the band with the best coverage (700 MHz).

The absolute system capacity here is illustrative only, and the relative coverage between the different spectrum bands is different in different environments. Furthermore, the total system capacity does not mean that any user would have access to the total system capacity, even if the system would be completely empty of other users. Resources are allocated to users based on demand and additionally the device capability and other limitations will impact how much capacity any single user is allocated. The total capacity is distributed to the different users in the service area at any given time. When assessing the mobile networks' ability to carry the traffic generated by C-ITS services, the total system capacity is a good measure of the ability of the network to serve the traffic originating from and terminating to multiple individual users.

In the following sub chapters, an example system capacity is presented for the different main environments, i.e., urban, suburban, rural and sparse rural.

2.1.1 Urban capacity

Urban mobile networks have historically largely been built using the mid-band (1-3 GHz) spectrum bands. Majority of the urban base station sites today have multiple mid-band spectrum bands, complemented with low-band (< 1 GHz) spectrum for improved coverage and the 3,5 GHz spectrum for increased capacity using 5G technology.

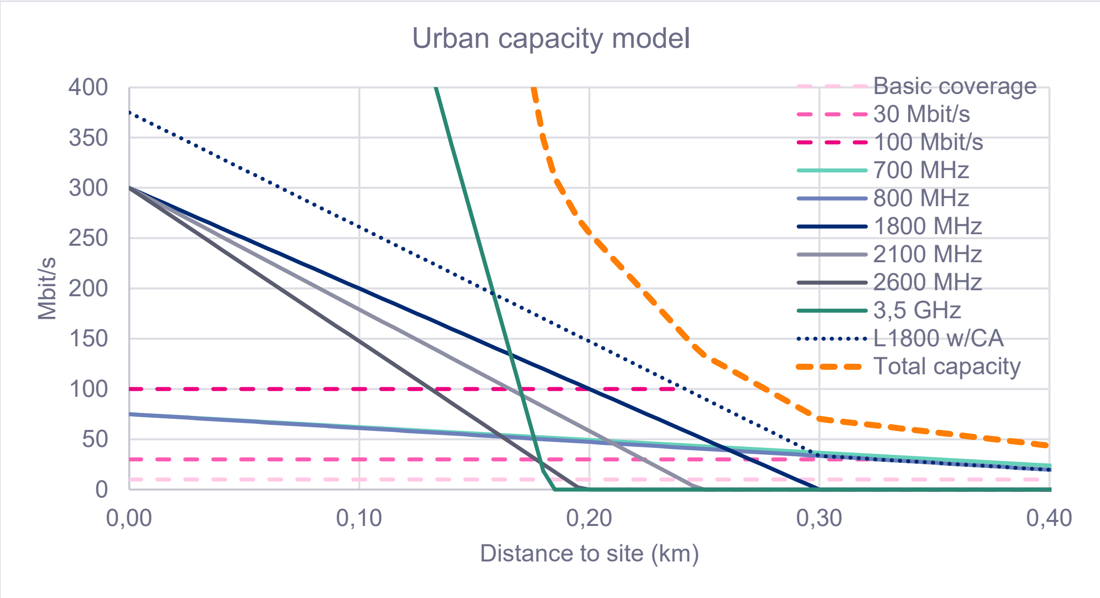


Figure 25. Urban capacity model for mobile networks.

The urban capacity model is illustrated in Figure 25, with capacity of each spectrum band visualised separately. The estimated coverage of the different speed tiers collected by Traficom (Basic coverage, 30 Mbit/s coverage and 100 Mbit/s coverage) are also illustrated for reference based on LTE 1800 MHz coverage with carrier aggregation ('L1800 w/CA' in the figure). In typical cases, the farthest carrier aggregation coverage is achieved with the combination of lowest mid band (1800 MHz) and a sub-GHz band (800 MHz). Based on this urban capacity model, a minimum of 100 Mbit/s is available at close to 250 metres from the base station, 30 Mbit/s at 330 metres, and basic coverage at 470 metres from the base station. In practice, the service distance of individual urban area base stations is very rarely over 200 metres, which means that on the edge of service areas between two base stations, the available speed tier is well over 100 Mbit/s.

For the total capacity assessment, the included spectrum bands are listed in Table 47. For this assessment, only 900 MHz band is excluded from the urban configuration. In practice, some urban area sites do not include all the included spectrum bands, but this represents a typical urban area mobile network site.

Table 47. Urban spectrum carriers for mobile networks.

Spectrum	Technol-ogy	Bandwidth in 4G/5G	Urban
3,5 GHz	5G	100 MHz (UL/DL)	Yes
2600 MHz	4G	2x20 MHz (UL+DL)	Yes
2100 MHz	4G/5G	2x20 MHz (UL+DL)	Yes
1800 MHz	4G	2x20 MHz (UL+DL)	Yes
900 MHz	4G/5G	2x5-10 MHz (UL+DL)	No
800 MHz	4G	2x10 MHz (UL+DL)	Yes
700 MHz	5G	2x10 MHz (UL+DL)	Yes

The total urban capacity is visualised in Figure 26. The total capacity near the base station can be over 2 000 Mbit/s (2 Gbit/s) depending on the availability of 3,5 GHz 5G deployment and still ~250 Mbit/s at 200 metres from the base station, where 3,5 GHz 5G is no longer available.

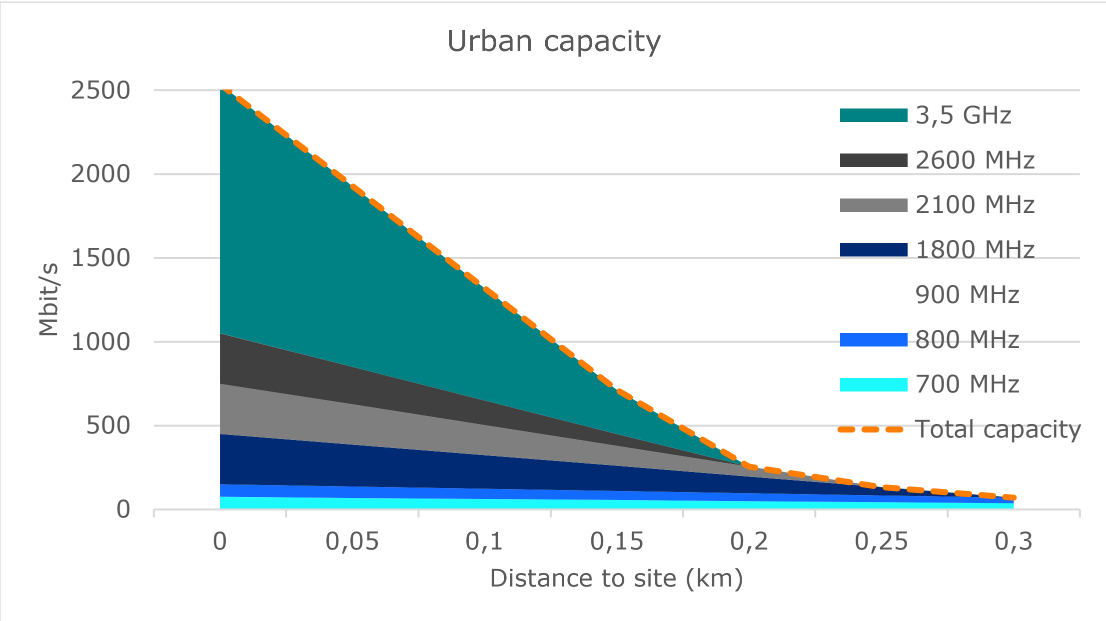


Figure 26. Total urban sector capacity for mobile networks.

The typical inter-site distance in dense urban areas is 200-300 m between the site locations. Therefore, the urban mobile base station sector typically serves up to distances of 133-200 meters (2/3 of ISD) before the next base station takes over. As a result, the urban area capacity is typically between 900-250 Mbit/s at the edge of the sector service area. Assuming the average inter-site distance at 250 m, the average sector service area range would be 167 metres, with service area edge capacity close to 500 Mbit/s. With the average inter-site distance, the average capacity in the whole service area is estimated at ~1 100 Mbit/s, calculated over the whole service area.

Depending on the density of the site deployment in the urban environment, the overall capacity in the area varies. Table 48 presents the estimated capacity of urban mobile network sectors with different inter-site distance assumptions.

Table 48. Example urban capacity estimates for mobile networks.

Urban site density	Inter-site distance	Sector service range	3-sector site service area	Sector edge capacity	Average capacity
Maximum	200 m	133 m	35 000 m² (0.035 km²)	900 Mbit/s	1 400 Mbit/s
Average	250 m	167 m	54 000 m² (0.054 km²)	470 Mbit/s	1 100 Mbit/s
Minimum	300 m	200 m	78 000 m² (0.078 km²)	250 Mbit/s	900 Mbit/s

2.1.2 *Suburban capacity*

Suburban mobile network coverage has been typically built using mid bands and complemented with low bands for improved continuous coverage and recently with 3,5 GHz to offer high-speed data services to households as an option to fast fixed connections. As a result, the capacity in suburban areas is often comparable to urban areas, but with larger service areas. When the capacity is spread out over a larger area, the average capacity per area is naturally lower.

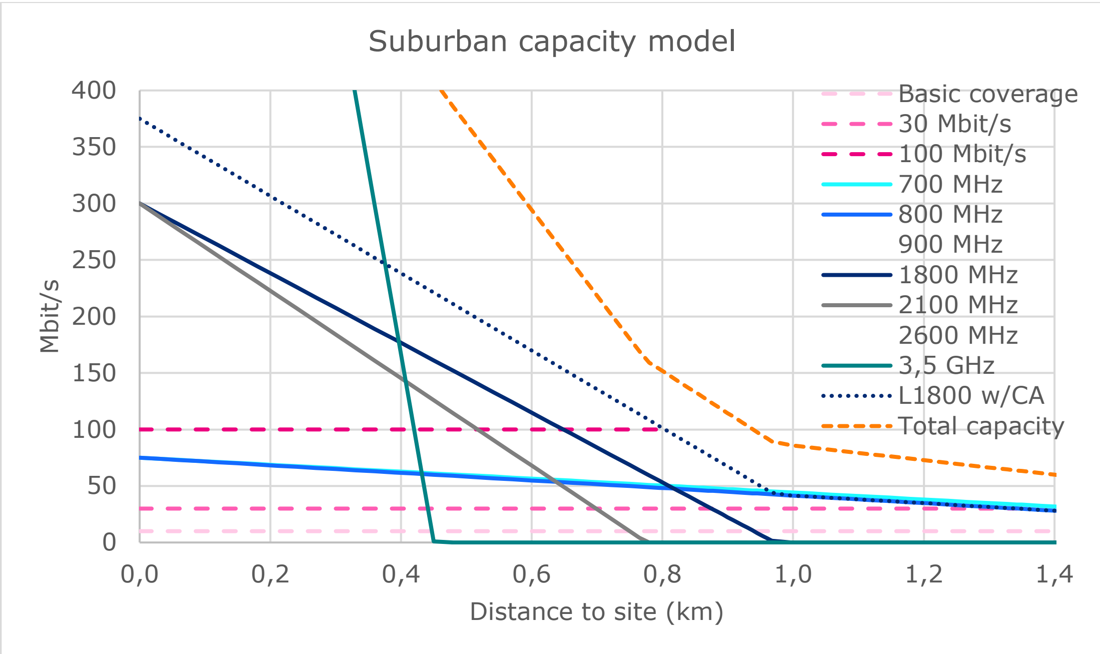


Figure 27. Suburban capacity model for mobile networks.

The suburban capacity model is illustrated in Figure 27, with capacity of each spectrum band and the total sum indicated separately. Based on this suburban capacity model, using LTE 1800 MHz with CA (together with LTE 800 MHz), a minimum of 100 Mbit/s is available at close to 800 metres from the base station, 30 Mbit/s at 1.3 kilometres, and basic coverage still at 1.9 kilometres from the base station (not visible in the selected range).

For the total suburban capacity assessment, the included spectrum bands are listed in Table 49. For this assessment, 900 and 2600 MHz bands are excluded from the suburban configuration, although used to some extent in individual sites is suburban areas. In practice, some suburban sites do not have all the included spectrum bands, but this represents a typical suburban mobile network site.

Table 49. Suburban spectrum carriers for mobile networks.

Spectrum	Technol-ogy	Bandwidth in 4G/5G	Suburban
3,5 GHz	5G	100 MHz (UL/DL)	Yes
2600 MHz	4G	2x20 MHz (UL+DL)	No
2100 MHz	4G/5G	2x20 MHz (UL+DL)	Yes
1800 MHz	4G	2x20 MHz (UL+DL)	Yes
900 MHz	4G/5G	2x5-10 MHz (UL+DL)	No
800 MHz	4G	2x10 MHz (UL+DL)	Yes
700 MHz	5G	2x10 MHz (UL+DL)	Yes

The total suburban capacity is visualised in Figure 28. The total capacity near the base station can be over 2 000 Mbit/s (2 Gbit/s) if 3,5 GHz 5G is deployed and still over 350 Mbit/s at 500 metres from the base station, where 3,5 GHz 5G is no longer available.

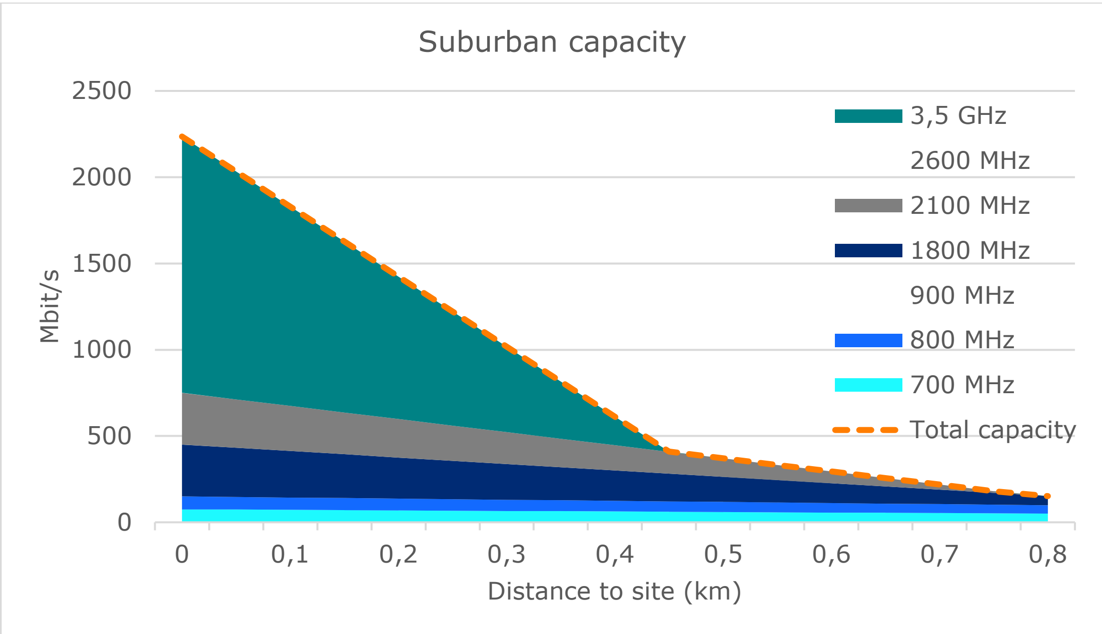


Figure 28. Total suburban sector capacity for mobile networks.

The typical inter-site distance in suburban areas is 500 m - 1 km between the site locations. The suburban mobile base station sector therefore typically serves up to distances of 333-667 meters (2/3 of the ISD). Based on this, the suburban area capacity is typically between 250-800 Mbit/s at the edge of the sector service area. Assuming the average inter-site distance at 750 m, the average sector service area range would be 500 metres, with service area edge capacity of ~350 Mbit/s. With the average inter-site distance, the average capacity in the whole service area is estimated at 800 Mbit/s.

Depending on the density of the site deployment in the suburban environment, the overall capacity in the area varies. Table 50 presents the estimated capacity of suburban mobile network sectors with different inter-site distance assumptions.

Table 50. Example suburban capacity estimates for mobile networks.

Suburban site density	Inter-site distance	Sector service range	3-sector site service area	Sector edge capacity	Average capacity
Maximum	500 m	333 m	0.22 km²	770 Mbit/s	1 200 Mbit/s
Average	750 m	500 m	0.49 km²	360 Mbit/s	800 Mbit/s
Minimum	1 000 m	667 m	0.87 km²	230 Mbit/s	600 Mbit/s

As the 3,5 GHz 5G rollouts are still on-going, there are still suburban areas without the 3,5 GHz spectrum deployed. For some areas, the 3,5 GHz spectrum may not be deployed at all if the demand in the area is not deemed sufficient by the operators. Therefore, a special low-capacity scenario for suburban environments is included for reference. The total suburban capacity in the low-capacity scenario is visualised in Figure 29. The total capacity in close proximity to the base station is ~700 Mbit/s compared to over 2 000 Mbit/s if 3,5 GHz 5G is deployed. The deployment of 3,5 GHz 5G does not have a big impact the capacity in sector service area edge but does impact the average over the whole sector service area.

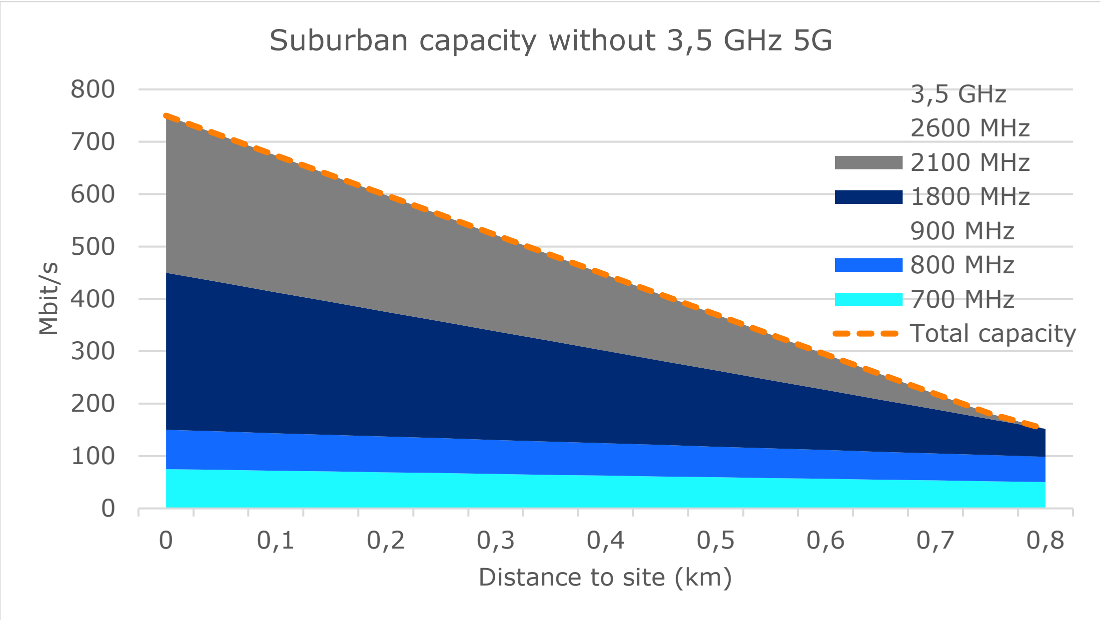


Figure 29. Total suburban sector capacity for mobile networks.without 3,5 GHz 5G deployment.

Table 51 presents the estimated capacity of suburban mobile network sectors without 3,5 GHz 5G deployment with the different inter-site distance assumptions. With the average site density assumption in this scenario, the average capacity of the sectors is 60% compared to the scenario with 3,5 GHz 5G (480 Mbit/s vs. 800 Mbit/s).

Table 51. Example suburban capacity estimates for mobile networks without 3,5 GHz 5G deployment.

Suburban site density	Inter-site distance	Sector service range	3-sector site service area	Sector edge capacity	Average capacity
Maximum	500 m	333 m	0.22 km²	480 Mbit/s	550 Mbit/s
Average	750 m	500 m	0.49 km²	360 Mbit/s	480 Mbit/s
Minimum	1 000 m	667 m	0.87 km²	230 Mbit/s	390 Mbit/s

2.1.3 *Rural capacity*

Typical rural sites are located near smaller villages or a cluster of households. It is therefore typical, that the sites have both 700 MHz and 800 MHz bands deployed for 5G and 4G coverage respectively, and in addition a mid-band (typically 1800 MHz and/or 2100 MHz) to provide additional capacity to the households in closer proximity.

The rural capacity model is illustrated in Figure 30, with capacity of each spectrum band and the total sum indicated separately. Based on this rural capacity model using LTE800 CA with LTE1800, a minimum of 100 Mbit/s is available at 5 kilometres from the base station, 30 Mbit/s at 7 kilometres, and basic coverage still at over 11 kilometres from the base station.

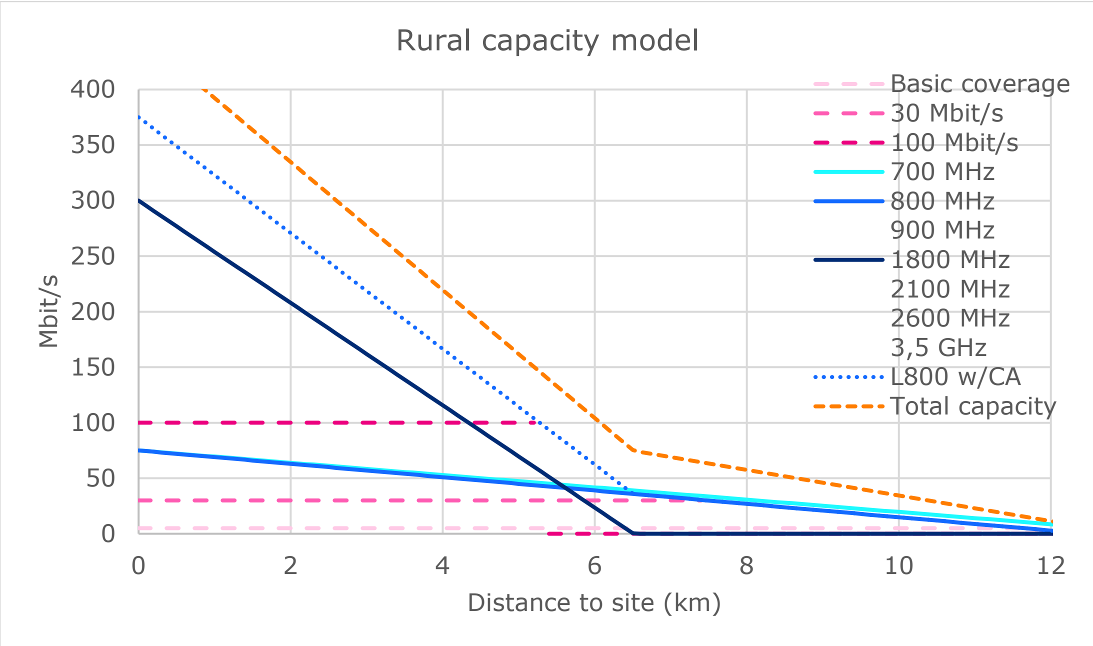


Figure 30. Rural capacity model for mobile networks.

For the total rural capacity assessment, the included spectrum bands are listed in Table 52. This assumes typical rural sites with low-band 700 and 800 MHz carriers for 5G and 4G coverage with additional 4G capacity for nearby households from the 1800 MHz band. This is supported by the availability of 4G 100 Mbit/s coverage presented in Figure 12 earlier, where small 4G 100 Mbit/s coverage areas are present in predominantly rural areas. With low-band spectrum only, 100 Mbit/s coverage cannot be achieved with currently used technologies and requires at least a combination of low-band and mid-band spectrum.

Table 52. Rural spectrum carriers for mobile networks.

Spectrum	Technology	Bandwidth in 4G/5G	Rural
3,5 GHz	5G	100 MHz (UL/DL)	No
2600 MHz	4G	2x20 MHz (UL+DL)	No
2100 MHz	4G/5G	2x20 MHz (UL+DL)	No
1800 MHz	4G	2x20 MHz (UL+DL)	Yes
900 MHz	4G/5G	2x5-10 MHz (UL+DL)	No
800 MHz	4G	2x10 MHz (UL+DL)	Yes
700 MHz	5G	2x10 MHz (UL+DL)	Yes

The total rural capacity is visualised in Figure 31. The total capacity in close proximity to the base station can be over 400 Mbit/s where 1800 MHz provides additional capacity and ~70 Mbit/s at 7 kilometres from the base station, where 1800 MHz is no longer available. It is worth noting that majority of the devices available do not support carrier aggregation between the low bands (< 1 GHz) due to physical transmitter/receiver size limitations, and thus a single user would only have access to one low-band spectrum carrier at a time. As devices develop, the use of carrier aggregation between sub-GHz bands may become more commonplace, enabling higher speeds in areas where only sub-GHz coverage from multiple bands is available. For the purpose of this assessment however, carrier aggregation is not relevant, as the C-ITS services under investigation do not require high throughput per single user. The total capacity is key in assessing the ability of the mobile networks to carry the total data traffic demand of multiple C-ITS users.

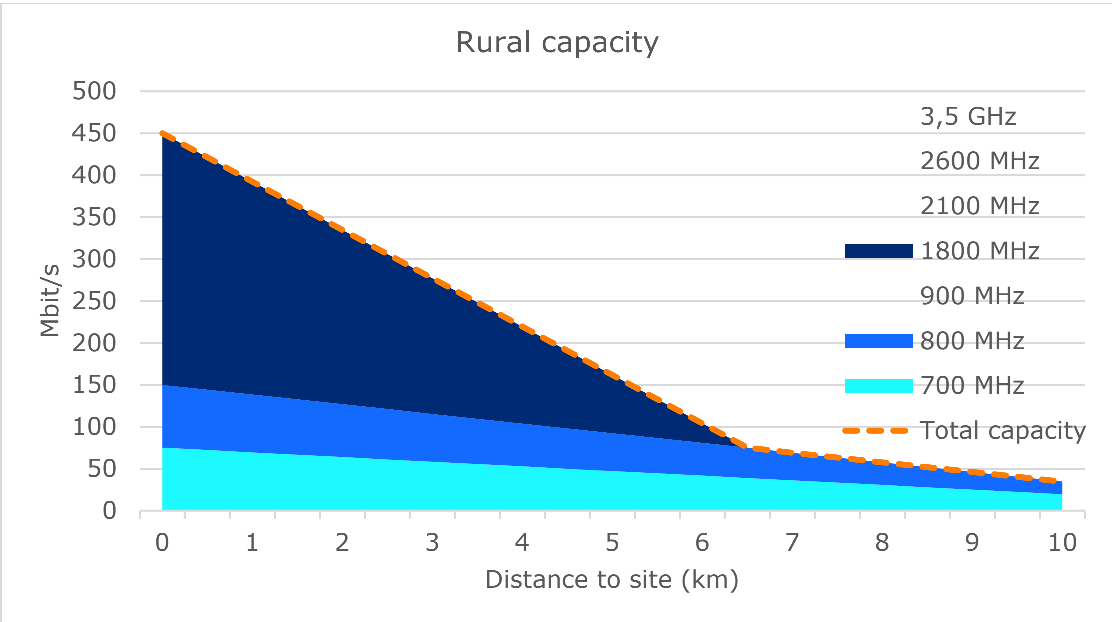


Figure 31. Total rural sector capacity for mobile networks.

The typical inter-site distance in rural areas is 5 - 10 km between the site locations. The rural mobile base station sector therefore typically serves up to distances of 3,3-6,7 kilometres. Based on this, the rural area capacity is typically between 70-250 Mbit/s at the edge of the sector service area. Assuming the average inter-site distance at 7,5 km, the average sector service area range would be

5 kilometres, with service area edge capacity of ~160 Mbit/s. With this average inter-site distance, the average capacity in the whole service area is estimated at 250 Mbit/s.

Depending on the density of the site deployment in the rural environment, the overall capacity in the area varies. Table 53 presents the estimated capacity of rural mobile network sectors with different inter-site distance assumptions.

Table 53. Example rural capacity estimates for mobile networks.

Rural site density	Inter-site distance	Sector service range	3-sector site service area	Sector edge capacity	Average capacity
Maximum	5 km	3.3 km	21.7 km²	250 Mbit/s	320 Mbit/s
Average	7.5 km	5 km	48.8 km²	160 Mbit/s	250 Mbit/s
Minimum	10 km	6.7 km	86.7 km²	70 Mbit/s	190 Mbit/s

2.1.4 Sparse rural capacity

In addition to the rural area sites that are built near inhabited areas, there are remote sites that are mainly serving remote road sections and sparsely distributed houses or wilderness. These sites typically do not have mid-bands deployed but may still have both 800 MHz for 4G and 700 MHz for 5G coverage. These sites are also typically built with very high towers, upwards of 80 metres from the ground, to enable very large coverage areas.

The sparse rural capacity model is illustrated in Figure 32, with capacity of the low-band spectrum carriers and the total sum indicated separately. Based on this rural capacity model, 30 Mbit/s is available at 9 kilometres from the base station, and basic coverage still at over 14 kilometres from the base station. A minimum of 100 Mbit/s is not available within the sparse rural coverage. As indicated before, carrier aggregation between sub-GHz bands is not widely used due to transmitter/receiver physical limitations in end-user devices, and therefore the speed tier coverage is estimated only based on one carrier in the sparse rural model.

