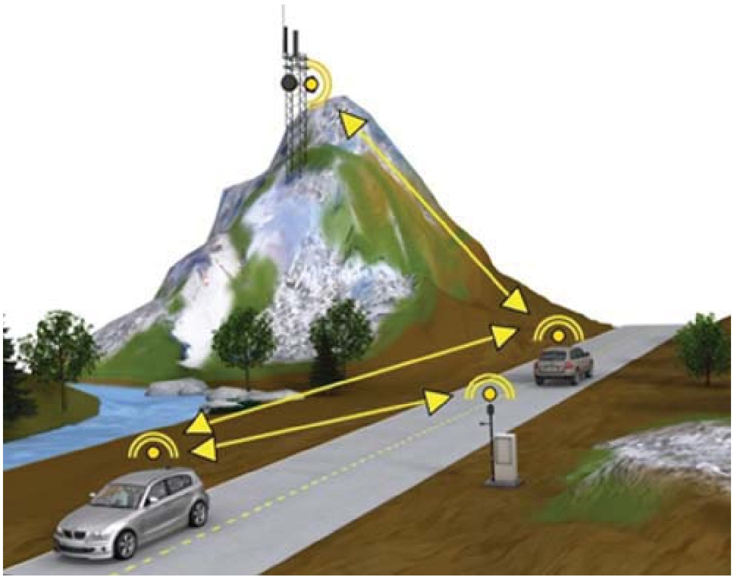
2020:00884- Unrestricted

Report

LambdaRoad

Summarizing the main findings of work package 1: System and organizational requirements for CCAM

Authors
Petter Arnesen
Trond Foss
Jan Erik Håkegård
Odd A. Hjelkrem
Randi Fagerholt
Arne Lie
Hanne Seter



SINTEF Community
Digitalization in Transport
2020-09-10

SINTEF Community
SINTEF Community
Address:
Postboks 4760 Torgarden
NO-7465 Trondheim
NORWAY
Switchboard: +47 40005100

info@sintef.no

Enterprise /VAT No:
NO 919 303 808 MVA

Report

LambdaRoad

Summarizing the main findings of work package 1: System and organizational requirements for CCAM

KEYWORDS:
ITS/C-ITS
Hybrid communication
ITS-G5
Cellular network
Value network
Path loss models
Planning tool

VERSION
1.0

DATE
2020-09-10

AUTHORS
Petter Arnesen
Trond Foss
Jan Erik Håkegård
Odd A. Hjelkrem
Randi Ann Fagerholt
Arne Lie
Hanne Seter

CLIENT
Norwegian Public Roads Administration

CLIENT'S REF.
295811

PROJECT NO.
102020548

NUMBER OF PAGES:
84

ABSTRACT
This report is a collection of the memos written in work package 1 of the LambdaRoad project, where the overall project objectives is to study the need and requirements for electronic communication (ecom) in the future transport system in Norway and develop a planning tool for ecom for the transport sector. Introductory studies were performed in work package 1 and documented in this report. In particular we 1) have established value networks for ecom in Norway, 2) described the crucial terms in C-ITS ecom, including motivation for the planning tool, 3) established a comprehensive state of the art study for path loss models, a crucial part of the planning tool to be developed, 4) studied the literature to summarize the ecom requirements in the future transport system, and 5) conducted in-depth semi-structured interviews to reveal the requirements and needs of the planning tool in LambdaRoad for the project partners. Please note that some of the memos included might change during the rest of the project period, and that updates may occur.

PREPARED BY
Petter Arnesen

SIGNATURE
Petter Arnesen

CHECKED BY
Per Johan Lillestøl

SIGNATURE
Per J. Lillestøl

APPROVED BY
Roar Norvik

SIGNATURE
Roar Norvik

REPORT NO.	**ISBN**	**CLASSIFICATION**	**CLASSIFICATION THIS PAGE**
2020:00884	978-82-14-06547-3	Unrestricted	Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1.0	2020-09-10	Final version

Table of contents

1 Introduction

Petter Arnesen

Many Norwegian cities, as well and cities on an international scale, struggle with increasing traffic, hampering the development towards a more efficient, environmentally friendly, and safe transport system. Cooperative intelligent transport systems (C-ITS) are expected to provide important solution towards reaching these political goals, and towards the future of fully autonomous vehicles. To achieve cooperability, knowledge and involvement from the electronic communication sector, such as the telecom industry, must be considered to ensure a communication infrastructure that fulfils the requirements of the future transport system.

In Europe, two solution to meet these requirements that traditionally have been looked upon as competing solutions are the present and future mobile network, e.g. 5G, and the ITS-G5 solution of the OEMs (original equipment manufacturers – or vehicle manufacturers). In LambdaRoad, these two solutions will be considered in a hybrid communication system, combining the strength and weakness of each technology. A solution also supported by many national road authorities.

In particular LambdaRoad sets out meet the following two objectives:

1) Develop a model for mapping and planning of hybrid communication infrastructure
2) Develop a collaboration platform for stakeholders from the communication and transport sector.

λRoad is a collaboration project between Norwegian Public Roads Administration, Norwegian Communications Authority, Q-Free, Telenor, NTNU and SINTEF, and this report is a collection of the memos written in work package 1: "System and organizational requirements for CCAM (Cooperative connected and automated mobility)". This report includes five main aspects:

1) **A value network for ITS communication services.** This activity sets out to describe the generic value network model developed for ITS communication services supporting the provision of ITS services.
2) **Hybrid communication for C-ITS as described in ISO standards.** In this part we describe the crucial terms in C-ITS communication focusing on hybrid communication for CCAM and give motivation for the λRoad project and its two main objectives.
3) **State-of-the-art of path loss modelling.** In a model for electronic communication along the road network an important building block would be wireless signal propagation between transmitters and receivers. Here we review the literature of such propagation model to prepare for the training and implementation of the planning tool in later stages of the project.
4) **Communication requirements for the future road transport system.** I this part we study the literature to summarize requirements for communication in the future transport system with focus on KPIs such as data rate and latency.
5) **Requirements and needs – planning tool λRoad.** Lastly, in depth-interviews were conducted in this work package as a direct input to the planning tool to be developed in λRoad in terms of requirements and needs of the project partners.

2 A value network for ITS communication services

Trond Foss

2.1 Introduction

The main objectives of this section are:

- describe the generic value network model developed for ITS communication services supporting the provision of ITS services
- provide an input to the development of a tool for analysing and predicting ITS communication coverage and signal strength
- provide an input to the development of a cooperation platform for stakeholders in the application of ITS-G5 and 5G protocols in ITS communication

The basis for the value network model is the conceptual model for value networks described by Allee in 2005 [2]. The value network is defined as a web of relationships that generates economic value and other benefits through complex dynamic exchanges between two or more individuals, groups or organisations. Any organisation or group of organisations engaged in both tangible and intangible exchanges can be viewed as a value network, whether private industry, government or public sector.

The value networks cover more than just transactions around goods, services and revenue [1]. It also covers the knowledge and intangible value or benefits. Hence, the values in a value network are grouped in the following [1]:

- *Goods, services and revenues* that covers exchanges for services or goods, including all transactions involving contracts and invoices, return receipts of orders, request for proposals, confirmations or payment. Knowledge products or services that generate revenue are part of the flow of goods, services and revenues.
- *Knowledge* which covers exchanges of strategic information, planning knowledge, process knowledge, technical know-how, collaborative design, policy development etc. which flow around and support the core product and value chain.
- *Intangible benefits* that covers exchanges of value and benefit that go beyond the actual service and that are not accounted for in traditional financial measures, such as a sense of community, customer loyalty, image enhancement or co-branding opportunities

This chapter focuses only on the tangible values (first bullet point) like goods, services and revenues (payments). Knowledge and intangible values are not included in the analysis for simplicity reasons and lack of information. However, the value flows on knowledge will be further studied later in the project.

This chapter also includes the crucial terms and definitions that are used including the preferred Norwegian terms and definitions. Some of the most crucial terms are terms defined in the Norwegian Act relating to electronic communication (ekomloven).

Five generic roles and their responsibilities are defined enabling the generic role and responsibility model to be applied for any configuration of real-life actors.

2.2 Terms and definitions

Table 1: Terms and definitions

Term	Definition	Definition in Norwegian
actor	a real-world entity, e.g. a person, a company or an authority, fulfilling parts or the whole of a *role* set of responsibilities	*aktør* – en virkelig enhet, f.eks. en person, et selskap eller en myndighet som oppfyller deler av eller hele settet med ansvarsområder for en *rolle*
business model	description of means and methods a firm employs to earn the revenue projected in its plans. (Business Dictionary – www.businessdictionary.com May 2017)	*forretningsmodell* – en beskrivelse av de midlene og metodene et firma tar i bruk for å oppnå den planlagte inntekten
ecomm end-user	any physical or legal person that enters into an agreement giving the person access to ecomm networks or ecomm services for his/her own benefit or lending (Norwegian law on electronic communication definition on end-user)	enhver fysisk eller juridisk person som inngår avtale om tilgang til elektronisk kommunikasjonsnett eller -tjeneste til eget bruk eller utlån.
ecomm network provider	any physical or legal person that provides access to ecomm networks to other physical or legal persons, e.g. an ecomm service provider	enhver fysisk eller juridisk person som tilbyr andre tilgang til elektronisk kommunikasjonsnett
ecomm provider	any physical or legal person that provides access to ecomm network or ecomm services to other physical or legal persons (Norwegian law on electronic communication definition for provider)	enhver fysisk eller juridisk person som tilbyr andre tilgang til elektronisk kommunikasjonsnett eller -tjeneste.
ecomm service provider	any physical or legal person that provides ecomm services to other physical or legal persons, e.g. to a road operator being an ITS communication user	enhver fysisk eller juridisk person som tilbyr andre kommunikasjonstjenester
ecomm user	any physical or legal person who uses ecomm networks or ecomm services for his/her own benefit or as support for the production and/or provision of other services (Norwegian law on electronic communication definition for user)	enhver fysisk eller juridisk person som bruker elektronisk kommunikasjonsnett eller -tjeneste til egen bruk eller som innsatsfaktor for produksjon av andre tjenester.
electronic communication (ecomm)	communication by an electronic communication network (Norwegian law on electronic communication)	*elektronisk kommunikasjon* - kommunikasjon ved bruk av et elektronisk kommunikasjonsnett
electronic communication network (ecomm network)	System for transfer of signals that enables transmission of sound, text, pictures or other data by means of electromagnetic signals by air or wire including radio equipment, switches, other coupling or routing equipment, associated equipment and functions, also including non-active network elements (Norwegian law on electronic communication)	*elektronisk kommunikasjonsnett* - system for signaltransport som muliggjør overføring av lyd, tekst, bilder eller andre data ved hjelp av elektro-magnetiske signaler i fritt rom eller kabel der radioutstyr, svitsjer, annet koplings- og dirigeringsutstyr, tilhørende utstyr eller funksjoner inngår, herunder

Term	Definition	Definition in Norwegian
		nettverkselementer som ikke er aktive
electronic communication service (ecomm service)	Service that fully or partly covers communication of signals in electronic communication networks and that usually is provided for a remuneration (Norwegian law on electronic communication)	*elektronisk kommunikasjonstjeneste* - tjeneste som helt eller i det vesentlige omfatter formidling av signaler i elektronisk kommunikasjonsnett og som normalt ytes mot vederlag
ITS communication service	an electronic communication service that enables and supports the provision of an ITS service	*ITS kommunikasjonstjeneste* – en elektronisk kommunikasjonstjeneste som muliggjør og støtter leveransen av en ITS-tjeneste
ITS service	a functionality provided to users of intelligent transport systems designed to increase safety, sustainability, efficiency and/or comfort. (ISO 14813-1 and ISO 21217)	*ITS-tjeneste* - en funksjonalitet som intelligente transportsystemer (ITS) yter til en bruker av ITS hvor denne funksjonaliteten skal oppfylle brukerens krav til sikkerhet, trygghet, komfort, effektivitet, tilgjengelighet og/eller miljøvern.
Public electronic communication service (public ecomm service)	An electronic communication service available for the public or intended to be used by the public (Norwegian law on electronic communication)	*offentlig elektronisk kommunikasjonstjeneste* - elektronisk kommunikasjonstjeneste som er tilgjengelig for allmennheten eller beregnet til bruk for allmennheten
role	an abstract entity defined by a set of responsibilities	*rolle* – en abstrakt enhet som er definert gjennom et sett av ansvarsområder
transport infrastructure	traffic areas that are available for transport means providing the transport service, e.g. roads, streets and parking places	*Transportinfrastruktur* – trafikkarealer som er tilgjengelig for de transportmidlene som leverer en transporttjeneste, f.eks. veger, gater og parkeringsplasser
transport service	the movement of persons or goods from A to B in one or more transport infrastructures with one or more transport means	*transporttjeneste* - flytting av person(er) eller gods fra A til B i en eller flere transport-infrastrukturer og med en eller flere transportmidler
value network	a web of relationships that generates economic value and other benefits through complex dynamic exchanges between two or more individuals, groups or organisations Verna Allee, (2005). www. Vernaallee. Com/ value_networks/Understanding_Value_Networks. Html	*verdinettverk* – et nettverk av relasjoner som skaper økonomiske verdier og andre fordeler gjennom komplekse og dynamiske utvekslinger mellom to eller flere individer, grupper eller organisasjoner

2.3 The ITS service

The ARKTRANS ITS framework for transport services [6], has divided the transport domain in 5 subdomains. The same methodology could be applied for a framework for ITS services provided to road infrastructure users, ref. Figure 1. Each sub-domain covers roles that are logically, legally, functionally or commercially linked together.

The core sub-domain called *ITS service demand* covers roles that request ITS services. The major role here is the *ITS service user* that defines, requests, benefits from and eventually pays for the ITS service, e.g. a driver of an automated vehicle could request the ITS service *Automated highway operation* defined in [4], see 2.4.1 for more information on the example.

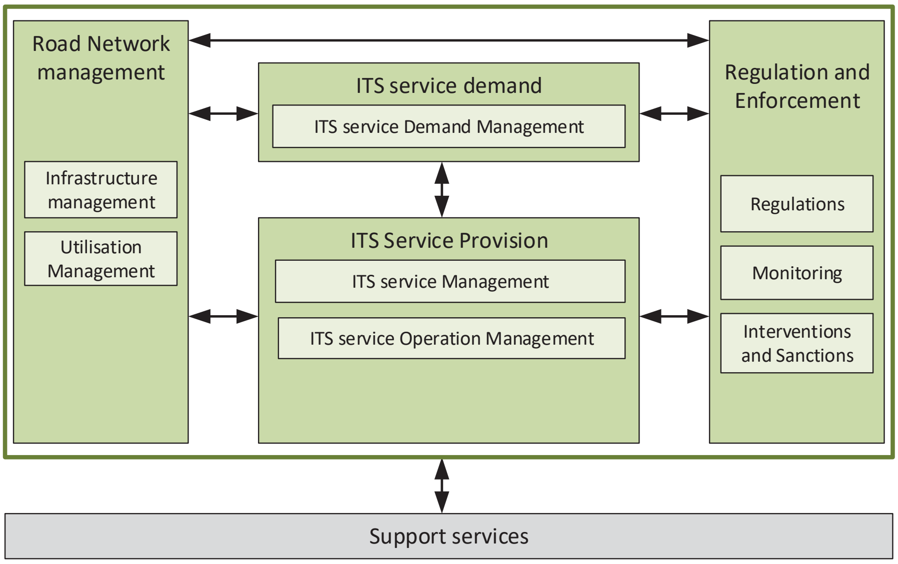


Figure 1: ITS service subdomains

The main counterpart of the ITS service demand is the *ITS service provision*. The subdomain is divided in two sub-subdomains. The major role in the *ITS service Management* domain is the *ITS service manager* being the contractual counterpart to the ITS service user concerning the ITS service to provided. The major role in the *ITS service operation management* domain is the *ITS service operator* being the role that delivers the ITS service to the ITS service user. The ITS service manager and the ITS service operator are in many cases the same legal entity. However, in the example above (ITS service Automated highway operation) they are two different legal entities. The ITS service manager will be the entity selling the vehicle to the owner of the vehicle, i.e. the car dealer. The ITS service operator will be the entity that produced the vehicle and installed the ITS service application in the vehicle providing the requested ITS service to the user of the vehicle. So, in this ITS service example the ITS service operator will be the car manufacturer.

The LambdaRoad project deals with road vehicles that are moving around in a road network. The subdomain *Road Network management* covers two sub-subdomains. The major role in the *Infrastructure management* domain is the *Road infrastructure manager* being responsible for the planning, building and maintenance of the road network also including roadside equipment. The major role in the *Utilisation Management* is the *Road Operator* being responsible for the daily operation of the road network, e.g. regulation of the vehicles being present in the road network by signs, signals and in-vehicle information with the main objective of optimising the traffic safety and network capacity. This also includes prioritisation of specific groups of transport means, e.g. vehicles used by public transport operators.

The Regulation and Enforcement sub-domain is divided in three sub-subdomains. The major role in the first domain covers the responsibilities related to the provision of the regulations that govern the activity in the network. For a road network this will typically be a road authority or Transport Ministry[1]. For an ecomm network this would typically be an electronic communication authority or Communication Ministry[2].

The second domain is *Monitoring* where the responsibilities of the major role covers monitoring that the activities in the network are compliant with the regulations. The role maybe fulfilled by several actors, e.g. road authorities and police for road networks.

The third domain is called *Interventions and Sanctions* and covers the responsibilities related to handling of violations of the regulations for the network. Typical actors could be authorities, police and law courts.

The *Support services* domain covers the roles providing external services that are needed for the provision of the ITS service. Typical examples are Payment service providers (PSP), ecomm network providers and ITS equipment manufacturers.

2.4 The ITS communication service

2.4.1 The service

The main objective of the ITS communication service is to support the provision of ITS services. The LambdaRoad project focuses on ITS services for Cooperative, Connected and Automated Mobility (CCAM).

Figure 2 shows an overview of the ITS communication studied in the LambdaRoad project. The figure shows vehicles cooperating using the Vehicle to Vehicle (V2V) communication. It also shows vehicles connected to the external ITS service providers, e.g. Road administrations, by the Vehicle to Infrastructure communication (V2I) and infrastructure to vehicle communication (I2V). The main focus of the LambdaRoad project will be on the V2I and I2V communication services based on 4G/5G and ITS-G5 and the analysis of their coverage and signal strength. Later, in chapter 3.4.3 we discuss why the latter of these, communication via ITS-G5, is better denoted by V2R and R2V communication. The communication service could be both one-way and two-way. Examples on one-way communication could be a road authority broadcasting a warning message to all vehicles in a defined area or vehicles reporting to the road operator about events registered by the vehicle sensor system, e.g. black ice on the road surface. An example on two-way communication could be a vehicle ITS application requesting information on traffic conditions, road status and condition and weather conditions from different information providers.

[1] E.g. in Norway: Norwegian Public Roads Administration and Ministry of Transport and Communication.
[2] E.g. in Norway: Norwegian Communications Authority and Ministry of Transport and Communication

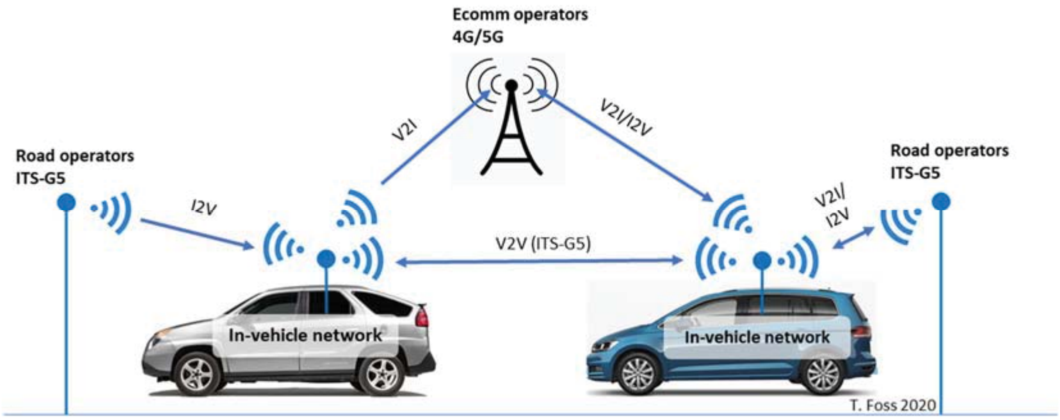


Figure 2: Overview of the studied ITS communication service

Typical ITS services supporting CCAM are ITS services belonging to the ITS service group Vehicle services in [4]. One example from the ITS services in this group is the ITS service Automated highway operation (automated driving, see Figure 3) defined as:

This ITS service enables vehicles to operate without the intervention of their drivers over a dedicated transport network or specific part(s) of the road network that are equipped for automatic highway operation. Only suitably equipped and operating vehicles shall be allowed to access the dedicated transport network or these part(s) of the road network, the drivers of all other vehicles being required to find alternative routes.

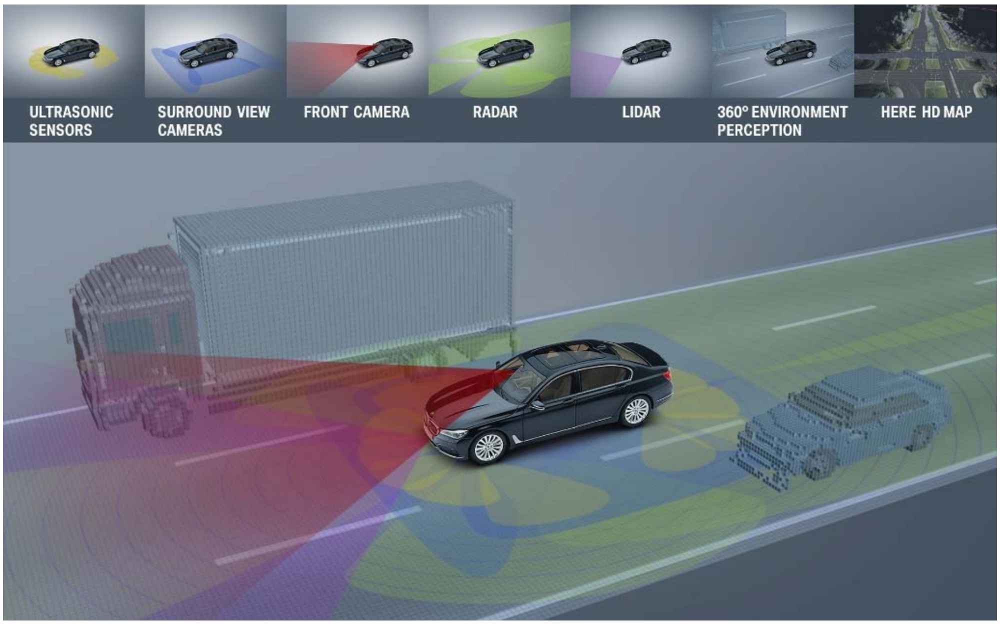


Figure 3: Automated Driving BMW Group Level 3 **Photo: press.bmwgroup.com**

The ITS communication service supports the provision of an ITS service and some examples on the ITS communication service are shown in Figure 2. The ITS communication service architecture is defined in [5] and is the communication that takes place between the four ITS subsystems defined in [5] and shown in Figure 4.

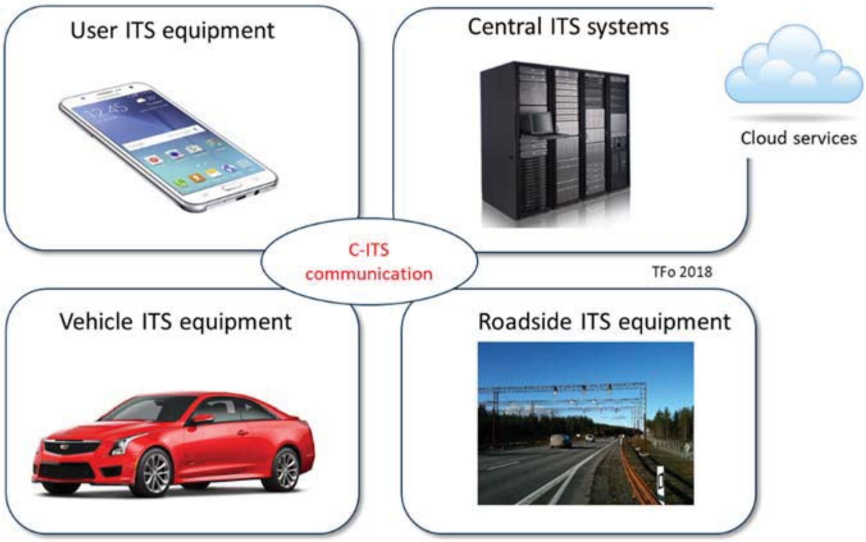


Figure 4: The four ITS subsystems

The Vehicle ITS equipment more or less equals the In-vehicle network in Figure 2 and the Roadside ITS equipment more or less equals the Road operator ITS-G5 in the same figure. The Central ITS system is most often operated by the ITS service provider. However, the ITS service providers are depending on the communication services provided by the ecomm operators 4G/5G in Figure 2.

2.4.2 The ITS communication service framework

The ARKTRANS methodology applied for the ITS service could also be applied for the ITS communication service defining the roles and their responsibilities, see Figure 5.

The core sub-domain called ITS communication service demand covers roles that request ITS communication services. The major role here is the *ITS communication service user* that defines, requests, benefits from and eventually pays for the ITS communication service. A road operator, e.g. the Norwegian Public Roads Administration, providing ITS services to road users is a typical example on an ITS communication service user. The ITS service could for instance be provided to the ITS service user via ITS-G5 in ITS Roadside sub-system and ITS Vehicle ITS sub-system.

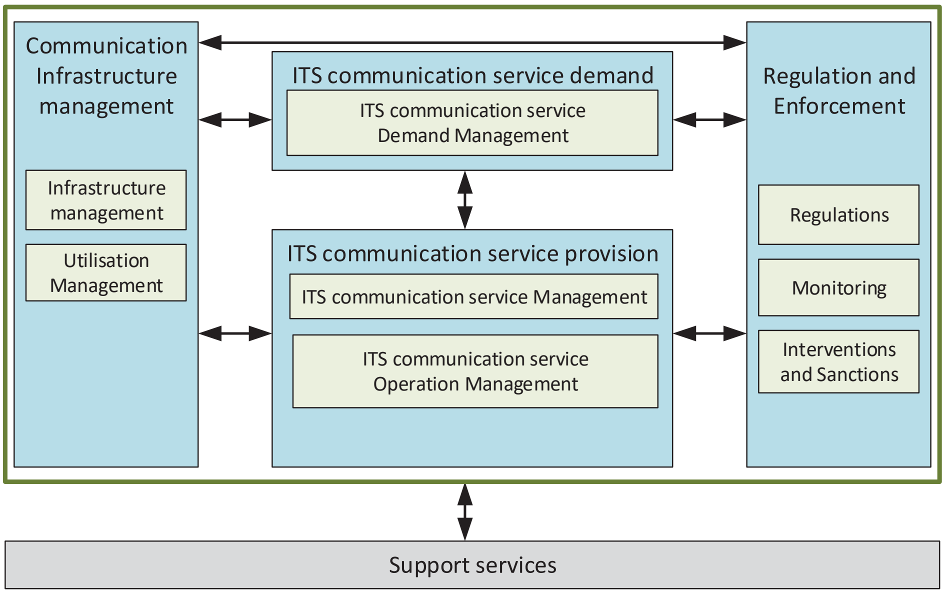


Figure 5: The ITS communication framework

The main counterpart of the ITS communication service demand is the *ITS communication service provision*. The subdomain is divided in two sub-subdomains. The major role in the *ITS communication service Management* domain is the *ITS communication service manager* being the contractual counterpart to the ITS communication service user concerning the communication service to be provided. The major role in the *ITS communication service operation management* domain is the *ITS communication service operator* being the role that delivers the ITS communication service to the ITS communication service user. The ITS communication service manager and the ITS communication service operator are in many cases the same legal entity, e.g. Telia and Telenor.

The subdomain *Communication infrastructure management* covers two sub-subdomains. The term 'communication infrastructure' equals the term ecomm network (see Clause 2.2 Terms and definitions). The major role in the Infrastructure management domain is the *Infrastructure manager* being responsible for the planning, building and maintenance of the communication infrastructure. The major role in the Utilisation Management is the *Infrastructure Operator* being responsible for the daily operation of the communication infrastructure, e.g. control of the data packages sent in the communication infrastructure with the main objective of optimising the infrastructure capacity avoiding overloading and loss of data. This also includes prioritisation of specific groups of data packages, e.g. information related to safety ITS services.

The Regulation and Enforcement sub-domain is divided in three sub-subdomains. The major role in the first domain covers the responsibilities related to the provision of the regulations that govern the activity in the communication infrastructure. For an ecomm network this would typically be an electronic communication authority or Communication Ministry[3].

The second domain is *Monitoring* where the responsibilities of the major role covers monitoring that the activities in the communication infrastructure are compliant with the regulations.

[3] E.g. in Norway: Norwegian Communications Authority (NKOM) and Ministry of Transport and Communication

The third domain is called *Interventions and Sanctions* and covers the responsibilities related to handling of violations of the regulations for the communication infrastructure. Typical actors could be authorities and law courts.

The *Support services* domain covers the roles providing external services that are needed for the provision of the ITS communication service. Typical examples are Payment service providers (PSP) and ITS and communication equipment providers.

2.5 The ITS communication service context

The ITS communication service context could be defined as a set of interacting services where the ITS communication service is the core service. Figure 6 depicts the main services in the ITS communication service context.

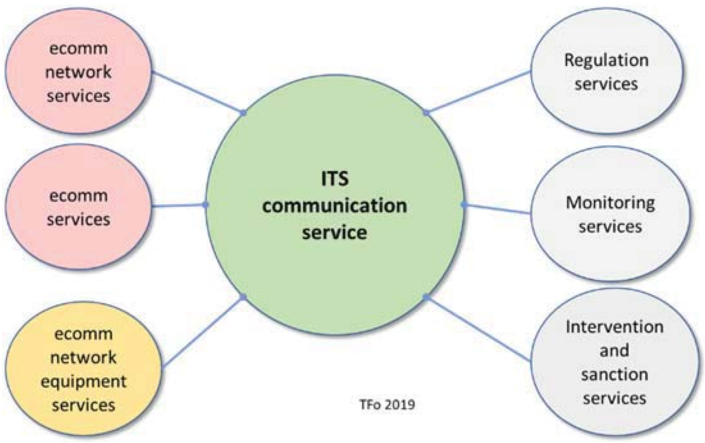


Figure 6: The ITS communication service context

It should be noted that to be compliant with the terms defined in the Norwegian law on electronic communication, some of the role names introduced in the ITS communication service framework in Clause 2.4 have been transformed to the ecomm law role definitions. In [7] the term *ecomm provider* has been defined as 'any physical or legal person that provides access to ecomm network or ecomm services to other physical or legal persons'. In the LambdaRoad project the role ecomm provider has been split into two roles:

- The *ecomm network provider* being any physical or legal person that provides access to ecomm networks to other physical or legal persons, e.g. an ecomm service provider. Hence, the ecomm network provider is responsible for the provision of the *ecomm network services.*
- The *ecomm service provider* being any physical or legal person that provides ecomm services to other physical or legal persons, e.g. to a road operator being an ITS communication user. Hence, the ecomm service provider is responsible for the provision of the *ecomm services*.

The Table 2 shows the transition of the terms used in the Clause 2.4 and in Figure 5 and the terms used in this clause and later clauses adapting the terminology used in the Norwegian law on electronic communication. In most cases the *ecomm network manager* and the *ecomm network operator* are the same legal entity and for simplicity reasons they are merged to *ecomm network provider*. Telia, Telenor and Ice are typical Norwegian examples on ecomm network providers. However, the Norwegian Public Roads Administration (NPRA) will also be an *ecomm network provider* in those cases where the NPRA builds

Roadside ITS-subsystems implementing and operating ITS-G5 communication with vehicles passing the Roadside ITS-subsystem.

Table 2: Transition of terms

Term in Clause 2.4 and in Figure 5	Terms used in this and later clauses	
Infrastructure manager	*ecomm network manager*	For simplicity reasons merged to *ecomm network provider*
Infrastructure Operator	*ecomm network operator*	
ITS communication service manager	*ecomm service manager*	For simplicity reasons merged to *ecomm service provider*
ITS communication operator	*ecomm service operator*	

The LambdaRoad research project also has partners that delivers ecomm network equipment (hardware and software). Their services have been included as ecomm network equipment services in the ITS communication context.

Services in the Regulation and enforcement domain are:

- *Regulation services* covering the preparation, issuing and maintenance of the legal framework governing the ecomm network and service domain. This also includes the responsibilities of an ecomm registrar, e.g. keeping registers for unique IDs needed for a secure and effective communication in ecomm networks. It also includes authorisation of actors in the ecomm domain, type approval of network equipment, ecomm standardisation, frequencies used for different types and purposes of communication and ecomm security.
- *Monitoring services* covering the control of that actors in the ecomm domain are compliant with the ecomm laws, regulations and concessions. It also covers monitoring the issuers of electronic certificates and control of ecomm equipment in the market and/or in ecomm networks.
- *Interventions and sanction services* covering arbitration between actors in the ecomm domain and sanctions, e.g. fines in those cases where an actor in the ecomm domain does not fulfil instructions given as part of the monitoring services.

These services could be provided by different entities. However, in the LambdaRoad project the three services are provided by a role that has been named the *ecomm regulator*. In Norway the ecomm regulator is the Norwegian Communication Authority (NKOM).

In [7] the term *user* has been defined as ' any physical or legal person who uses ecomm networks or ecomm services for his/her own benefit or as support for the production and/or provision of other services'. The very similar term *end-use*r has been defined as 'any physical or legal person that enters into an agreement giving the person access to ecomm networks or ecomm services for his/her own benefit or lending'. The main difference between the roles *user* and *end-user* seems to be that the *user* uses ecomm networks and/or ecomm services and the *end-user* enters into an agreement enabling the end-user to benefit from ecomm networks and services, i.e. becoming a *user*. In the LambdaRoad project these two roles have been merged into one role called the *ITS communication user* described by the following responsibilities:

- define the ITS communication service that the ITS communication user needs for his provision of an ITS service
- request the ITS communication service from potential providers and enter into an explicit or implicit contract with the ecomm service provider

- benefit from and control that the ITS communication service is provided in line with the user request and provider description
- pay for the ITS communication service except in those cases where the communication service is a public communication service free of charge. It might also be the case that the ITS communication user is the same legal entity as the ITS communication service provider (ecomm provider), see the example in the paragraph just before Table 2 on page 17.

2.6 Services, roles and value flows

2.6.1 The ecomm network service

The ecomm network service covers the provision of an ecomm network (system for transport of signals) enabling ecomm service providers to manage, offer and provide ecomm services. The ecomm network service domain has four major roles involved in the provision of the service:

ecomm network provider who:

- builds, manages, maintains and operates an ecomm network infrastructure, e.g. the infrastructure for 4G/5G or ITS-G5 communication
- adapts to the regulations issued by ecomm regulator
- accepts the transport regulator monitoring and adepts to any instructions given by the ecomm regulator
- defines and markets the ecomm network services, including the prerequisites and constraints related to the use of the ecomm network service that shall be offered and delivered to the ecomm service provider, e.g. a telecom service provider.
- enters into a contract with an ecomm service provider giving the ecomm service provider access to the ecomm network

ecomm service provider who:

- defines, manages, markets and operates the ecomm services that shall be offered and delivered to the ITS communication users
- enters into a contract with the ITS communication user
- enters into a contract with the ecomm network provider giving the ecomm service provider access to the ecomm network
- pays for the use of the ecomm network service

ecomm regulator who provides regulation services, monitoring services and interventions and sanctions services, see Clause 2.5 for more details. The services are provided both to the ecomm network provider and the ecomm service provider.

ecomm network equipment providers who provides cables, optical fibres, radio equipment, switches, other coupling or routing equipment, associated equipment and functions, also including non-active network elements. This also includes equipment installed in vehicles, e.g. On-Board Equipment or Vehicle ITS-sub-systems.