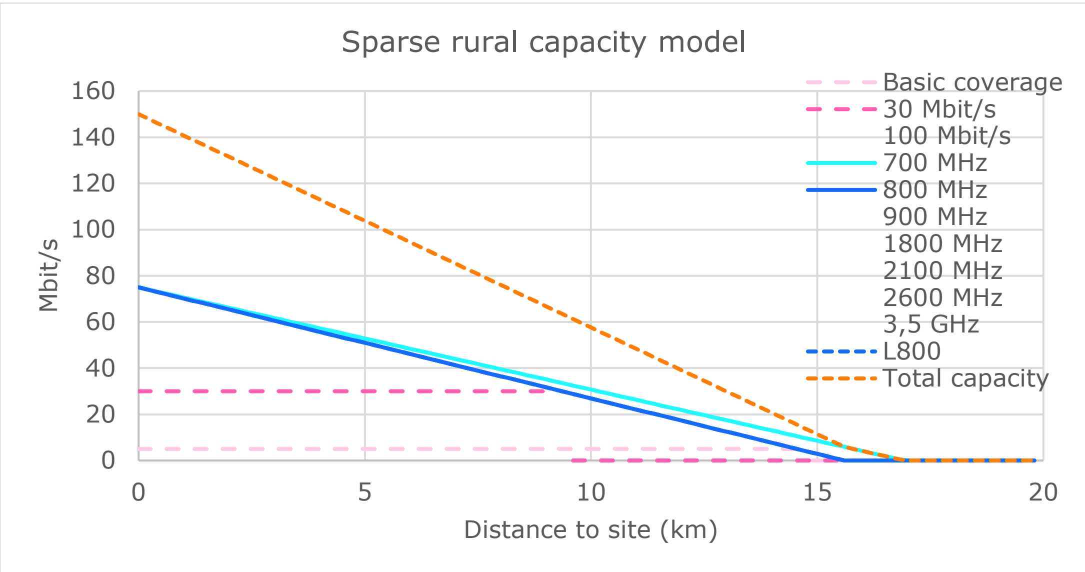


Figure 32. Sparse rural capacity model for mobile networks.

For the total sparse rural capacity assessment, this assumes typical sparse rural sites with only low-band 700 and 800 MHz carriers for 5G and 4G coverage, without any other bands deployed. The total rural capacity is visualised in Figure 33. The total capacity in close proximity to the base station can be close to 150 Mbit/s, and ~60 Mbit/s at 10 kilometres from the base station.

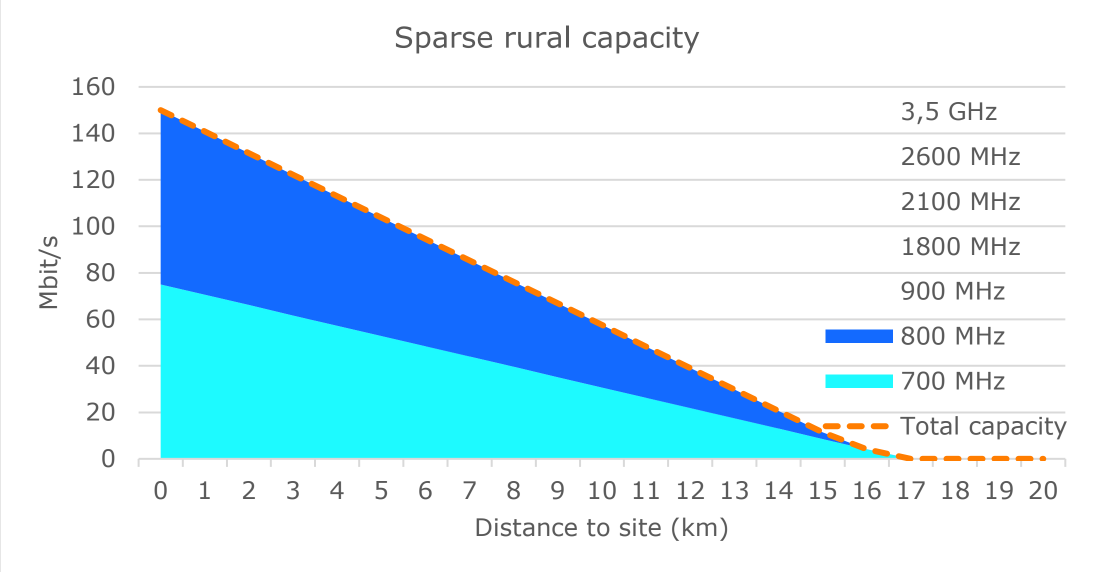


Figure 33. Total sparse rural sector capacity for mobile networks.

The typical inter-site distance in sparse rural areas may be anywhere from 10 - 30 km, typically in the range of 10 - 15 km between the site locations. The sparse rural mobile base station sector therefore typically serves up to distances of 7 - 10 kilometres. Based on this, the sparse rural area capacity is typically between 60 - 85 Mbit/s at the edge of the sector service area. Assuming the average inter-site distance at 12,5 km, the average sector service area range would be 8,3 kilometres, with service area edge capacity of ~70 Mbit/s. With this average inter-site distance, the average capacity in the whole service area is estimated at 95 Mbit/s.

Depending on the density of the site deployment in the rural environment, the overall capacity in the area varies. Table 54 presents the estimated capacity of rural mobile network sectors with different inter-site distance assumptions. For an extreme case scenario, a sparse rural roadside example is also included, where a 2-sector roadside base station provides coverage only to the roads crossing a largely uninhabited area. In such a case the inter-site distance can be around 30 km, and the sector service range would be half of the inter-site distance. In the extreme case, the sector edge capacity would be ~10 Mbit/s and the average capacity over the whole coverage area ~55 Mbit/s.

Table 54. Example sparse rural capacity estimates for mobile networks.

Sparse rural site density	Inter-site distance	Sector service range	3-sector site service area	Sector edge capacity	Average capacity
Maximum	10 km	6.7 km	87 km²	85 Mbit/s	105 Mbit/s
Average	12.5 km	8.3 km	135 km²	70 Mbit/s	95 Mbit/s

Sparse rural site density	Inter-site distance	Sector service range	3-sector site service area	Sector edge capacity	Average capacity
Minimum	15 km	10 km	195 km²	60 Mbit/s	85 Mbit/s
Sparse rural roadside extreme (2-sector site)					
Roadside	30 km	15 km	290 km² (2-sector site)	10 Mbit/s	55 Mbit/s

2.1.5 *Conclusions on mobile network capacity*

The results from the analysis in the previous sub-chapters are collected in Table 55. While the built spectrum capacity in urban and high-capacity suburban areas is similar, the coverage area in suburban areas is typically much larger (close to 10x) which results in lower average capacity in the coverage area. As there are plenty suburban areas without 3,5 GHz deployed, this suburban area scenario is relevant for the analysis.

Table 55. Mobile network capacity in different environments.

Environment		Urban	Suburban	Suburban (no 3,5 GHz)	Rural	Sparse rural
Average capacity over coverage area (Mbit/s)						
	Average	1100 Mbit/s	800 Mbit/s	480 Mbit/s	250 Mbit/s	95 Mbit/s
	Minimum	900 Mbit/s	600 Mbit/s	390 Mbit/s	190 Mbit/s	85 Mbit/s
	Maximum	1400 Mbit/s	1200 Mbit/s	550 Mbit/s	320 Mbit/s	105 Mbit/s
	Roadside					55 Mbit/s
Base station coverage area (km²)						
	Average	0.054 km²	0.49 km²	0.49 km²	48.8 km²	135 km²
	Minimum	0.078 km²	0.87 km²	0.87 km²	86.7 km²	195 km²
	Maximum	0.035 km²	0.22 km²	0.22 km²	21.7 km²	87 km²
	Roadside					293 km²
Speed tier coverage: distance (km) and area (km²)						
	Basic coverage	0.5 km 0.4 km²	1.9 km 7.2 km²	1.9 km 7.2 km²	11.6 km 262.4 km²	14.5 km 410.0 km²
	30 Mbit/s coverage	0.3 km 0.2 km²	1.3 km 3.5 km²	1.3 km 3.5 km²	7.4 km 106.8 km²	9.2 km 165.0 km²
	100 Mbit/s coverage	0.2 km 0.1 km²	0.8 km 1.2 km²	0.8 km 1.2 km²	5.2 km 52.7 km²	Not available

In urban and suburban areas, the capacity of mobile networks is on average very high because of the extensive deployment of the different available spectrum bands. In rural areas the higher spectrum bands cannot provide coverage to large enough areas to justify large-scale deployment, and the capacity options for operators are therefore limited. Therefore, the capacity of the rural areas remains notably lower, while the service areas can be 10 to 30 times larger than suburban areas.

3 Mobile network development metrics for C-ITS

3.1 Current mobile network development monitoring metrics

This chapter presents more detailed review of the currently collected information on commercial mobile network development and how to use this information to assess the feasibility of the service level framework from Part A "Definition of service level framework for mobile networks" and Part B "Measurement methodologies and techniques" in mobile networks.

3.2 Coverage predictions

The accuracy of a normal 2-dimensional coverage prediction cannot be guaranteed at any single prediction area, within which the actual coverage level varies. The prediction is aimed at providing an overview of the coverage area, and the frequency band specific propagation models are tuned (by radio network planners or RF engineers of network operators) to provide the most accurate overview. The process of propagation model fine-tuning aims to minimize the standard deviation between empirical field measurements and simulation result. However, also the accuracy of the used digital maps in predictions, including clutter types, terrain heights and (new) buildings, as well as antenna radiation modelling patterns, have significant impact on the simulation outcome. Further localised predictions can be used for increased accuracy in any given location, but however, these require significant efforts for localised fine-tuning of the prediction models and parameters and are thus not suitable for nationwide predictions.

Figure 34 below illustrates a practical example of fine-tuned coverage prediction result from one base station site with one single frequency carrier, overlayed with the measurement results of the signal strength from drive test measurements (both the prediction and the measurement were conducted by Omnitele Ltd). Example road sections where the measurement significantly deviates from the prediction are highlighted. This illustrates the challenges in providing accurate information in a specific location using prediction models aimed at providing the most accurate overview of the coverage area.

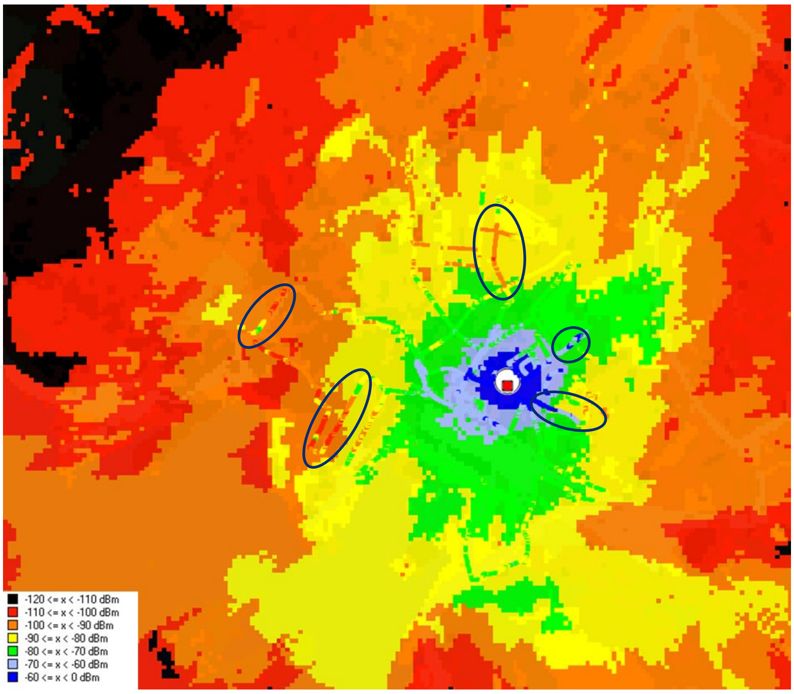


Figure 34. Example coverage prediction comparison to field measurements (Omnitele).

Currently Traficom collects, on a regular basis, coverage estimates from mobile network operators about LTE network basic coverage and the coverage of different speed tiers, e.g., 30 Mbit/s and 100 Mbit/s services in LTE networks as well as 100 Mbit/s, 300 Mbit/s and 1 Gbit/s services in 5G networks (Traficom, Definitions for communications services and networks used in Traficom's statistics and requests for information, 2023). Nonetheless, the guidelines for generating the coverage predictions allow quite high level of flexibility for the reporting party.

The basic LTE coverage is specified with a single signal strength (RSRP, Reference Signal Received Power) threshold of -110 dBm, regardless of used spectrum band. However, for example 30 Mbit/s LTE service level coverage estimate is more ambiguous as it is dependent on the carrier layer deployments and could be achieved alternatively as follows:

- On sub-GHz band, like LTE800: -85 dBm
- On sub-GHz band with CA, like LTE800+LTE1800: -100 dBm
- On mid-band, like LTE1800: -100 dBm
- On mid-band with CA, like LTE1800+LTE2600: -110 dBm.

As the network coverage prediction, requested quarterly by Traficom, is generated countrywide by the operators, including different types of areas with different sector configurations/bands, it is strongly operator specific how the rules are applied in the predictions in practice. Additionally, the RSRP thresholds are rather arguable as the achievable throughput is dependent also on other factors, for example, signal quality or network equipment (radio hardware) receiver sensitivity.

The following graphs illustrate the evolution of the different coverage estimates per service category. Results are presented either as population coverage (households) or as geographical coverage.

Figure 35 illustrates the development of the availability of the different speed tiers and basic LTE coverage for a percentage of households, as collected and published by Traficom at regular intervals (Traficom, Mobile network access of residential customers, 2023). These are combined results from all the mobile networks, i.e., not representing the coverage of any single operator.

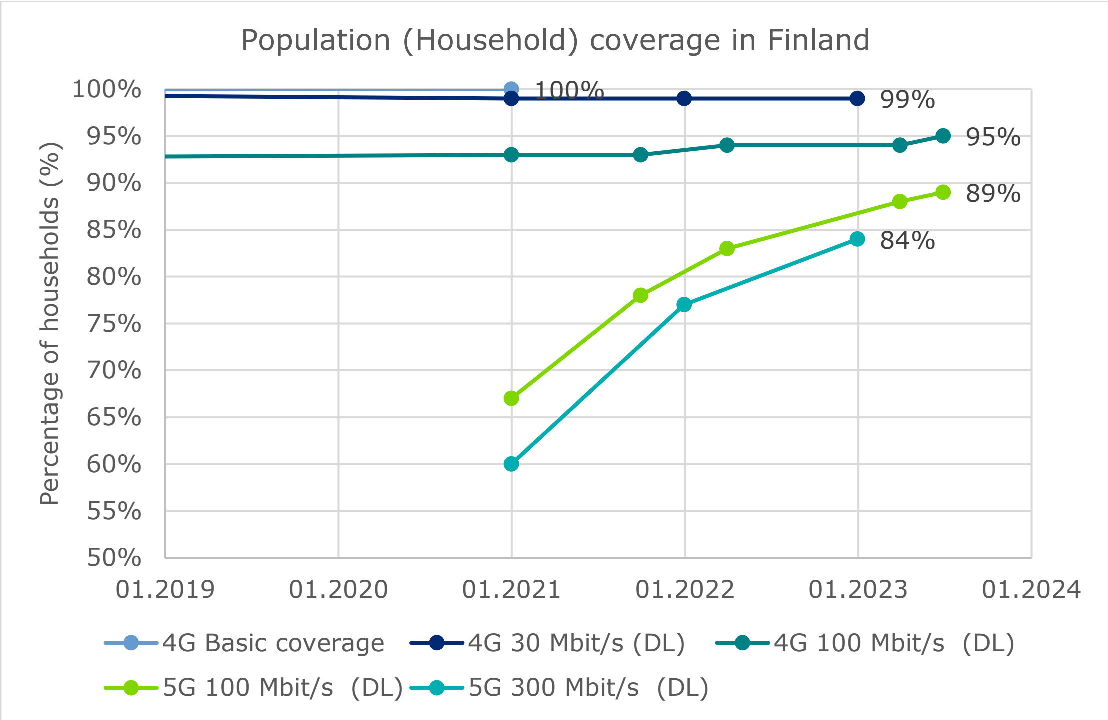


Figure 35. Population (household) coverage per 4G/5G service levels.

The publication of 4G basic coverage has been discontinued after the end of 2020 results. It is to be noted that 4G basic coverage has been available to 100% of households within rounding error accuracy.

Figure 36 illustrates the development of availability of the different speed tiers and basic LTE coverage as share of land area covered, as collected and published by Traficom at regular intervals (Traficom, Geographical coverage of mobile network by region, 2023). When compared to household coverage, the coverage is very different. For example, the geographical coverage of 4G 100 Mbit/s is 21% (30.6.2023), while the household coverage of the same speed tier is 95%.

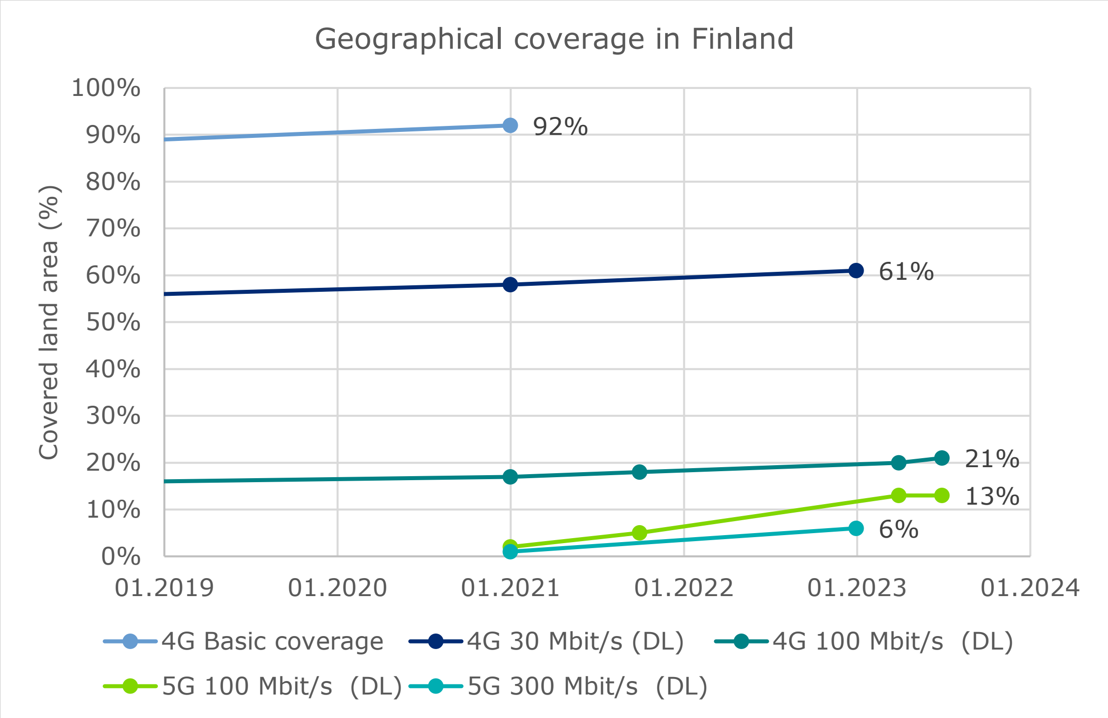


Figure 36. Geographical coverage per 4G/5G service levels.

Figure 37 presents the results from an analysis published by Traficom (Traficom, Coverage of fast data connections on traffic routes, 2023) that investigated the development of fast data connection coverage on the road network. The results show that 100 Mbit/s 4G connections covered 60% of main roads by the end of 2022. In Finland there are around 13 000 km of main roads in total (Väylävirasto, 2022). The 5G coverage was still notably behind, with only 38% of main roads covered by at least 100 Mbit/s 5G connections.

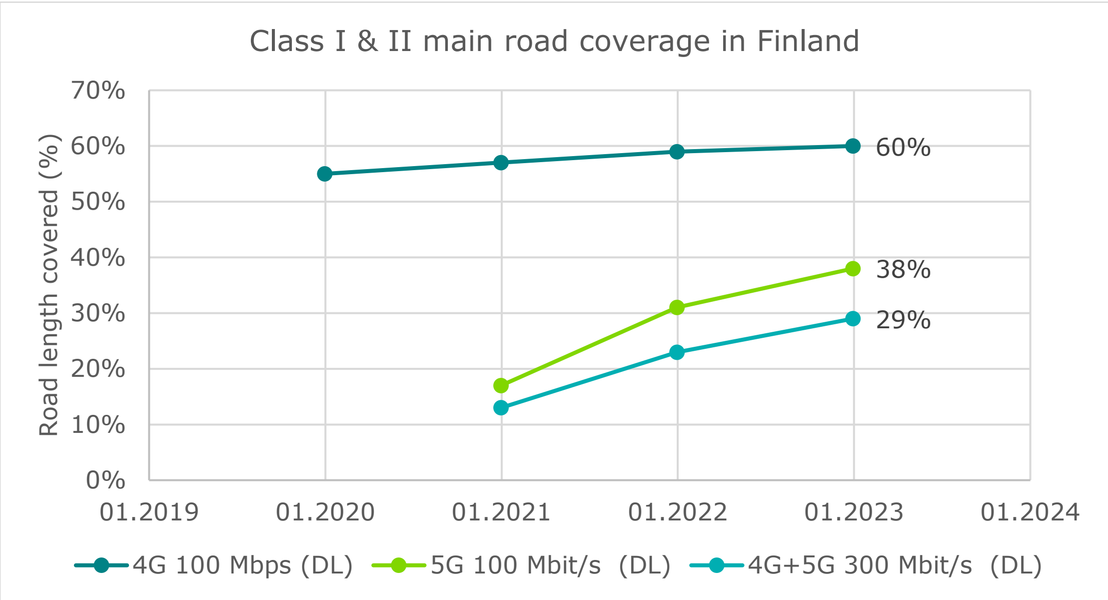


Figure 37. Main road coverage per 4G/5G service levels.

3.2.1 Verification of coverage estimates using field measurements

The following maps in this sub-chapter illustrate the combined (i.e. including collected data from all national operators) coverage estimates of LTE basic coverage (light purple colour) and 30 Mbit/s LTE service level coverage (dark purple colour), information provided by Traficom to support this assessment. The combined coverage data is collected and combined by Traficom from the operator-specific coverage data. Maps illustrate the situation as per end of year 2022. The current situation would be somewhat better since new site deployments have been implemented on the area by the operators in order to enhance the LTE coverage and service level. Figure 38 shows scanner results derived from drive test measurements carried out by Traficom in northern Finland area in the end of year 2022 for concrete comparison between predictions and actual measurements.

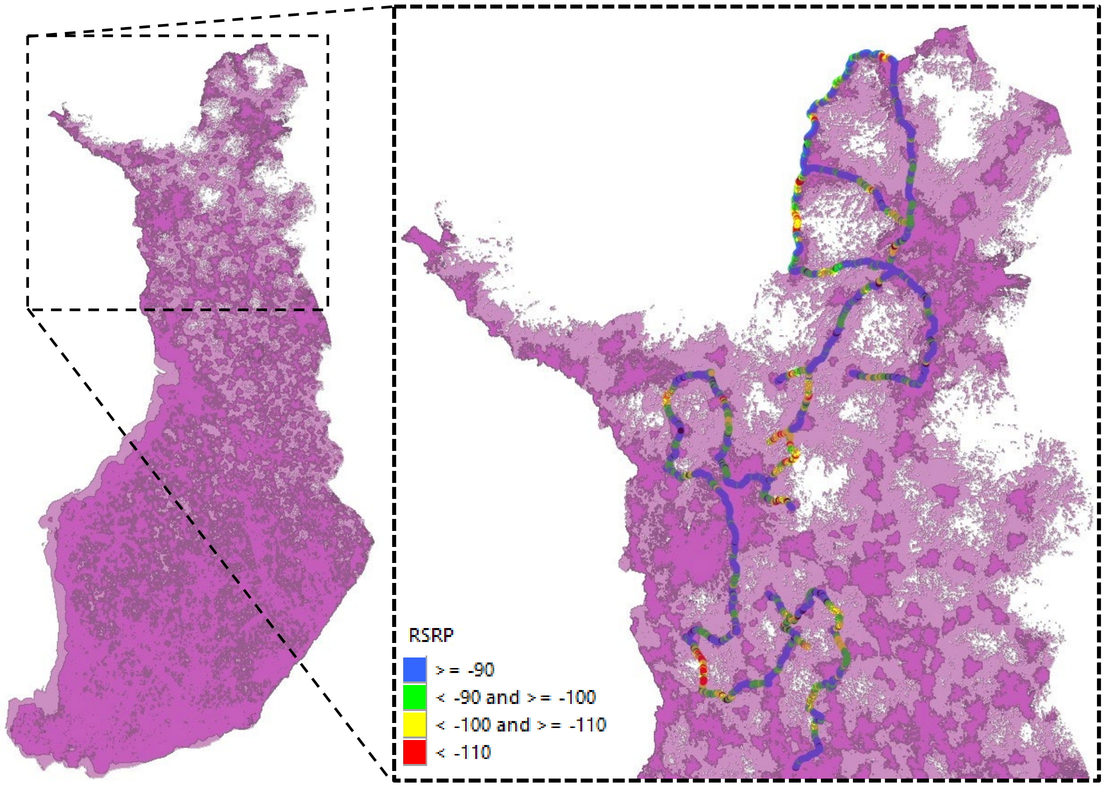


Figure 38. Traficom's combined coverage estimates of LTE basic coverage (light purple) and 30 Mbit/s LTE service level coverage (dark purple) as well as field measurements (RSRP, Reference Signal Received Power) executed on selected main roads in northern Finland area. All information presents the situation as per end of 2022.

Considering the specifications of the combined predictions (RSRP of -110 dBm for basic coverage and RSRP of around -90 dBm for 30 Mbit/s LTE service level coverage), it was further analyzed how well they match with empirical tests. This enabled the evaluation of the accuracy of the coverage estimates. The comparison between coverage estimates and field measurements is divided into the following three regions for more detailed analysis per area:

- Inari – Utsjoki (the northernmost part)
- Kittilä – Enontekiö – Muonio – Inari (the middle part)
- Sodankylä – Rovaniemi – Kolari – Pello (the southernmost part).

Inari – Utsjoki region

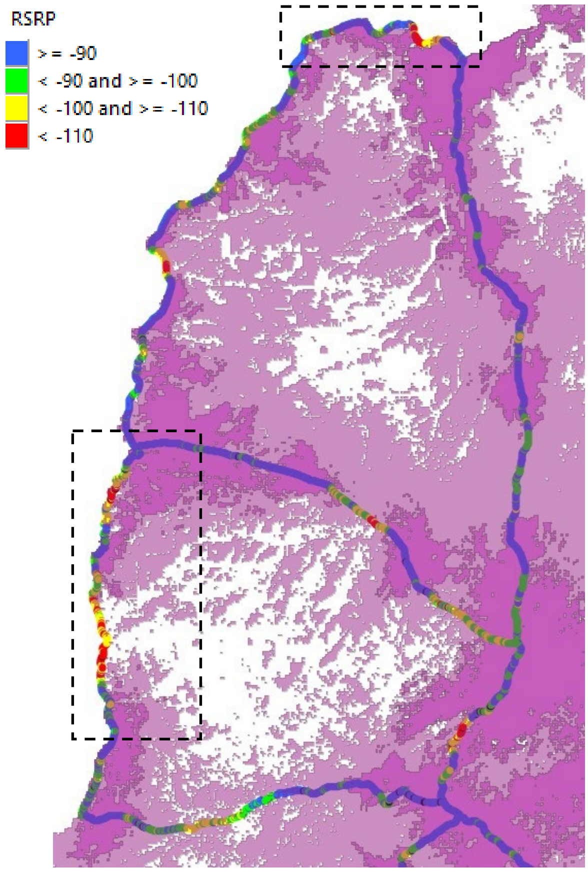


Figure 39. Comparative analysis between the coverage estimate and field measurements in the northernmost part: Inari – Utsjoki region.

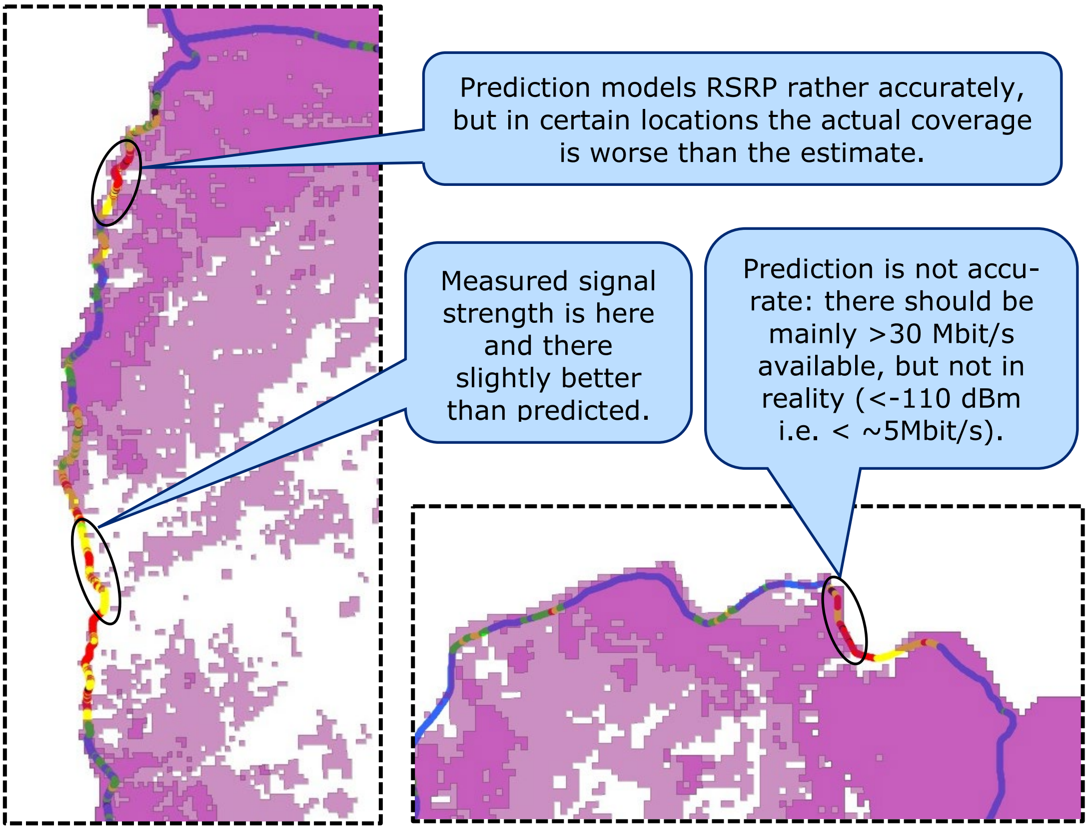


Figure 40. Detailed analysis of poor coverage locations on area 1.

Kittilä – Enontekiö – Muonio – Inari region

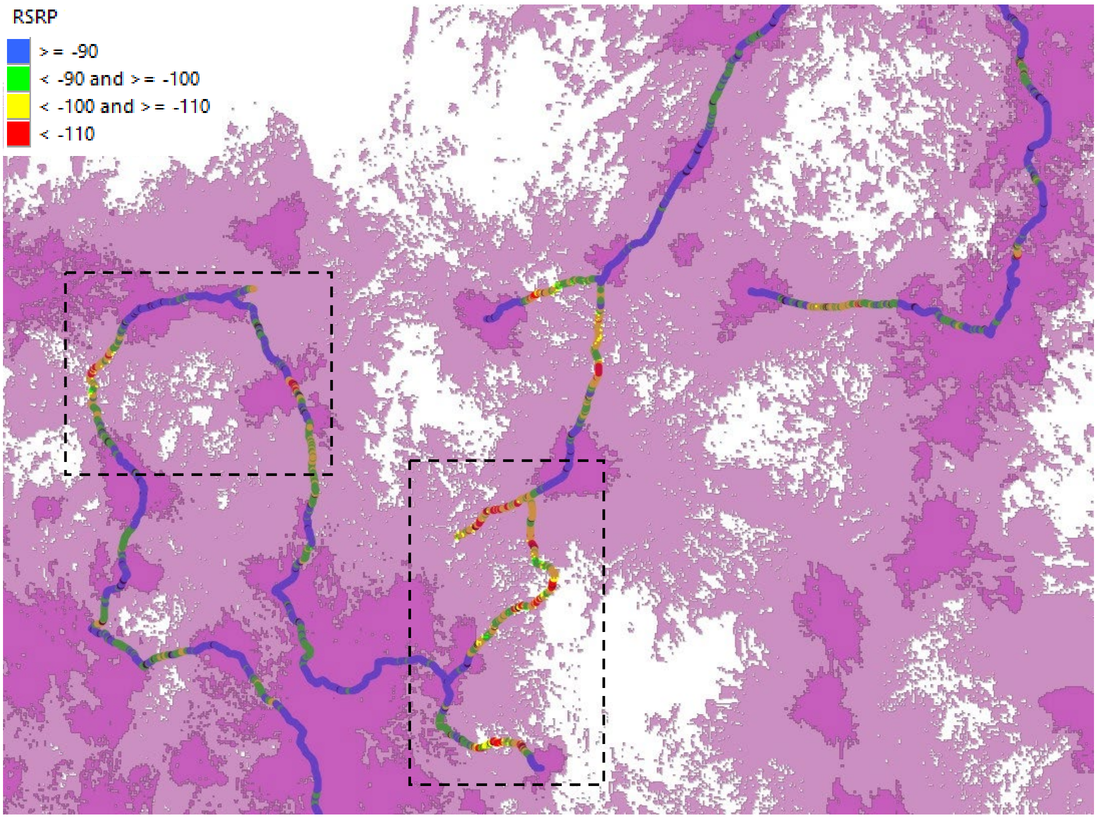


Figure 41. Comparative analysis between the coverage estimate and field measurements in the middle part: Kittilä – Enontekiö – Muonio – Inari region.

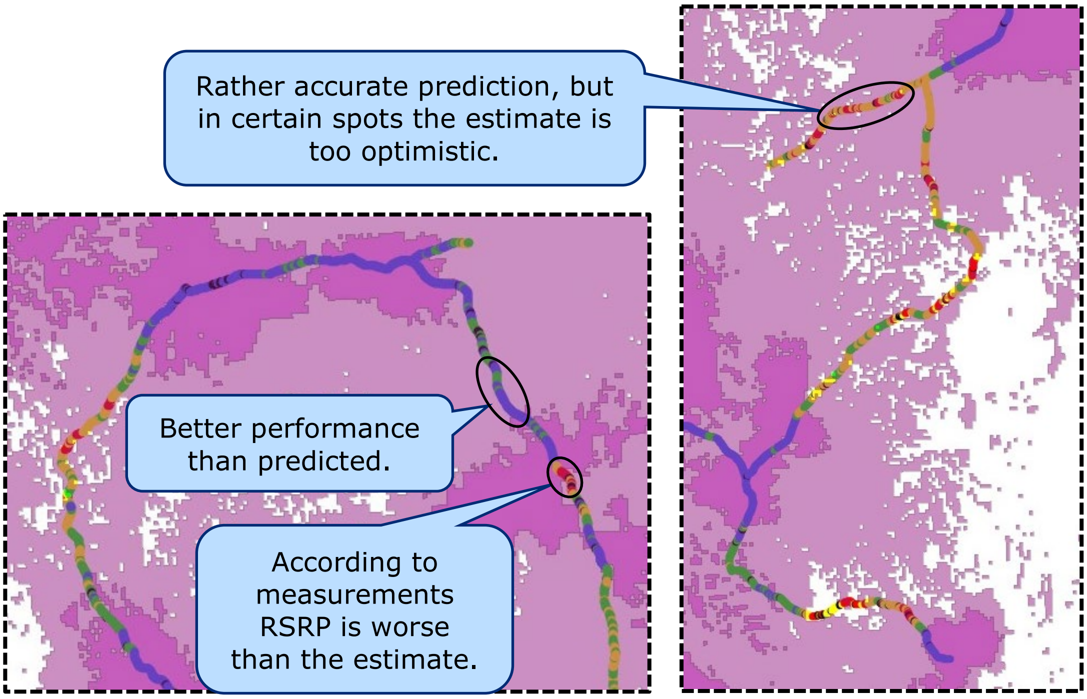


Figure 42. Detailed analysis of poor coverage locations on area 2.

Sodankylä – Rovaniemi – Kolari – Pello region

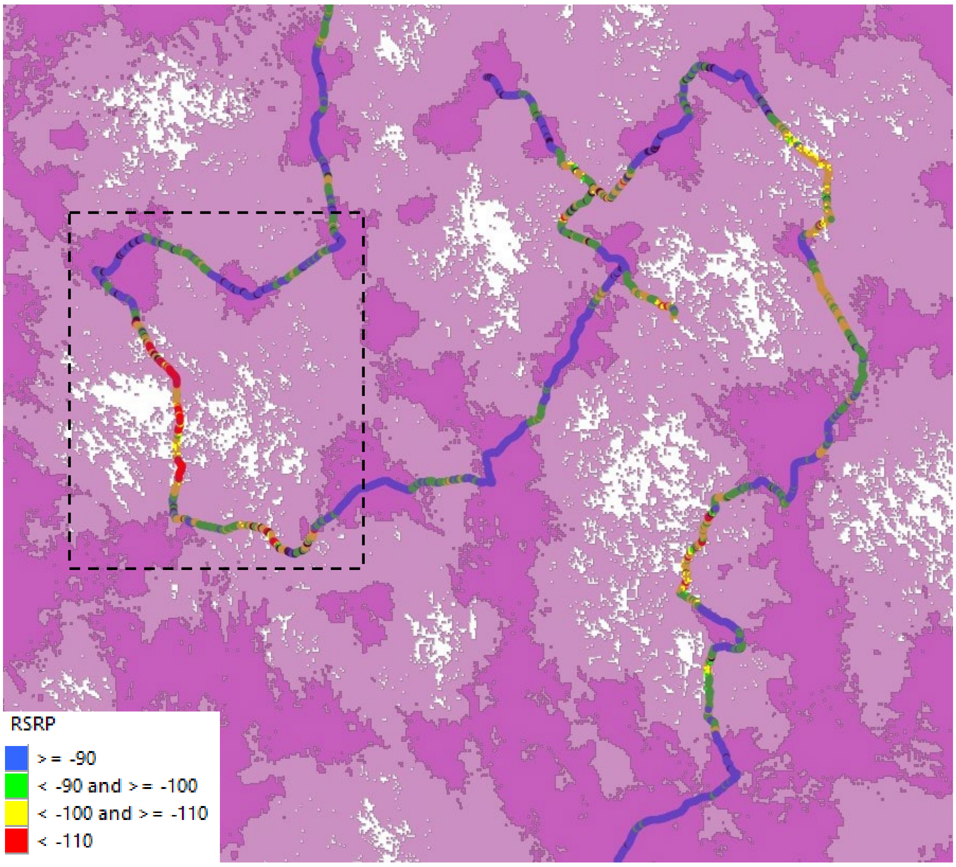


Figure 43. Comparative analysis between the coverage estimate and field measurements in the southernmost part: Sodankylä – Rovaniemi – Kolari – Pello region.

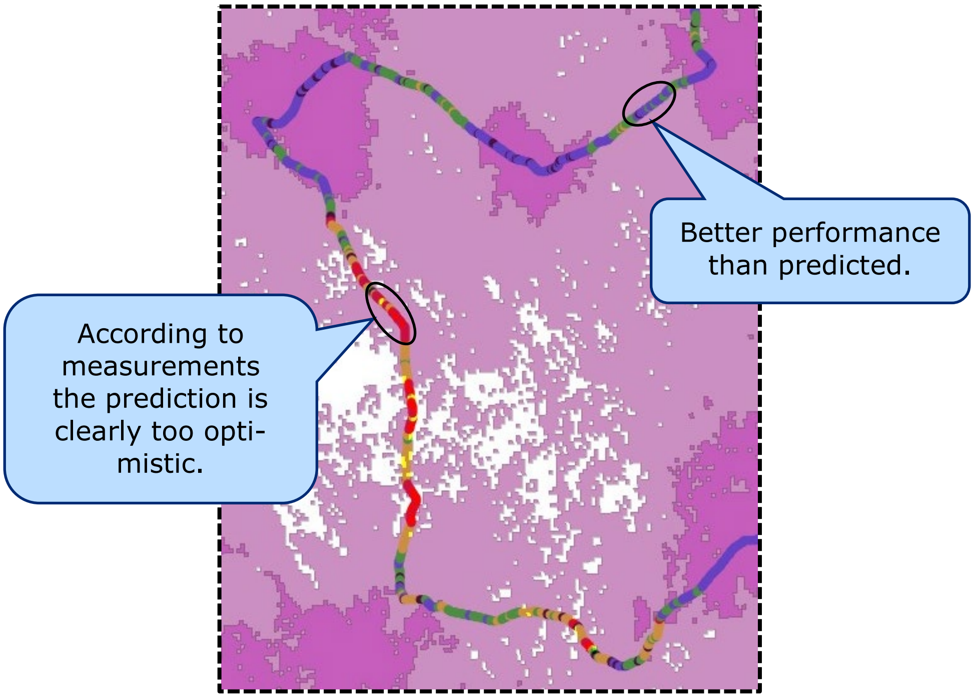


Figure 44. Detailed analysis of poor coverage locations on area 3.

Based on the presented comparative analysis it can be concluded that with coverage predictions it is possible to estimate service availability on desired large-scale area rather well on general level. However, there is quite much variation in the accuracy when drilling down to certain geographical locations or spots. Therefore, based on the coverage prediction it is quite challenging to precisely determine the actual service quality level in a specific spot. Whether the service is available or not, and a ballpark service quality level (whether it is ~5-10 Mbit/s or >100 Mbit/s) can be estimated with satisfying accuracy in majority of the locations.

3.2.2 Identifying coverage problems and availability issues with predictions

In any case, coverage predictions are a useful tool to identify potential service availability issues, coverage holes and problematic locations with poor user experience, which can be then further verified with field measurements and carefully planned and conducted tests. The following coverage maps present the combined LTE basic coverage in northern Finland area.

Basic LTE coverage

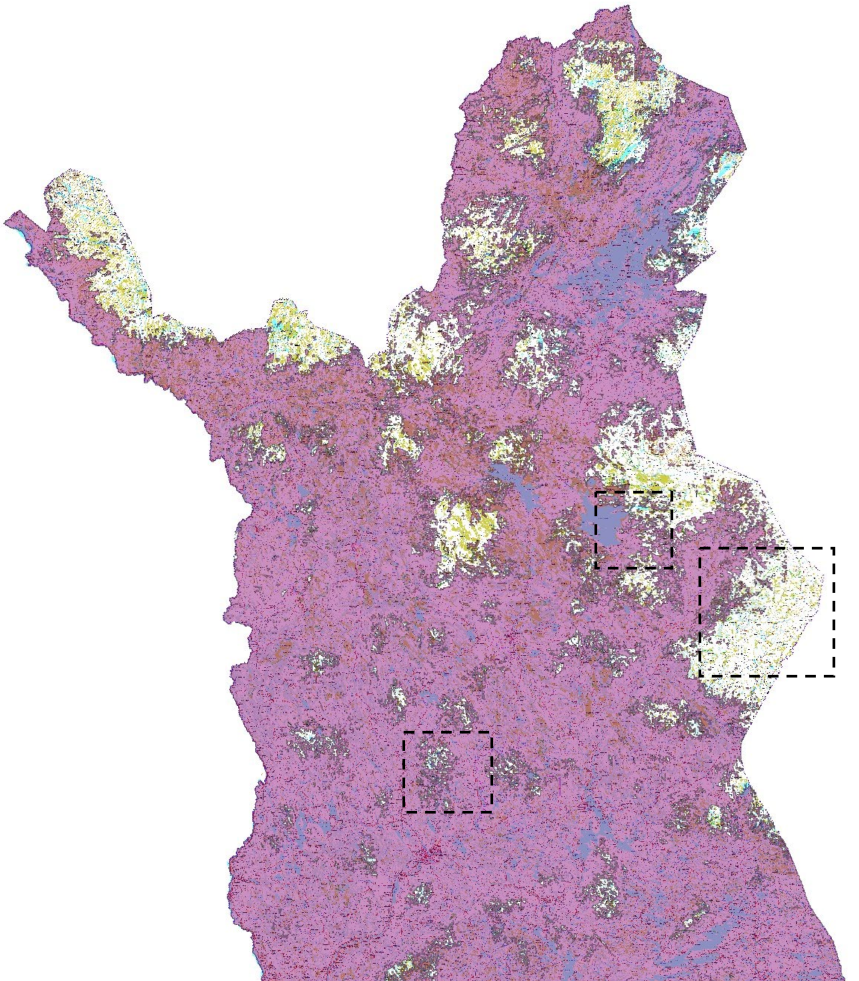


Figure 45. Combined basic LTE coverage in northern Finland.

Areas commonly lacking LTE basic coverage are either fells, swamps or deep forests without any proper roads nearby. It should also be noted that at eastern national border of Finland there are restrictions regarding 800 MHz band usage affecting the LTE deployments and baseline coverage. Some typical examples of coverage holes on road areas are illustrated below. Mainly the issues are just with some local and connecting roads (paikallis- ja yhdystiet).

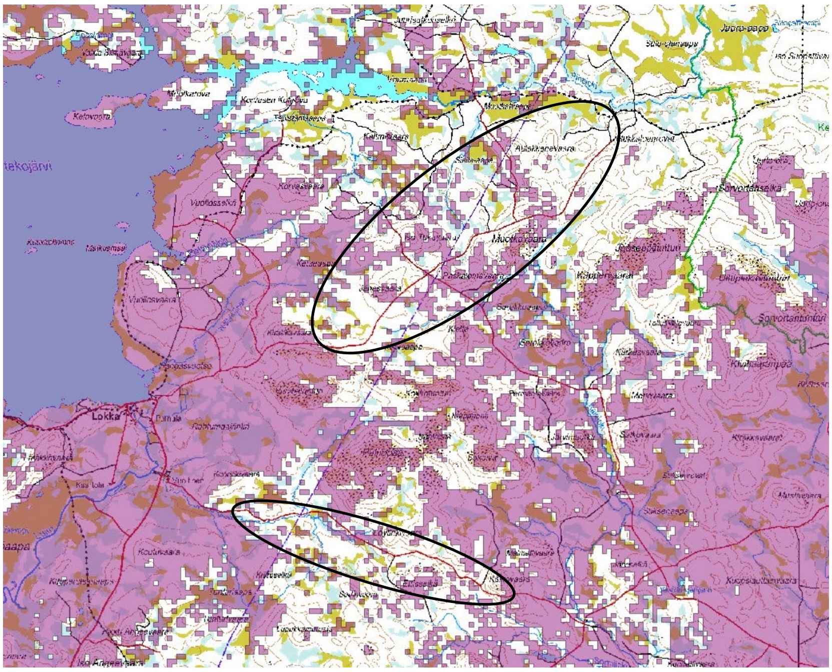


Figure 46. Example of basic LTE coverage holes on local and connecting roads.

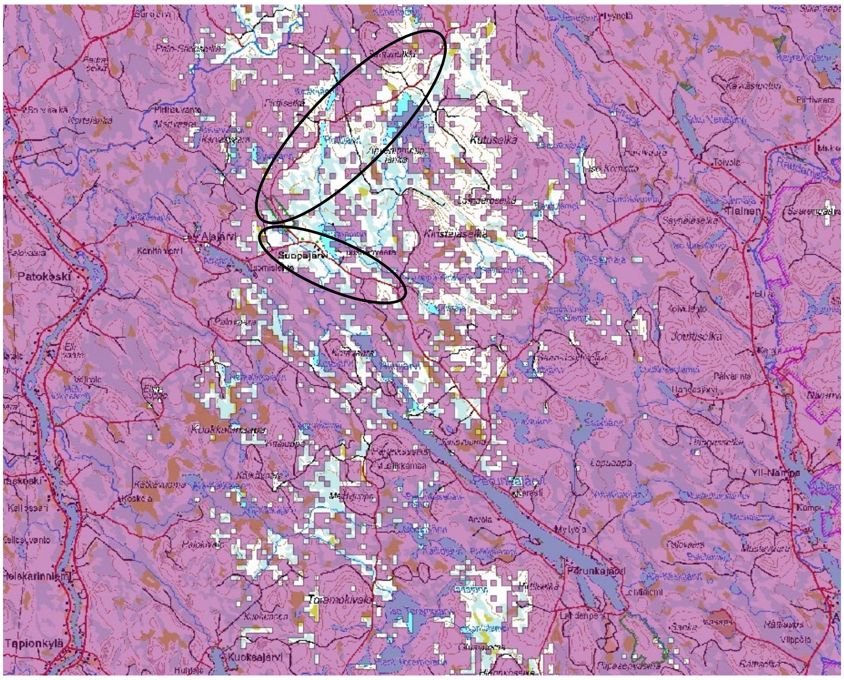


Figure 47. Example of basic LTE coverage holes on local and connecting roads.

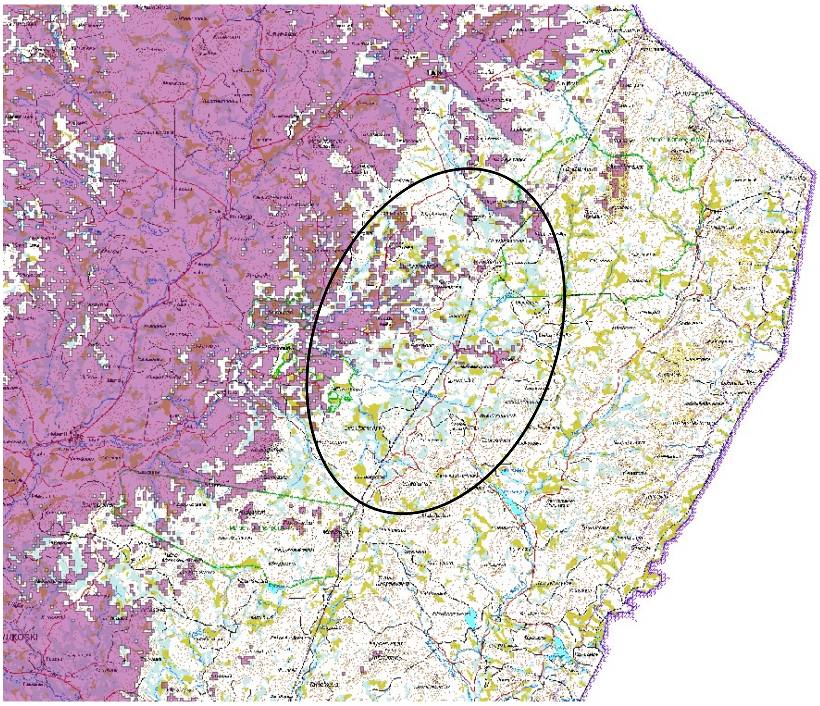


Figure 48. Example of basic LTE coverage hole on local roads.

30 Mbit/s LTE service coverage

When analysing the 30 Mbit/s LTE service predictions it’s obvious from the coverage map below that service is primarily concentrated on populated areas, as well as on main roads (valta- ja kantatiet).

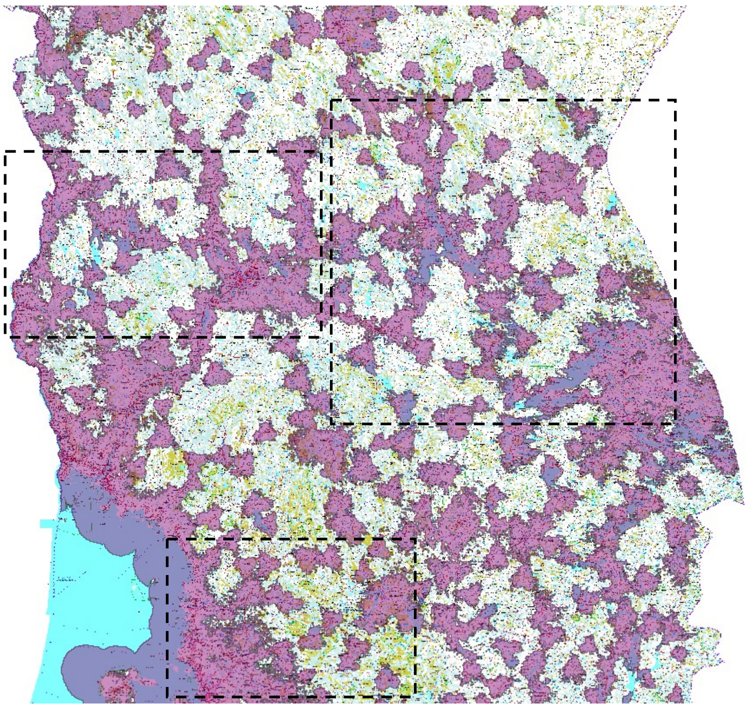


Figure 49. Combined 30 Mbit/s LTE coverage in northern Finland.

Some examples regarding typical coverage holes on road areas are illustrated below. In addition to local and connecting roads, there are several areas on regional roads (seututiet), but also locations on some main roads, without adequate signal strength.

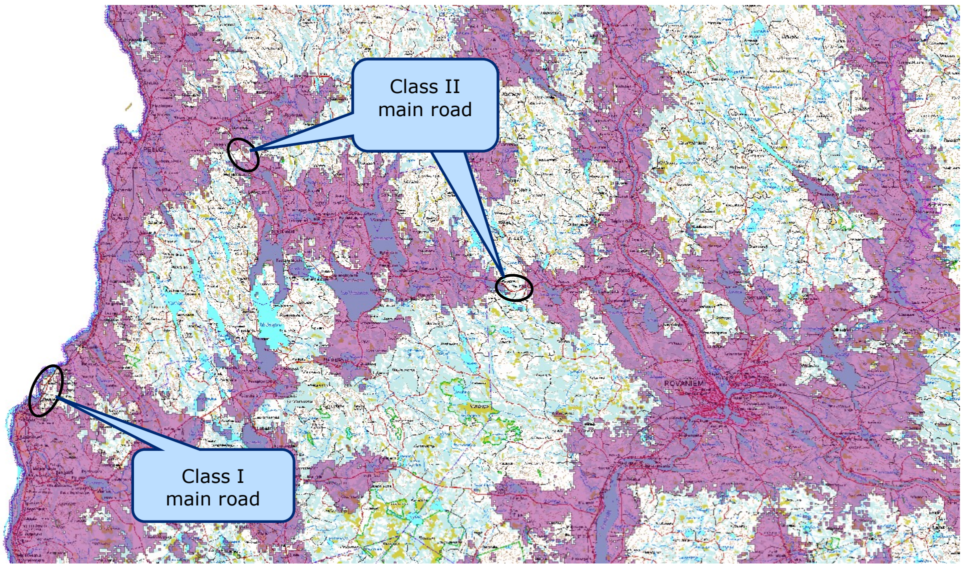


Figure 50. Example of 30 Mbit/s LTE service coverage holes on main roads.

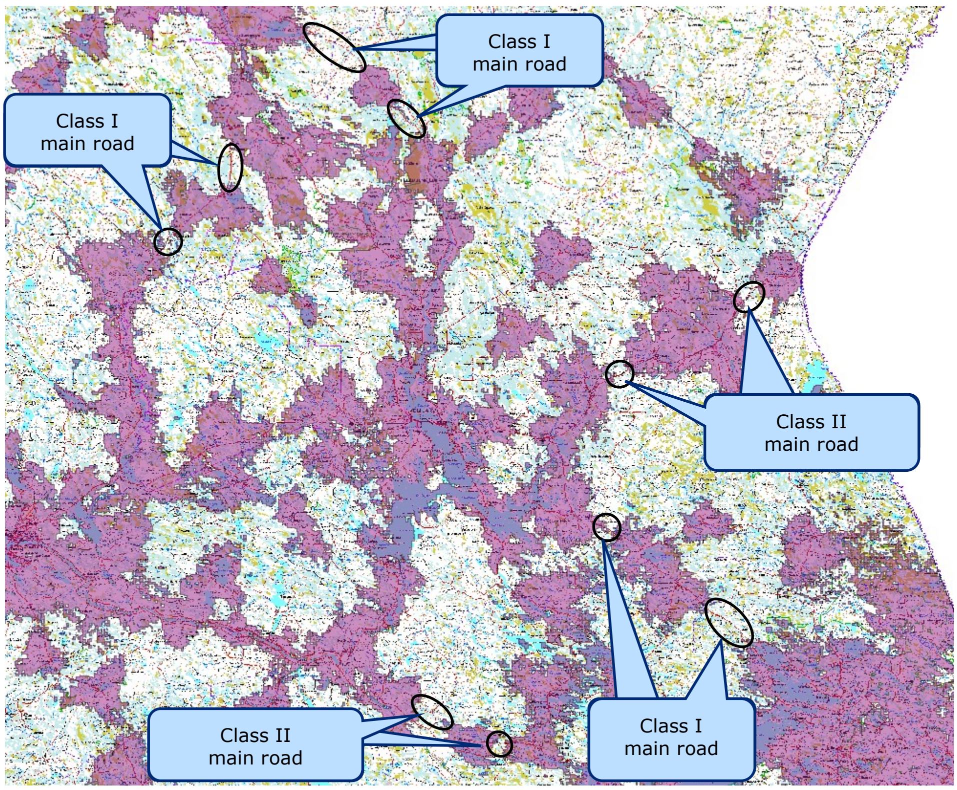


Figure 51. Example of 30 Mbit/s LTE service coverage holes on main roads.

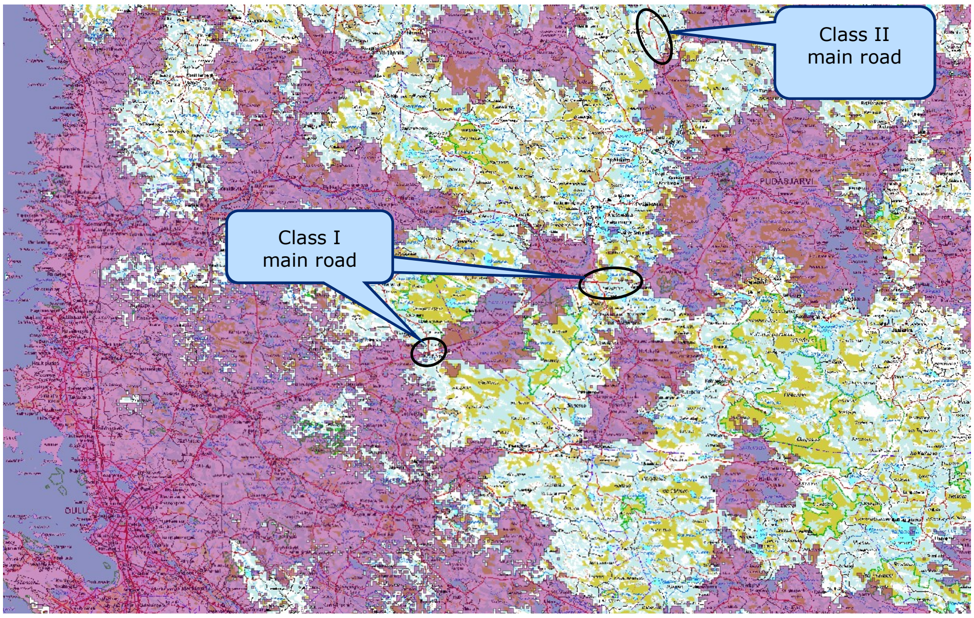


Figure 52. Example of 30 Mbit/s LTE service coverage holes on main roads.