The simplified value network between the four roles is shown in Figure 7.

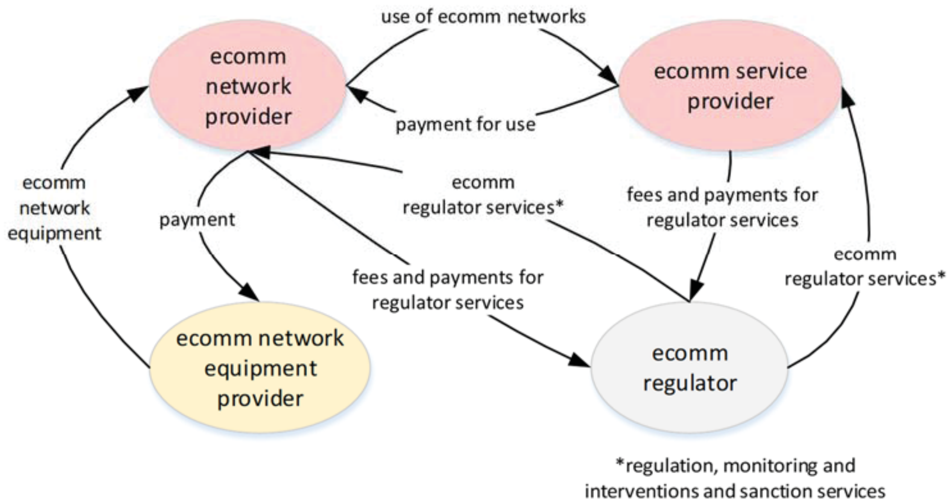


Figure 7: Value flows related to the provision of the ecomm network service

Figure 8 shows examples on Norwegian actors fulfilling the responsibilities of the roles in Figure 7. *It should be noted that the one legal entity (actor) may fulfil the responsibilities of more than one role.*

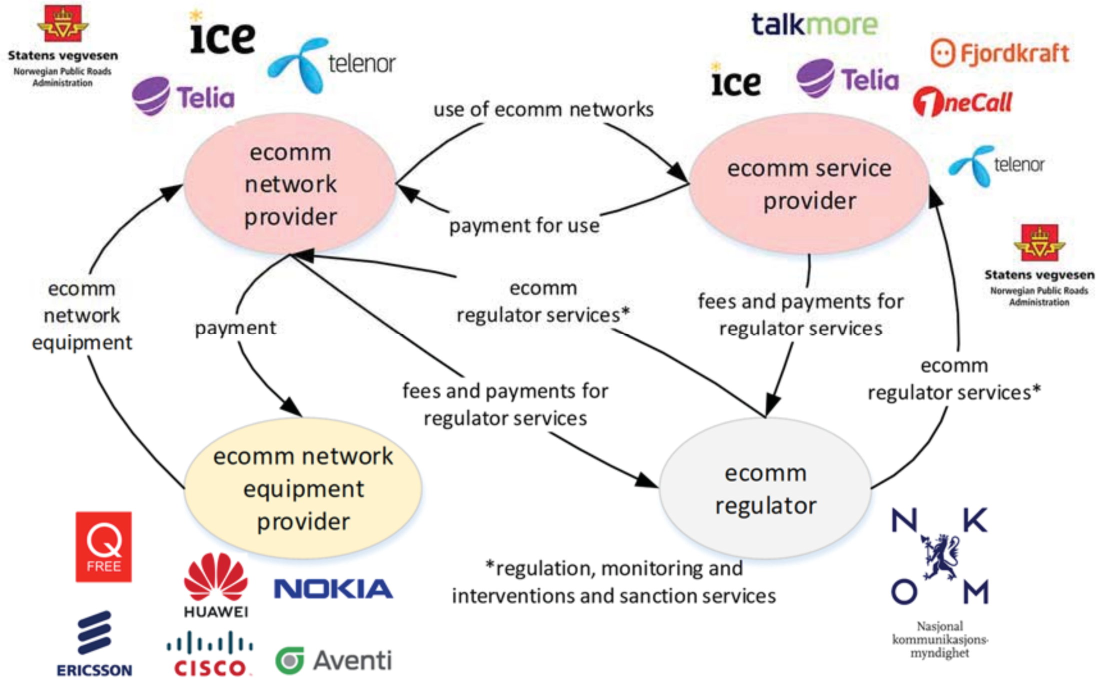


Figure 8: Examples on Norwegian actors

The Norwegian Public Roads Administration is included in the figure having in mind that they may install, operate and use ITS-G5 networks in Roadside ITS-subsystems.

2.6.2 The ecomm service

The ecomm service covers the provision of an ecomm service (service that fully or partly covers communication of signals in electronic communication networks system for transport of signals) enabling ITS communication service users to manage, offer and provide ITS services. The ecomm service domain has three major roles involved in the provision of the service:

ecomm service provider who:

- defines, manages, markets and operates the ecomm services that shall be offered and delivered to the ITS communication service users
- enters into a contract with an ecomm network service provider, e.g. a provider of an optical fibre network
- enters into a contract with the ITS communication service user
- pays for the use of the ecomm network service

ITS communication service user who:

- define the ITS communication service that the ITS communication user needs for his provision of an ITS service, e.g. communication of ITS application data to a group of vehicles within a defined zone
- request the ITS communication service from potential providers and enter into an explicit or implicit contract with one or more ecomm service provider
- benefit from the ITS communication service and control that the service is provided in line with the user request and provider description
- pay for the ITS communication service except in those cases where the communication service is a public communication service free of charge. It might also be the case that the ITS communication user is the same legal entity as the ITS communication service provider (ecomm provider), see the example in the paragraph just before Table 2 on page 17.

ecomm regulator who provides regulation services, monitoring services and interventions and sanctions services, see Clause 2.5 for more details on the services.

The simplified value network between the three roles is shown in Figure 9.

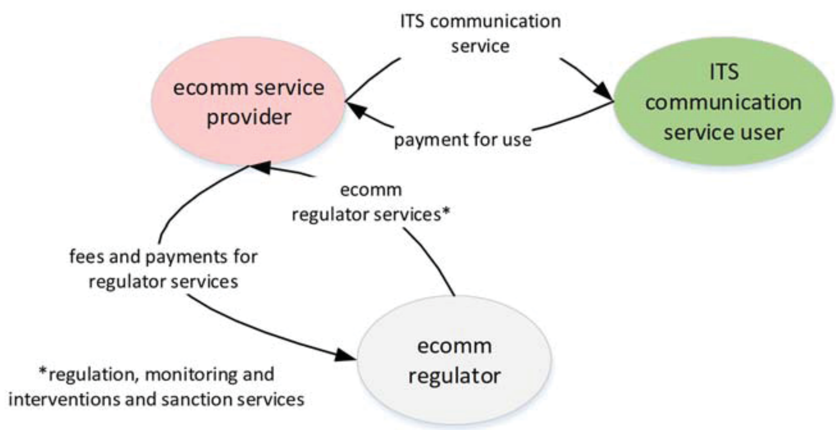


Figure 9: Value flows related to the provision of the ecomm service

Figure 10 shows an example on Norwegian actors fulfilling the responsibilities of the roles in Figure 9.

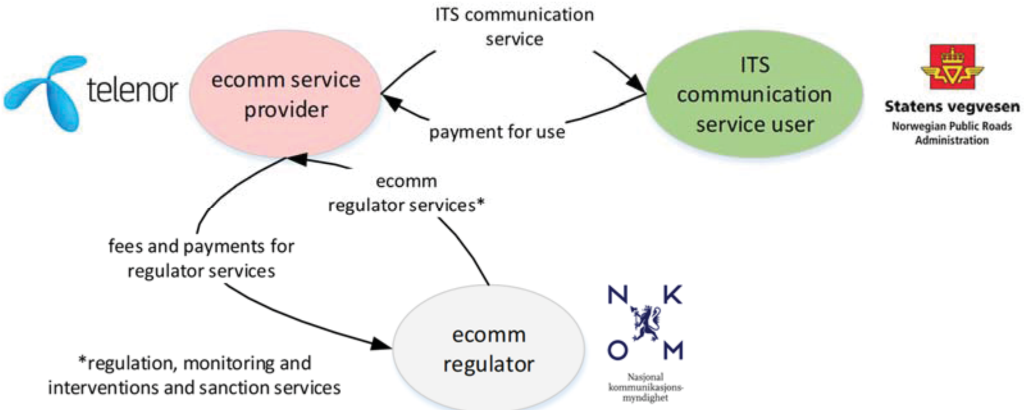


Figure 10: An example on Norwegian actors

2.6.3 Ecomm network equipment service

This service covers the provision of network equipment. Examples from [7] are air or wire networks including radio equipment, switches, other coupling or routing equipment, associated equipment and functions, also including non-active network elements. Ordinary ICT equipment, e.g. computers, servers, wi-fi networks etc. are used by all actors in the ecomm domain but not seen as part of the ecomm network-specific equipment.

The ecomm network equipment service domain has three major roles involved in the provision of the service (see previous sub-chapters for a more detailed description of the role responsibilities):

ecomm network equipment providers who provides cables, optical fibres, radio equipment, switches, other coupling or routing equipment, associated equipment and functions, also including non-active network elements. This also includes equipment installed in vehicles, e.g. On-Board Equipment or Vehicle ITS-sub-systems.

ecomm network provider who builds, manages and operates an ecomm network infrastructure, e.g. the infrastructure for 4G/5G or ITS-G5 communication.

ecomm regulator who provides regulation services, monitoring services and interventions and sanctions services, see Clause 2.5 for more details on the services.

The simplified value network between the three roles is shown in Figure 11.

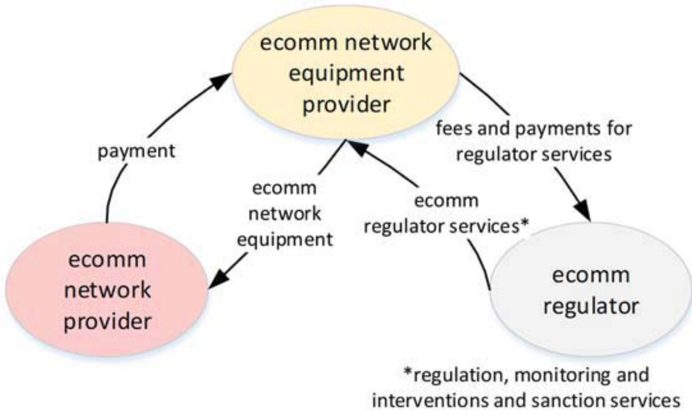


Figure 11: Value flows related to the provision of the ecomm network equipment service

Figure 12 shows an example on Norwegian actors fulfilling the responsibilities of the roles in Figure 11.

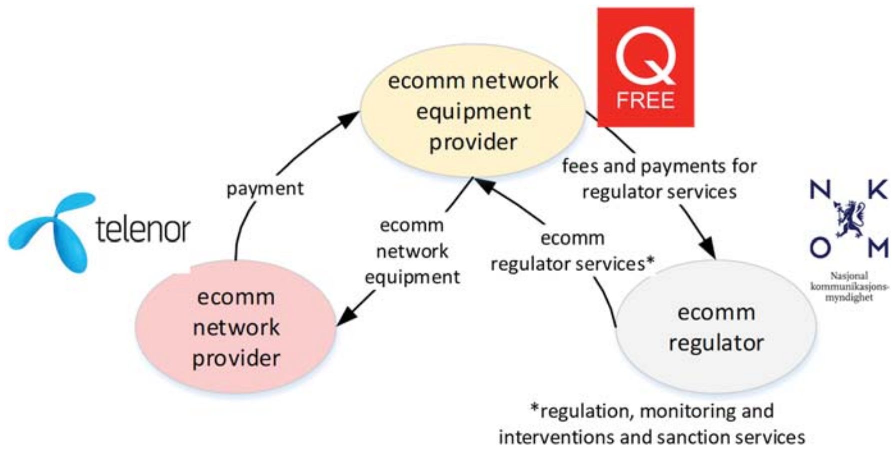


Figure 12: An example on Norwegian actors

2.7 The generic value network model

The generic value network model for the ITS communication service is shown in Figure 13. The figure is simplified in relation to the more detailed figures and descriptions above.

The figure shows all the main actors (nodes) in the value network. The figure shows an overall viewpoint without focusing on any specific actor.

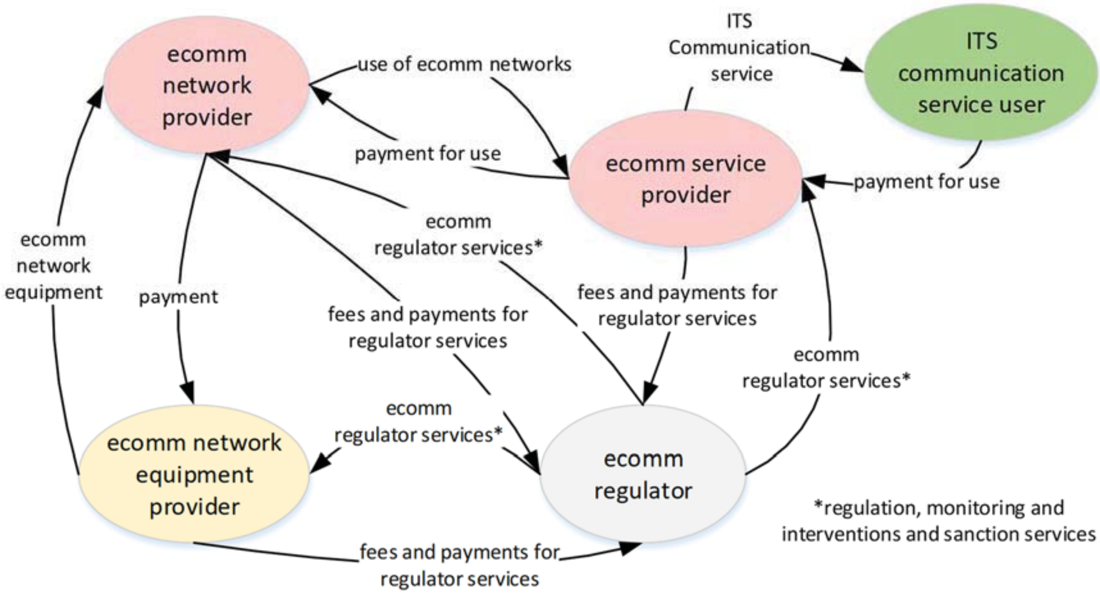


Figure 13: Value network for the ITS communication service

2.8 Bibliography

[1] Allee, V., (2000), *Reconfiguring the Value Network*, Journal of Business Strategy, Vol. 21, N4, July-Aug 2000

[2] Allee, V. (2005) *Understanding value networks*. A brief article by Verna Allee. http://www. vernaallee. com/value_networks/Understanding_Value_Networks. html (2005).

[3] Allee, V. *The Future of Knowledge: Increasing Prosperity through Value Networks*, Butterworth-Heinemann 2003

[4] ISO 14813-1 Intelligent Transport Systems – Reference model architecture(s) for the ITS sector – Part 1: ITS service domains, service groups and services

[5] ISO 21217 Intelligent transport systems -- Communications access for land mobiles (CALM) -- Architecture

[6] Natvig, M, et al. (2009), *ARKTRANS The multimodal ITS framework architecture Version 6*, brage.bibsys.no/xmlui/handle/11250/2389176

[7] Lov om elektronisk kommunikasjon (ekomloven). LOV-2019-06-21-56 fra 01.07.2019. Norwegian Act relating to electronic communication.

3 Hybrid communication for C-ITS as described in ISO standards

Trond Foss

3.1 Introduction

The main objectives of the LambdaRoad project are 1) to develop a planning tool for communication infrastructure for ITS services provided to road users, e.g. telecom base stations and Roadside ITS stations, and 2) to develop a commercial and contractual platform for actors involved in the provision of communication and ITS services. The platform will be based on value networks for the communication services and communication infrastructure operations.

The primary objective of this section is to describe the crucial terms in C-ITS communication focusing on hybrid communication for connected and cooperating automated mobility (CCAM). This section also includes a description of the motivation for the LambdaRoad project.

After the motivation clause this section describes the essential terms ITS service, ITS application and ITS station as they are defined in several ISO standards issued by ISO TC 204 ITS. The ITS service and application providers are the users of the hybrid communication and the main stakeholders to put forward the requirements for the hybrid communication. The vehicle ITS station (or the vehicle ITS equipment) and eventually the personal ITS station are the end-nodes that benefit from the hybrid communication.

This section is primarily based on the new (2020) ISO Technical Report ISO/TR 21186-2:2020 on Hybrid communications [1] prepared by ISO/TC 204 ITS/WG 18 Cooperative systems, but also on other relevant ISO and ETSI ITS standards referenced in Clause 6. The purpose of the ISO/TR 21186-2 is as follows:

> *The purpose of this document is to inform about relevant standards and to describe the functionalities of the ITS station infrastructure defined in support for hybrid communication technologies. It is intended to serve as a guideline to structure the development of new C-ITS standards and to harmonise the deployment of C-ITS services relying on the use of hybrid communication technologies. It also intends to give support to the developers of standards defining C-ITS services and to the developers of C-ITS solutions and ITS applications complying with the ITS station architecture and its set of functionalities supporting hybrid communications.*

Moreover, this section is also based on [2].

3.2 Motivation for the LambdaRoad R&D project

Different C-ITS services have different communication requirements, e.g. distribution area, amount of data, delivery delay, privacy, confidentiality and availability. It is stated in [1] that 'no single communication technology is able to fulfil all of these requirements at once'. This requires 'the combination of several access technologies and protocols to ensure reliability, interoperability and sustainable development of C-ITS services'. And further, 'this requires a common approach to the way security, communications and data are handled'.

The Norwegian Public Roads Administration regards so far cellular communication as the primary type of communication for C-ITS services in rural areas with reduced access to energy and communication infrastructure provided by cable and fibre networks. However, the Norwegian topography is a challenge for cellular communication and there is a need for reliable tools that can support the development of cellular networks in the most efficient way.

There are three cellular network operators in Norway (Telenor, Telia and Ice) and Figure 14 shows the 4G mobile data coverage (Very good quality) for an area in the middle of Norway provided by one of the operators (Telia). The roads marked as E6 and 3 (green boxes) are the two main roads connecting the south and north of Norway. The road marked as 29 connects the two roads and is an important link when the traffic is diverted from E6 to 3 or vice versa if either E6 or 3 is closed, e.g. due to snowstorm or an accident blocking the road. As the map shows there are several sections of these roads without a high quality 4G communication. Lowering the 4G quality level to 'Good' shows that all 'blank' road sections without 4G Very good quality are covered by the 4G Good quality level. So far 5G is not available in the area shown in Figure 14.

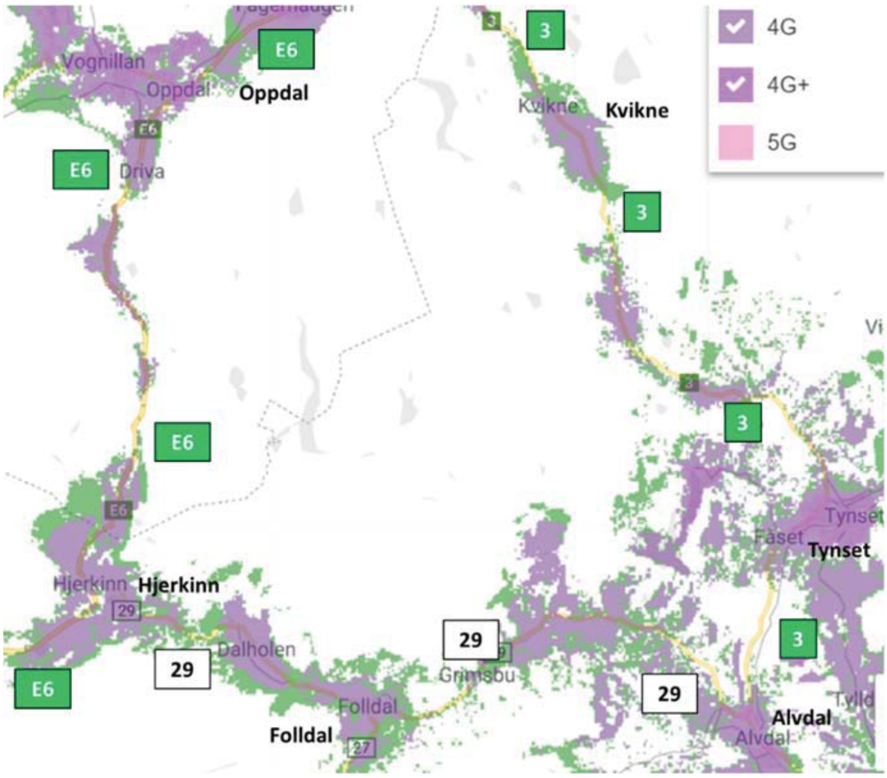


Figure 14: Example on 4G mobile data coverage (telia.no)

The tool to be developed in the LambdaRoad project for networked and localised communication services will enable the NPRA to:

- quantify the quality on the existing and planned digital communication networks covering the Norwegian main road network
- focus on road sections with communication quality that do not fulfil the requirements for the required C-ITS services
- recommend new communication infrastructure based on an optimisation of the requirements of the different C-ITS applications and investment and operational costs for the telecom base station or Roadside ITS station and required infrastructure for power and data, e.g. cable or fibre networks.
- ensure reliable communication for critical C-ITS services on critical sections of the main roads, e.g. mountain passes during wintertime

3.3 The essential terms ITS services, ITS application and ITS station

ITS service, ITS application and ITS station are essential terms regarding hybrid communication and their relationships are described in Figure 15. An *ITS service* is defined in ISO 21217 [3] as a 'functionality provided to users of intelligent transport systems designed, e.g. to increase safety, sustainability, efficiency or comfort'. The provision of ITS services is in most cases supported by C-ITS (co-operative ITS) that is defined in ISO/TR 17465-1 [4] as 'a subset of overall ITS that communicates and shares information between ITS stations to give advice or facilitate actions with the objective of improving safety, sustainability, efficiency and comfort beyond the scope of stand-alone systems'. This is the definition used in other ISO C-ITS standards.

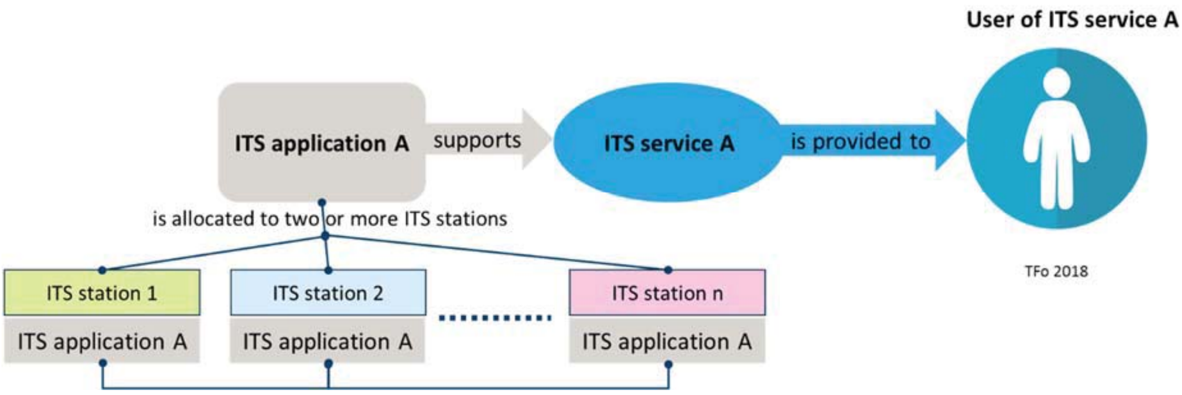


Figure 15: Crucial terms and their relationships

The term *ITS station* is a crucial term in the C-ITS definition, and it is defined as a 'functional entity comprised of an ITS-S facilities layer, ITS-S networking and transport layer, ITS-S access layer, ITS-S management entity, ITS-S security entity and ITS-S applications entity providing ITS services' [3]. The term ITS station (ITS-S) refers to a set of functionalities. The proper name of a physical installation of an ITS-S is ITS station unit (ITS-SU). The functional and communication capabilities of an ITS station are defined in many ISO and ETSI standards.

Figure 15 shows the relationships between the terms ITS service, ITS application and ITS station. An ITS service just called ITS service A is provided to the User of the ITS service A. This service is per definition a functionality provided by the intelligent transport system. The ITS service A is enabled by the support of the *ITS application* A. An ITS application is defined in ISO 21217 as 'an instantiation of an ITS service that involves an association of two or more complementary ITS station application processes'. A simpler interpretation of this definition is that the ITS application A in this case is distributed to two or more ITS stations that are cooperating in delivering the ITS service A to the user. This is C-ITS as defined in ISO/TR 17465-1 [4]. The ISO 21217 also add in a note to the definition of the ITS application that 'fragments of an application may reside in nodes that are not ITS stations'. This could be interpreted as other ITS equipment than ITS stations could be part of the cooperation and provision of the ITS service if they can communicate with 'real' ITS stations and share functions and data.

The ITS applications are categorised in three types of applications in [3]:

- Road safety
- Traffic Efficiency
- Other applications

The three categories of applications and the ITS services within each category have different communication requirements. Some of them require direct vehicle-to-vehicle communications, e.g. anti-collision systems while other are not time critical and can allow for several seconds of communication delays, e.g. traveller information.

There are four typical instantiations, i.e. ITS Station Unit (ITS-SU), of an ITS station as shown in

Figure **16**.

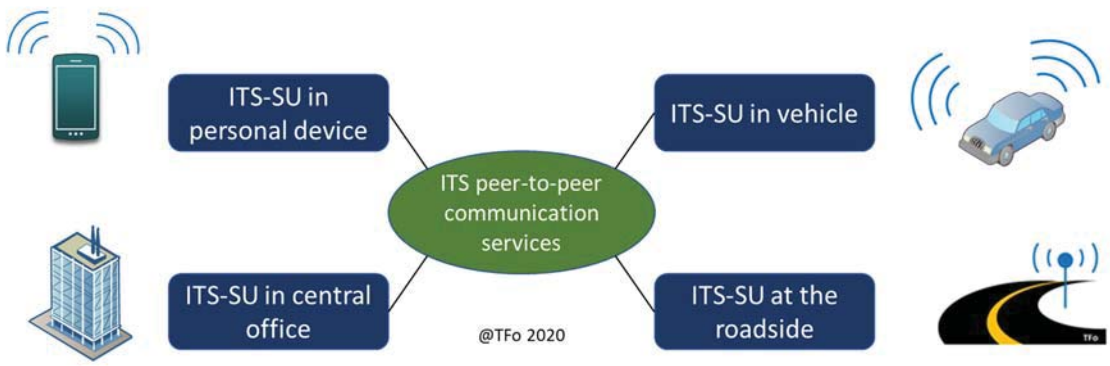


Figure 16: Typical ITS stations units

The ITS-SU in the vehicle is also often called Vehicle ITS station. In the same way the other ITS-SU are called Roadside ITS station, Personal ITS-station and Central ITS station. The Vehicle ITS station is connected to the internal ICT system of the car and the Roadside ITS station is connected to external sensors, signs and signals used for different ITS services.

The provision of ITS services must be supported by communication services (ITS peer-to-peer communication in Figure 16) as C-ITS implies communication and co-operation between the ITS stations. Hence, the communication is supported by communication systems both wired and wire-less. The communication services may vary from short-range communication like DSRC[4], Bluetooth and Wi-fi to long-range communication like 4G and 5G (cellular networks).

3.4 Hybrid communication

3.4.1 Introduction

C-ITS services are often based on the exchange of services and data between vehicles and between vehicles and infrastructure, e.g. roadside equipment and traffic management servers. There will be many C-ITS services with different requirements and there will be multiple communication technologies that are fundamentally different supported by the ITS station units. Supporting multiple access technologies and communication protocols, also referred to as hybrid communication is a design principle of the ITS station architecture. In ISO 21217 [3] hybrid communications is defined as 'composition of multiple access technologies and communication protocols combined to provide complementary or redundant communication channels', see an simplified example in Figure 17. The term access technology is defined as 'technology employed in a communication interface to access a specific medium'. Wireless access to ITS stations by means of cellular networks (4G/5G) and short-range communications like ITS-G5 and DSRC are typical examples on access technologies.

[4] Dedicated Short Range communication at 5,8 GHz, e.g. used in European tolling systems

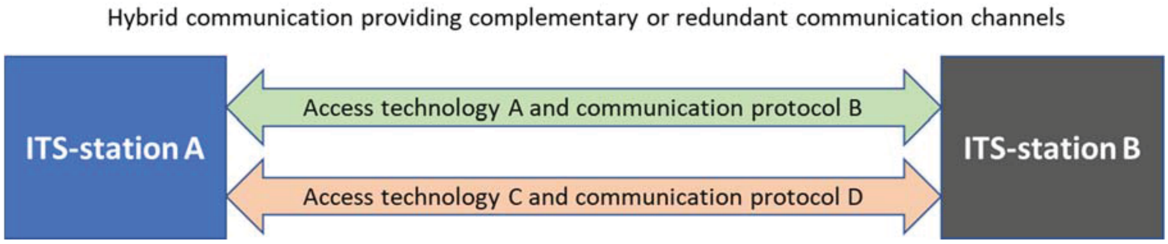


Figure 17: Example the Hybrid communication principle

Security is an important issue in communication between ITS-stations as threats may jeopardise the communication and cause injuries and fatalities in traffic safety C-ITS services. Hence, security should both cover authentication of broadcast messages and secure sessions as part of C-ITS services.

The ITS-stations have been specified to support several access technologies like all kinds of cellular access technologies e.g. 3G/4G/5G, satellite communications and technologies like infrared, ultra-wideband communications, vehicular Wi-Fi, e.g. ITS-G5 and DSRC, optical light communications and LTE-V2X. The specification also covers communication protocols like GeoNetworking/BTP from ETSI, FNTP from ISO, WSMP from IEEE and TCP/IP from IETF with supporting specifications from ISO.

3.4.2 Selection of the communication profile

The communication profile[5] selection principle is described in [1]. The selection of the appropriate access technology and communication protocol is shown in Figure 18. The C-ITS service application module in the ITS-S forwards its requirements and objectives for a specific message to the ITS-S Management module. The requirements could e.g. be related to level of priority, amount of data to be transmitted, expected level of security and expected end-to-end transmission delay.

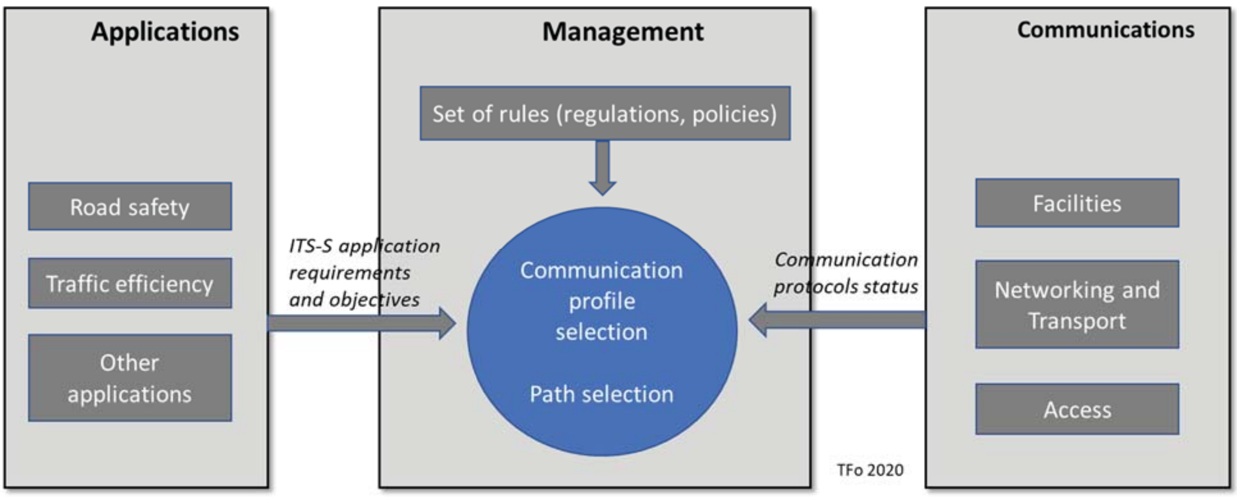


Figure 18: Principle for communication selection

The Management module continuously updates its information on the status of the three layers in the communication module, the local regulation and policies (Set of rules) and the present computing and communication load of the ITS station unit. An example on a local regulation could be forcing the use of a

[5] Defined in [1] as 'Parameterised ITS-S communication protocol stack (set of protocols composing all the ITS station layers) that allows communication end points to communicate with one another'

specific access technology and/or communication protocol, e.g. a cellular network and TCP/IP in an area without any short-range communication facilities. The Management module then selects the best access technology and communication protocol for the message to be sent.

Also, the best ITS-S path is selected. An ITS-S path as defined in [3] starts at its source node and ends up at a destination source. There may be zero or more intermediate nodes in the ITS-S path between the source node and the destination node.

Figure 19 shows an example on three different paths for a message, e.g. CAM or DENM (see next paragraph), from the source node (blue car) to the destination node (red car). Path 1 is a direct communication channel between the source and destination node with no intermediate nodes. Path 2 is a communication channel between the source and destination node that goes via the Roadside ITS station as an intermediate node. Path 3 is a communication channel via a telecom network and a central ITS station, e.g. a Traffic management centre. Path 3 could be the only feasible solution in cases where the distance between the source and destination vehicles are too long for communication solutions enabled by Path 1 and 2. The message may be delayed in the path which make the path solution less feasible for high priority messages, e.g. messages used in traffic safety applications. This is a relevant scenario for roads with low traffic in rural areas.

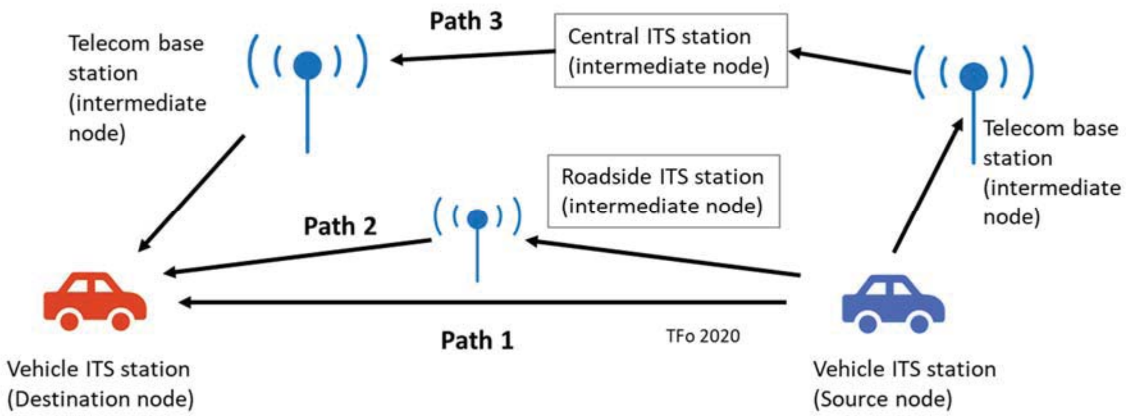


Figure 19: Multiple communication paths

Cooperative Awareness Message (CAM) is a typical message in Path 1. In automated driving mode the vehicles inform each other on critical data like position, speed, direction, time and physical parameters describing the size of the vehicle. CAM also carries the basic information required in many C-ITS services, e.g. traffic safety services like Collision Risk Warning and traffic management services like Traffic Light Optimal Speed Advisory. The CAM is defined in [7].