Like the previous examples highlighted, coverage predictions provide a good indication of the available service level generally. Predictions are a useful tool in identifying problematic locations in means of service availability that can be then further verified with field measurements on desired area. Due to the high degree of flexibility regarding guidelines in generating the coverage estimates, it is strongly operator specific how the rules are applied in the predictions in practice. Consequently, coverage predictions should be considered also operator specific and analysed separately, as one may provide sufficient coverage in a certain area and other(s) don't. Furthermore, the available service quality level (throughput) may vary significantly between the operators, depending on their local site deployments and network strategy.

3.3 Field measurements

Traficom collects information on network status via field measurements when needed, typically triggered by consumer complaints or large-scale reports of insufficient service in a given area. Typical measurements are carried out by drive tests, using both a user terminal and a frequency scanner. An overview of the proposed additions to current Traficom field measurement methodology is presented in Table 56.

Table 56. Proposed field measurement methodology overview.

Test case	Current methodology	Proposed methodology
Frequency scanner	☑ Measure all frequencies of all operators	☑ OK: Measure all frequencies of all operators
Voice service	☑ Voice call success	☒ Not relevant for C-ITS
Data service	☑ Ping tests	☑ OK: Ping tests ☑ Add: Throughput measurement (stress test)

Application simulation (option)	☒ none	☐ service-level tests (option) ☐ service-specific tests (option)

The current measurement methodology focuses on testing the basic functionality of mobile services, testing voice call functionality and data service availability with ping tests while continuously scanning the available mobile network frequencies. As discussed earlier, the proposed additions to the measurement methodology are primarily using well-established typical field measurement methods. The main proposed addition to the measurement methodology is the inclusion of throughput testing, to validate the availability of sufficient throughput to support the identified C-ITS requirements for different service levels. A stress test is preferred due to its ability to analyse available throughput and feasibility for different service levels. With service-level-specific testing, only the feasibility of the tested service level can be validated. With service-specific testing, only the specific service functionality is validated. Those two (service-level / service-specific tests) can be considered as optional test cases which aim to simulate the application usage.

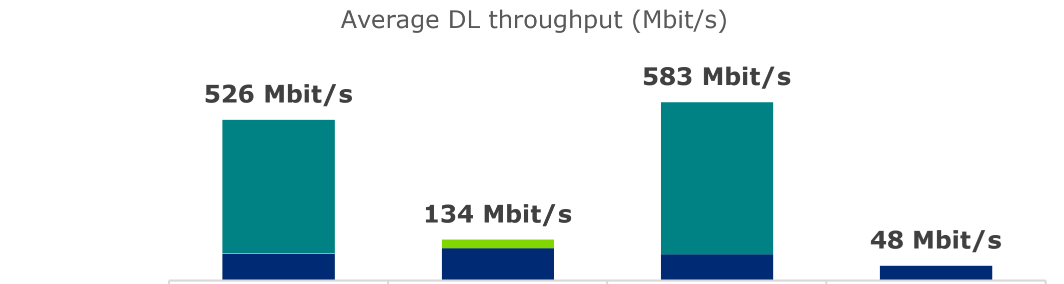
In summary, a stress test will measure the network capability and allows flexibility in assessing the availability of sufficient capacity and coverage for different services and service levels. The service-level- and service-specific tests are still very much relevant for validating the actual functionality of the combination of services and individual services, but for overall network development monitoring, stress test measurements provide additional analysis flexibility and furthermore, allow keeping the measurement methodology similar over the years for comparable results, even if the service-specific or service-level-specific requirements would change as the services are developed further.

3.3.1 Stress test measurements

With stress test measurements, the capability of the network in a given area can be measured. Figure 53 illustrates the overall results from example download throughput performance measurements. The result consists of over 20 hours of drive test measurement, with ~550 km covered at an average speed of 27 km/h. The average download throughput over the whole measurement period was 526 Mbit/s. The measurements were carried out mainly in urban and suburban areas in and around one city, including also some rural areas near the city. The measurements covered the main roads in the area and majority of streets within the city.

It is worth noting that the actual capacity available to multiple users is at least what is measured to be available in stress test for one device for two main reasons: 1) one device may not be able to use all the capacity available due to limitations in device capability to aggregate all the spectrum capacity available or due to subscription limitations, and 2) the prioritisation and allocation of capacity is typically based on allocating a fair share of capacity to each user based on both the number of users competing for resources as well as the demand of each user.

In these measurements, only download throughput is considered. For C-ITS service level validation, upload throughput measurements and latency tests are also required for a complete validation. These measurements are provided as an example for illustrative purposes.



	Average	When 5G: 700 MHz	When 5G: 3.5 GHz	When no 5G
Total	526	134	583	48
NR3500	435		497	
NR700	3	28		
4G	87	106	86	48
Share	100%	12%	87%	1%

Figure 53. Example overall download throughput results from drive test measurements.

Figure 53 shows the result breakdown from different technology and spectrum combinations. The relative share of time when different combinations were used is provided for reference, to indicate how the overall average over time is achieved. As previously discussed, 4G and 5G can operate in dual connectivity mode, whereby users will have access to both 4G and 5G networks simultaneously and can utilise the capacity of both networks. However, 5G deployments differ quite significantly depending on the spectrum band, i.e., with 700 MHz spectrum (10 MHz bandwidth), the additional throughput capacity to users is only a fraction of what it is with the 3,5 GHz spectrum band (100 MHz bandwidth). This is well illustrated in Figure 53, where the average result is depicted separately for when different 5G spectrum is used. When 700 MHz is providing the 5G capacity, it provides roughly ~30 Mbit/s additional boost to the achievable throughput, but when 3,5 GHz is providing the additional 5G capacity, there is close to 500 Mbit/s additional throughput boost.

In Figure 54, the result is further broken down to ~2 min 30 s averages, which illustrate the variation of the results in the drive test. The minimum value in the example is 95 Mbit/s and the maximum value is 916 Mbit/s.

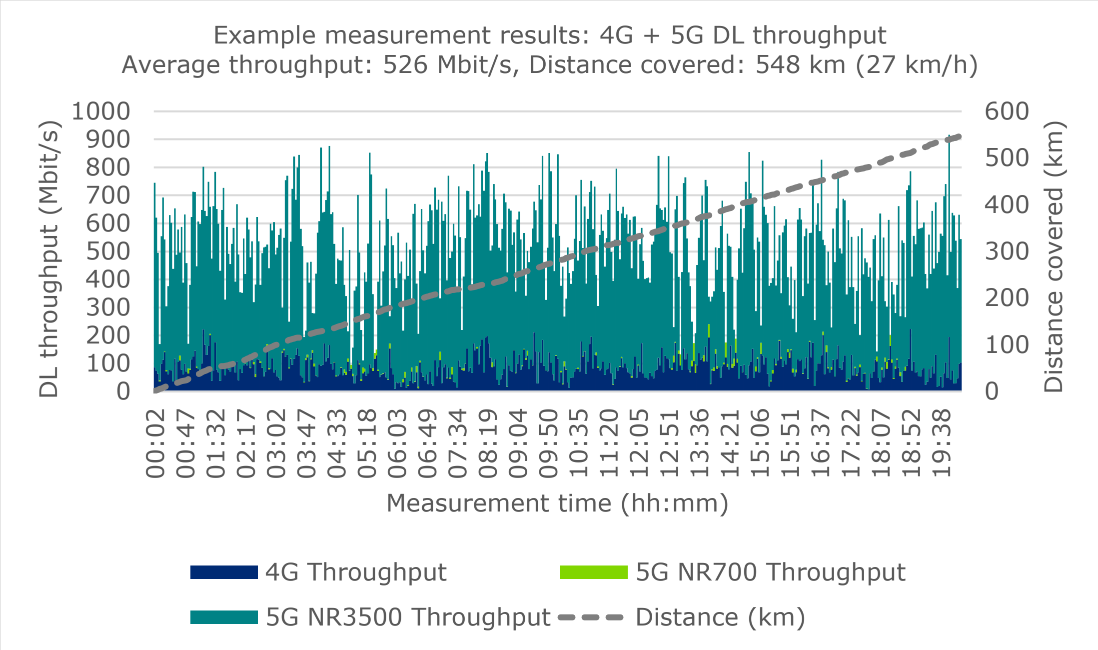


Figure 54. Example breakdown (in time) of download throughput results from drive test measurement.

The result can be further broken down to collected samples, which in this case are with a sample rate of two per second, i.e., each sample represents an average over 0.5 seconds. With typical measurement equipment, the samples are stored for further post-processing, and contain a set of metrics that can be used to assess the network status. From the samples, the results can be processed to for example illustrate the availability of specific service levels in the area of analysis.

For illustration purposes, four separate snapshots are depicted in more detail in Figure 55, illustrating the results of the 300 0.5-second samples.

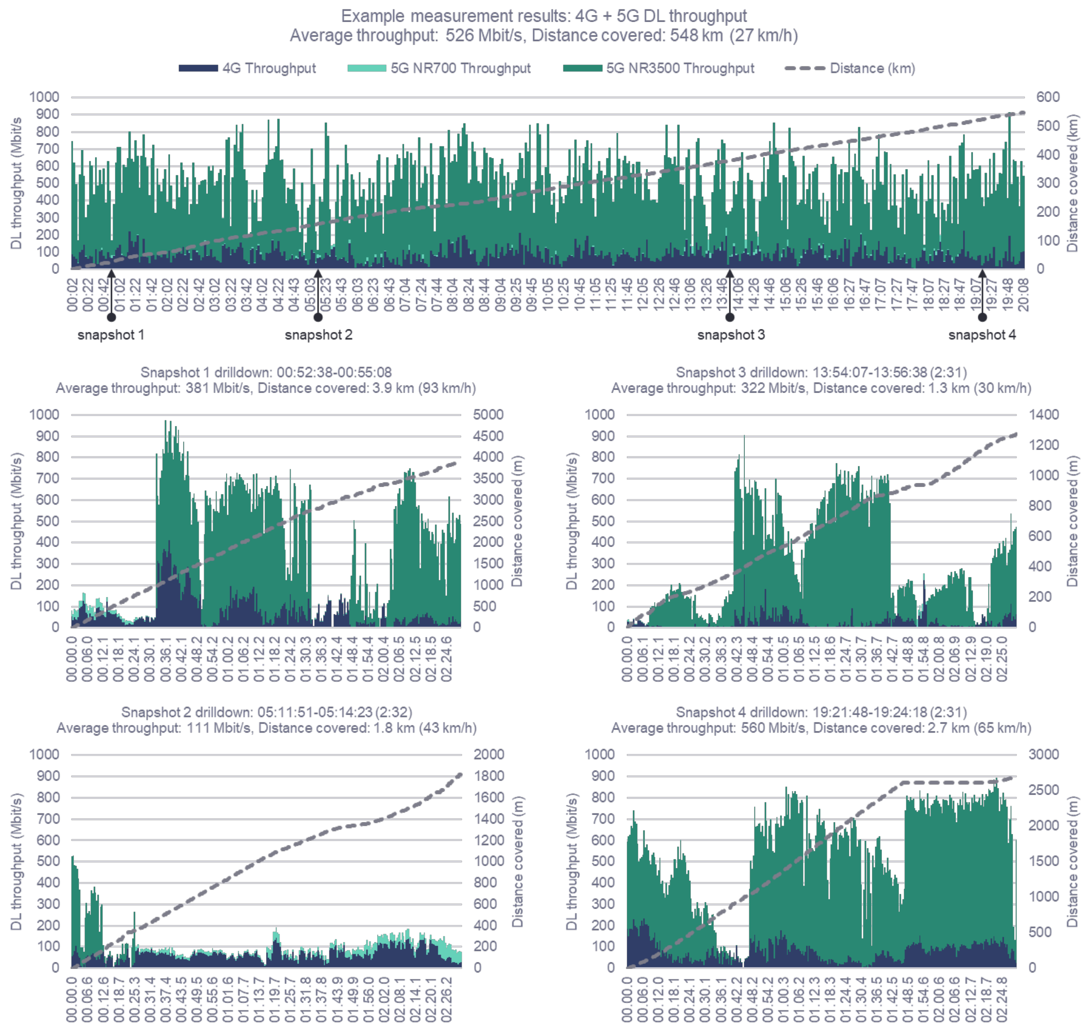


Figure 55. Example measurement result breakdown into four example snapshots.

The presented breakdown to 2 min 30 s snapshots reveals further variation.

Snapshot 1: the samples are from a road section, where the average speed is over 90 km/h, and almost 4 km is covered in the 2 min 30 second snapshot. The availability of 3,5 GHz 5G varies during the snapshot, and the available downlink throughput is at times over 500 Mbit/s, and at other times well below 50 Mbit/s.

Snapshot 2: in the selected snapshot, the measurements are from an area where majority of the time, there is no 3,5 GHz 5G available. The average downlink throughput is therefore only 111 Mbit/s, and below 100 Mbit/s for majority of the time.

Snapshot 3: in this snapshot, the 3,5 GHz 5G is well available throughout the measurement period, but the available service level varies significantly due to changing signal coverage conditions.

Snapshot 4: the samples are from a road section, where the average speed is close to 90 km/h before ending up in a stationary position, likely traffic lights, towards the end of the snapshot. When travelling at high speeds, the available throughput can change quickly, especially when moving quickly between the service area of different sectors or base station sites.

3.3.2 Analysis of stress test measurements

When the stress test measurements are carried out using the proposed methodology with sufficient sampling rate, the analysis of the results is flexible. The example measurements presented in chapter 3.3.1 of Part C are used to further illustrate the analysis facilitated by field measurements.

The results can be analysed to identify the extent of availability of the different defined C-ITS service levels. Table 57 presents the share of service-level specific download throughput over the whole example measurement. Even though the measurements were carried out in mostly urban and suburban areas where average available throughput is well over service level 3 target, there are still individual locations, where service level 3 or even service levels 1 and 2, are not available. Even in this measurement area, less than 1% of time and covered road length, there was less than 5 Mbit/s download throughput available.

Table 57. Service level (defined in Part A "Definition of service level framework for mobile networks") availability in the example measurements.

Service level	Level 0: <5 Mbit/s	Level 1: 5-20 Mbit/s	Level 2: 20-100 Mbit/s	Level 3: >100 Mbit/s	Total
Time	<1% 0h:8min:35 s	<1% 0h:8min:12 s	8% 1h:30min:52 s	91% 18h:20min:48 s	20 h, 8 min, 28 s
Distance	<1% 4.3 km	<1% 4.1 km	9% 47.2 km	90% 492.6 km	548.2 km

The example measurement results indicate that although the average performance is well above the required C-ITS service levels, the variation means that the Service level 3 operability is not consistently available. According to Part A "Definition of service level framework for mobile networks", the reliability requirements for service levels 2 and 3 are 95% and 99% respectively. This means that in the example measurements, Service level 2 operability would be well above the targets for downlink services (minimum 20 Mbit/s, >95% reliability), when in the example measurements, 20 Mbit/s successful data transmission was available ~99% of the time. For service level 3 requirements (minimum 100 Mbit/s, >99% reliability), there is still a gap between the target and the example measurements, which provided at least 100 Mbit/s successful downlink data transmission for 91% of the time.

These example measurements do not include upload measurements, but the analysis would be similar.

The share of availability of different service levels over the example measurements is illustrated Figure 56 where the distribution of different service levels within ~2 min 30 s averages are presented.

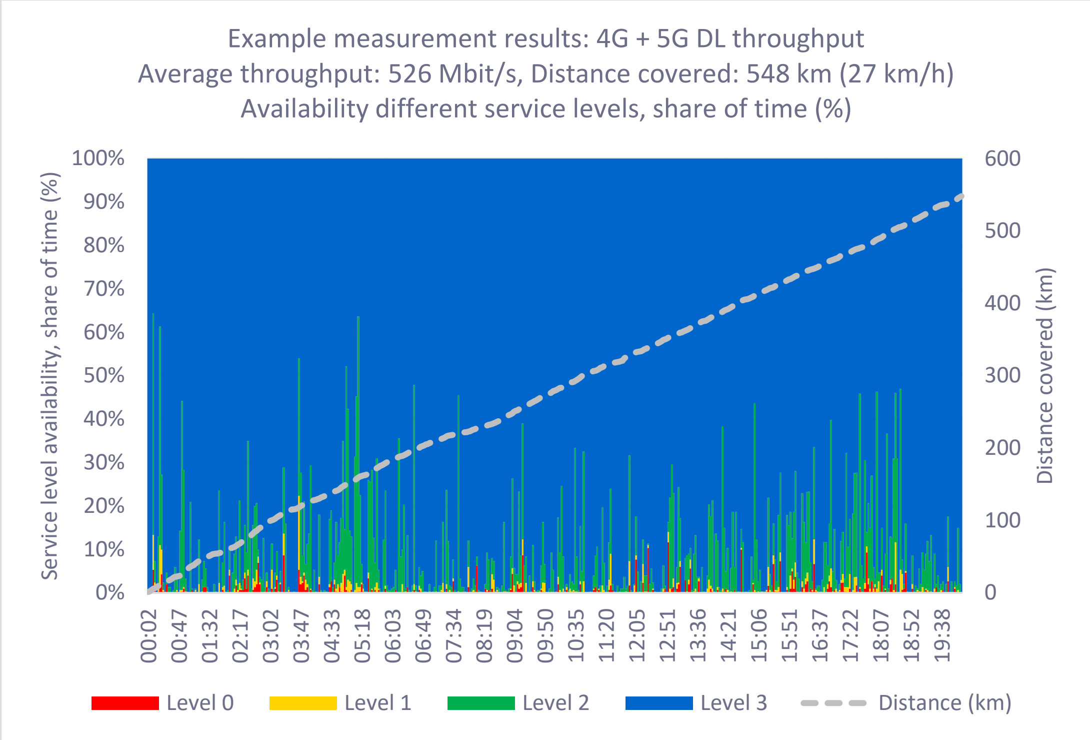


Figure 56. Service level availability in the example measurements.

The service level 0 (less than 5 Mbit/s) and 1 (5-20 Mbit/s) did not prevail for extended times nor in extended road areas but were present in sporadic locations throughout the measurements. Service level 2 (20-100 Mbit/s) was somewhat more consistently present on extended road sections, where sufficient capacity was not available.

A further example snapshot is selected to highlight this sporadic nature of service levels 0 and 1. The extent of measurement samples within the different C-ITS service levels is collected in Table 58. The measurement snapshot is visualised in Figure 57. This is a worst-case example selected from the example measurements to highlight a situation where there is poor availability of defined service levels in the example measurements.

Table 58. Availability of C-ITS service levels in example measurement snapshot.

Service level	Level 0 (<5 Mbit/s)	Level 1 (<20 Mbit/s)	Level 2 (<100 Mbit/s)	Level 3 (>100 Mbit/s)	Total
Time	4% (7 s)	1% (2 s)	9% (14 s)	85% (9 s)	02 min, 32 s
Distance	6% (79 m)	2% (22 m)	17% (228 m)	81% (1 082 m)	1.3 km

The graph in Figure 57 illustrates that the lower service levels are largely local. In the beginning of the snapshot, there is a 13-second timeframe (140 m), where Service Level 3 is not available. Furthermore, during the 13-second time, the available service level is also below Level 2 and even Level 1 thresholds. Towards the end of the snapshot, there is again a gap to Service Level 3, but this time above Level 2 threshold.

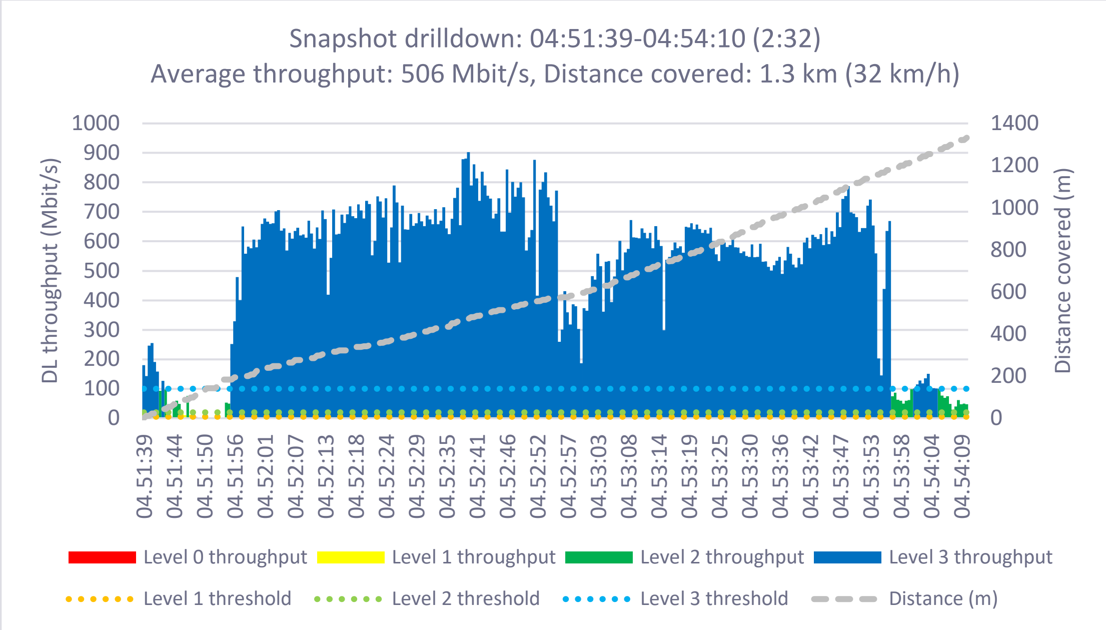


Figure 57. Illustration of C-ITS service levels in example snapshot.

In the following figure, the vertical axis examination is limited to 0-30 Mbit/s. This illustrates well that in the beginning, where there is a 13-second, 140-metre gap to service level 3, there is also a 6-second gap to service level 1. This gap is still within the allowed variation (>90%) of the Level 1 service during the measurement snapshot.

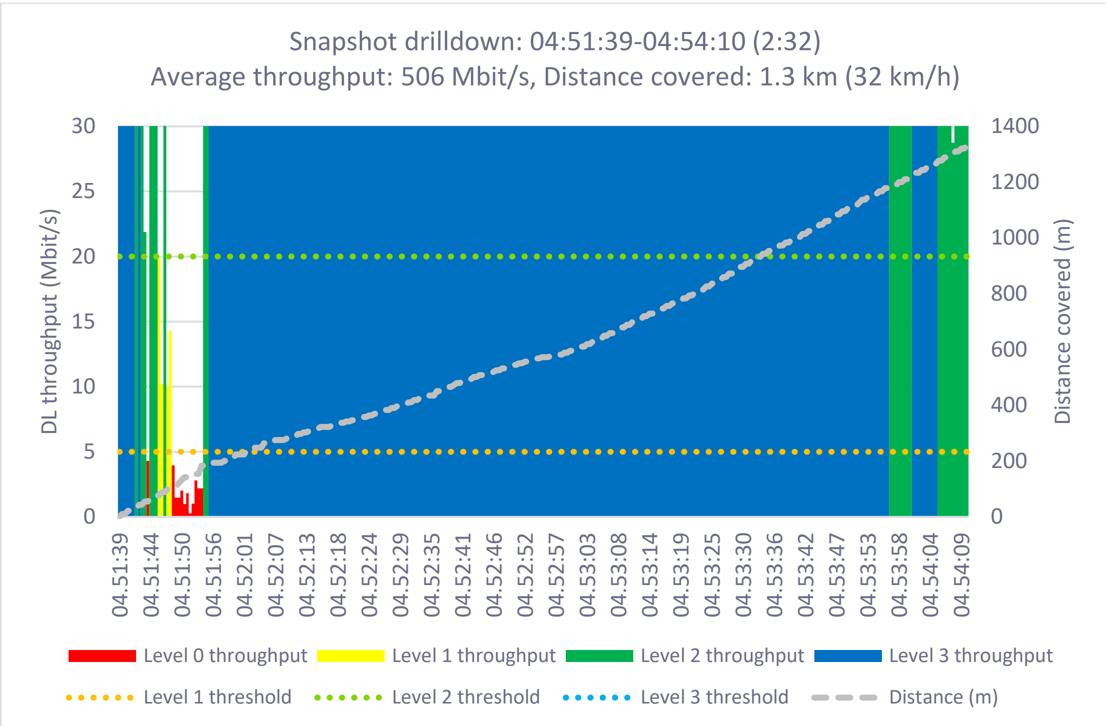


Figure 58. Illustration of C-ITS service levels in example snapshot (0-30 Mbit/s).

These results can be also plotted on a map for visualising the availability of different service levels, by for example selecting suitable colours for the different measured service level thresholds. Figure 59 below presents an example of this type of data rate plotting where service level 0 is shown with red colour, level 1 with yellow, level 2 with green and level 3 with blue respectively. White colour means other than download test case of which results are not presented.

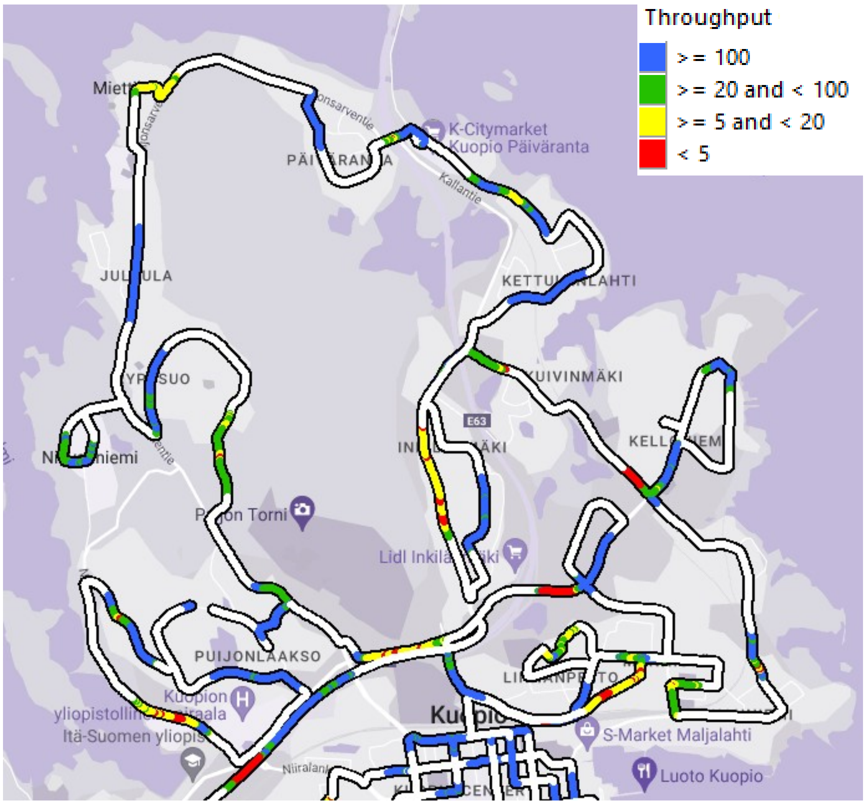


Figure 59. Example of measured downlink data rate plot on map.

3.4 Additional metrics for C-ITS feasibility assessment in commercial mobile networks

This chapter covers the suitability of the currently used development metrics in the previous chapter to assess the C-ITS feasibility potential. Furthermore, based on the measurement methodology analysis in Part B “Measurement methodologies and techniques” and the current metrics sufficiency, additional measurements and assessment metrics are compared and proposed for future use.

For example, in connection with intelligent traffic management and traffic light optimisation for more efficient traffic flow for heavy commercial traffic, there has been an identified need for targeted local measurements to assess the coverage and performance of mobile networks on the approaches leading to the specific intersections for effective communications between the vehicles, and the traffic management systems either in the intersections (edge) or in a central location (cloud, data centre). This type of local assessment of mobile network performance will likely be needed, especially in preparation for the C-ITS adoption. After adoption, the sufficiency of mobile network performance can be assessed by the C-ITS devices and reported to a central management system for trend analyses, to prepare for potential issues and to provide such warnings ahead of time to, e.g., the mobile network service provider.

Due to the rather static nature of the mobile networks and the growing mobility of connections with increasing number of connected and mobile devices, the need for different measurement and assessment metrics is increasing.

Different methodologies provide answers to different questions, and a more heterogenous combination of measurement and assessment methods is likely needed in the future to maintain adequate service levels for the different services, including C-ITS.

The proposed framework presented in this assessment in Part B "Measurement methodologies and techniques" consists of using coverage predictions to build a situation overview of the whole country complemented with targeted measurements to verify performance and identify where additional improvement actions are needed. This framework can be used both before and after the adoption of C-ITS services, and the proposed measurement framework will allow flexible analyses in the future, even if the service level requirements would change when the C-ITS development has advanced further.

Before and after widespread adoption of C-ITS

Coverage predictions to build a situation overview and to identify areas of interest	→	**Drive tests** to verify performance and identify improvements
	→	**Static measurements** to monitor and identify variation

Figure 60. Proposed methodology for assessing C-ITS feasibility before widespread adoption.

Further assessment will need to be undertaken for assessing the potential additional benefits and costs from, e.g., using the eventual vehicle fleet with C-ITS devices to collect information about the network and service performance, and which stakeholders should drive the development. Chapter 4 *Conclusions of Part C* will further consider the required collaboration between the different stakeholders involved and provide reasoning for further discussions in relevant forums.

Potential after adoption of C-ITS

Crowdsourced information to monitor service level performance and identify issues	→	**Drive tests** to verify performance and identify improvements
	→	**Static measurements** to monitor and identify variation

Figure 61. Proposed methodology for assessing C-ITS feasibility after adoption.

3.4.1 Coverage predictions

Coverage predictions will remain the most efficient way of assessing the feasibility of different services on a large-scale. Although several accuracy limitations have been identified in chapter 3.2 of Part C, the coverage prediction desktop study provides a quick way of assessing the availability of different service in Finland and identifying potential areas for further study.