Decentralized Environmental Notification Message (DENM) is also a typical message in all example paths in Figure 19. A DENM contains information related to a road hazard or an abnormal traffic conditions, such as its type and its position. A DENM could be sent from one vehicle directly (Path 1) or indirectly (Path 2) to other vehicles. It could also be sent to a Central ITS station, e.g. a traffic management centre that broadcasts the DENM to other vehicles close to or approaching the road hazard or abnormal traffic condition (Path 3). A variant of Path 3 could be that the DENM is not broadcasted to destination nodes via the telecom network but through Roadside ITS stations.

DENM is defined in [8] that describes the coding of about 25 events that can trigger DENM messages, e.g. Wrong way driving, Hazardous location – Obstacle on the road, Vehicle breakdown and Dangerous end of queue.

3.4.3 Network and localised communications

There are two types of communications according to [1]:

- *Networked communication* is based on communication using some form of infrastructure network, e.g. cellular, cable and fibre networks. An example given in [1] is cellular network access to Internet [5] with IPv6 [6] as a protocol stack for networked communications. Path 3 in Figure 19 is an example on networked communications.
- *Localised communications* which is used for direct exchange of information between vehicles and their nearby environment like other vehicles or road users (e.g. pedestrians) and roadside infrastructure e.g. roadside ITS stations and traffic signal controllers.

Localised communication is one of the basic support services enabling many C-ITS services to be provided. Many road safety applications, e.g. collision avoidance, require localised communication due to the quality of service requirements.

Localised communication covers several other terms often used as abbreviations:

- **V2V** meaning Vehicle-to-Vehicle. Path 1 in Figure 19 is an example on a V2V communication
- **V2R** meaning Vehicle-to-Roadside infrastructure
- **V2P** meaning Vehicle-to-Pedestrian
- **V2X** meaning Localised communication, i.e. covering both V2V, V2R and V2P

V2X is sometimes in literature meaning Vehicle-to-everything. This is confusing and should be avoided as it may imply both network and localised communication. Even if V2X means localised communication the term is not used in [1] to avoid confusion. Also, the term V2I (Vehicle-to-Infrastructure) is not recommended in [1]as it could be interpreted as vehicle to cellular network infrastructure or satellite network infrastructure and not V2R.

It should be noted that localised communication covers both broadcasting of messages (one-to-many and one-way) and point-to-point exchange of messages.

3.4.4 Message security

The messages sent between ITS stations have to ensure authenticity ('trusted devices'), confidentiality, integrity and availability independent of whether the communication is localised (V2X) or networked, e.g. sent via Path 1, 2 or 3 in Figure 19. The impact of a security breach is expected to be the same whether the message has been transmitted directly between two vehicles, via a Roadside ITS station or via a cellular network base station. This calls for a security concept that can be implied independent of communication access and protocol.

Authenticity means ensuring that a source or destination node is a real entity certified for sending and/or receiving messages being part of C-ITS services, i.e. being a trusted device. This requires two-ways or one-way authentication. A vehicle receiving a DENM broadcasted by another vehicle, Roadside ITS station or cellular base station should trust that the source node is a real and certified entity and not a fake source node with the objective of creating chaos in a road network.

Confidentiality means ensuring that a message is only accessible for one or more authorised destination node(s). Air interfaces, e.g. wi-fi communications, are vulnerable for unauthorised access as messages sent via air can be listened to by unauthorised entities and e.g. replayed later with dishonest objectives. Confidentiality is also an important measure ensuring privacy.

Integrity means ensuring that a message is not changed between the source node and the destination node. A changed message may have fatal consequences, e.g. the CAM messages sent by vehicles in a high-speed traffic flow are changed by a dishonest entity causing collisions and chaos with fatalities.

Availability means ensuring that the required message is available when there is a need for it by the actual C-ITS application. Automated driving on a high level is an example on a C-ITS application that are depending on that the CAMs transmitted by other vehicles are available when the vehicle system for automated driving has to know e.g. the position, speed and direction of other vehicles within the vehicle surroundings. Lack of one or more CAM may have fatal consequences. The same goes for security applications like Collision Risk Warning.

An extensive description of C-ITS security is given in [9]. The scope of the ISO TR is:

- Provide guidelines on security applicable in ITS related to communication and data access
- Analysis and best practice content are provided for secure ITS connectivity using ISO/TS 21177:2019 Intelligent transport systems — ITS station security services for secure session establishment and authentication between trusted devices
- Analysis and recommends application security, access control, device security and public key infrastructure requirements for a secure ITS ecosystem
-

The scope of the ISO/TS 21177 is:

- specifications for a set of ITS station security services required to ensure the authenticity of the source and integrity of information exchanged between trusted entities:
    - devices operated as bounded secured managed entities, i.e. "ITS Station Communication Units" (ITS-SCU) and "ITS station units" (ITS-SU) specified in ISO 21217, and
    - between ITS-SUs (composed of one or several ITS-SCUs) and external trusted entities such as sensor and control networks.

The three standards ISO 21217, ISO/TR 21186-3 and ISO/TS 21177 provide a framework for security in hybrid communication. However, there are barriers to overcome before the framework is implemented in a full scale. Some examples on barriers are certificates for interconnection between trusted devices and security key management. This is partly due to the cooperation between many different stakeholders, e.g. car industry, telecom operators and road operators and their different requirements and communication infrastructures.

CONCORDA (Connected Corridor for Driving Automation) is a European R&D project [10] that brings together the car industry and telecom operators. The project 'will contribute to the preparation of European motorways for connected and automated driving and high-density truck platooning, by providing adequate connected services and technologies in terms of interferences and interoperability'. CONCORDA will combine 802.11p and LTE-V2X connectivity and 'special attention will be placed on the evaluation of the different communication paths and also on the improvement of localization and positioning with the aim of enhancing the reliability and cost-effectiveness in the transmission of data'. The projects aims for a trial showing how a hybrid V2X (localised) communication system with ITS-G5, LTE connectivity and a consistent IT security architecture performs in practise [11].

3.5 Bibliography

[1] ISO/TR 21186-2:2020 Cooperative intelligent transport systems (C-ITS) — Guidelines on the usage of standards — Part 2: Hybrid communications

[2] Foss, T. (2019), A high-level view on C-ITS and Hybrid communication, SINTEF

[3] ISO 21217:2019 Intelligent transport systems – Station and communication - Architecture
[4] ISO/TR 17465-1:2014 Intelligent transport systems - Cooperative ITS - Part 1: Terms and definitions
[5] ISO 17515-1:2015 Intelligent transport systems — Communications access for land mobiles (CALM) — Evolved universal terrestrial radio access network (E-UTRAN) — Part 1: General usage
[6] ISO 21210:2012 Intelligent transport systems — Communications access for land mobiles (CALM) — IPv6 Networking
[7] ETSI TS 102 637-2 V1.2.1 (2011-03) Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service
[8] ETSI EN 302 637-3 V1.2.1 (2014-09) Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service
[9] ISO/TR 21186-3:2020 Cooperative intelligent transport systems (C-ITS) – Guidelines on the usage of standards – Part 3: Security
[10] https://connectedautomateddriving.eu/project/concorda/ as downloaded June 19,2020
[11] https://www.escrypt.com/en/news-events/hybrid-v2x-communication as downloaded June 19,2020

4 State-of-the-art of path loss modelling

Jan Erik Håkegård and Arne Lie

4.1 Introduction

An objective of the LambdaRoad project is to develop a model for the coverage of telecom networks along the road network. This model will be used to estimate and predict the quality of ITS services and other services for road users.

One building block of this model concerns the wireless signal propagation between transmitters and receivers. Modelling of wireless channels has been a topic of research for 100 years or more but is still a challenge in many environments. New models are proposed regularly, among others because new systems operating in previously less explored frequency bands are being developed.

In the planning of the project, the signal propagation modelling is limited to path loss. In this chapter however, also fading effects due to multipath propagation will briefly be described for completeness. It also opens for the possibility to extend the scope at a later stage to include multipath fading.

This chapter is structured as follows. In the next section, classifications of propagation models according to their key characteristics are proposed. In Section 4.3, non-geometrical empirical models are considered, i.e. models that do not use digital maps as inputs to provide information about the terrain between the transmitter and receiver. Section 4.4 contains information about geometrical models, and also provides an overview of the most relevant ITU recommendations. In Section 4.5 models developed for vehicle communication are considered, and in particular communications in tunnels and at intersections. Finally, in Section 4.6 models based on machine learning are considered.

4.2 Classification of propagation models

Due to the large variety of propagation models, it is useful to structure the models based on some of their key characteristics. These are:

- Output parameters (multipath fading versus path loss)
- Input parameters (geometrical models versus non-geometrical empirical models)
- Strategy (deterministic versus stochastic models)
- Methodology (classical models versus machine-learning based model)

Aspects related to the list of classification parameters are briefly described below. Then, in the following sections the state-of-the-art of the different types of models are reviewed.

4.2.1 Multipath fading models versus path loss models

Path loss models only have one output parameter, indicating how much the signal attenuates during propagation from the transmit antenna to the receive antenna. Typically, the path loss is modelled as function of distance r between the transmitted and the receiver. In free space, the signal power attenuates as $1/r^2$. In reality, the attenuation in most environments will be larger due to obstacles in the propagation environments. In addition, multipath fading will lead to fast fluctuations of the received signal power. Path loss models therefore typically model the *average* path loss and not the *instantaneous* path loss.

Multipath fading is due to reflections of the signal by the terrain and by any object located in the propagation environment. One effect of multipath propagation is that when a short impulse is transmitted, the receiver will receive signal energy over a time interval known as the delay spread due to different path lengths. This is equivalent to sending the signal through a filter. For mobile systems, another effect is that different signal components will be received with different Doppler shifts. This is known as Doppler spread, and lead to rapid fluctuations of the received signal power.

Multipath fading models are obviously more complex than path loss models. When designing wireless communication systems, an important criterion is that the radio should be able to handle the fading conditions it is expected to meet without significant loss in performance. Therefore, both ITS G5 and LTE radios for instance use multi-carrier modulation, as this is a way to make the radios more robust against long delay spreads.

When assessing whether or not to include multipath fading in the signal propagation modelling in this project, it is necessary to weight the benefit of including it against the additional complexity. In most environments, the radios used in ITS G5 and in LTE and 5G can be expected to be sophisticated enough to handle signal degradation due to fading without significant degradation of performance. In some challenging environments such as tunnels, this may however not always be the case.

4.2.2 Non-geometrical empitical models versus geometrical models

Some models are generic and may be used in a wide range of locations. They are based on empirical data and typically have fixed parameters for a limited set of environments, such as urban, suburban and rural environments. These models are often referred to as empirical models or non-geometrical models. Comparisons between measured path loss at a given location and the outputs from such models may be very large, as the path loss within e.g. urban areas varies greatly from location to location. Doing measurements in a large number of locations within one type of environment should however *on average* provide results close to those obtained from the model. The advantage of non-geometrical models is simplicity. If for instance the goal is to develop radio maps over Norway, using non-geometrical models may be the best or the only practical solution.

Geometrical models use databases or maps with terrain information as input parameters to predict the path loss for a particular link. These are specific to a location and will generally be more accurate for that location than non-geometrical models. Geometrical models may include blocking of the signal by terrain, vegetation, buildings etc. and bending of the signal around the edge of objects (diffraction). There are some challenges related to using geometrical models:

- The results are not easily transferred to other locations, as the terrain there will be different.
- High resolution maps constitute large amount of data. Both storage and processing time is therefore a challenge if geometrical models are to be used over large areas.
- The resolution of the mapping data will be of importance for the accuracy. In hilly terrain, a 10×10 meter grid may be sufficient to provide good accuracy for long range low frequency communication. For high frequency V2I communication, high resolutions such as 1×1 meter or better may be required.
- Not all relevant information within an area is included in maps such as changing vegetation and snow coverage, moving objects such as vehicles, as well as buildings and other structures.
- The properties of the surfaces in the propagation environment will be of importance for the accuracy. For instance, smooth surfaces (relative to the wavelength) will lead to specular reflections, while rough surfaces will lead to diffuse reflections. Also, the amount of attenuation due to absorption when the signal penetrates obstacles will vary.

When selecting between non-geometrical models and geometrical models it is necessary to consider the goal of the model. If the goal is to map the entire country, using non-geometrical models will most probably be the best choice, as using geometrical models with sufficient resolution and accuracy will be too time consuming. If accurate modelling of path loss along specific road segments is required, using geometrical models may be a better choice. The potential sources of error and inaccuracies using mapping data must however be considered.

4.2.3 Deterministic versus statistical models

Deterministic models make use of the laws of electromagnetic wave propagation to calculate the received power at a specific location. The output of the model is fully determined by the parameter values and the initial conditions. A simple deterministic model is the two-ray model containing a direct path and a ground reflection. More complex deterministic models typically require a complete 3-D map of the propagation environment. Raytracing is an example of deterministic modelling.

Stochastic models model the environment as a series of random variables and therefore possess some randomness. This implies that the same parameter values and initial conditions will lead to an ensemble of different outputs. Many empirical models are stochastic models, as large amounts of measurements within a type of environment can be used to derive statistical parameters like the mean and variance, or a probability density function (pdf). The stochastic channel models that are most referred to are Rayleigh fading (without line-of-sight), Rice fading (with line-of-sight) and log-normal distributed shadowing.

4.2.4 Classical models versus machine-learning based models

The number of classical models proposed in the literature is significant. This is illustrated by the attempt from 2013 to organize some models in a family tree shown in Figure 20.

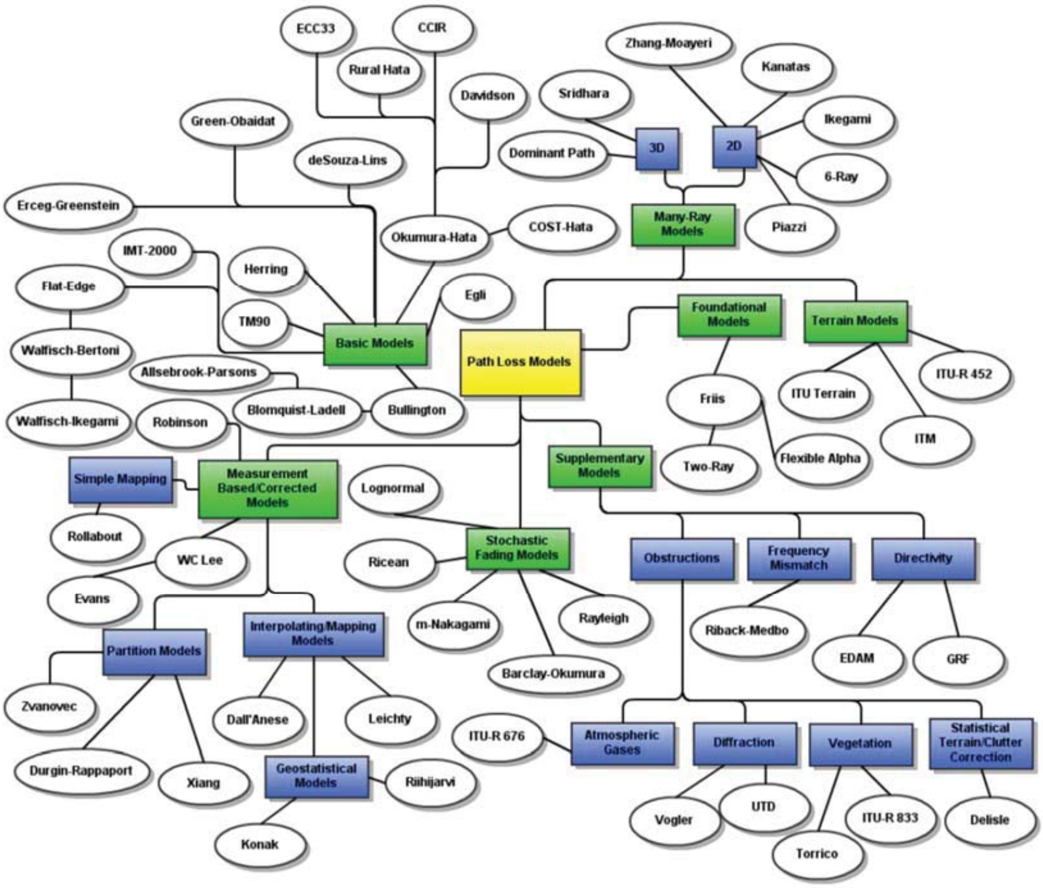


Figure 20: Path loss model family tree. Individual models are shown as circles and categories as are shown as rectangles. Major categories are green. Minor categories are blue. [1]

In recent years, machine-learning (ML) based methods have been proposed for path loss modelling and general channel modelling. Path loss prediction is essentially a supervised regression problem that lends itself to traditional supervised ML algorithms, including artificial neural network (ANN) as well as Support Vector Regression (SVR), Decision Tress (DT), K Nearest Neighbours (KNN) and Random Forest (RF). Many publications claim similar or better accuracy than empirical models in different environments and for different frequencies.