Based on the analysis and conclusions presented in chapter 3.2 of Part C, there is no immediate need to change the methodology of collecting coverage predictions from the operators. The currently collected basic coverage and the different speed tiers' coverage for both 4G and 5G are sufficient for Traficom to analyse and identify potential areas for further study.

From the C-ITS point of view, the key for monitoring the development of the mobile networks is to analyse the coverage of each operator separately.

3.4.2 Field measurements: drive tests

The most reliable picture of the current status of mobile networks can be built by conducting measurements in the area of interest. Drive-test measurements have been a staple of mobile network testing for decades, and although continuously complemented by other forms of information collection, remain the most reliable way of achieving comparable and accurate status of the network deployment and practical performance.

Because drive testing requires significant time investment to measure the service level performance, it is not an optimal way of building a situation overview of the road network in the whole country.

Stress test measurements are the most flexible way of gathering multi-purpose information from mobile networks. Stress test measurements reveal the best estimate of capacity that is available for different services and provide flexible post-processing options to analyse the measurement results, even if targets for different services or service levels would change.

Stress test measurements can be complemented with measurements aimed to simulate different specific services or service levels. However, these measurements are by nature providing only a view of the specifically measured service or service level, and as such provide less flexibility for later post-processing. The service and service level simulations are perhaps more relevant for the C-ITS service development to verify the service performance, rather than for the authorities building a situation overview of the service feasibility.

3.4.3 Field measurements: fixed point tests

Because drive tests are by nature a snapshot of the situation at a specific time, there may be need for additional static fixed-point measurements for continuously measuring road traffic hotspots, e.g., busy road sections or intersections to build a timeline of service availability. Static measurements cannot reasonably be conducted as continuous stress tests without severely impacting the service quality of other mobile network users. Static measurement design should therefore aim to reveal key performance metrics relevant to C-ITS services, e.g., by conducting the measurements at a reasonable interval instead of continuous measurement. Static fixed-point tests can be conducted with similar test scenarios as the drive tests, potentially aiming to simulate C-ITS services, if suitable measurement solutions are available.

3.4.4 C-ITS fleet collecting information

When C-ITS services start being introduced to vehicles in road operation, there is an opportunity to use the vehicle fleet for collecting information on the service level availability and mobile network performance and coverage. This crowdsourcing method is already well established in consumer devices, whereby either dedicated applications are used to collect performance indicators from the network performance via user-initiated stress tests or selected applications collect data from normal use in the background.

Crowdsourcing can be an efficient tool for monitoring service level performance and identifying potential issues in C-ITS operation. Developing the framework and incorporating the information collection to C-ITS end-devices will require collaboration and a common policy for information protection and usage framework between the different stakeholders, such as the C-ITS service developers and providers, communication equipment manufacturers, local authorities and vehicle manufacturers.

3.4.5 Capacity management

Capacity management is a process handled by the mobile network operators in their daily network planning activities. Careful monitoring of network performance data forms a basis for capacity control and generates initiatives for building capacity expansions depending on traffic needs per area.

Capacity management is business as usual for operators, and the role of Traficom or any other stakeholders should be more on providing supporting information on potential identified issues to the operators in order to jointly work towards developing mobile networks that can provide connectivity and capacity to the C-ITS services, and developing C-ITS services that are designed to work in the changing conditions of mobile network coverage and that do not unnecessarily load the mobile networks.

3.5 Feasibility of C-ITS services in current mobile networks

This chapter assesses the feasibility of providing the required capacity of serving 2030 C-ITS services as presented in the previous parts. First, an overview of the assessed traffic scenarios in 2030 is provided. Second, the traffic scenarios are compared to current (2023) estimated mobile network capacity in Finland in the different environments.

In the capacity sufficiency assessment, the potential gaps from today to 2030 are discussed. At the same time, the need for further assessment through measurements to validate the meeting of identified requirements is discussed.

3.5.1 C-ITS data traffic scenarios

C-ITS data traffic scenarios utilized in this study are based on the “Scenario analysis” chapter of Part A “Definition of service level framework for mobile networks”. Based on these road traffic and C-ITS service adoption estimates for the different C-ITS services, different scenarios for overall data traffic were calculated.

The outcomes of traffic scenario estimates for main streets (predominantly in and around cities) and high-traffic roads are presented below. The C-ITS scenario analysis results, shown in Figure 62 and Figure 63, are presented for four road traffic scenarios: low (traffic) flow, average (traffic) flow, congested (traffic) and badly congested (traffic). The background for these scenarios is more thoroughly described in the Part A chapters “Scenario framework” and “Scenarios for the study”. Basically, the traffic flow is variated in order to simulate the effect of different number of users for the C-ITS data traffic.

Furthermore, the three C-ITS service adoption scenarios, i.e., realistic, pessimistic and optimistic, are presented separately. Pessimistic scenario refers to low C-ITS service adoption level, whereas optimistic represents a more wide-spread adoption level with multiple C-ITS services and high number of users.

In addition, the variation range for the different traffic flow and service adoption scenarios is based on the C-ITS implementation assumptions, e.g., how often different messages are sent for the different C-ITS services. The framework for scenario analysis and the literature review that the different values are based on, is presented in more detail in the Part A report "Definition of service level framework for mobile networks". Briefly, the total capacity needs of a single C-ITS service is a product of number of vehicles receiving/sending a message, update rate of a message, information density (number of hazards, traffic control messages or traffic signals (n) in the length/area of relevance), and size of a message.

In order to estimate the total load that the C-ITS-services would cause to the mobile network, two environments are considered: main streets (primarily in urban and suburban areas like city/municipality centrums) and high-traffic roads (highways connecting cities). In Part A "Definition of service level framework for mobile networks" the selected C-ITS-services were studied separately, but in order to estimate the total load in real environment, all the C-ITS-services that could be active simultaneously are considered. Therefore, main streets include Signal Phase and Timing Information (SI) and Collective perception (CPM) services, and high-traffic roads include Lane closure (RWW), Temporarily slippery road (HLN), and Vehicle Data Collection (PVD) services. Length of relevance (km) or area of relevance (km^2) definitions depend on the nature of the service and area or location of the service usage. SI and CPM services are used in urban area streets where area of relevance is more suitable (km^2) due to proximity of parallel and intersecting streets. On the other hand, RWW, HLN and PVD services are used in high traffic roads, which are linear in nature, thus requiring analysis based on length of relevance (km).

The estimated data traffic (Mbit/s per km^2) in main streets is illustrated in Figure 62 and the detailed values and their variation in Table 59. In the realistic adoption scenario, the data traffic level in main streets is expected to be in the range of 2-6 Mbit/s when the road traffic flow is not congested. In times of congestion, the data traffic level can rise to 14 Mbit/s and up to 25 Mbit/s when traffic is badly congested.

Additionally, an extreme scenario has been identified, which would be potentially occurring in the busiest possible roads and at times of extreme congestion, relevant only for example on the likes of Ring I in Helsinki.

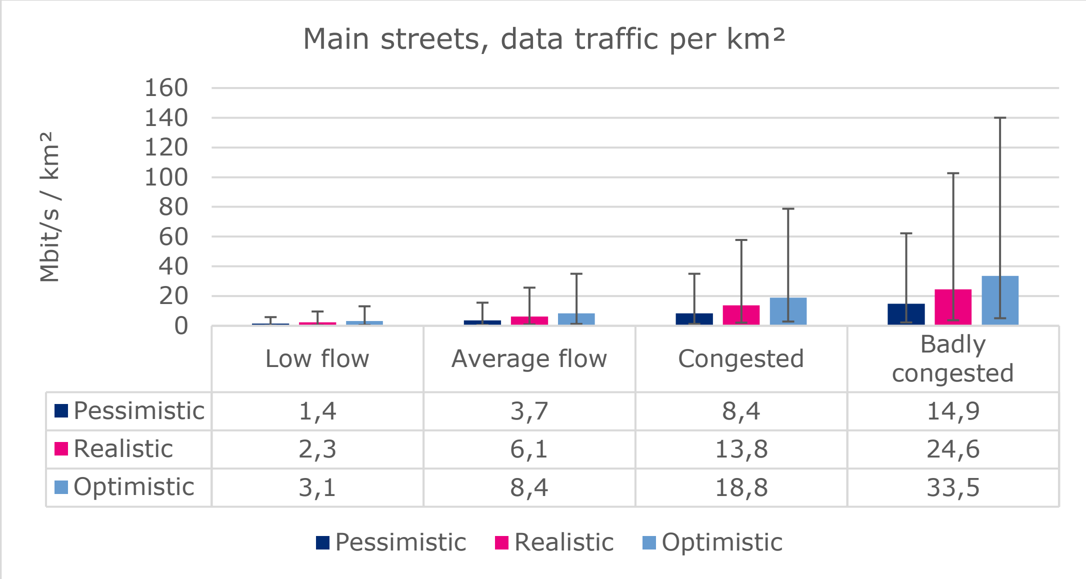


Figure 62. C-ITS scenario analysis results, main streets. Pessimistic refers to low adoption rate, Realistic to expected adoption rate and Optimistic to high adoption rate of C-ITS services.

Table 59. C-ITS scenario analysis results, main streets.

Main streets **Mbit/s/km²**	**Low flow**	**Average flow**	**Congested**	**Badly congested**
Pessimistic (low adoption)	1.4 Mbit/s/km² (0.2 – 5.8)	3.7 Mbit/s/km² (0.6 – 15.6)	8.4 Mbit/s/km² (1.3 – 35.0)	14.9 Mbit/s/km² (2.3 – 62.2)
Realistic	2.3 Mbit/s/km² (0.3 – 9.6)	6.1 Mbit/s/km² (0.9 – 25.7)	13.8 Mbit/s/km² (2.1 – 57.8)	24.6 Mbit/s/km² (3.7 – 102.7)
Optimistic (high adoption)	3.1 Mbit/s/km² (0.5 – 13.1)	8.4 Mbit/s/km² (1.3 – 35.0)	18.8 Mbit/s/km² (2.9 – 78.8)	33.5 Mbit/s/km² (5.1 – 140.0)
Extreme				288 Mbit/s/km²

The estimated traffic in high-traffic roads is illustrated in Figure 63 and the detailed values and their variation in Table 60. Data traffic on high-traffic roads is presented as Mbit/s/km, as the roads and used services are more linear in nature. In the realistic C-ITS adoption scenario, the data traffic level in high-traffic roads is expected to be in the range of 0.1 – 0.26 Mbit/s/km when traffic flow is not congested. In times of congestion, the data traffic level is expected to be from 0.6-1 Mbit/s/km when traffic is badly congested.

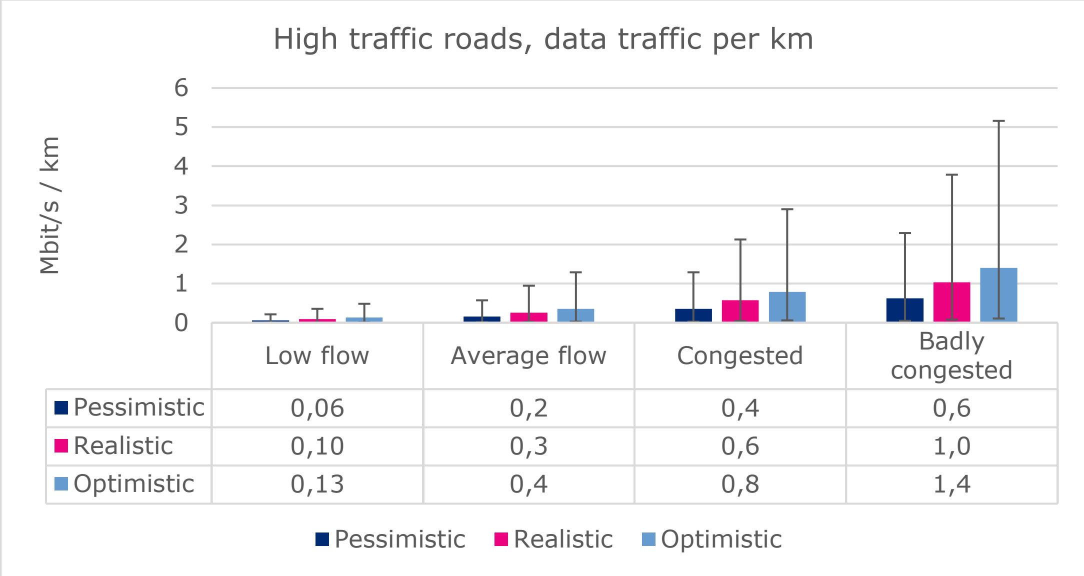


Figure 63. C-ITS scenario analysis results, high traffic roads. Pessimistic refers to low adoption rate, Realistic to expected adoption rate and Optimistic to high adoption rate of C-ITS services.

Table 60. Scenario analysis results, high traffic roads.

High traffic **Mbit/s/km**	**Low flow**	**Average flow**	**Congested**	**Badly con-gested**
Pessimistic (low adoption)	0.06 Mbit/s/km (0.00 – 0.22)	0.16 Mbit/s/km (0.01 – 0.57)	0.35 Mbit/s/km (0.03 – 1.29)	0.62 Mbit/s/km (0.05 – 2.29)
Realistic	0.10 Mbit/s/km (0.01 – 0.35)	0.26 Mbit/s/km (0.02 – 0.95)	0.58 Mbit/s/km (0.04 – 2.13)	1.03 Mbit/s/km (0.08 – 3.78)
Optimistic (high adoption)	0.13 Mbit/s/km (0.01 – 0.48)	0.35 Mbit/s/km (0.03 – 1.29)	0.79 Mbit/s/km (0.06 – 2.90)	1.40 Mbit/s/km (0.11 – 5.16)
Extreme				12.6 Mbit/s/km

3.5.2 Mobile network capacity for C-ITS data traffic

This chapter concludes the assessment analysed in the previous chapter regarding typical mobile capacity today versus the expected C-ITS load by 2030 in the different scenarios. The assessment compares the estimated mobile network capacity in different environments, from chapter 2 of Part C, with the C-ITS data traffic scenarios from chapter 3.5.1 of Part C. The analysis aimed to identify the magnitude of C-ITS data traffic in the different scenarios in relation to mobile network capacity in order to understand how capable the networks of today are to serve C-ITS data traffic.

In order to compare the expected C-ITS data traffic and the mobile network capacity, assumptions and estimates of road density in the different environments are needed. The estimated typical road densities are listed in Table 61. These represent a high road density estimate for each environment, i.e., a dense road network. These road density estimates are meant to represent only a relative extreme case in order to assess the sufficiency of the mobile network capacity.

Table 61. Road density in different environments.

Road density (km / km²)	Urban	Suburban	Rural	Sparse rural
Estimate	13.2	6.6	1.0	0.2

The estimated urban area road density is based on the high-level assumption that the streets in dense urban areas have a parallel distance of 1/6 km (167 m), and there are perpendicular streets at the same parallel distance interval. This dense urban road density is present in city centres. Figure 64 presents the view of Helsinki city centre (left) with an example of 167 m parallel road distance illustrated with arrows denoting the parallel distance between roads. The distances vary from shorter to longer, but similar distances are present in the area.

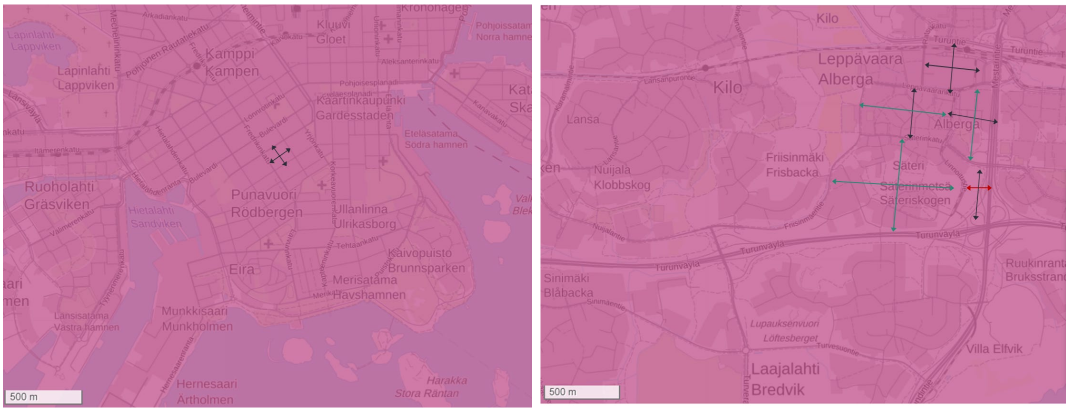


Figure 64. Urban and sub-urban road density example from Helsinki and Espoo

The suburban road density is similarly based on the high-level assumption regarding perpendicular streets but with parallel distance interval of 1/3 km (333 m), typical for smaller city centres and towns, as well as suburban areas outside dense urban city centre areas. The parallel distance between roads varies much more, as illustrated in Figure 64 (right), where black arrows are used to indicate 333 m parallel distance (green arrow indicates longer distance, red arrow indicates shorter distance).

Rural and sparse rural area road densities are based on different assumptions, whereby each sector in rural areas would cover 3 roads (1 main road and 2 local roads) and in sparse rural areas 1 main road and the length of each road in the coverage area is the coverage distance. For reference, over the whole of Finland, the average road density is 1.34 km / km² (454 000 km / 338 000 km²).

Table 62 presents the key mobile network capacity figures from the analysis in chapter 2 of Part C, and the estimated capacity per kilometre and square kilometre in the different environments.

Table 62. Estimated mobile network capacity figures and capacity per km and km²

Capacity estimates		Urban	Suburban	Suburban (no 3,5 GHz)	Rural	Sparse rural
Average capacity (Mbit/s)						
	Average	1100	800	480	250	95
	Minimum	900	600	390	190	85
	Maximum	1400	1200	550	320	105
	Roadside					55
Base station site coverage area (km²)						
	Average	0.054	0.49	0.49	48.8	135
	Minimum	0.078	0.87	0.87	86.7	195
	Maximum	0.035	0.22	0.22	21.7	87
	Roadside					293
Base station sites per km²						
	Average	18.5	2.1	2.1	0.021	0.007
	Minimum	12.8	1.2	1.2	0.012	0.005
	Maximum	28.8	4.6	4.6	0.046	0.012
	Roadside					0.003
Capacity per km² (Mbits/s/km²)						
	Average	1100	800	480	5.1	0.70
	Minimum	900	600	390	2.2	0.44
	Maximum	1400	1200	550	14.8	1.21
	Roadside					0.19
Capacity per km (Mbit/s/km)						
	Average	1100	249	149	5.1	3.5
	Minimum	874	105	68	2.9	2.6
	Maximum	1400	839	385	9.7	4.8
	Roadside					1.7

Based on the indicative capacity estimates presented in chapter 2 of Part C and the scenario analysis results presented above, the sufficiency of the typical capacity and feasibility of C-ITS services can be estimated. The estimate assumes that the C-ITS data traffic is evenly distributed to the three commercial networks.

As a general observation from the capacity analysis, the C-ITS traffic scenarios are expected to generate a level of data traffic, that can be carried by urban and suburban mobile networks without issues. At worst, in main streets in suburban areas without 3,5 GHz, the share of capacity required in times of bad or extreme congestion can rise to 10-20%. In uplink traffic (from device to network), this could potentially mean high-capacity utilisation, as the available average capacity is typically in the range of 1/3 to 1/5 of the downlink capacity in good signal conditions.

High-traffic roads in and near urban areas are expected to generate a C-ITS data traffic level that can be served by the urban and suburban mobile networks of today without any problems. In rural areas, using the same high-traffic road data traffic assumptions, there is potential for issues with capacity. However, even with the highest C-ITS adoption level (Optimistic) and with high messaging frequency (upper variation limit), in the badly congested traffic scenario, the average capacity utilisation is expected to be in the range of 50%. The probability of such road traffic and congestion on remote rural roads is likely to be low and at least anticipated. In such cases, if uplink traffic from vehicles to network would be in the same magnitude, a large share of the messages could not be delivered. Therefore, it is important to consider the uplink limitations in the design of C-ITS services.

The results of the capacity utilisation in main streets and high-traffic roads are presented in Table 64 and the capacity utilisation colour coding in Table 63. The capacity utilisation is estimated for each traffic scenario, consisting of assessment of traffic flow from low to badly congested, adoption of C-ITS services from pessimistic to optimistic, and the frequency and information density generated by the C-ITS services based on assumptions of the potential eventual implementation of the different C-ITS services. The capacity utilisation is assessed for the different environments separately.

Main streets capacity utilisation analysis was excluded for rural areas, as the main streets are located in urban and suburban areas. High-traffic road capacity utilisation analysis was included for each analysed environment.

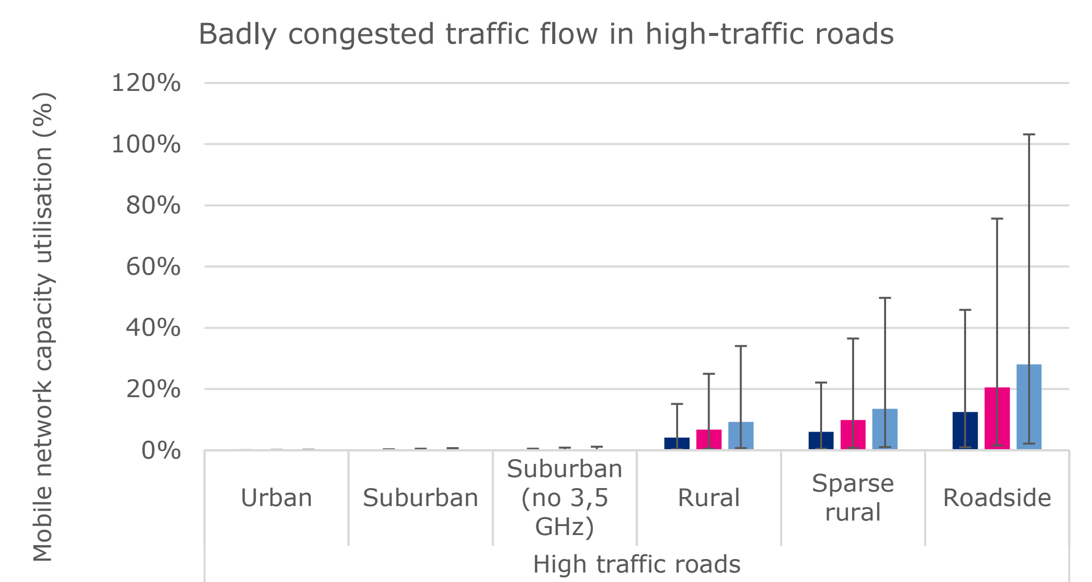
Table 63. Capacity utilisation colour coding.

Utilisation										
Low		Medium			High					
0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

Table 64. Mobile network capacity utilisation in different C-ITS traffic scenarios.

	Main streets capacity utilisation Capacity per km^2 (Mbits/s/km^2)				High traffic roads capacity utilisation Capacity per km (Mbit/s/km)				
Area:	**Urban**	**Suburban**	**Suburban** (no 3,5 GHz)		**Urban**	**Suburban**	**Suburban** (no 3,5 GHz)	**Rural**	**Sparse rural**
Low flow	-	-	-	-	-	-	-	-	-
Pessimistic	0.0%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.4%	0.6%
Realistic	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.6%	0.9%
Optimistic	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.9%	1.3%
Low: Pessimistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.0%	0.0%
Low: Realistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.0%	0.1%
Low: Optimistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.1%	0.1%
High: Pessimistic	0.2%	0.2%	0.4%	-	0.0%	0.0%	0.0%	1.4%	2.1%
High: Realistic	0.3%	0.4%	0.7%	-	0.0%	0.0%	0.1%	2.3%	3.4%
High: Optimistic	0.4%	0.5%	0.9%	-	0.0%	0.1%	0.1%	3.2%	4.7%
Average flow	-	-	-	-	-	-	-	-	-
Pessimistic	0.1%	0.2%	0.3%	-	0.0%	0.0%	0.0%	1.0%	1.5%
Realistic	0.2%	0.3%	0.4%	-	0.0%	0.0%	0.1%	1.7%	2.5%
Optimistic	0.3%	0.3%	0.6%	-	0.0%	0.0%	0.1%	2.3%	3.4%
Low: Pessimistic	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.1%	0.1%
Low: Realistic	0.0%	0.0%	0.1%	-	0.0%	0.0%	0.0%	0.1%	0.2%
Low: Optimistic	0.0%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.2%	0.3%
High: Pessimistic	0.5%	0.6%	1.1%	-	0.0%	0.1%	0.1%	3.8%	5.5%
High: Realistic	0.8%	1.1%	1.8%	-	0.0%	0.1%	0.2%	6.2%	9.1%
High: Optimistic	1.1%	1.5%	2.4%	-	0.0%	0.2%	0.3%	8.5%	12.4%
Congested	-	-	-	-	-	-	-	-	-
Pessimistic	0.3%	0.3%	0.6%	-	0.0%	0.0%	0.1%	2.3%	3.4%
Realistic	0.4%	0.6%	1.0%	-	0.0%	0.1%	0.1%	3.8%	5.6%
Optimistic	0.6%	0.8%	1.3%	-	0.0%	0.1%	0.2%	5.2%	7.6%
Low: Pessimistic	0.0%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.2%	0.3%
Low: Realistic	0.1%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.3%	0.4%
Low: Optimistic	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.4%	0.6%
High: Pessimistic	1.1%	1.5%	2.4%	-	0.0%	0.2%	0.3%	8.5%	12.4%
High: Realistic	1.8%	2.4%	4.0%	-	0.1%	0.3%	0.5%	14.0%	20.5%
High: Optimistic	2.4%	3.3%	5.5%	-	0.1%	0.4%	0.6%	19.2%	28.0%
Badly congested	-	-	-	-	-	-	-	-	-
Pessimistic	0.5%	0.6%	1.0%	-	0.0%	0.1%	0.1%	4.1%	6.0%
Realistic	0.7%	1.0%	1.7%	-	0.0%	0.1%	0.2%	6.8%	9.9%
Optimistic	1.0%	1.4%	2.3%	-	0.0%	0.2%	0.3%	9.3%	13.5%
Low: Pessimistic	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.3%	0.5%
Low: Realistic	0.1%	0.2%	0.3%	-	0.0%	0.0%	0.0%	0.5%	0.8%
Low: Optimistic	0.2%	0.2%	0.4%	-	0.0%	0.0%	0.0%	0.7%	1.0%
High: Pessimistic	1.9%	2.6%	4.3%	-	0.1%	0.3%	0.5%	15.1%	22.1%
High: Realistic	3.1%	4.3%	7.1%	-	0.1%	0.5%	0.8%	25.0%	36.5%
High: Optimistic	4.2%	5.8%	9.7%	-	0.2%	0.7%	1.2%	34.1%	49.8%
Busiest roads	-	-	-	-	-	-	-	-	-
Extreme	8.8%	12.0%	20.1%	-	0.4%	1.7%	2.8%	83.0%	121.4%

In addition to the presented results in Table 64, the impact of C-ITS data traffic generated by high-traffic road on a potential rural roadside base station is assessed. Typically, rural roadside base stations are not covering high-traffic roads. But in extreme situations, such as mass events in rural areas, extreme traffic with congestion could occur in a very rural area. The capacity utilisation results for badly congested traffic flow scenario in high-traffic roads in different environments are illustrated in Figure 65.



	Urban	Suburban	Suburban (no 3,5 GHz)	Rural	Sparse rural	Roadside
Pessimistic	0%	0%	0%	4%	6%	12%
Realistic	0%	0%	0%	7%	10%	21%
Optimistic	0%	0%	0%	9%	14%	28%

Figure 65. Capacity utilisation during badly congested traffic flow in high-traffic roads in different environments. Pessimistic refers to low adoption rate, Realistic to expected adoption rate and Optimistic to high adoption rate of C-ITS services.

The results indicate that with the assumed C-ITS message frequency and size the mobile network capacity should be able to serve the C-ITS traffic levels. However, due to the uncertainty around the potential C-ITS messaging implementation regarding, e.g., messaging frequency, there could be issues in serving C-ITS traffic in sparse rural areas and in rural roadside base stations in the very worst-case scenario.

The worst-case scenario likelihood is rather low, and it can be accounted for in the development of C-ITS, by planning the messaging in a way to prepare for situations of extreme congestion.

4 Conclusions of Part C.

Central research questions related to the Part C and the analysis and answers to these questions were following:

1. How are current commercial mobile networks in Finland suited to serve C-ITS services and what are the key deficiencies/bottlenecks, if any?

   In general, from coverage availability and system capacity points of view, the mobile networks of today are well suited to carry the average expected C-ITS messaging traffic levels. However, the commercial mobile networks are inherently very much environment-dependent, and spots of poor service levels will persist, individually per each national operator, depending on their local network deployments (site/technology grid) and network strategy. This is important to consider for all development and planning of C-ITS service implementation.

2. How can the network development progress for C-ITS services be assessed currently and what information is needed to assess the progress in the future?

   The currently collected coverage predictions are well suited for the situation overview of C-ITS feasibility. As was seen in chapter 3.2 of Part C, coverage predictions enable to identify potential areas of concern for the feasibility. As a complement to coverage predictions, a measurement framework is proposed to verify the feasibility of C-ITS services through network stress tests. This measurement framework aims to complement the currently available and used information to accurately estimate the C-ITS feasibility in mobile networks.

The presented C-ITS service level framework resulted in estimated C-ITS messaging traffic scenarios with different variables, including road traffic flow, C-ITS adoption rate, and C-ITS messaging implementation details such as messaging frequency. There is a rather high degree of uncertainty around the potential C-ITS implementations, but this traffic scenario analysis, including sensitivity analysis, can provide insight into the needed considerations for any C-ITS implementation development, in order to evaluate the likelihood of various scenarios and consequently prepare for, e.g., situations of extreme congestion in areas without adequate capacity.