The performance of supervised ML algorithms heavily depends on the amount and quality of the training data. It is often difficult to obtain sufficient amounts of data due to the high cost of conducting measurements, especially for new environments and new frequencies. Data expansion solutions can be used to obtain enough data.

The input features to a ML algorithm can be divided into two categories, system dependent parameters and environmental parameters. System parameters include carrier frequency and position of transmitter and receiver. Environmental-dependent parameters are determined by the geographic environment such as terrain, vegetation and various structures.

A key challenge when applying ML methods for path loss modelling will be the feature selection and scaling. ML algorithms like ANN are "black boxes" in the sense that understanding of the relation between the input and output is lacking. The effect of selecting different features may therefore be difficult to predict. Evaluation metrics include prediction accuracy, generalization property and complexity.

4.3 Non geometrical empirical path loss models

Quite a few empirical models have been developed based on tweaking simple models to real measurement results, and claiming validity for certain type of terrain, e.g., rural (hilly, forest, flat, etc), typical suburban, and typical urban. Examples of such models are Okumura/Hata [2, 3] and COST 231 [4] models.

In the following, some empirical path loss models are briefly described. Note that for the Okumura/Hata and Walfish/Bertoni models, their intention is to model all losses, including diffraction/terrain clutter loss. Others, like Blomquist/Ladell, require separate calculations of diffraction loss L_D and local area clutter loss L_C to get the full picture.

4.3.1 Basic free-space loss

Several of the models described in the continuation make use of the basic free-space loss L_{bf} as one of its components. It is given as

$$L_{bf} = 32.44 + 20 \log_{10} R + 20 \log_{10} f_c \tag{1}$$

where R is distance between sender and receiver in km and f_c is carrier frequency in MHz.

4.3.2 Okumura/Hata (and COST-Hata-Model)

The Hata equations from the 1980 paper [3] are based on Okumura's measurements 12 years earlier [2]. The core propagation loss model is dependent on carrier frequency, Tx-Rx distance, and the effective Tx and Rx antenna heights, as (in dB)

$$L_{OH} = 69.55 + 26.16 \log_{10} f_c - 13.82 \log_{10} h_{Te} - a(h_R) + (44.9 - 6.55 \log_{10} h_{Te}) \log_{10} R \tag{2}$$

where valid range for f_c is 150–1000 MHz and R is 1–20 km. h_{Te} is the *effective* BTS antenna height (see Section 4.3.5 on page 40). $a(h_R)$ is the correction term for receiver antenna height different from 1.5 m, which for medium-sized cities is given by

$$a(h_R) = (1.1 \log_{10} f_c - 0.7) h_R - 1.56 \log_{10} f_c + 0.8 \tag{3}$$

and for large cities

$$a(h_R) = \begin{cases} 8.29(\log_{10} 1.54 h_R)^2 - 1.10, f_c \leq 200\ MHz \\ 3.2(\log_{10} 11.75 h_R)^2 - 4.97, f_c \geq 400\ MHz \end{cases} \tag{4}$$

Eq. (2) is valid for typical urban areas according to Hata, while for suburban and open areas, the following dB-factors shall be subtracted (thus, the loss becomes less):

$$K_r = 2\left(\log_{10} \frac{f_c}{28}\right)^2 + 5.4 \tag{5}$$

for *suburban areas* and

$$Q_r = 4.78(\log_{10} f_c)^2 + 18.33 \log_{10} f_c + 40.94 \tag{6}$$

for *open areas*. As a numerical example, the propagation loss is distance dependant at about $35 \log_{10} R$ for base antenna sizes of 20–50 meters, which is somewhat less than flat earth loss ($40 \log_{10} R$).

The original Hata model is reported to give good correlation with measurements in "quasi smooth terrain" in urban environment but can overestimate the losses in LOS areas.

COST231 modified the Hata equations somewhat to extend the validity range:

- f_c: 1500–2000 MHz
- R: in original COST231 book the range is still given as 1–20 km, but other sources have claimed upper range can be extended to 100 km (still is most probable affected by BTS antenna height).

COST-Hata-Model equations are:

$$L_{CH} = 46.3 + 33.0 \log_{10} f_c - 13.82 \log_{10} h_{Te} - a(h_R) + (44.9 - 6.55 \log_{10} h_T) \log_{10} R + C_m \quad (7)$$

where $a(h_R)$ is given by Eq. (3) and (47), and

$$C_m = \begin{cases} 0, & \text{(dB) for medium sized city and suburban centres w/ medium tree density} \\ 3, & \text{(dB) for metropolitan centres} \end{cases} \quad (8)$$

4.3.3 Blomquist & Ladell

The Blomquist & Ladell model from 1974 [5] is composed by free space loss L_{bf} plus a correction term comprised by diffraction loss L_D and a term F_B that takes both antenna height and dielectric constants at Tx and Rx site into account. The equations for propagation loss L_T are

$$L_T = \begin{cases} L_{bf} + \sqrt{F_B^2 + L_D^2}, F_B \le 0 \\ L_{bf} + \sqrt{L_D^2 - F_B^2}, 0 < F_B \le |L_D| \\ L_{bf} - \sqrt{F_B^2 - L_D^2}, 0 < |L_D| < F_B \end{cases} \quad (9)$$

where

$$F_B = 10 \log_{10} \left| \left(\frac{4\pi h_b^2}{\lambda d} + \frac{\lambda \epsilon_b^2}{\pi d(\epsilon_b - 1)} \right) \left(\frac{4\pi h_m^2}{\lambda d} + \frac{\lambda \epsilon_m^2}{\pi d(\epsilon_m - 1)} \right) \right| + Y \quad (10)$$

where

$$Y = \begin{cases} -2.8x, x < 0.53 \\ 6.7 + 10 \log_{10} x - 10.2x, 0.53 \le x < 2 \end{cases} \quad (11)$$

and

$$x = \left(\frac{2\pi}{\lambda} \right)^{\frac{1}{3}} (ka)^{-\frac{2}{3}} d. \quad (12)$$

The following summarises the equation set parameters not explained earlier:

- L_D: Diffraction loss.
- F_B: B&L propagation factor (dB)
- Y: B&L correction factor (dB)
- a: earth radius ($6.371 \cdot 10^6$ m)
- k: earth radius correction factor (normally $k = 4/3$ is used [6])
- ϵ_b, ϵ_m: dielectric constants at base and mobile stations, respectively (normally equal to 10 over normal dry terrain)

For 900MHz and above, the factors involving the dielectric constants are negligible compared to the other terms, and F_B reduces to the difference between free space loss L_F and B&L loss. The originality of B&L is therefore their "geometric mean" of F_B and diffraction loss L_D, without their paper giving insight into its motivation. B&L model shows good agreement with measurements in 900 MHz band [7].

4.3.4 Walfisch & Bertoni

This model [8] is most suited for urban environments only. Note that this model, together with work by Ikegami [9], was used to produce the COST231-Walfisch-Ikegami (CWI) model for urban propagation modelling. The CWI model is presented in

In the Walfisch & Bertoni model they assume that the buildings are of homogeneous rectangle shape of height h and have a separation of d_h, both given in meters, see Figure 21.

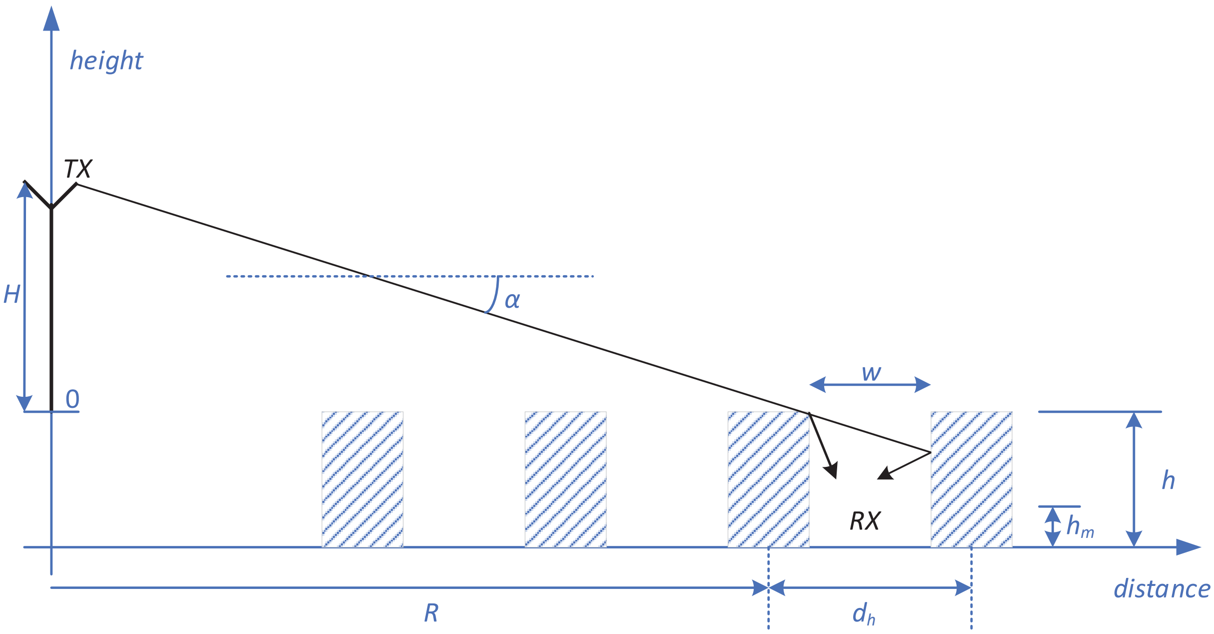


Figure 21: Modelling assumptions and parameters of Walfisch & Bertoni

The path loss is calculated as:

$$L^{WB} = L_{bf} + L_{ex} \tag{13}$$

where L_{bf} again is free space loss and L_{ex} is the excess path loss in dB caused by buildings and is given as:

$$L_{ex} = 57.1 + A + \log_{10} f_c + 18 \log_{10} R - 18 \log_{10} H - 18 \log_{10} \left[1 - \frac{R^2}{17H}\right] \tag{14}$$

where f_c is frequency in MHz and R is distance between base station and mobile given in km, and H is height of the base station antenna above the roof level h in meters. The A parameter takes care of the diffracted path loss from the nearest building, and is given by

$$A = 5 \log_{10} \left[\left(\frac{d_h}{2} \right)^2 + (h - h_m)^2 \right] - 9 \log_{10} d_h + 20 \log_{10}\{\tan^{-1}[2(h - h_m)/d_h]\} \tag{15}$$

where h is the averaged building height and h_m is the mobile antenna height. Figure 21 indicate that the only rays that are assumed to contribute to the received signal field strength are the diffracted rays over the nearest roof edge, both via reflected and direct path seen from that edge. Equation (14) also takes into account the transmitted energy absorbed by the intervening buildings. Note that the last term in Eq. (14) is a correction term for earth curvature. The Walfisch & Bertoni (WB) model is validated at ranges R less than the radio horizon distance, which can be calculated as:

$$R_{\text{hor}} = \sqrt{2HR_e} \tag{16}$$

where R_e is the effective earth radius approximated as $R_e \approx 4/3 \cdot 6371 = 8494.7$ km.

4.3.5 COST 231 Walfisch-Ikegami model

The CWI model first decouple the WB model L_{ex} into two modified terms: L_{msd}^{WB} expressing the loss from multi-screen diffraction over roof tops, plus L_{rts}^{WB} expressing path loss from roof top to the receiver. Then, CWI replaces L_{rts}^{WB} with L_{rts}^{I} , i.e. the Ikegami's model rts term [9], which takes road orientation compared to incident wave direction into consideration as angle parameter ϕ (in degrees, which is 0 when the road direction is along incident wave, and 90 degrees when it is perpendicular). Finally, it modifies slightly both terms to make it fit more closely to measurements conducted by COST231. The resulting $L_{ex}^{CWI} = L_{msd}^{CWI} + L_{rts}^{CWI}$ consists of [10]:

$$L_{rts}^{CWI} = -16.9 - 10 \log_{10} w + 20 \log_{10}(h - h_m) + L_{ori} \tag{17}$$

where

$$L_{ori} = \begin{cases} -10.0 + 0.354\phi, 0° < \phi < 35° \\ 2.5 + 0.075(\phi - 35°), 35° \leq \phi < 55° \\ 4.0 - 0.114(\phi - 55°), 55° \leq \phi \leq 90° \end{cases} \tag{18}$$

and finally

$$L_{msd}^{CWI} = L_{bsh} + k_a + k_d \log_{10} R + k_f \log_{10} fc - 9 \log_{10} d_h \tag{19}$$

where

$$L_{bsh} = \begin{cases} -18\log_{10}(H+1), H > 0 \\ 0, H \leq 0 \end{cases} \tag{20}$$

and

$$k_a = \begin{cases} 54, H > 0 \\ 54 - 0.8H, R \geq 0.5, H \leq 0 \\ 54 - 1.6H \cdot R, R < 0.5, H \leq 0 \end{cases} \tag{21}$$

and

$$k_d = \begin{cases} 18, H > 0 \\ 18 - \frac{15H}{h}, H \leq 0 \end{cases} \tag{22}$$

and

$$k_f = -4 + \begin{cases} 0.7\left(\frac{f_c}{925} - 1\right), \text{ urban and suburban} \\ 1.5\left(\frac{f_c}{925} - 1\right), \text{dense urban (metropolitan)} \end{cases} \tag{23}$$

The total path loss is then calculated as

$$L_{NLOS}^{CWI} = \begin{cases} L_{bf} + L_{msd}^{CWI} + L_{rts}^{CWI}, L_{msd}^{CWI} + L_{rts}^{CWI} > 0 \\ L_{bf}, L_{msd}^{CWI} + L_{rts}^{CWI} \leq 0 \end{cases} \tag{24}$$

when in NLOS, and

$$L_{LOS}^{CWI} = 42.6 + 26\log_{10} R + 20\log_{10} f_c, R \geq 0.020 \tag{25}$$

when in LOS (based on measurements performed in the city of Stockholm).

The valid range of the parameters are as follow:

- $f_c \in [800,2000]$ MHz
- $R \in [0.02,5]$ km
- $h \in [4,50]$ m
- $h_m \in [1,3]$ m

The CWI model is suggested modified by several entities to fit other uses and cover a larger range of valid parameter values, e.g., the work of ITU resulting in ITU-R P.1411.

4.3.6 Effective antenna heights

There exist a few different algorithms to calculate the effective antenna height of the transmitter and/or receiver, which are all based on physical position and surrounding terrain to some degree. Some popular methods are listed in the following.

4.3.6.1 Averaging terrain

In the loss formula of Hata/COST231, the effective BTS antenna height is in most references calculated as the antenna height relative to the average terrain height in front of the mobile antenna. In Figure 22 we see that this average will be highly dependent of which range D_{avr} is used when calculating this average.

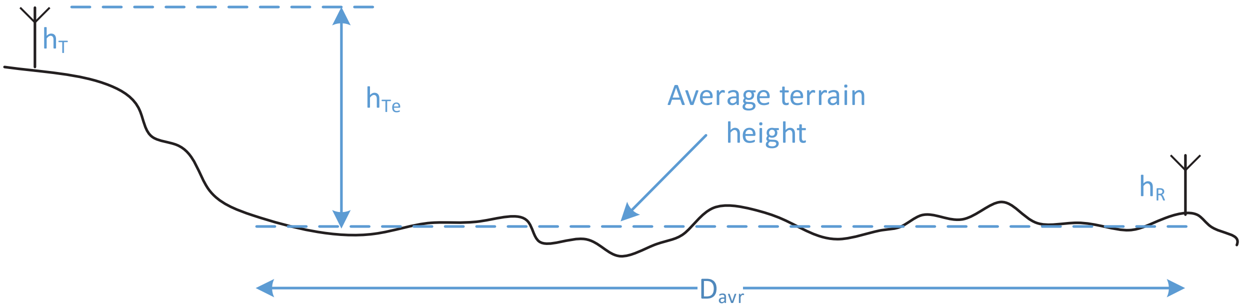


Figure 22: Averaged terrain height in front of receiving antenna used to calculate effective BTS antenna height

4.3.7 Lee effective antenna height

In [11] William Lee argues that the overall terrain profile need to be adjusted for when calculating effective antenna heights. Lee divides the terrain types into two main types: **Type A** and **Type B** (see Figure 23). Further, he divides into two different Conditions 1 and 2. In his model, there is a direct wave between the antennas h_T and h_R, and one or two reflected waves via ground (by Snell's law):

- **Condition 1**: the geometrical shape governed by D, d, H, h_T, and h_R, is such that there can only be *one reflected wave* reaching h_R:
  - Type A: $D < D_1 = \frac{dh_T}{h_T+h_R+H}$ (26)
  - Type B: $D < D_1 = \frac{dh_R}{h_T+h_R+H}$ (27)
- **Condition 2**: the geometrical shape governed by D, d, H, h_T, and h_R, is such that there will be *two reflected waves* reaching h_R:
-
  - Type A: $D > D_1 = \frac{dh_T}{h_T+h_R+H}$ (28)
  - Type B: $D > D_1 = \frac{dh_R}{h_T+h_R+H}$ (29)

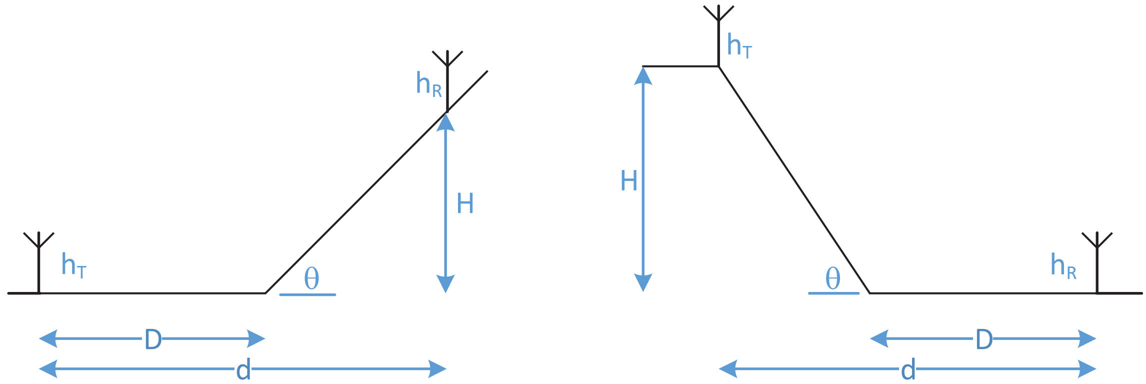


Figure 23: Lee divides the terrain types into Type A (left) and Type B (right)

The distance D_1 denotes the critical distance that divides into these two Conditions. However, later in the paper he argues that the second reflected wave, which is reflected via ground close to the transmitting antenna, will be highly diffusely scattered, and thus, very little of its power will reach the receiving antenna. Thus, Condition 1 and 2 merges, and the dominant reflected wave is the one reflected via ground close to the receiving antenna. His loss equation then equals in form that of flat earth loss as

$$L_L = -20\log_{10} h_{Te} - 20\log_{10} h_{Re} + 40\log_{10} d \tag{30}$$

where

$$h_{Te} \approx \begin{cases} h_T + \dfrac{DH}{d-D}, & \text{for Type A} \\ h_T \cos(\Theta), & \text{for Type B} \end{cases} \tag{31}$$

and

$$h_{Re} \approx \begin{cases} h_R, & \text{for Type A} \\ h_R + \dfrac{DH}{d-D}, & \text{for Type B} \end{cases} \tag{32}$$

are geometrical approximations of effective antenna heights, assuming H is small compared to d.