The capacity analysis in chapter 3.5.2 of Part C indicates that mobile networks are already today largely capable of carrying the estimated 2030 C-ITS messaging traffic levels. However, due to the nature of mobile networks, local coverage and service level availability issues are very likely. This variation is presented in the example measurement analysis in chapter 3.3.2 of Part C. In extreme cases, if the uplink traffic from vehicles to network would be in the same magnitude as the downlink traffic, a large share of the messages could not be delivered. Therefore, it is important to consider the uplink limitations in the design of C-ITS services.

Part D. Development paths for C-ITS deployment

1 Introduction

This Part builds up on the conclusions made in Part C and studies possible solutions to answer plausible coverage and service availability issues of mobile networks. This Part also takes a wider perspective and discusses the possibilities and alternative routes for large-scale deployment of C-ITS services, and also the importance of mobile communications network for the transportation segment now and in the future. Lastly, recommendations are made to ramp up the adoption and deployment of C-ITS services nationally.

Methods

Finnish mobile network operators were interviewed for this Part of the study in order to gather their insights how they see the transportation segment as a use case for mobile networks and what kind of future development paths they expect. dditionally, a workshop was organised with stakeholders from national relevant authorities, mobile network operators and ITS service providers in order to gain insights on mobile network utilisation in C-ITS service deployment. In addition, expert assessment and collaboration in the project management group were utilised in this Part.

2 Solutions

In order to find solutions for potential local coverage and service availability issues, presented in Part C, five solutions were selected for closer inspection. These solutions are network expansion, neutral host networks, network slicing, network monitoring, and data traffic congestion mitigation.

2.1 Network expansion

As it is already concluded in this study, the mobile network expansion (in terms of coverage and capacity) is driven by regulation and business potential. From the regulation point of view there are certain requirements for geographic and population coverage. From the business potential perspective, the mobile network operators (MNOs) build network capacity where the users are, in other words close to accommodation, offices, industrial areas and other hot spots (public transportation hubs, shopping malls or events). As the most likely issues with the mobile network capacity were recognized to be localised and temporary by nature, would comprehensive network capacity expansion mean excess capacity in many cases. In cases with beforehand anticipated capacity overload, for example with some events in rural areas, the MNOs already have working operational models, where they bring temporary base stations to offer extra capacity for the events.

The business model for the MNOs' proactive investments to tackle temporary and very local challenges isn't therefore very viable. Neither would it be very reasonable to implement obligatory regulation for excess capacity from the authority's point of view except for a very valid reason such as public safety or national security. Providing investment support with the public funding might also be questionable because of the low return of the investment.

Technological development will bring new capacity with the fifth-generation mobile network adoption, but this development will focus in the areas where there already is sufficient coverage. Regulatory obligations will ensure the necessary minimum coverage on nationwide road network, but the local and temporary capacity issues recognised in this study still remain plausible. Potential future technological solutions for coverage issues are Non-Terrestrial-Networks (NTN), which are based on satellite communication. Satellites can provide a very good fall-back option to terrestrial mobile networks, being able to cover much larger geographical areas from above. However, there are certain limitations, such as the availability of sufficient and affordable satellite connectivity options for mobile vehicles in Finland. Many traditional satellite data connectivity services are provided from geosynchronous or geostationary orbits that require a fixed antenna dish to be aimed at close to the southern horizon in Northern Finland. Mobile vehicles cannot likely have a traditional satellite antenna dish mounted on the roof and would therefore require the availability of more suitable services from lower orbit and sufficient northern region coverage. The satellite data connectivity market and coverage are developing fast with new innovations and multiple new entrants providing global connectivity services emerging over the last decades. The availability and affordability of satellite connectivity can be expected to improve further even way before 2030. The development of satellite connectivity directly to mobile devices would facilitate satellite connectivity also in vehicles without the need for separate satellite connectivity equipment. Otherwise, the vehicles or C-ITS equipment need to be equipped with suitable transmitters/receivers for satellite communication in order to enable satellite fall-back when terrestrial mobile network connectivity is not available. It is worthwhile noting that satellite connections may have a longer transmission delay, depending on the data traffic route, and switching from terrestrial to non-terrestrial connection may result in momentary loss of connection.

The costs related to the passive infrastructure are always a considerable part of investments with mobile network capacity expansions. The passive infrastructure includes for example electricity, network fibre and construction related costs. Finnish MNOs already have existing operation models for sharing the investment costs of passive infrastructure, but long-term cooperation planning between MNOs and road operators would also be beneficial in order to build cost effective passive infrastructure for mobile networks. There is already legislation (Joint Construction Act 276/2016) in place in Finland, obliging parties to comply to joint communication infrastructure construction requests when another party requests to join in on the planned infrastructure deployment. This joint construction can reduce the communication infrastructure costs for each party deploying the infrastructure and allows better utilisation of the resources for deployment and the deployed infrastructure. Furthermore, the legislation mandates that operators allow other operators to access existing infrastructure on fair and reasonable terms when feasible. Existing legislation puts a set of practices and procedures in place, but the actual utilisation rate and broader impact assessments of the Joint Construction Act were not evaluated as a part of this study.

Typically, in urban areas, MNOs lease space from buildings to place the mobile network antennas and other equipment and cabling to the premises. In sub-urban and rural areas, the mobile networks are largely built using various tower or pole structures. The MNOs or their tower-company subsidiaries or partners build new towers and lease tower space to each other. Especially roadside towers in sparse rural areas may not have a positive business case after the minimum coverage obligations have been met, unless other MNOs agree to also expand to the location, participating in covering the costs through a lease agreement. A road operator could potentially offer existing or new roadside infrastructure for the use of MNOs to deploy a more extensive road coverage solution, for example, by deploying higher-capacity, higher-frequency solutions in road lighting poles or other densely placed roadside structures. The higher-frequency communication solutions can be much smaller in size but provide much higher capacity in the immediate area. For the C-ITS services under investigation in this report, the dense high-capacity solutions on busy traffic roads are not necessary, but for more advanced solutions with more strict requirements for data transfer volumes and real-time communication, the cooperation between MNOs and road operators may be one solution to cost-effectively build the required infrastructure and connectivity networks.

2.2 Neutral host networks

The neutral host network is an operational model that allows mobile network capacity sharing for one or more communication service providers. In this kind of operation model, a neutral host actor is not necessarily a communication service provider itself and thereby the operation model differs from joint investment model, introduced in the previous chapter.

The business model for neutral host networks has proven to be commercially viable in the sense that it brings down the initial investment costs for communication service providers as they can lease the set-up infrastructure and concentrate on providing services to the end users. Another beneficial use case is areas of temporarily high-capacity demand, such as stadiums and event venues. In such areas, it might not be beneficial for multiple MNOs to build the needed communication infrastructure but rather to lease the needed capacity from the neutral host network.

From the technological perspective the implementation of 5th and eventually 6th generation mobile networks might also benefit from neutral host networks since the higher frequency bands require denser base station network. This might not be commercially viable or even desirable from the city planning perspective for each MNO to build on their own. When considering the city planning perspective in wider and especially in smart city context, the neutral host actors could have a role broader than a mere mobile network connectivity provider. They could include services from air quality and weather monitoring as well as digital support for automated vehicles and drones. Such visions have been piloted in projects like LuxTurrim5G (LuxTurrim5G, 2024).

A neutral host model could be applicable to improving the availability of services on road sections when a certain party would have an incentive to improve the available service quality. Such party could deploy the necessary communication infrastructure and even the network equipment and offer the resulting connectivity to MNOs with fair and equal terms to try to ensure that the deployed network and infrastructure will be used. A neutral host could deploy equipment that can support the frequency spectrum held by each MNO with their spectrum licenses and provide the MNOs with access to the built network. Such operating model is already used in stadiums and underground railway networks for example.

In the context of C-ITS connectivity and even more so for future automotive services requiring more capacity or better reliability, potential applicable areas for neutral host networks could be, for example, road tunnels. Although the coverage in tunnels may already be at a good level, the proactive investment to improve the service level beyond the current level may not be justified based on demand alone. The deployment of multiple separate mobile network infrastructure in tunnels is not cost efficient, and joint construction may not be the highest priority for MNOs. A third party with incentive to ensure the latest technology and highest service level on road sections, including tunnels, could deploy multi-operator network equipment on the road sections, enabling the latest technological advancements to be adopted at a lower total cost and without relying on MNOs' motivation to invest.

The neutrally hosted multi-operator networks may introduce new challenges in sharing of responsibilities of the different parties, to ensure for example that the network operation, maintenance and management is not neglected. However, with commercial agreements and compensation, these issues can be mitigated.

Typically, MNOs will keep investing in areas such as residential and commercial districts where they already have customers, and the demand increase is verifiable. The MNOs are unlikely to heavily invest in road communication improvements before the demand increases. A neutral host operating model can drive investment to network improvement already before widespread adoption, that is, before the demand increases. In the case of road networks, a neutral host with incentive to invest in the improvement of road communication can ensure that development is proactive, and the networks are in place for the demand.

2.3 Network slicing

Network slicing is one potential way of trying to secure sufficient capacity for C-ITS services. Slicing would mean that operators would secure for times of data traffic congestion a certain minimum agreed capacity that would be guaranteed for C-ITS services. This would have certain implications for C-ITS service providers and especially MNOs, which aim to maximize the cost efficiency of their investments on network resources and would need to identify clear business drivers for such capacity reservation. Consequently, either a commercial or regulatory framework would be needed for how this would be ensured.

The 5th generation mobile network is a technological enabler for the network slicing, and there are already existing demonstrations for utilizing slicing in 5G network. However, network slicing does not create any additional capacity for the users and is rather a tool to allocate ensured capacity to the desired application, use case, user group or customer. This means that in the areas of low capacity, the capacity that can be reserved with network slicing for certain applications or services is also low. The implementation of network slicing can be done dynamically in a way that when the overall demand for network capacity is low, the whole network capacity is divided for different users regarding the network design principles. But when there’s not enough capacity to answer the demand, the network slicing ensures that certain minimum capacity can be utilized for example safety critical services. This kind of implementation model ensures that the overall network capacity is utilised efficiently.

As the network efficiency is a high priority for MNOs an issue to be solved is the adequate capacity dedicated to certain applications or services with network slicing. This study has concentrated on the C-ITS-services and one key result is the service level framework formed in the Part A of this report. The service level framework could be utilized when considering the suitable capacity in order to ensure the necessary support for C-ITS-messages. As the framework is categorised with four different levels, the suitable service level could be chosen for example specific road sections. Even though the service level framework includes other aspects as well, such as latency and packet loss rate, secured throughput level via network slicing would guarantee the realisation of the service level in a majority of cases.

Slicing is typically seen as a good alternative for traditional prioritisation to ensure that a certain minimum communication capacity can always be made available for critical communications. This means that for example public safety officers can communicate over potential heavy commercial traffic in critical situations in connection with mass events. In the case of heavy road traffic causing the mobile network congestion, a dedicated slice would not improve the ability of all the vehicles to send and receive the traffic, as each vehicle would be considered prioritised traffic. Rather, the slicing could enable reserving communication capacity for the most critical messages.

In Finland for example, the national public safety communication service operator Erillisverkot, based on bilateral commercial agreement, acquires 4G and 5G services from a commercial MNO, whereby the MNO manages the radio access network of the communication service operator. Typically, the public safety communication networks have been dedicated networks, requiring a separate rollout of network equipment for the specific public safety network across the country. The details of the agreement between the parties are not publicly available, but both 4G and 5G technologies enable assigning higher priority for critical communications and the use of network slicing is possible with 5G technology. Furthermore, in 4G and 5G technologies there is a possibility for pre-emption, whereby existing lower priority commercial traffic sessions can be terminated to make room for critical communication in case of network congestion. The use of prioritisation and pre-emption is also made possible by Finnish legislation (917/2014, § 250 b) ensuring the right for providing the necessary service level for public safety communication in commercial networks. This case is an example of critical communications needs being served by commercial mobile networks, showcasing the flexibility offered by the latest mobile communication technologies in providing higher priority to certain types of applications, use cases or customers. The Erillisverkot example also showcases how a commercial agreement works as a mechanism to enable the mobile network operator to invest in the necessary additional coverage and required functionality for effective critical communications.

Costs and investments related to the network slicing would in many cases be linked to the MNOs' operations. Therefore, there should either be a solid business case to cover the costs of network slicing or a solid regulation to ensure adequate capacity for the e.g. safety critical services. In the first case, for example a C-ITS-service provider or a driverless fleet operator would purchase the needed capacity from the MNOs in order to ensure proficient operations of their services. Such service providers or fleet operators don't yet exist in large-scale, or they consider the mobile network capacity adequate as it is, so some network operators have started to introduce the possibilities of network slicing with different demonstrations and pilot projects in order to create demand. In the latter case the road operator, or other national authority, would bear the costs of network slicing and this kind of investment could be justifiable from the perspective of road safety for example. C-ITS services can improve road safety so it would be road and transport authorities' interest to ensure the needed mobile network capacity for this kind of messages to be transmitted in a timely manner.

Regulation related challenges might arise from the network neutrality point of view. European Union adopted the Open Internet Regulation in 2015 to ensure all data traffic would be treated equally without discrimination, restriction, or interference. As network slicing is expected to consider more businesses than individual users, the essential question is whether the Open Internet Regulation is applied to businesses and how are the exceptions recognised in the Regulation applied. In the Open Internet Regulation, the businesses are included in the definition of end users and therefore implies that network slicing will likely have to comply with the Regulation's mandates. Regulation recognises exceptions regarding reasonable network traffic management and specialised services. In the first case the applicability depends on whether basis of network traffic management is considered to be technical or commercial. Other definition under the reasonable traffic management is that the duration should not be longer than necessary. Network slicing is continuous by nature, so this exemption hardly applies. In the latter case exemption of network neutrality is granted for specialised services, and this regulatory provision might bring network slicing into compliance with the EU's

Open Internet Regulation (Yoo, 2023). Lack of this kind of legal certainty might hinder the innovation and deployment of full potential of the 5G networks. In Finland Traficom has stated that network slicing for commercial purposes is possible (Traficom 2020). The interviewed Finnish mobile network operators seemed to believe in some level of regulatory vagueness in the framework for the network slicing but believed also that these things would be dealt with as the applications become more common.

Intelligent service design, as referred to also earlier in the context of preparing for cases of poor connectivity or extreme congestion, can still be the most viable approach in ensuring the effectiveness of C-ITS data traffic flow. Intelligent service design can aim to mitigate situations of C-ITS data traffic causing the mobile network congestion, and thus mitigating the need for solutions such as slicing from the network side, which would necessitate a separate commercial agreement between the relevant service provider(s) and mobile network operator(s).

2.4 Network monitoring

To assess the needed metrics and methodologies for validating the feasibility of C-ITS services in the different scenarios a measurement framework is proposed in the Part B of this report. The proposed framework presented in this assessment consists of using coverage predictions to build a situation overview of the whole country complemented with targeted measurements to verify the mobile network performance and to identify where additional improvement actions are needed.

As a part of the measurement framework, the stress test measurements presented are the most flexible way of gathering multi-purpose information from mobile networks. Stress test measurements reveal the best estimate of capacity that is available for different services and provide flexible post-processing options to analyse the measurement results, even if targets for different services or service levels would change. This framework can be used both before and after the adoption of C-ITS services, and the proposed measurement framework will allow flexible analyses in the future, even if the service level requirements would change when the C-ITS development has advanced further. When C-ITS services are in road operation, there is an opportunity to use the vehicle fleet for collecting information on the service level availability and mobile network performance and coverage. This crowdsourcing method can be an efficient tool for monitoring service level performance and identifying potential issues in C-ITS operation.

In terms of costs and investments, an important perspective is which organisation would be monitoring the mobile network and for what reason. As it is already stated in this study, MNOs have a business incentive to monitor the network performance and to deal with disturbances, and this is already part of their everyday operations. Additionally, any blind spots in the network coverage are something that MNOs take into account when improving their network infrastructure. Many national regulatory authorities (like Traficom in Finland) monitor the mobile network coverage by collecting coverage predictions from MNOs and implementing field measurements if needed. This study does not recognize any clear need to collect more detailed information from the MNOs. Agreeing on more detailed delivery statistics or ensuring service level agreements would require commercial agreement (a model to compensate MNOs) or changes in regulation (what kind of information is required from operators by the authorities). From the C-ITS service providers perspective the interest to monitor mobile network performance would be related to the functionality of their services. For this kind of monitoring, the crowdsourcing method would be useful as the C-ITS service providers application could monitor the mobile network performance in the background. However, this information would only indicate the problems with network connection, not the root causes causing the problems. In order to get into the root causes, the stress test measurements proposed would be needed.

The service-level agreement model is a typical way of ensuring that the party acquiring connectivity services from an MNO is provided with a certain minimum service quality and the MNO is incentivized to maintain and develop the network to provide the agreed service quality. Service-level agreements may include a stipulation for providing proof of the service level in the form of collected statistics from service usage or similar. The service-level agreements are dependent on the increased demand for connectivity in the service provider's business and subject to technical and commercial understanding between the service provider and the MNO.

Developing the framework and incorporating the information collection to C-ITS end-devices will require a clear vision on how to utilize this information. For example, quality of service requirements or service level agreements for the crucial part of the road network in order to support the implementation of C-ITS-services would be a concrete use case for such information collection. In order to set up such agreements, collaboration would be required between the different stakeholders, such as the C-ITS service developers and providers, communication equipment manufacturers, fleet operators, local authorities and vehicle manufacturers. The monitoring functionality can be introduced in C-ITS equipment to ensure that sub-target service quality occurrences are registered, and necessary action can be taken to prevent or mitigate such occurrences in the future. The minimum information collection could be implemented in a way that the source vehicle is not identified in the collected information, only registering the occurrence and location of the occurrence for further investigative activities, such as field measurements and/or analyses on network coverage and performance.

2.5 C-ITS-services data communication mitigation techniques

The estimate of current mobile network readiness to serve C-ITS data traffic highlights some of the potential issues to be accounted for in the development of C-ITS services, by planning the system in a way to prepare for situations of extreme congestion and the inherent service level variation in mobile networks. Some of these aspects have already been mentioned in this study in Part A with the mitigation techniques and congestion control algorithms. These include for example communication protocol error handling, the rules for C-ITS message generation and data content as well as delivering the messages from push or pull interfaces.

Intelligent planning of the C-ITS services by understanding the mobile network limitations is critical to ensure the network capacity adequacy. With the larger adoption rates of C-ITS-services and multiple service providers this could also mean cooperation between different C-ITS service operators in order to avoid transferring duplicate information. Such cooperation models don't yet exist but could be part of the future development such as the C-Roads Platform's actions related to IP based Interchange Node communication.

Mitigation techniques could also be extended to cover the themes of network expansion, neutral host networks, network slicing and network monitoring. For example, if the C-ITS service provider or OEM receives information or prediction of mobile network availability or capabilities on the road network, the system can adapt and mitigate possible service delivery issues beforehand. Similarly, possible dynamic network slicing and resource allocation could offer a mitigation technique for traffic management service providers in case of extreme network congestion and road traffic emergency, which could be further supported by the network monitoring.

2.6 Summary of possible solutions

In order to sum up the solutions that were chosen for a closer inspection it can be stated that the technological capabilities will not be limiting factors. Regarding network development and expansion, the current mobile network technology is already capable and next generation mobile networks even more capable to answer the increased demand. For network monitoring there are existing technologies already widely implemented. Technologies needed for neutral host networks and network slicing include minor uncertainties but there are also implemented demonstrations and piloting activities already going on.

Regulation for these solutions is also quite well defined, as commercial mobile network operations are being based on European legislation and Finnish Transport and Communications Agency Traficom’s radio license, including certain coverage obligations for the operators as presented earlier in Part B of this report. Network development monitoring related regulation is also well defined in its current form. Traficom collects information from network development from the different network operators. The definitions of required information to be delivered to Traficom can be amended if deemed necessary, as has been the case already before. This information collected by Traficom is deemed sufficient also for assessing the development of coverage and service level for C-ITS services. However, neutral host networks and network slicing related regulation is not as widely applied in practice and would benefit from clarifications.

When considering the costs and investments related to the inspected solutions it can be noted that the business models are an aspect least established in many cases. Regarding the mobile network expansion and development, it is quite clear that the obvious business model is commercial development of the networks, but in other solutions the business logic is not as clear. This relates to the early market phase that the C-ITS services are in as there’s not yet great demand for the services. Hence, there are no real incentives to invest for example in network capacity dedicated to these services. This implies a need for cooperation and an ecosystem approach to ramp up the availability of C-ITS services and supporting infrastructure.

3 Discussion

3.1 Large-scale deployment of C-ITS services

C-ITS services offer a multitude of benefits by leveraging connectivity and technology to enhance road safety, traffic management, environmental sustainability, and overall transportation efficiency. Necessary technology and connectivity are available, successful pilots have been conducted over the years, various players in the ecosystems and value chain have demonstrated their interest and the maturity of regulation is fairly well established. However, the C-ITS services are not yet available, and the large-scale breakthrough seems to be years ahead. The development has halted or at least not progressed as steadily as has been expected. For example, Nordic Way 2 report (Innamaa, et al. 2020) predicted about one third of road users having these C-ITS services in use in 2030. Currently there are no C-ITS services available in Finland.

While the C-ITS messages itself are well understood and agreed, the debate over the short-range communication technology (ITS-G5 vs. 5G-V2X) has delayed the development in Europe. Finally, there seems to be light at the end of the tunnel. The ITS Directive update providing the needed datasets for certain C-ITS services has been approved and the major European OEM carmakers have shared a press release through the joint 5GAA community, where they confirm their commitment to 5G-C2X technology and communication in the mobile networks instead of additional investments on the roadside Wi-Fi technology. The selected approach is technology agnostic but seems to pave the way towards the large usage of mobile networks in the C-ITS communication. (5GAA, 2023)

The use of the mobile network significantly reduces the need for public investment. And, as concluded in this study, mobile networks are very capable of managing the C-ITS data traffic. When the idea of large-scale network investments in short-range communications can be disregarded, investments can be targeted to produce new data according to C-ITS specifications and e.g., to update roadside infrastructure like traffic lights to be capable to communicate and deliver the valuable data. Regulation and incentives are needed so that states and municipalities make at least the minimum infrastructure investments in harmonised way. The update of the ITS Directive provides a good framework for this in terms of timetables, priority of C-ITS messages, and different road types. Some data sets required by the C-ITS messages are available and more will gradually appear. However, the significant impact will go into the 2030s.

As also European vehicle manufacturers are deploying 5G-V2X, the C-Roads specifications will likely follow up to determine the appropriate terminal device and PKI certificate technology for 5G-V2X communications as well.

User interface of C-ITS services has not been defined, but a decent user interface for consumers and end users is essential. In the 2030s, the consumer user interface will likely be integrated into vehicles, but before that, the possibility lies in mobile phones. Android-Auto or iOS CarPlay type of infotainment solutions can enable the use of C-ITS services in a safe manner. Consumers and other car owners are not very much geared towards additional devices like navigators or other optional accessories.

The national orchestration of the C-ITS services is also needed. The roles of the authorities in the implementation and operational use of C-ITS services in Finland is discussed in more detail in the report of Kotilainen et al. (2024), but in short can be said that the authors of the study have suggested Traffic Management Company Fintraffic Ltd or Fintraffic Road Ltd and municipalities an essential role as a C-ITS central station operator. Fintraffic already has a role as the National Access Point (NAP) operator collecting all the national data and sharing it for different stakeholders and service providers.

It is worth noting that the actual impact assessment of C-ITS services has not been part of the study (other than the impact to the capacity needs) so the benefits mentioned in the beginning of this chapter are not studied in more detail. Previous impact assessment results such as NordicWay projects Innamaa et al. (2020) were referred in the Part A of the study. Another perspective that has not been part of this study is the nature of the services itself. There is considerable difference whether the information provided by the C-ITS service is taken purely informative or obligatory. Obligatory C-ITS messages would have greater impact to the transport system, and it would give more tools for the traffic management centres. However, this would also increase the responsibilities of the data and service producers (regarding to the data quality, correctness, and timeliness for example). There might also be regulatory issues to be solved or at least clarified with the current legislation, before the information provided by the C-ITS messages could be taken obligatory (this would be the case especially with In-Vehicle Signage and Signalized Intersections services), as currently legislation states that the physical signs are directive. These topics are being issued in ISO/CEN standardisation bodies with the METR work (Management of Electronic Traffic Regulation).

One potential user group for C-ITS services are vulnerable road users (VRUs), including pedestrians and cyclists as well as riders of mopeds and motorbikes. This user group was ruled out from this study as the study focuses on the Day 1 C-ITS services defined in C-Roads specifications (concentrating more on vehicle road users). VRU specific services are recognised in Day 1.5 C-ITS services as presented in Part A of this study, but they there are no C-Roads specifications for these services/messages. Especially pedestrians and cyclists rely on their mobile phones as terminal devices and in order to serve these user groups it would be important to have PKI certificate technology for 5G-V2X communications as well. Otherwise, C-Roads compatible C-ITS services might neglect this user group, which could lead to lost safety benefits especially in urban mobility.

3.2 Alternative routes for the C-ITS services implementation

A possible EU and Finland vision of how C-ITS services will become more common is presented in previous chapter. This regulation driven approach is a very good and solid long-term plan but has a very slow deployment schedule. There are many C-ITS service benefits including road safety and technology strategies waiting for the C-ITS implementation and adding value for the European citizens, but it takes 10-15 years before the large-scale benefits are available. Additionally, it is good to consider whether the US, China or Asia will dominate the whole C-ITS service landscape while the EU is still planning. In book "Crossing the Chasm" Geoffery Moore has introduced his famous theory how early technology adapters can dominate the market in the future and a risk exists that the EU will be left behind. (Moore 1991).

Mobile network communication has been used as a primarily communication medium by the Nordic countries of Denmark, Finland, Norway, and Sweden in the European Union Connecting European Facility (EU CEF) NordicWay projects (2015–2023) to exchange safety related traffic information such as C-ITS messages. The C-ITS deployment pilot projects of the NordicWay project were carried out in collaboration between public authorities and private industry partners. A key NordicWay projects' result has been the concept of an Interchange Network (cloud to cloud communication). The network of several Interchange Nodes or message brokers (public or private) can be used by data and service providers to gather and stream data. The Interchange Node has been harmonised via common European specifications in the EU CEF funded C-Roads Platform as a part of the hybrid communication specifications. The concept of the interchange network origins from the Nordic conditions of long road network, sparsely populated regions, and profound experience as well as good availability of mobile networks.

One example of a large-scale use of Interchange Node (approximately 750 million messages per day), or traffic information message broker, that uses mobile network and IP communication, is the TLEX platform from company Monotch in Netherlands (NordicWay 3 Final Webinars 2023). The platform provides an alternative approach for data collection and data sharing through commonly used free apps. In the Netherlands they are running a nationwide deployment and already serving millions of road users and C-ITS-like services, not fully compatible with PKI credentials (EU CCMS). The progress was initiated by the governmental driven "Talking Traffic" public-private collaboration project with multiple stakeholders. As an outcome of well spent public money there is now a platform with good capabilities, and they demonstrate that C-ITS is ready to provide value for the road users today and there is no need to wait until the late 2030s. In the beginning, all services and definitions do not need to be in place nor do the data management platforms need to solve everything. This is also one way to understand what the technology agnostic approach means in practice. A flexible platform can utilise the standardisation available but not be limited by it. In terms of finance, progress has not happened free of charge. Public sector investments have been used for smart devices and the TLEX platform.

Another option in Finland are the mobile applications of private service providers, which can exchange traffic information via the mobile network. These mobile applications could use the interchange network interfaces to exchange data and therefore provide a larger collaborative impact on traffic safety and flow. One example of such traffic app is the Finnish government owned Traffic Management Company Fintraffic Ltd's *Fintraffic Mobiili* app. By many means the *Fintraffic Mobiili app* has already high amount of relevant data and a mobile network-based approach to share the data with the end users, and the app is free of charge to the users. C-ITS services as specified by C-Roads are not yet available, but an approach for safety related and real time traffic data management platform is there.

Fintraffic has already demonstrated good capabilities to continuously include new data sets and drive the development forward. Fintraffic is already an existing National Access Point (NAP) operator of transport service providers' data and also a candidate in Finland to act as a C-ITS central station operator (Kotilainen et al.

2024). In any case, as a traffic management operator in Finland, Fintraffic has a strong incentive to deal with C-ITS messages in the future. Possible technical limitations in terms of processing real-time messages and latency need to be further discussed.

Other potential applications like Google Maps and Waze could also have a role in the large-scale C-ITS services deployment. They have successfully implemented their business model and already have very large end user customer base. However, the necessary commitment to exchange information, e.g., via the interchange nodes, might be out of their interest and authorizing multi-national companies acting as an Interchange Node operator in Finland might not be the best option. This kind of business model has a potential conflict with the investments and ownership of smart devices needed for C-ITS. Leveraging these applications as an additional end user interface and keeping them more like collaborators than competitors seem more realistic.

The implementation of C-ITS services in Finland and in the EU will not happen overnight. Instead, a roadmap that combines the current capabilities and existing C-ITS services with a fully harmonised and regulated approach should be considered. For Finland, it is very clear that such a roadmap should heavily build on the use of mobile networks. While national level selections may vary, the long-term vision has been clarified remarkably by the latest decisions. Fintraffic's approach has already demonstrated many strengths and an opportunity to deploy mobile networks and 5G-V2X based solutions to simplify the landscape. According to C-Roads operational model practical 5G-V2X-deployment will lead to C-Roads specifications.