4.4 Geometrical models for diffraction loss

An important propagation phenomenon in wireless communication is diffraction, which means that signals are slightly bending around edges of objects. Diffraction models are typically geometrical models, as the terrain profile will have an impact on the amount of diffraction.

4.4.1 Diffraction theory

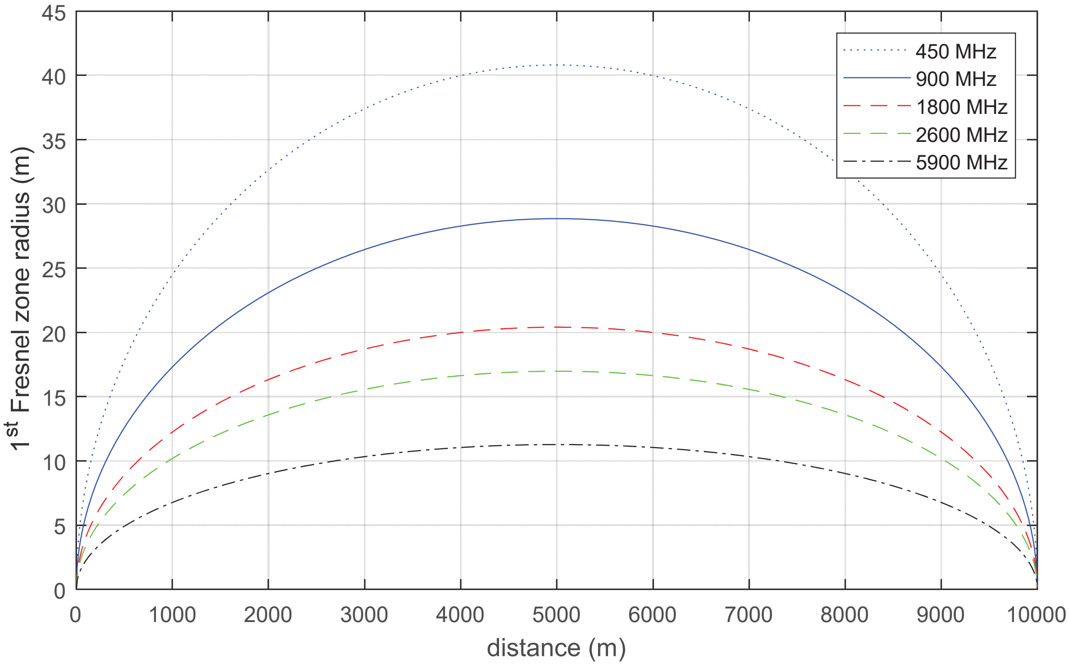


Figure 24: Illustration of first Fresnel zone

In diffraction theory, the definition of Fresnel ellipsoids and Fresnel zones is fundamental. The Fresnel zones are defined as a family of ellipsoids with focal points at A and B, and so that any point M on the ellipsoid satisfies the relation:

$$AM + MB = AB + \frac{n\lambda}{2} \tag{33}$$

where n is the index of the Fresnel zone. According to diffraction theory, the direct path between the transmitter and the received needs a clearance of 60% of the radius of the first $(n = 1)$ Fresnel zone to achieve free-space propagation conditions. In such cases, the diffraction loss can be considered to be zero. If this is not the case, diffraction over the peaks of the obstructions in the signal path must be considered, adding loss to the free-space path loss. Figure 24 illustrates the size of the first Fresnel zone for the relevant frequencies and a link distance of 10 km.

The diffraction loss depends on the type of terrain. The diffraction loss is maximum for a smooth spherical Earth, and lowest for a single knife-edge obstruction. According to ITU-R P.526 [12], the surface can be considered smooth if terrain irregularities are in the order of or less than $0.1R$, where R is the maximum radius of the first Fresnel zone.

If the surface can be considered as smooth, the diffraction loss will depend on whether the distance between transmitter and receiver is shorter or longer than the marginal line-of-sight (LOS) distance. The marginal LOS distance is calculated using the equivalent Earth radius, which is larger than the actual Earth radius due to atmospheric refraction that bends the signal towards the Earth surface. Calculation of the equivalent Earth radius is described in Recommendation ITU-R P.834. When no other information is provided, the equivalent Earth radius is set to 8500 km.

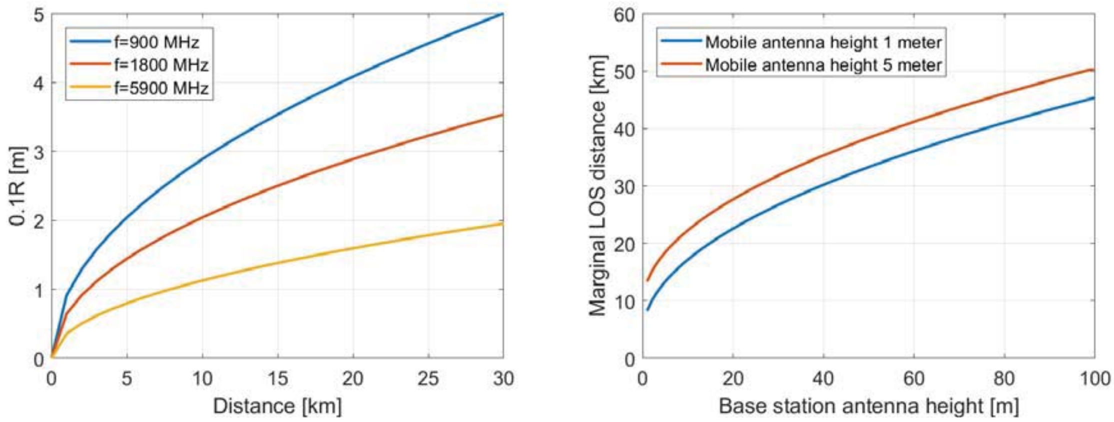


Figure 25: Left: Condition for smooth Earth. Right: Marginal LOS distance for smooth Earth

Figure 25 illustrates the sizes of the terrain irregularities determining if a smooth Earth model can be applied for different frequencies, and the marginal LOS distance for different antenna heights. From the curves, it can be concluded that the smooth Earth models for diffractions are rarely applicable in Norway, as irregularities along the propagation path in most cases are larger than a few meters. In the case where it can be applied, the length of the links will in most cases be shorter than the marginal LOS distance.

4.4.1.1 Smooth spherical Earth diffraction

A numerical method to predict the diffraction over a spherical Earth is provided in [12]. The method includes both LOS and non-LOS (NLOS) transmissions.

For the NLOS part of the model, the normalized length of the path and the normalized antenna heights, where the curvature of the Earth is compensated for, are calculated using equations given in Sec. 3.1.1.2 of [12]. The diffraction field strength is then calculated using these three normalized values applying equations provided in the recommendation.

For the LOS part of the model, the smallest clearance height between the curved-Earth path and the ray between the antennas is calculated. If the smallest clearance height is outside the first Fresnel zone, there is no additional diffraction loss. If it is within the first Fresnel zone, a modified effective Earth radius is calculated and the NLOS model used to calculate the diffraction loss using the modified effective Earth radius.

4.4.1.2 Knife-edge diffraction

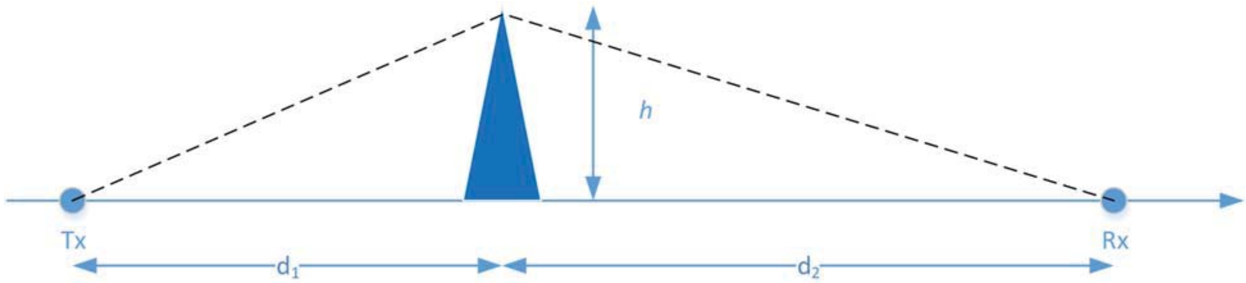


Figure 26: Geometry for Fresnel zone and Fresnel argument ν considerations

Many of the diffraction loss models approximate mountain peaks and ridges by knife-edges. Knife-edge diffraction (see Figure 26) is given by the Fresnel integral

$$F(\nu) = \frac{1+j}{2}\int_{\nu}^{\infty} \exp\left(-j\frac{\pi}{2}t^2\right) dt \tag{34}$$

where Fresnel argument ν is given by

$$\nu = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}}. \tag{35}$$

The Fresnel zone radius is given by

$$R_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}} \tag{36}$$

where R_1 denotes 1st Fresnel zone. This radius is illustrated in meters for 900, 1800, 2600, and 5900 MHz carrier in Figure 24 for a 10 km link.

Since the exact Fresnel integral is complex to solve, a popular approximation in dB given by

$$L_D = -10\log_{10}|F(\nu)| = \begin{cases} 6.02 + 9\nu + 1.65\nu^2, -0.8 \le \nu \le 0 \\ 6.02 + 9.11\nu - 1.27\nu^2, 0 < \nu \le 2.4 \\ 13 + 20\log_{10}\nu\,, \nu > 2.4 \end{cases} \tag{37}$$

is often in use, and where $\nu < -0.8$ gives zero loss. Eq. () matches the simpler equation set from [12] for large ν, but is more accurate for small and negative values of ν. If the wedge tip touches exactly the line-of-sight straight line, this equation states 6 dB diffraction loss.

In Figure 27, it is shown how the diffraction loss varies when the relative wedge height h increases from -28.8 m to +28.8 m at the mid-distance of the link as depicted in Figure 24. The figure confirms the 60% clearance of the first Fresnel zone is required to avoid additional diffraction loss.

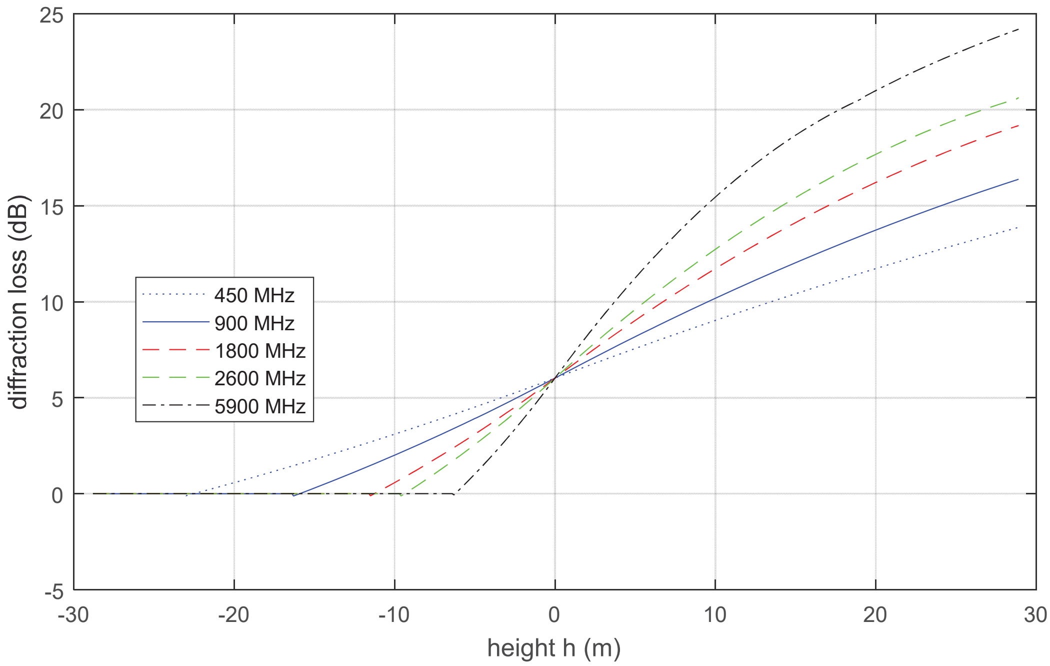


Figure 27: Diffraction loss as function of single knife-edge height and carrier frequency

4.4.2 Diffraction models

Models using terrain data to predict diffraction loss are called geometrical diffraction models. When the transmit and receive antenna heights are known and the elevation profile between transmitter and receiver is available through maps or databases, diffraction over the tops of the obstacles in the signal path can be predicted. A large number of geometrical models have been proposed during the last eighty years or so. Two of the most commonly used model in recent years are Bullington and Deygout, and they are described more in detail in this section, followed by a briefer description of other models.

4.4.2.1 Bullington model

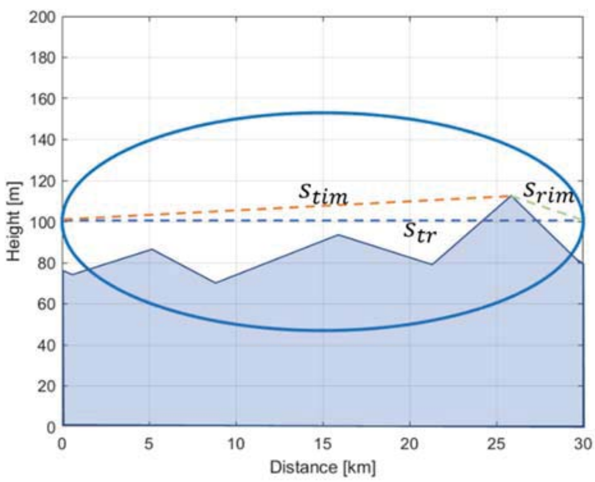


Figure 28: Illustration of Bullington model

The Bullington model only takes into account the principal obstruction of the signal path, which is called the Bullington point. The model has three key input parameters. The highest slope from the transmitter to any intermediate profile point s_{tim}, the highest slope from the receiver to any intermediate profile point s_{rim}, and the slope from the transmitter to the receiver s_{tr}. The model includes two cases. First, that there is LOS between transmitter and receiver, i.e. $s_{tim} < s_{tr}$, and where there is NLOS, i.e., $s_{tim} \geq s_{tr}$. The intermediate profile points are defined as distances from the transmitter d_i with corresponding heights above sea level h_i. The transmit and receive antenna heights are denoted h_{tr} and h_{rs}, and the distance between transmitter and receiver d. The model then states:

1) LOS case ($s_{tim} < s_{tr}$):

$$v_{max} = \max\left\{\left[h_i + 500C_e d_i(d-d_i) - \frac{h_{ts}(d-d_i) + h_{rs}d_i}{d}\right]\sqrt{\frac{0.002d}{\lambda d_i(d-d_i)}}\right\} \quad (38)$$

where C_e is the effective Earth curvature in 1/km. The knife-edge loss for the Bullington point is given by:

$$L_{uc} = J(v_{max}) \quad (39)$$

where J is given in [12] as:

$$J(v) = \begin{cases} 0, & v \leq 0.78 \\ 6.9 + 20\log\left(\sqrt{(v-0.1)^2+1} + v - 0.1\right) & v > 0.78 \end{cases} \quad (40)$$

It should be noted that equation (7) provides a better approximation to the exact Fresnel integral than equation (10).