3.3 The importance of mobile communication networks for the transportation segment

It is already concluded in this study that the role of mobile communication networks is significant for the wider adoption of C-ITS services. It is also quite clear that connectivity of vehicles and road users will increase in the future and so will the demand for mobile network capacity. The mobile network capacity will also develop with next generation mobile network technologies, and it can be expected that these technologies will be well suited to serve the increased needs. This study hasn't recognised any fundamental gaps between available network capacity and demand from C-ITS services. As stated earlier, local and temporary issues may arise, and these should be taken into consideration in the cooperation of mobile network operators, road operators (including other relevant authorities), fleet operators, and service providers.

The European Union has taken a strong initiative supporting and funding 5G deployment in the transport and mobility sector. European Commission Europe's Digital Decade Strategy and Sustainable and Smart Mobility Strategy both acknowledge the importance of 5G communication. Already in 2017, the Member States and industry agreed to establish an EU network of 5G corridors. Previously, the European Commission's 5G Public Private Partnership has supported, with Horizon 2020 co-funding, 5G cross-border corridor trial projects for Connected and Automated Mobility (CAM) solutions. The Connecting Europe Facility (CEF) Digital Programme (2022–2027) has further provided financial support to large-scale deployment of 5G cross-border corridors along European transport paths. (EC 5G cross-border corridors 2023)

Another aspect to consider is the broader perspective for a transportation segment as a use case for mobile network connectivity. This study has been considering the C-ITS services and it has been concluded that this is quite modest use case in terms of requirements for throughput levels and latency in the mobile networks. The same mobile network capacity will be shared with all the different use cases outside and within the transportation segment. Therefore, it would be beneficial to consider a broader perspective for a transportation segment as a use case of mobile networks to make better estimates for the capacity demands in the future. It can be expected that use cases related to automated mobility, for example remote operations and monitoring, will be more demanding in terms of network capacity and latency. With automated mobility, the themes presented in this report, such as network slicing, will be even more important for the proficient support for the vehicles.

Under the theme of automated mobility there will be also new modes of transport in addition to the road transport use cases. Urban air mobility use cases, such as drones, are also dependent on sufficient connectivity, in many cases mobile networks. With the urban air mobility use cases there are even more uncertainties as the mobile networks are not designed to support aerial applications in higher altitudes, and this is one aspect to consider when expanding the mobile networks.

Additionally, it's important to consider the constraints outlined in this report impacting the requirements and growth necessities of mobile networks. Specifically, the assessment does not encompass vehicle-to-vehicle (V2V) short-range communication or potential requirements for remote monitoring and operation associated with autonomous driving. Furthermore, the rapid expansion of non-C-ITS information data traffic presents significant challenges for mobile networks.

In conclusion, it would be beneficial to consider the transportation segment and all its use cases as an entity when estimating the capability of mobile networks. This would also help to recognise all the actors involved and ensure that sufficient cooperation models could be formed between the parties. It is also worth remembering that even if the transport related applications will be important use case for the mobile networks, the largest use case in terms of capacity needs will be entertainment related applications, such as video streaming or social media applications.

4 Recommendations

As the chapter 2 *Solutions* took a closer look on the possible solutions for securing the needed capacity for the C-ITS services, such as network expansion, neutral host networks, network slicing and network monitoring it was summarized that technological development and maturity of these solutions are quite well defined. Instead, regulatory and business model related aspects would benefit from clarifications. Especially, it would be beneficial to move from regulatory push to market pull approach. In the same context the benefits of cooperation were introduced. This study recommends the following high-level actions for C-ITS service deployment:

1. Cooperation model for shared vision and goals.

2. National C-ITS implementation strategy and road map.

4.1 Cooperation model for shared vision and goals

The approach for the recommended cooperation model should be forward looking in the sense that even if the current mobile network capacity and assumed development path are seen sufficient for the transportation related use cases, the future includes a lot of uncertainties, for example with the adoption rate of C-ITS services, as further explained in chapter 3 *Discussion*. The central part of the cooperation model would be to tackle this uncertainty with shared view and situational awareness between actors.

In general, the different actors needed for the cooperation are mobile network operators, road operators and other national regulatory authorities, large fleet operators as well as C-ITS service providers. The roles of Finnish authorities in C-ITS implementation have been studied in more detail in *Authorities' roles in implementation and operational use of C-ITS services in Finland (Kotilainen et al. 2024)*. There is already well functioning dialogue between individual organisations in many countries, as well as in Finland, but to stronger ramp up the adoption of C-ITS services or other mobility services relying on connectivity, a national cooperation group and model with shared vision and goals could ensure a better outcome. For example, in the Netherlands there has been successful cooperation between road authorities and private parties concentrating on a set of standards and protocols to connect traffic light controllers and enable traffic light related C-ITS services (Malta & Burgsteden 2023). In Finland, a similar approach would be beneficial, and crucial aim for the cooperation would be to clarify standards and protocols to ensure compliance with C-Roads specifications and other relevant regulation. Strong involvement of road operators and other national regulatory authorities would also increase the predictability and therefore make it easier for commercial operators to invest in implementation of these services. Cooperation model would also clarify the issues regarding the cost and revenue sharing between actors, as it would be the task of cooperation group to create prerequisites for operations also from the business model perspective. This is further elaborated in the chapter *4.2 National C-ITS implementation strategy and road map*.

Another central task for this kind of cooperation would be influencing the European C-ITS legislation and specifications. This is particularly important with C-Roads Platform, as their operational model is rather reactive in the sense that they will create specifications after successful implementation. This kind of approach enables the first ones in the market to have strong impact on the specifications. As highlighted in the chapter 3 *Discussion*, the appropriate terminal device and PKI certificate specifications for 5G-V2X communication should be determined. Possibilities to utilise C-ITS services via mobile applications and Interchange Nodes, as in the Netherlands, would speed up the adoption rate and make it more inclusive for all road users, including VRUs.

Resiliency should also be one of the crucial themes of this proposed coordination group. Resiliency is built by increasing the awareness of risk management on C-ITS services, especially in situations such as malfunctions of mobile communication networks. All the parties involved, service providers, fleet operators, MNOs and especially public authorities should understand the possible consequences of weakened or missing mobile network availability to different C-ITS services, vehicle, and driver-assistance systems as well as road sections. Building this kind of resiliency would increase the cybersecurity of C-ITS services. Part of resilience planning is to remember the possibilities of intentional vandalism and manipulation of intelligent devices. Although large-scale vandalism is difficult, it is possible to cause local disruptions to traffic safety and flow. Identification of risks with a wide perspective enables better measuring, preparation, and mitigation actions.

A concrete task for the cooperation group could also be more comprehensive impact assessment on the deployment of the C-ITS services. As mentioned earlier in this report, the benefits of C-ITS services are taken as given in this study (based on the literature review) and in order to justify investments in the large-scale deployment of the C-ITS services it would be necessary to comprehensively evaluate the impacts to the transportation system as well as individual road users. Currently the lack of data on the impacts of C-ITS services is adding uncertainty to the assessments and therefore a scenario-based simulation model could be the recommended approach to evaluate the impacts on different scenarios.

4.2 National C-ITS implementation strategy and road map

The shared goal for the proposed cooperation model could be a national C-ITS implementation strategy and road map. Basically, the strategy would aim for a certain timeline with a minimum set of C-ITS services available in the most critical parts of the road network. A road map would help to prioritise and scale up the operations in terms of available C-ITS services and road network coverage.

First steps in such a process would include selection of the services that would need to be available. The selection criteria utilised in this study is a good baseline for the selection of services in the first phase of the road map. As mentioned in the chapter 3 *Discussion*, currently there are no C-ITS services operating in Finland (in compliance with C-Roads specifications and EU CCMS), and the business model for emergence of commercial operators is somewhat unclear.

In Finland possible roles of authorities in C-ITS deployment have been studied in Kotilainen et al. (2024), where roles in legislative framework, management, and administration as well as system operation of C-ITS are discussed. A possible role for management and administration of C-ITS implementation could include public authority funding, e.g. road authority and municipalities, and procurement in a similar manner as it is currently the case, for example with road maintenance.

This might be the initial step to start the C-ITS services in Finland, and the road map should include more detailed plan for wider emergence of commercial service providers. Possible candidates for C-ITS system operation, such as central C-ITS station implementation, could be municipalities and Fintraffic (organisation responsible for road traffic control and management), latter being government owned and Finnish Transport Infrastructure Agency funded as well as the operator of NAP and therefore already administrating the relevant data. Cloud to cloud communication-based interchange network, created in NordicWay projects and utilising mainly mobile network, could enable the operation of commercial operators and be part of the NAP implementation of C-ITS. (Kotilainen et al. 2024)

The road network coverage targets for C-ITS services could be connected to the main road network and to the larger cities. TEN-T classification (e.g., core network and comprehensive network) could be utilised when planning for the road network coverage. A suitable timeline for the road map could be aligned for example with the EU regulation regarding the ITS Directive and the timeframe that the recognised data types should be available. However, this is a minimum requirement and there’s no reason why the national implementation couldn’t be faster.

As important as enabling commercial operations is enabling cross-border interoperability, and this theme should be covered in the national implementation strategy as well. European specifications for C-ITS cross-border harmonisation and interoperability have been implemented in C-Roads platform. The C-Roads Task Force 4 Hybrid Communication has published C-ITS IP Based Interface Profile including implementation for long-range mobile network communication. The Nordic countries have had a successful collaboration establishing the Interchange Node, mainly using mobile network communication, which has been harmonised in the C-Roads Hybrid Communication specifications. Recognising this work in the national implementation strategy and road map would ensure that the solutions of commercial operators would be also functional in other member states and therefore make it easier to scale up their operations in Europe. Other relevant European harmonisation work such as the National Access Point Coordination Organisation for Europe (NAPCORE) should also be included in the strategy for relevant parts.

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Appendix 1

Tiivistelmä

Tämä tiivistelmä on tiivis yleiskatsaus tämän kattavan tutkimuksen pääkohdista, keskeisistä havainnoista ja suosituksista. Lisäksi tiivistelmä antaa hahmotelman tutkimuksen rakenteesta, sekä opastaa kuinka tutkimuksen sisällön kanssa tulee edetä saadakseen tarkempia tietoja käsiteltävästä aiheesta.

Tutkimuksen rakenne

Tämä tutkimus sisältää neljä osaa, joista jokainen perustuu edellisen löydöksiin.

Osa A tarkastelee C-ITS-palveluiden ominaisuuksia ja määrittelee tarvittavat mittarit, keskeiset tulosindikaattorit (Key Performance Indicators, KPI) ja palvelun laatuvaatimukset. Osa A esittelee palvelutason viitekehyksen, joka toimii pohjana tutkimuksen myöhemmille osille. Lisäksi pohjustetaan skenaariokehystä hyödyntäen skenaarioanalyysiä ja ennusteita C-ITS:n käyttöönotosta Suomessa vuoteen 2030 asti.

Osa B keskittyy matkaviestinverkkoteknologioihin ja mittausmenetelmiin sekä tekniikoihin ja niiden soveltuvuuteen tutkimuksen osassa A määriteltyjen keskeisten tulosindikaattorien mittaamiseen. Osa B:n keskeisin tulos on kehitetty mittausmenetelmäkehys, jolla arvioidaan kaupallisten verkkojen soveltuvuutta C-ITS-palvelujen käyttöön.

Osa C yhdistää edellisten osien havainnot arvioimalla eri matkaviestinverkkoteknologioiden ja kaupallisten verkkojen suorituskykyä Suomessa. Määriteltyjen C-ITS-kehitysskenaarioiden toteutettavuus (perustuu osassa A määriteltyyn skenaariokehykseen) ja suorituskykymittarit (soveltamalla osassa B kehitettyä mittausmenetelmäkehystä) sisältyvät osaan C. Osan C keskeinen lopputulos on kaupallisten matkaviestinverkkojen arvioitu valmius mahdollistaa C-ITS-palvelujen käyttöönotto.

Osa D tutkii C-ITS-palvelujen verkkokehityksen edistymistä ja ehdottaa ratkaisuja tarvittavan kapasiteetin turvaamiseksi. Lisäksi annetaan suosituksia C-ITS-palvelujen laajempaan käyttöönottoon kansallisessa kontekstissa.

Valintakriteerit ja tutkimukseen valitut C-ITS-palvelut

Cooperative Intelligent Transport Systems (C-ITS) tarkoittaa älykkäitä liikennejärjestelmiä (ITS), jotka vaihtavat reaaliaikaisia C-ITS-viestejä ajoneuvojen, muiden tienkäyttäjien, infrastruktuurin ja muun ympäristön kanssa käyttämällä luotettavaa ja suojattua viestintää. EU:n C-ITS-järjestelmien turvatunnusten hallintajärjestelmä EU CCMS on Euroopan unionin C-ITS-kehys luotettavalle ja turvalliselle C-ITS-viestinnälle käyttämällä julkisen avaimen infrastruktuuria (PKI).
Analyysi perustuu rajoitettuun määrään palveluita, jotka on valittu strategisten, teknisten ja automatisoidun ajamisen kriteerien perusteella seuraavasti:

- Strategiset kriteerit
  - Strategia ja lainsäädäntö: Päivän 1 ja päivän 1.5 viestit ja palvelut, joita eurooppalainen strategia ja lainsäädäntö tukevat sekä jo olemassa olevat C-Roads Platform -spesifikaatiot.
  - Suomen tarpeet, odotettavissa olevat turvallisuusvaikutukset ja meneillään oleva pilotointi Suomessa.
- Tekniset kriteerit
  - C-ITS viestityyppi: DENM ja CAM viestejä vertailtavaksi.

  - Viestintä infrastruktuurista ajoneuvoon, Infrastructure to Vehicle (I2V) (tai satelliitti-maayhteys) ja ajoneuvosta infrastruktuuriin, Vehicle to Infrastructure (V2I) (tai maasatelliittiyhteys). Tämän takia V2V ja V2X, joissa on suojattoman tienkäyttäjän eli VRU-viestiliikennettä, ovat poissuljettuja.
  - Vaadittu viestintätekniikka tutkimuksessa on mobiiliverkko.
  - Vaikutus matkaviestinverkon käyttöön.
- Automaattinen ajo ja muut käyttötapauskriteerit
  - CAM, kollektiiviset havaintoviestit eli Collective Perception (CPM) ja jotkin IVIM-palvelut ovat erityisen tärkeitä.

Analyyseihin valitut C-ITS-palvelut ja käyttötapaukset olivat:

1. Vaarallisten paikkojen ilmoituspalvelu, Tilapäisesti liukas käyttötapaus (HLN-TSR) (C-Roads v2.0.5 2022)
2. Tietöiden varoituspalvelu, kaistan sulkemisen käyttötapaus (ja muut rajoitukset) (RWW-LC) (C-Roads v2.0.5 2022)
3. Signaloitu risteyspalvelu, signaalin vaihe ja ajoitustietojen käyttötapaus (SI-SPTI) (C-Roads v2.0.5 2022)
4. Probe Vehicle Data -palvelu, ajoneuvotietojen keräämisen käyttötapaus (PVD-VDC) (C-Roads v2.0.5 2022)
5. Collective Perception Service (CPS) (ETSI TS 103 324).

Katso lisätietoja kappaleesta *Part A. Chapter 3 C-ITS Services*.

Keskeiset tulosindikaattorit

Suorituskykymittarit on määritelty mittaamaan C-ITS-palvelun suorituskykyä kvantitatiivisilla mittauksilla. Keskeiset tulosindikaattorit (KPI) ovat tärkeimmät valitut mittarit C-ITS-palveluiden suorituskyvyn arvioimiseksi.

Palvelun laatu (QoS) viittaa palvelun yleiseen suorituskykyyn, jonka palvelun käyttäjä usein kokee tai jota arvioidaan suorituskykymittareiden avulla. Laatuvaatimukset ovat vähimmäistavoitearvoja (tai laatutasoja, rajoja), jotta C-ITS-palvelu täyttää asetetut palvelun laatukriteerit.

KPI-kategorioiden analyysi sisältää C-ITS-palveluiden suorituskykymittareita kirjallisuuskatsauksesta ja 3GPP:stä sekä ETSI-standardeista. Analyysi päätyy kolmeen ehdotettuun keskeiset tulosindikaattorit -luokkaan C-ITS-palveluviestinnässä matkaviestinverkkoja hyödyntäen: 1) käytettävyys, 2) luotettavuus ja 3) eheys. Ehdotetut KPI:t näkyvät Taulukossa 1.

Taulukko 1. Keskeiset tulosindikaattorit (KPI) C-ITS-palveluviestinnässä matkaviestinverkkoja hyödyntäen.

Keskeinen tulosindikaattori (KPI)	Kuvaus	Yksikkö	Huomautuksia palvelun laadun määritelmästä
Saatavuus – Verkon kattavuus	Myös maantieteellinen kattavuus. Tieverkon prosenttiosuus ja/tai tieluokkien valinta (tapauskohtaisesti), joissa matkapuhelinverkko on käytettävissä. (Mukautettu EU EIP 2022)	%	Matkapuhelinverkon saatavuus mitattuna verkon kattavuuden KPI:llä. Verkon kattavuus tässä binäärisesti: "ei verkon kattavuutta" tai "varmennettu verkon kattavuus".
Luotettavuus - Pakettien katoamisnopeus	Paketit, joita kohdesovellus ei ole vastaanottanut kyseisen sovelluksen suurimman sallitun päästä päähän -viiveen aikana.	%	-
Eheys – Viive: Päästä päähän -viive	Aika viestin lähettämisestä sen vastaanottamiseen sovellustasolla	ms	Päästä päähän -latenssisuositus on arvo, jonka alapuolella viive on 99 % tapauksista.
Eheys - Suorituskyky (verkko, kapasiteetti), viestintä	Välitön tiedonsiirtonopeus/suoritusteho verkkokerroksessa.	bps	Sisältää lataus- ja lähetysnopeudet

Katso lisätietoja kappaleesta *Part A. Chapter 4.5 Analysis and summary of C-ITS performance metrics and Key Performance Indicators (KPI).*

Palvelutasokehys

Palvelutasokehys määritellään C-ITS:lle määriteltyjen palvelun laatuvaatimusten perusteella. Valittujen keskeisten tulosindikaattoreiden (KPI) kynnysarvot noudattavat palvelun laatukirjallisuuskatsauksen tuloksia ja asiantuntija-arvioita. Palvelutasoja ja tässä kuvattuja määriteltyjä skenaarioita käytetään myöhemmin tutkimuksessa palvelutasojen analysointiin ja luokitteluun. Se tarkoittaa skenaarioarvojen laskemista eri liikenneolosuhteissa sekä verkon kattavuusanalyysistä ja kenttämittauksista kerätyn tiedon hyödyntämistä.

Palvelutasokehys on esitetty alla taulukossa 2. Kehys on jaettu neljään tasoon, jotka ovat epäluotettava, perustaso, keskitaso ja korkea.

Taulukko 2. Palvelutasokehys C-ITS-palveluille, jotka hyödyntävät matkapuhelinverkkoa.

Keskeinen tulosindikaattori (KPI)	Taso 0: Epäluotettava käytettävyys	Taso 1: Peruskäytettävyys	Taso 2: Keskitason käytettävyys	Taso 3: Korkea käytettävyys
Saatavuus Verkon kattavuus	Ei lainkaan tai epäluotettava	Vahvistettu	Vahvistettu	Vahvistettu
Luotettavuus Luotettavuus Pakettien katoamisnopeus	< 90 % > 10 %	> 90 % < 10 %	> 95 % < 5 %	> 99 % < 1 %
Eheys E2E viive Suoritusteho DL Suoritusteho UL	> 1 s < 5 Mbit/s < 5 Mbit/s	< 1 s > 5 Mbit/s > 5 Mbit/s	< 500 ms > 20 Mbit/s > 20 Mbit/s	< 100 ms > 100 Mbit/s > 25 Mbit/s

Taso 0: Epäluotettava käytettävyys tarkoittaa, että verkko ei täytä C-ITS-palvelujen toiminnan vähimmäisvaatimuksia. Tämä voi esimerkiksi viitata siihen, ettei MNO-kattavuutta ole sillä maantieteellisellä alueella, jolla ajoneuvo- tai kenttämittaus suoritettiin, tai että toiminnan/mittauksen aikana oli verkkokatkos tai vastaava jatkuva ongelma. Jos käytettävyyttä ei ole, eli verkon kattavuutta ei ole, ei voi myöskään olla luotettavuutta eikä eheyttä. Lieventämistekniikoilla ja algoritmisuunnittelulla on tärkeä rooli siinä, miten kukin palvelu on riippuvainen verkon kattavuuden saatavuudesta.

Taso 1: Peruskäytettävyys takaa varmennetun verkon kattavuuden ja sen, että yksittäinen ajoneuvo tai palvelu voi aina käyttää suurinta osaa Päivän 1 V2I/I2V C-ITS -palveluista. Joissakin palveluissa saattaa esiintyä ajoittain hidastelua suhteellisen korkeiden viivevaatimusten vuoksi, mutta palvelut ovat saatavilla. Taso 1 saattaa haitata C-ITS-viestien reaaliaikaista lähetystä.

Taso 2: Keskitasoinen käytettävyys takaa, että yksittäinen ajoneuvo tai palvelu voi käyttää C-ITS-palveluita, jotka vaativat normaalin suorituskyvyn ja latenssin. Palveluissa ei saa esiintyä ajoittaista hitautta ja verkon tulee toimia yhdenmukaisesti annettujen parametrien suhteen. Enemmän reaaliaikaista lähetystä vaativat C-ITS-palvelut voidaan toteuttaa, jos tietyt reaaliaikaiset vaatimukset täyttyvät.

Taso 3: Korkeatasoinen käytettävyys takaa, että yksittäinen ajoneuvo tai palvelu voi käyttää kehittyneitä C-ITS-palveluita, jotka vaativat teoreettisen reaaliaikaisen lähetyksen ja korkean suorituskyvyn. Kaikkien valittujen C-ITS-palvelujen tulee toimia yhdenmukaisesti ja reaaliaikaisesti.

Katso lisätietoja kappaleesta *Part A. Chapter 5 Service level framework*.

Skenaariokehys ja analyysi

Skenaariot pyrkivät kuvaamaan kokonaiskuormitusta, jonka erilaiset C-ITS-palvelut voivat aiheuttaa matkaviestinverkolle. Tämä huomioi muuttujat, jotka liittyvät C-ITS-sanomia vastaanottamaan ja lähettämään pystyvien ajoneuvojen määrään, liikenteen määrään sekä C-ITS-sanomien tietotiheystekijöihin. C-ITS-viestien vastaanottamiseen ja lähettämiseen pystyvien ajoneuvojen määrän vaihtelemiseksi tämä tutkimus pitää realistisena skenaariona, että vuonna 2030 ajoneuvojen V2I-solukkoviestintää käyttävien ajoneuvojen prosenttiosuus on 33 %. Optimistisen skenaarion C-ITS-on-board -yksiköiden käyttöönottoasteen katsotaan olevan 45 % ja pessimistisen 20 %. Liikennemäärää muutetaan tarkastelemalla neljää eri skenaariota ruuhkaliikenteen osuuden osalta päivittäisestä liikennemäärästä ja ruuhka-ajan ajoneuvojen nopeudesta. Näillä muuttujilla voidaan laskea osallistuvien ajoneuvojen lukumäärä tiekilometriä tai km^2 kohti.

C-ITS-sanomien tietotiheyskertoimia vaihdellaan eri skenaarioiden kokonaisvaltaisen tutkimisen varmistamiseksi. Kolme tarkasteltavaa näkökulmaa ovat: Korkea, keskitaso ja matala informaatiotiheys. Vaihtelevat parametrit ovat päivitysnopeus ja tiheys (sisältää mm. vaaratekijöiden tai liikenteenohjauksen viestien määrän ja liikennevalosignaalit alueella).

Muuttujia ja niiden arvoja koskeva skenaariokehys on esitetty taulukossa 3.

*Taulukko 3. Valittujen C-ITS-palveluiden skenaarioiden käyttötapaukset ja tietotiheysteki-jät. *Äärimmäinen tapaus vilkkaimmilla teillä 366 ajon./km.*

Käyttötapaus / Tietotiheystekijät	**RWW: Kaistan sulkeminen (ja muut rajoitukset)**	**HLN: Tilapäisesti liukas tie**	**SI: Signaalin vaihe ja ajoitustieto**	**PVD: Ajoneuvotietojen kerääminen**	**Kollektiivinen havainto**
Osallistuvat ajoneuvot per tie km (Vilkkaan liikenteen tie) / km^2 (Pääkadut)*	Vilkkaan liikenteen tie: 6-150	Vilkkaan liikenteen tie: 6-150	Pääkadut: 25-127	Vilkkaan liikenteen tie: 6-150	Pääkadut: 5-127
Päivitysnopeus (tai sensorin päivitysnopeus) (Hz)	0.1 Hz	0.1 - 1 Hz	0.5 - 4 Hz	0.1 - 1 Hz	1 - 10 Hz
Tiheys Relevanssialueen pituuteen (10 km tai 1 km2) sisältyvät parametrien arvot - Vaaratilanteiden tai liikenteenohjausviestien lukumäärä - liikennevalot (n) alueella (km2) - ajoneuvojen osallisuusprosentti (%) - uusien havaintojen määrä ajoneuvoa kohden (CPM)	1 - 5 (arvioitu per 10 km relevanssipituus)	1 - 10 (arvioitu per 10 km relevanssipituus)	5 - 19 (Arvioitu per km^2)	100 %, 50 %, 10 % (suositeltu kirjallisuudessa, mutta sisältyy jo osallistuvien ajoneuvojen ennusteeseen)	10 - 43 (suositeltu)
Relevanssin pituus (km) tai relevanssialue (km2)	Pituus: 10 km	Pituus: 10 km	1 km^2	Pituus: 10 km (10 x 1 km)	1 km^2
ETSI C-ITS viestityyppi	DENM	DENM	SPAT (4 signaalia)	CAM	CPM
Viestien koko (tavua)	400	400	1600	100	1000 -1600

Arvioitu dataliikenne pääkaduilla (Mbit/s/km²) ja vilkkaasti liikennöidyillä teillä (Mbit/s/km) on esitetty taulukossa 4. Realistisessa käyttöönottoskenaariossa dataliikenteen tason odotetaan olevan 2-6 Mbit/s pääkaduilla, kun tieliikennevirta ei ole ruuhkautunut. Ruuhka-aikoina dataliikenteen taso voi nousta 14 Mbit/s ja jopa 25 Mbit/s, kun liikenne on pahasti ruuhkautunutta. Vilkkaasti liikennöidyillä teillä realistisen C-ITS:n käyttöönottoskenaarion yhteydessä dataliikenteen tason odotetaan olevan välillä 0,10–0,26 Mbit/s/km, kun liikennevirta ei ole ruuhkainen, ja ruuhka-aikoina dataliikenteen tason odotetaan olevan 0,6-1 Mbit/s/km.

Lisäksi on tunnistettu äärimmäinen skenaario, joka potentiaalisesti esiintyisi vilkkaimmilla mahdollisilla teillä ja äärimmäisinä ruuhka-aikoina, ja se on relevantti vain esimerkiksi Helsingin Kehä I:llä.

Taulukko 4. C-ITS skenaarioanalyysin tulokset, pääkadut & vilkkaan liikenteen tiet.

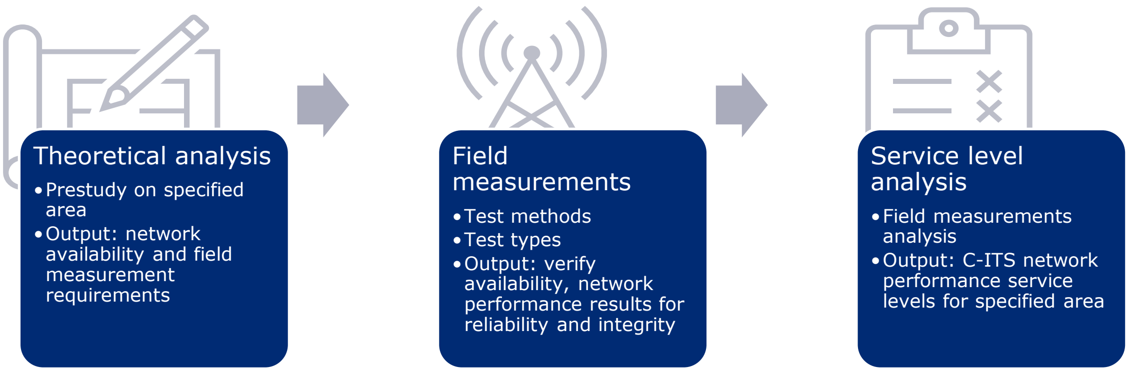
	Matala virta	Keskimääräinen virta	Ruuhkainen	Erittäin ruuhkainen
Pääkadut (Mbit/s/km²)				
Pessimistinen (matala omaksu-minen)	1.4 Mbit/s/km²	3.7 Mbit/s/km²	8.4 Mbit/s/km²	14.9 Mbit/s/km²
Realistinen	2.3 Mbit/s/km²	6.1 Mbit/s/km²	13.8 Mbit/s/km²	24.6 Mbit/s/km²
Optimistinen (korkea omaksu-minen)	3.1 Mbit/s/km²	8.4 Mbit/s/km²	18.8 Mbit/s/km²	33.5 Mbit/s/km²
Äärimmäinen				288 Mbit/s/km²
Vilkkaan liikenteen tiet (Mbit/s/km)				
Pessimistinen (matala omaksu-minen)	0.06 Mbit/s/km	0.16 Mbit/s/km	0.35 Mbit/s/km	0.62 Mbit/s/km
Realistinen	0.10 Mbit/s/km	0.26 Mbit/s/km	0.58 Mbit/s/km	1.03 Mbit/s/km
Optimistinen (korkea omaksu-minen)	0.13 Mbit/s/km	0.35 Mbit/s/km	0.79 Mbit/s/km	1.40 Mbit/s/km
Äärimmäinen				12.6 Mbit/s/km

Katso lisätietoja kappaleesta *Part A. Chapter 6 Scenario analysis* and *Part C. Chapter 3.5.1 C-ITS data traffic scenarios*.

Mittausmenetelmäkehys

Kehitetty mittausmenetelmäkehys on esitetty kuviossa 1 ja se on jaettu kolmeen vaiheeseen:

1. Teoreettinen analyysi (saatavilla olevien tietojen katsaus)
2. Kenttämittaukset (lisätietovaatimukset)
3. Palvelutason analyysi (palvelutason validointi).



Kuvio 1. Mittausmenetelmäkehys.

Teoreettinen analyysi sisältää tutkimuksen verkon kattavuusennusteista, jotka ovat hyödyllinen työkalu mahdollisten palvelun saatavuuteen liittyvien ongelmien, kattavuusaukkojen ja ongelmallisten paikkojen tunnistamiseen, joissa käyttökokemus on huono. Kattavuusennusteita voidaan edelleen vahvistaa kenttämittauksilla ja huolellisesti suunnitelluilla ja suoritetuilla testeillä.

Kenttämittauksia tehtäessä päätetään noudatettavat periaatteet sekä vaihtoehtoisten kenttämittaustyyppien määrittely ja kuvaus, joita voidaan käyttää erilaisiin tarpeisiin. Suurin ehdotettu lisäys Traficomin nykyiseen mittausmenetelmään on suoritustehotestaus. Syynä tähän on varmistaa riittävän suorituskyvyn saatavuus, joka tukee tunnistettuja C-ITS-vaatimuksia eri palvelutasoilla. Stressitesti on suositeltavampi, koska se pystyy analysoimaan käytettävissä olevan suorituskyvyn ja toteutettavuuden eri palvelutasoilla.

Palvelutasoanalyysi antaa ohjeita kerätyn tiedon käyttämiseen ja hiomiseen verkon palvelutasojen analysointia varten käyttämällä C-ITS-palveluvaatimuksien mittareita ja kynnysarvoja. Tutkimuksessa analysoidaan esimerkkimittausaineistoa, jotta voidaan havainnollistaa kenttämittausten mahdollistamaa analyysiä. Mittaukset tehtiin pääosin taajama- ja esikaupunkialueilla, joissa keskimääräinen käytettävissä oleva suoritusteho ylittää selvästi palvelutason 3 tavoitteen, mutta on silti yksittäisiä paikkoja, joissa palvelutasoa 3 tai edes palvelutasoja 1 ja 2 ei ole saatavilla. Esimerkkimittaustulokset osoittavat, että vaikka keskimääräinen suorituskyky on selvästi vaadittujen C-ITS-palvelutasojen yläpuolella, vaihtelu tarkoittaa, että palvelutason 3 toimivuus ei ole jatkuvasti saatavilla.

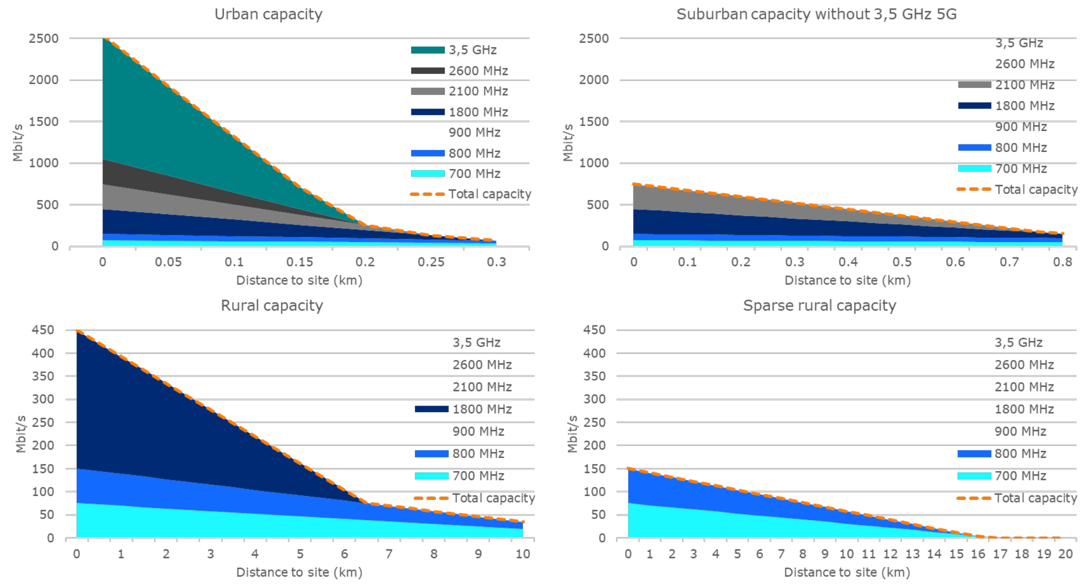
Katso lisätietoja kappaleesta *Part B. Chapter 5 Measurement method framework* and *Part C. Chapter 3 Mobile network development metrics for C-ITS*.

Matkaviestinverkon kapasiteetin arviointi

Matkaviestinverkon järjestelmän kapasiteetti riippuu kolmesta avaintekijästä, 1. spektri, 2. teknologia, ja 3. topologia. Tässä tutkimuksessa esitetyn arvioinnin kannalta olennaisia muuttujia eri ympäristöissä ovat eri alueilla käytetty spektri (1.) ja verkkotopologia (3.). Kun etäisyys tukiasemaan kasvaa, signaalin voimakkuus heikkenee äkillisesti, mikä johtaa alhaisempaan maksimikapasiteettiin. Pienemmällä signaalinvoimakkuudella voidaan lähettää vähemmän bittejä spektriyksikköä kohden, eli pienemmällä spektritehokkuudella. Korkeamman spektrin kaistat voivat tarjota suuren kapasiteetin, mutta vain rajoitetulle etäisyydelle verrattuna alempiin kaistoihin.

Järjestelmän kokonaiskapasiteetti ei tarkoita, että kenelläkään käyttäjällä olisi pääsy järjestelmän kokonaiskapasiteettiin, vaikka järjestelmä olisi täysin tyhjä muista käyttäjistä. Resursseja allokoidaan käyttäjille kysynnän perusteella ja lisäksi laitteen ominaisuudet ja muut rajoitukset vaikuttavat siihen, kuinka paljon kapasiteettia yksittäiselle käyttäjälle varataan. Kokonaiskapasiteetti jaetaan palvelualueen eri käyttäjille kulloisellakin hetkellä. Arvioitaessa matkaviestinverkkojen kykyä kuljettaa C-ITS-palveluiden tuottamaa liikennettä, järjestelmän kokonaiskapasiteetti on hyvä mittari verkon kyvylle palvella useilta yksittäisiltä käyttäjiltä lähtevää ja heille päättyvää liikennettä.

Kuviossa 2 on esitetty esimerkkijärjestelmän kapasiteetti eri pääympäristöille (kaupunki, esikaupunki, maaseutu ja harvaan asuttu maaseutu) tyypillisen spektrin ja tukiaseman etäisyyden perusteella.



Kuvio 2. Matkaviestinverkkojen sektorin kokonaiskapasiteetti eri ympäristöissä.

Katso lisätietoja kappaleesta *Part C. Chapter 2 Mobile network system capacity in different environments*.

C-ITS:n toteutettavuusarviointi

Analyysin tavoitteena on tunnistaa C-ITS-dataliikenteen suuruus eri skenaarioissa suhteessa matkaviestinverkon kapasiteettiin, jotta voidaan ymmärtää, kuinka nykypäivän verkot pystyvät palvelemaan arvioitua C-ITS-dataliikennettä vuonna 2030. Ohjeellisten matkaviestinverkon kapasiteettiarvioiden ja edellä esitettyjen skenaarioanalyysitulosten perusteella voidaan arvioida C-ITS-palvelujen tyypillisen kapasiteetin riittävyyttä ja toteutettavuutta. Arvion oletus on, että C-ITS-dataliikenne jakautuu tasaisesti kolmeen kaupalliseen verkkoon.

Kapasiteettianalyysin yleinen huomio on, että C-ITS-liikenneskenaarioiden odotetaan tuottavan dataliikennettä, joka voidaan kuljettaa kaupunkien ja esikaupunkien mobiiliverkoissa ilman ongelmia. Vilkkaan liikenteen teiden, jotka ovat kaupunkialueilla ja niiden lähellä, odotetaan tuottavan C-ITS-dataliikennetasoa, jota nykyiset kaupunkien ja esikaupunkien mobiiliverkot voivat palvella ongelmitta. Maaseutualueiden vilkkailla teillä samoja verkkoliikenneoletuksia käytettäessä esiintyy mahdollisia kapasiteettiongelmia. Kuitenkin jopa korkeimmalla C-ITS:n käyttöönottotasolla ja korkealla viestintätiheydellä, pahoin ruuhkaisessa liikenteessä keskimääräisen kapasiteetin käyttöasteen odotetaan olevan 50 prosentin luokkaa. Tällaisen tieliikenteen ja ruuhkautumisen todennäköisyys syrjäisillä maaseututeillä on todennäköisesti pieni ja ainakin ennakoitu. Tällaisissa tapauksissa, jos uplink-liikenne ajoneuvoista verkkoon olisi samaa suuruusluokkaa, suurta osaa viesteistä ei voitaisi toimittaa.
ö
Pääkatujen ja vilkkaiden teiden kapasiteetin käyttöasteen tulokset on esitetty taulukossa 5. Kapasiteetin käyttöastetta arvioidaan kullekin liikenneskenaariolle, joka koostuu liikennevirtojen arvioinnista alhaisesta ruuhkaiseen, C-ITS-palveluiden omaksumisesta pessimististä optimistiseen sekä C-ITS-palvelujen tuottamasta toistumistiheydestä ja informaatiotiheydestä perustuen oletuksiin eri C-ITS-palvelujen mahdollisesta toteutuksesta. Kapasiteetin käyttöastetta arvioidaan eri ympäristöissä erikseen.

Taulukko 5. Matkaviestinverkon kapasiteetin käyttöaste eri C-ITS-liikenneskenaarioissa. Taulukossa alhainen kapasiteetin käyttöaste on 0 – 10 % (vihreät värit), keskitaso 20 – 40 % (keltaiset värit) ja korkea >50 % (punaiset värit).

	Pääkatujen kapasiteetin käyttöaste Kapasiteetti per km² (Mbits/s/km²)				Vilkkaan liikenteen teiden kapasiteetin käyttöaste Kapasiteetti per km (Mbit/s/km)				
Alue:	**Kau-punki**	**Esikaupunki**	Esikaupunki (ei 3,5 GHz)		**Kaupunki**	**Esikau-punki**	Esikaupunki (ei 3,5 GHz)	**Maaseutu**	**Harvaan asuttu maa-seutu**
Matala virta	-	-	-	-	-	-	-	-	-
Pessimistinen	**0.0%**	**0.1%**	**0.1%**	**-**	**0.0%**	**0.0%**	**0.0%**	**0.4%**	**0.6%**
Realistinen	**0.1%**	**0.1%**	**0.2%**	**-**	**0.0%**	**0.0%**	**0.0%**	**0.6%**	**0.9%**
Optimistinen	**0.1%**	**0.1%**	**0.2%**	**-**	**0.0%**	**0.0%**	**0.0%**	**0.9%**	**1.3%**
Matala: Pessimistinen	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.0%	0.0%
Matala: Realistinen	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.0%	0.1%
Matala: Optimistinen	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.1%	0.1%
Korkea: Pessimisti-nen	0.2%	0.2%	0.4%	-	0.0%	0.0%	0.0%	1.4%	2.1%
Korkea: Realistinen	0.3%	0.4%	0.7%	-	0.0%	0.0%	0.1%	2.3%	3.4%
Korkea: Optimistinen	0.4%	0.5%	0.9%	-	0.0%	0.1%	0.1%	3.2%	4.7%
Keskimääräinen virta	-	-	-	-	-	-	-	-	-
Pessimistinen	**0.1%**	**0.2%**	**0.3%**	**-**	**0.0%**	**0.0%**	**0.0%**	**1.0%**	**1.5%**
Realistinen	**0.2%**	**0.3%**	**0.4%**	**-**	**0.0%**	**0.0%**	**0.1%**	**1.7%**	**2.5%**
Optimistinen	**0.3%**	**0.3%**	**0.6%**	**-**	**0.0%**	**0.0%**	**0.1%**	**2.3%**	**3.4%**
Matala: Pessimistinen	0.0%	0.0%	0.0%	-	0.0%	0.0%	0.0%	0.1%	0.1%
Matala: Realistinen	0.0%	0.0%	0.1%	-	0.0%	0.0%	0.0%	0.1%	0.2%
Matala: Optimistinen	0.0%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.2%	0.3%
Korkea: Pessimisti-nen	0.5%	0.6%	1.1%	-	0.0%	0.1%	0.1%	3.8%	5.5%
Korkea: Realistinen	0.8%	1.1%	1.8%	-	0.0%	0.1%	0.2%	6.2%	9.1%
Korkea: Optimistinen	1.1%	1.5%	2.4%	-	0.0%	0.2%	0.3%	8.5%	12.4%
Ruuhkainen	-	-	-	-	-	-	-	-	-
Pessimistinen	**0.3%**	**0.3%**	**0.6%**	**-**	**0.0%**	**0.0%**	**0.1%**	**2.3%**	**3.4%**
Realistinen	**0.4%**	**0.6%**	**1.0%**	**-**	**0.0%**	**0.1%**	**0.1%**	**3.8%**	**5.6%**
Optimistinen	**0.6%**	**0.8%**	**1.3%**	**-**	**0.0%**	**0.1%**	**0.2%**	**5.2%**	**7.6%**
Matala: Pessimistinen	0.0%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.2%	0.3%
Matala: Realistinen	0.1%	0.1%	0.1%	-	0.0%	0.0%	0.0%	0.3%	0.4%
Matala: Optimistinen	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.4%	0.6%
Korkea: Pessimisti-nen	1.1%	1.5%	2.4%	-	0.0%	0.2%	0.3%	8.5%	12.4%
Korkea: Realistinen	1.8%	2.4%	4.0%	-	0.1%	0.3%	0.5%	14.0%	20.5%
Korkea: Optimistinen	2.4%	3.3%	5.5%	-	0.1%	0.4%	0.6%	19.2%	28.0%
Erittäin ruuhkainen	-	-	-	-	-	-	-	-	-
Pessimistinen	**0.5%**	**0.6%**	**1.0%**	**-**	**0.0%**	**0.1%**	**0.1%**	**4.1%**	**6.0%**
Realistinen	**0.7%**	**1.0%**	**1.7%**	**-**	**0.0%**	**0.1%**	**0.2%**	**6.8%**	**9.9%**
Optimistinen	**1.0%**	**1.4%**	**2.3%**	**-**	**0.0%**	**0.2%**	**0.3%**	**9.3%**	**13.5%**
Matala: Pessimistinen	0.1%	0.1%	0.2%	-	0.0%	0.0%	0.0%	0.3%	0.5%
Matala: Realistinen	0.1%	0.2%	0.3%	-	0.0%	0.0%	0.0%	0.5%	0.8%
Matala: Optimistinen	0.2%	0.2%	0.4%	-	0.0%	0.0%	0.0%	0.7%	1.0%
Korkea: Pessimisti-nen	1.9%	2.6%	4.3%	-	0.1%	0.3%	0.5%	15.1%	22.1%
Korkea: Realistinen	3.1%	4.3%	7.1%	-	0.1%	0.5%	0.8%	25.0%	36.5%
Korkea: Optimistinen	4.2%	5.8%	9.7%	-	0.2%	0.7%	1.2%	34.1%	49.8%
Vilkkaimmat tiet	-	-	-	-	-	-	-	-	-
Äärimmäinen	**8.8%**	**12.0%**	**20.1%**	**-**	**0.4%**	**1.7%**	**2.8%**	**83.0%**	**121.4%**

Katso lisätietoja kappaleesta *Part C. Chapter 3.5.2 Mobile network capacity for C-ITS data traffic*.

Johtopäätökset

Kaikki digitaalisen matkaviestinverkkoteknologian sukupolvet huomioon ottaen jopa 4G-verkkotekniikat voivat tarjota tarvittavan liitettävyyden ja kapasiteetin, ja 5G-teknologioiden tuleva kehitys voi mahdollisesti jopa parantaa kykyä palvella korkean laitetiheyden ja korkean viestitaajuuden palveluita, kuten C-ITS-kehyksessä.

Yleisesti ottaen kattavuuden saatavuuden ja järjestelmäkapasiteetin näkökulmasta nykyiset matkaviestinverkot sopivat hyvin kuljettamaan keskimääräistä odotettua C-ITS-viestiliikennettä. Kaupalliset matkaviestinverkot ovat kuitenkin luonnostaan hyvin riippuvaisia ympäristöstä, ja heikkoja palvelutasoja esiintyy edelleen kussakin kotimaisessa operaattorissa, riippuen niiden paikallisen verkon käyttöönotosta (paikka/teknologiaverkko) ja verkkostrategiasta. Tämä on tärkeää ottaa huomioon kaikessa C-ITS-palvelun toteutuksen kehittämisessä ja suunnittelussa.

Latenssin suhteen nykyiset verkkoteknologiat ovat myös riittäviä, kun verrataan verkon latenssin kynnysarvoja osassa A määriteltyyn palvelutason viitekehykseen. On kuitenkin syytä huomata, että kokonaislatenssi koostuu useista komponenteista, kuten päätelaitteesta ja itse palvelusta. Verkon latenssi on vain yksi tekijä. Tällä hetkellä kerätyt kattavuusennusteet sopivat hyvin C-ITS:n toteutettavuuden tilannekatsaukseen. Kattavuusennusteiden avulla voidaan tunnistaa mahdolliset toteutettavuuden huolenaiheet. Kattavuuden ennusteiden täydennykseksi ehdotetaan mittauskehystä, jolla varmistetaan C-ITS-palvelujen toteutettavuus verkon stressitestien avulla. Tämän mittauskehyksen tarkoituksena on täydentää tällä hetkellä saatavilla olevaa ja käytettyä tietoa C-ITS:n toteutettavuuden arvioimiseksi tarkasti matkaviestinverkoissa.

Mahdollisiin paikallisiin palvelujen saatavuuden ja kattavuuden ongelmiin valitaan viisi ratkaisua, joita tarkastellaan tarkemmin. Näitä ratkaisuja ovat *verkon laajentaminen, neutraalit isäntäverkot, verkon viipalointi, verkon valvonta* ja *dataliikenteen ruuhkautumisen estäminen*. Todettiin, että teknologiset valmiudet eivät olisi rajoittavia tekijöitä näiden ratkaisujen toteuttamisessa. Näiden ratkaisujen sääntelyyn liittyvät asiat ovat myös varsin hyvin määriteltyjä, mutta tarkasteltuihin ratkaisuihin liittyviä kustannuksia ja investointeja tarkasteltaessa voidaan todeta, että liiketoimintamallit ovat monessa tapauksessa vähemmän vakiintuneita.

Katso lisätietoja kappaleesta *Part C. Chapter 4 Conclusions of Part C* and *Part D. Chapter 2 Solutions*.

Suositukset

Tämä tutkimus suosittelee seuraavia korkean tason toimia C-ITS-palvelun käyttöönotolle:

1. **Yhteistyömalli yhteiselle visiolle ja tavoitteille.** Yhteistyömallin keskeinen osa olisi puuttua epävarmuuteen C-ITS-palvelujen laajamittaisesta käyttöönotosta toimijoiden yhteisellä näkemyksellä ja tilannetietoisuudella. Yhteistyössä tarvitaan eri toimijoita, kuten matkaviestinverkko-operaattoreita, tieyhtiöitä ja muita kansallisia valvontaviranomaisia, suuria kalustoyhtiöitä sekä C-ITS-palveluntarjoajia. Tienpitäjien ja muiden kansallisten sääntelyviranomaisten vahva osallistuminen lisäisi myös ennustettavuutta ja helpottaisi kaupallisten toimijoiden investointeja näiden palvelujen toteuttamiseen. Toinen keskeinen tehtävä tällaiselle yhteistyölle olisi vaikuttaminen eurooppalaiseen C-ITS-lainsäädäntöön ja spesifikaatioihin. Kestävyyden pitäisi myös olla yksi tämän ehdotetun koordinointiryhmän keskeisistä teemoista. Kestävyyttä rakennetaan lisäämällä tietoisuutta riskienhallinnasta C-ITS-

palveluissa erityisesti esimerkiksi matkaviestinverkkojen toimintahäiriötilanteissa. Jotta investoinnit C-ITS-palvelujen laajamittaiseen käyttöönottoon olisivat perusteltuja, olisi tarpeen arvioida kokonaisvaltaisesti näiden palvelujen vaikutukset liikennejärjestelmään sekä yksittäisiin tienkäyttäjiin.

2. **Kansallinen C-ITS-toteutusstrategia ja etenemissuunnitelma.** Yhteinen tavoite ehdotetulle yhteistyömallille voisi olla kansallinen C-ITS-toteutusstrategia ja etenemissuunnitelma. Pohjimmiltaan strategian tavoitteena olisi tietty aikajana, jossa tieverkon kriittisimmissä osissa on saatavilla vähimmäismäärä C-ITS-palveluita. Etenemissuunnitelma auttaisi priorisoimaan ja skaalaamaan toimintoja saatavilla olevien C-ITS-palvelujen ja tieverkoston kattavuuden suhteen. Ensimmäiset askeleet tällaisessa prosessissa sisältäisivät niiden palvelujen valinnan, joiden tulisi olla saatavilla. Tässä tutkimuksessa käytetyt valintakriteerit ovat hyvä lähtökohta palveluiden valinnalle etenemissuunnitelman ensimmäisessä vaiheessa. Mahdollinen hallinnan ja hallinnoinnin rooli C-ITS-toteutuksessa voisi olla viranomaisrahoitus, mm. tieviranomaisten ja kuntien taholta, sekä hankinnat samoin kuin nykyäänkin, esimerkiksi tienhoidossa. Tämä saattaa olla ensimmäinen askel C-ITS-palvelujen käynnistämiselle Suomessa, ja etenemissuunnitelmaan pitäisi sisältyä tarkempi suunnitelma kaupallisten palveluntarjoajien laajemmasta markkinoilletulosta. C-ITS-palvelujen tieverkon kattavuus voitaisiin liittää päätieverkkoon ja suurempiin kaupunkeihin. Tieverkon kattavuutta suunniteltaessa voitaisiin hyödyntää TEN-T-luokitusta (esim. ydinverkko ja kokonaisverkko). Sopiva aikataulu etenemissuunnitelmalle voitaisiin linjata esimerkiksi EU:n ITS-direktiiviä koskevan asetuksen kanssa ja koska tunnustettujen tietotyyppien pitäisi olla saatavilla. Tämä on kuitenkin vähimmäisvaatimus, eikä ole mitään syytä, miksi kansallinen täytäntöönpano ei voisi olla nopeampaa. Yhtä tärkeää kuin kaupallisen toiminnan mahdollistaminen on rajat ylittävän yhteentoimivuuden mahdollistaminen, ja tätä teemaa tulisi käsitellä myös kansallisessa toteutusstrategiassa. C-Roads Platformissa tehdyn työn huomioiminen kansallisessa toteutusstrategiassa ja etenemissuunnitelmassa varmistaisi, että kaupallisten toimijoiden ratkaisut olisivat toimivia myös muissa jäsenmaissa ja helpottaisivat siten toiminnan laajentamista Euroopassa.

Katso lisätietoja kappaleesta *Part D. Chapter 4 Recommendations*.

Appendix 2

ETSI TS 122 185. LTE; Service requirements for V2X services. (3GPP 2022)

5 Requirements

5.1 Overall Requirements

[R-5.1-001] The message transmission shall be under control of the 3GPP network when the transmitting UE is served by the E-UTRAN.

[R-5.1-002] A UE supporting V2X application shall be able to be pre-configured by the 3GPP network with parameters to be used for the transmission and reception of messages when not served by E-UTRAN supporting V2X communication.

[R-5.1-003] A UE supporting V2X application shall be able to transmit and receive messages when served or not served by E-UTRAN supporting V2X communication.

[R-5.1-004] An RSU shall be able to transmit/receive messages to/from a UE supporting V2X application.

[R-5.1-005] The 3GPP system shall be able to support message transfer between UEs when served or not served by the same PLMN supporting V2X communications.

[R-5.1-006] The 3GPP system shall be able to provide means to prioritize message transmission among UEs supporting V2X application

[R-5.1-007] The 3GPP system shall be able to provide means to prioritize transmission of messages according to their type (e.g. safety vs. non-safety).

[R-5.1-008] The 3GPP system shall be able to vary the transmission rate and range of the V2X communication based on service conditions (e.g., UE speed, UE density).

[R-5.1-009] The 3GPP system shall be able to distribute information in a resource efficient way to large numbers of UEs supporting V2X application.

[R-5.1-010] A UE supporting V2X application shall be able to identify whether E-UTRAN supports V2X communication.

[R-5.1-011] The 3GPP system shall be able to provide means for an application server and the RSU to control the area and the size of the area where the messages are being distributed.

[R-5.1-011a] The 3GPP system shall be able to provide means for distribution of messages from a UE supporting V2X application to locally relevant application servers.

[R-5.1-012] The E-UTRA(N) shall be able to support a high density of UEs supporting V2X application.

[R-5.1-013] Both the HPLMN and VPLMN operators shall be able to charge for network resource usage when messages are transferred by a UE supporting V2X application.

[R-5.1-014] For UE supporting V2X application with limited resources (e.g., battery), the impact on its resources (e.g., battery consumption) due to message transfer should be minimized.

[R-5.1-015] The 3GPP network should make available any supported positional accuracy improvement techniques (e.g., DGPS and/or OTDOA) in a resource efficient way to a subscribed UE supporting V2X application.

5.2 Specific Service Requirements

5.2.1 Latency/ Reliability Requirements

[R-5.2.1-001] The E-UTRA(N) shall be capable of transferring messages between two UEs supporting V2V/P application, directly or via an RSU, with a maximum latency of 100ms.

[R-5.2.1-002] For particular usage (i.e., pre-crash sensing) only, the E-UTRA(N) should be capable of transferring messages between two UEs supporting V2V application with a maximum latency of 20ms.

[R-5.2.1-003] The E-UTRA(N) shall be capable of transferring messages between a UE supporting V2I application and an RSU with a maximum latency of 100ms.

[R-5.2.1-004] The E-UTRAN shall be capable of transferring messages via 3GPP network entities between a UE and an application server both supporting V2N application with an end-to-end delay no longer than 1000 ms.

[R-5.2.1-005] The E-UTRA(N) shall be able to support high reliability without requiring application-layer message retransmissions.

5.2.2 Message Size Requirements

[R-5.2. 2-001] The E-UTRA(N) shall be capable of transferring periodic broadcast messages between two UEs supporting V2X application with variable message payloads of 50-300 bytes, not including security-related message component.

[R-5.2. 2-002] The E-UTRA(N) shall be capable of transferring event-triggered messages between two UEs supporting V2X application with variable message payloads which can be up to 1200 bytes, not including security-related message component.

NOTE: 3GPP only handles the transport of messages for V2X services/applications based on message characteristics (e.g., latency, message size) and is agnostic to message types.

5.2.3 Frequency Requirements

[R-5.2.3-001] The E-UTRA(N) shall be able to support a maximum frequency of 10 messages per second per transmitting UE .

NOTE: It is assumed that V2X application provides messages to 3GPP layer for transport either periodically and/or triggered by certain events.

5.2.4 Range Requirements

[R-5.2.4-001] The E-UTRAN shall be capable of supporting a communication range sufficient to give the driver(s) ample response time (e.g. 4 seconds).

5.2.5 Speed Requirements

[R-5.2.5-001] The 3GPP system shall be capable of transferring messages between UEs supporting V2V application, while the maximum relative velocity of the UEs is 500 km/h, regardless of whether the UE(s) are served or not served by E-UTRAN supporting V2X communication.

[R-5.2.5-002] The 3GPP system shall be capable of transferring messages between UEs supporting V2V and V2P application, respectively, while the UE's maximum absolute velocity is 250 km/h, regardless of whether the UE(s) are served or not served by E-UTRAN supporting V2X communication.

[R-5.2.5-003] The 3GPP system shall be capable of transferring messages between a UE and an RSU both supporting V2I application, while the UE's maximum absolute velocity is 250 km/h, regardless of whether the UE or the RSU is served or not served by E-UTRAN supporting V2X communication.

5.3 Security Requirements

[R.5.3-001] The 3GPP network shall provide a means for the MNO to authorize a UE supporting V2X application to perform V2X communication when served by E-UTRAN supporting V2X communication.

[R.5.3-002] The 3GPP network shall provide a means (e.g., pre-authorization) for the MNO to authorize a UE supporting V2X application to perform V2X communication when not served by E-UTRAN supporting V2X communication.

[R.5.3-003] The 3GPP network shall provide a means for the MNO to authorize UEs supporting V2X application separately to perform V2N communication.

[R.5.3-004] The 3GPP system shall support integrity protection of the transmission for a V2X application.

[R.5.3-005] Subject to regional regulatory requirements and/or operator policy for a V2X application, the 3GPP system shall support pseudonymity and privacy of a UE using the V2X application, by ensuring that a UE identity cannot be tracked or identified by any other UE beyond a certain short time-period required by the V2X application.

[R.5.3-006] Subject to regional regulatory requirements and/or operator policy for a V2V/V2I application, the 3GPP system shall support pseudonymity and privacy of a UE in the use of a V2V/V2I application, such that no single party (operator or third party) can track a UE identity in that region.

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