2) NLOS case ($s_{tim} \geq s_{tr}$):

The slopes are given by:

$$s_{tim} = \max\left\{\frac{h_i + 500C_e d_i(d-d_i) - h_{ts}}{d_i}\right\} \quad (41)$$

$$s_{rim} = \max\left\{\frac{h_i + 500C_e d_i(d-d_i) - h_{rs}}{d-d_i}\right\} \quad (42)$$

Both slopes are expressed in m/km. The distance between the transmitter and the Bullington point is given by

$$d_b = \frac{h_{rs} - h_{ts} + S_{rim} d}{S_{tim} + S_{rim}} \tag{43}$$

It should be noted that when the transmitter and receiver have different horizons, the Bullington point is defined where the extended horizon rays intersect.

$$\nu_b = \max\left\{\left[h_{ts} + S_{tim} d_b - \frac{h_{ts}(d - d_i) + h_{rs} d_b}{d}\right] \sqrt{\frac{0.002d}{\lambda d_b (d - d_b)}}\right\} \tag{44}$$

The knife-edge loss for the Bullington point is in this case given by:

$$L_{uc} = J(\nu_b) \tag{45}$$

The Bullington diffraction loss is then calculated using either of the equations (9) or (15) for L_{uc}:

$$L_b = L_{uc} + \left[1 - \exp\left(-\frac{L_{uc}}{6}\right)\right](10 + 0.02d) \tag{46}$$

4.4.2.1.1 Delta-Bullington

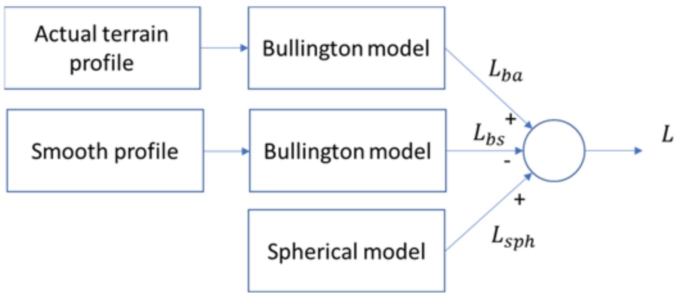


Figure 29 Principle of the Delta-Bullington method

It is observed that the Bullington model under-predicts diffraction loss, in particular for long paths, and has limited accuracy for spherical-earth diffraction for smooth or sea paths. The Delta-Bullington model addresses these issues and is often preferred over the classical Bullington model.

The principle of the Delta-Bullington model is illustrated in Figure 29. First, the Bullington diffraction loss L_{ba} is calculated as in the classical Bullington model using the actual terrain profile. Then, the effective transmitter and receiver heights relative to the smooth surface is calculated, the profile heights set to zero, and the Bullington diffraction loss L_{bs} for this modified profile calculated. Finally, the spherical loss L_{sph} is calculated using the spherical Earth loss model described in Sec. 4.4.1.1. The predicted loss is then given as:

$$L = L_{ba} - L_{bs} + L_{sph} \tag{47}$$

The idea is that the first two terms of the equation $L_{ba} - L_{bs}$ provides an estimate of the diffraction loss relative to spherical-earth, and that the mean errors of the model will tend to cancel due to the subtraction. For a completely smooth surface, L_{ba} will be equal to L_{bs}, and the result will be equal to that of the spherical model.

Several publications have proposed alternative ways to calculate the knife-edge loss of the Bullington point. As an example, in [13] a alternative way of calculating the loss in the LOS case was proposed. None of these modifications are however yet validated and recommended by ITU-R.

It should also be noted that the Delta method is a general approach that may be used by other diffraction models than Bullington.

4.4.2.2 Deygout model

The Deygout model is an alternative to the Bullington model, and also models the obstructions of the signal path as knife-edges. While the Bullington model only considers the principal obstacle, the Deygout model considers several obstructions. It has sometimes been referred to as the Cascade Knife Edge (CKE) model [14].

In the example depicted at Figure 30 (assuming effective Earth radius already corrected), the Tx antenna sees 01 edge as radio horizon, and the Rx antenna sees edge 04 as horizon. Seen from 01 edge against Rx, the 03 edge is the next horizon, in which the 04 edge agrees on seeing the path towards Tx. In the Deygout way of calculating effective diffraction loss of multiple edges, the losses due to each of the edges are calculated in the absence of the others. This means, Tx–01–Rx, Tx–03–Rx, and Tx–04–Rx diffraction loss shall be calculated in legacy way, and the one generating largest loss $L_{D,max}$ is then termed main edge. If this happens to be the 03 edge in our example, the Tx–01–03 and 03–04–Rx paths are also calculated, (naming these $L_{D,1}$ and $L_{D,4}$, respectively). The total diffraction loss is then:

$$L_D = L_{D,1} + L_{D,max} + L_{D,4} \tag{48}$$

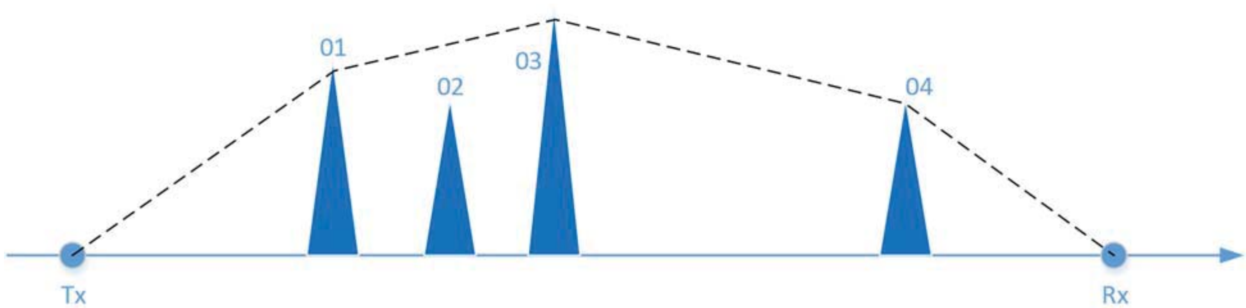


Figure 30: Deygout modelling selecting 03 as main edge

4.4.2.2.1 Modified Deygout with equivalent Bullington edge

In the Deygout model, the number of edges can be larger than three, by recursively follow the method in order of decreasing diffraction losses. In the Modified Deygout model however, the number of edges are reduced to a maximum of three. The edges seen as radio horizon from Tx and Rx is termed T-edge and R-edge, respectively. The third, fictive edge, is constructed at the cross section of the lines starting at these two edges towards their respective radio horizons, by the principles of Bullington [15]. In Figure 31 this edge is coloured differently compared to the "real" edges. The diffraction loss is then calculated using the same principles as in the Deygout method.

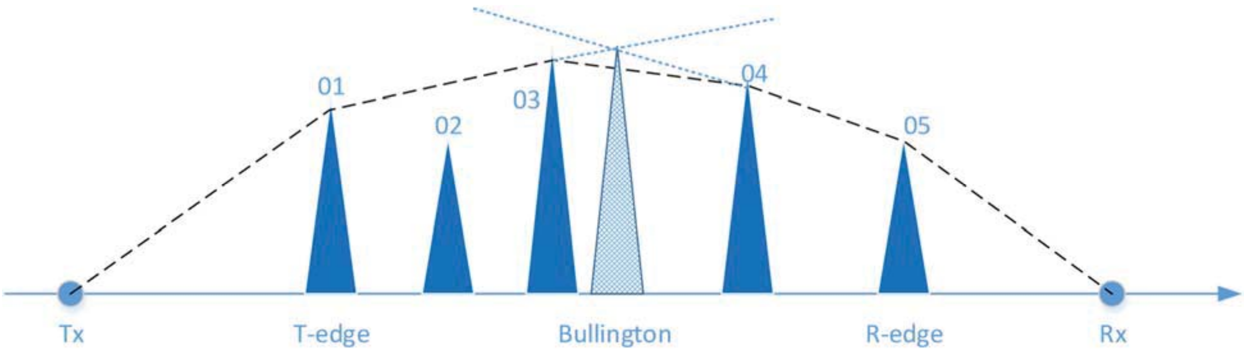


Figure 31: In Modified Deygout a Bullington equivalent edge is constructed

4.4.2.3 Alternative models

There are a number of computationally complex models available to predict the diffraction loss. The numeric parabolic equation (PE) approach [16, 17] implies solving the wave equation for electromagnetic waves which derives from the Maxwell equations using a parabolic equation. This approach is more accurate than the simpler methods like Bullington and Deyout that use knife-edges to replace mountain peaks and ridges. It is however too computationally complex to be applicable in most cases.

In 1962 Keller presented a geometrical theory of diffraction (GTD) [18] as an extension of geometrical optics. The uniform theory of diffraction (UTD) is an extension of GTD. Diffraction coefficients are calculated for each diffracting obstacle, and the coefficients are used to calculate the field strength and phase for each direction away from the diffracting point. The Luebbers model [19] takes into consideration all possible combination of diffraction paths between transmitter and receiver. This model has been denoted as the combinational-UTD (CUTD) model [20].

Vogler [21] presented a rigorous method for solving knife-edge models, originating from the Huygens-Fresnel theory [14].

The Epstein-Peterson model [22] and the Giovanelli model [23] are examples of knife-edge models similar to Bullington and Deygout. They both estimate the total diffraction loss as sum of the several knife-edge losses.

In recent years, the use of Artificial Neural Networks (ANN) in prediction of diffraction loss has been explored. In [24], the ANN is used as an auxiliary tool to the Delta-Bullington and Deygout models to improve their accuracy.

4.4.3 Comparison between geometrical diffraction loss models

There have been done several comparisons between the different proposed models, see e.g. [14, 20, 25]. When it comes to computational speed, the PE approach requires in the order of minutes to predict the path loss, the C-UTD approach and Vogler's method require in the order of seconds, while the simple knife-edge methods require in the order of micro-seconds. According to [25], the Bullington metod is the fastest. The Epstain method is five times slower, Deygout about eight timest slower, and Gioveneli about 12 times slower.

When it comes to accuracy, the PE and C-UTD approaches outperform the simpler methods. Vogler's method has more or less the same accuracy as the simpler methods. Among the simple knife-edge methods, the conclusions are diverting. In the references [14, 25], the original Bullington method and not the Delta-Bullington method was considered. According to both of these studies, Gioveneli is found to be the most accurate model. According to [20], which includes the Delta-Bullington model, Deygout significantly overestimate the prediction loss caused by terrain diffraction and Delta-Bullington performs significantly better.

The international community, represented by ITU-R, recommends that the Delta-Bullington model is used when terrain data are available. Some of the relevant ITU-R recommendations are briefly described in the next subsection.

4.4.4 ITU recommendations

The selected models should be validated and accepted by the community. This is the case for channel models reviewed by ITU-R Study Group 3 (SG3). These models are updated, as additional data becomes available. Most of the models passing though the approval process and accepted as an approved Recommendation tend however to be stable over many years, and it is very rare that a model is deleted.

4.4.4.1 Propagation by diffraction

Reommendation ITU-R P.526-14 [12] is the most relevant recommendation for this activity. The recommended method to predict the diffraction loss for a general terrain profile is the Delta-Bullington model as described in Sec. 4.4.2.1.1.

It should be noted that until 2012, the recommended method was the Deygout model. As the Delta-Bullington models proved more accurate than Deygout in most cases, this was however changed.

Where there are buildings and vegetation along the profile and no a priori information as to such obstructions, ITU-R P.526 proposes to add a representative clutter height to the bare terrain height to improve accuracy.

4.4.4.2 A path-specific propagation prediction method for point-to-area terrestrial services

Recommendation ITU-R P.1812 [26] presents a model for predicting the coverage from a single point. It predicts the signal level exceeded for a certain percentage of an average year for a number of locations within an area. The model is path-specific and consists of a series of point-to-point predictions uniformly distributed over the service area.

Although the model covers several propagation characteristics, such as tropospheric scatter and ducting, the frequencies and ranges that are relevant in this context reduces the model to include free-space path loss and diffraction. As for recommendation P.526, the Delta-Bullington model is recommended to predict the diffraction loss. This also implies that the model only provides the median value, i.e. the locations within the service area that 50% of the time experience a path loss equal and larger than a certain value.

4.4.4.3 Method for point-to-area predictions for terrestrial services

In Recommendation ITU-R P.1546 [27], an alternative non-geometrical approach to predict path loss for terrestrial systems operating in the frequency range 30 MHz to 3 GHz and for distances up to 1000 km is presented. This method does not calculate the diffraction loss and is based on statistical analyses of experimental data. Curves based on measurement data are provided for several frequencies and for different regions and climate zones. Interpolation and extrapolation of the values provided must be used to obtain values for any given frequency, and correction methods are used to find values for any antenna heights.

For practical use, the values are provided in tables for computational implementation. Entering the operating frequency, antenna heights, link distance and type of environment, the model provides the path loss.

This method is best used when no terrain data is available, and when the recommendations P.526 and P.1812 cannot be used. According to the recommendation, it provides similar results to the Okumura-Hata method for distances up to 10 km, mobile antenna height 1.5 meter and clutter height 15 meter.

4.4.4.4 A general purpose wide-range terrestrial propagation model

Recommendation ITU-R P.2001 [28] describes a model including both diffraction and fading statistics that are well suited for use in Monte-Carlo simulations. As the fading statistics due to rain, atmospheric attenuation etc. has little impact on the system considered in this activity, also this model ends up being deterministic. As for the other recommendations, the Delta-Bullington model is used for predicting the diffraction loss.

4.4.4.5 Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems

Recommendation ITU-R P.1411 [29] proposes non-geometrical models for short range systems, including pedestrian and vehicular users. Most of it is targeted towards urban environment, although it also defines a rural environment. It is a statistical model that do not use terrain data.

The recommendation addresses propagation through vegetation, which is of interest for this project. Two major propagation mechanisms can be identified:

- Propagation through (not around or over) trees.
- Propagation over trees.

Propagation through trees predominates when both antennas are below the three tops, which may be the case for ITS G5 communication. Propagation over trees predominates when the base station is elevated above the treetops. The attenuation is strongly affected by multipath scattering initiated by diffraction of the signal energy both over and through the tree structures. For propagation through trees, the specific attenuation in vegetation can be found in Recommendation ITU-R P.833 (see next sub-section).

In situations where the propagation is over trees, diffraction is the major propagation mode over the edges of the trees closest to the low antenna. This propagation mode can be modelled most simply by using an ideal knife-edge diffraction model (see Recommendation ITU-R P.526), although the knife-edge model may underestimate the field strength, because it neglects multiple scattering by tree-tops, a mechanism that may be modelled by radiative transfer theory.

4.4.4.6 Attenuation in vegetation

Recommendation ITU-R P.833 [30] presents several models for predicting the effect of vegetation for a variety of vegetation types and for various path geometries. The attenuation due to vegetation will come as an addition to the free-space path loss and the diffraction loss. The level of attenuation varies greatly, and depends on the species, the water content and the density of the vegetation. According to the recommendation, attenuation through threes in leaf is about 20% (dB/m) greater than for leafless trees.

4.5 Models developed for VANETs

As vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication has received increasing attention, channel models particularly targeting Vehicle Ad Hoc Networks (VANETs) have been proposed. They are motivated by the fact that the propagation environment around modern road infrastructure have some particularities compared to traditional propagation environments. These may include structures such as complex interchanges, flyovers, underpasses and road tunnels, and urban environments containing street corners. Moreover, large moving obstacles such as buses, trailers and trucks may have an impact on the propagation conditions.

There have been reported some results of measurements along road networks using e.g. ITS G5 radios, where different path loss models are compared with measurements. One of these is from Michigan, USA, where deterministic, stochastic and geometrical models are compared in terms maximum likelihood estimates and packet reception ratio. The packet loss ratio is estimated using a receiver power threshold (sensitivity) [31]. Most of the models were able to estimate the average packet reception rate well. The time correlation of the channels was also considered, and as many of the models make i.i.d. assumptions, they poorly estimate periods with bad reception. The results using geometrical models were affected by the fact that many of the buildings in the environment were not included in the maps.

In the remaining of this section, two environments are considered: tunnels and corners in urban environments.

4.5.1 Tunnels

There have been some publications during the resent years targeting propagation modelling in road tunnels. The proposed techniques fall into two categories, deterministic models and empirical models [32].

There are currently three main deterministic techniques that are used to model signal propagations in tunnels [33]:

- The first one is the Geometrical Optical (GO) approach. The basis for that is Snell's law. When a signal is reflected, the angle of incidence is equal to the reflection angle. However, radio waves spreading behind obstacles cannot be described just by reflection. Therefore diffraction is introduced in the propagation model [34]. The path loss is then numerically predicted by summing the contributions of rays undergoing reflections off tunnel walls and diffraction near tunnel wedges. This technique requires large amount of information about the environment and is computationally demanding.
- The second one is the waveguide model. The tunnel geometry and the conductivity of the construction materials suggest that radio propagation in tunnels will be similar to that of a waveguide. The waveguide effect appears when the transvers dimensions of the tunnel are several times larger than the wavelength of the signal, which will be the case for both ITS G5 (wavelength 5 cm) and 4G/5G (wavelength ranging from about 8 cm to 43 cm) communication. The result is that the path loss can be significantly lower than in free space. Several papers investigate the effect of tunnel geometry and the electromagnetic properties of tunnel walls on the propagation conditions. Signal propagation in a straight and empty tunnel has quite similar characteristics as a waveguide. If the tunnel is not straight, or there are other obstacles such as cars in the tunnel, the waveguide approach is less suitable [34].
- Finally, the full wave model, such as finite-difference time-domain (FDTD) techniques, models the Maxwell's equations. The models provide very accurate results for any tunnel geometry, but the computational requirements may be unrealistically high even for short tunnels.

Empirical models usually try to adapt an n-slope path loss curve to measurements. Empirical models may provide good prediction of path loss with large amounts of measurements but will alone not provide any understanding of the physics behind the results. In many publications, theoretical models attempting to describe the physical phenomena are proposed, where the results are validated using measurements.

The number of slopes n of a path loss model is typically is equal to two [35], but three [36], four [37] and even five [38] have been proposed. For two-slope models, the path loss curve is divided into two regions, typically referred to as near region and far region. In the near region, the path loss is often modelled as free space path loss. The guided propagation has not been well established and high order modes are significant. In the far region, the waveguide effect appears, and the high order modes are highly attenuated. In this region the path loss slope is reduced significantly. The breakpoint between the two regions depends on the geometry of the tunnel and the operating frequency, and can be estimated as:

$$d_{BP} = \max\left(\frac{a^2}{\lambda}, \frac{b^2}{\lambda}\right)$$

where a and b are the height and width of an equivalent rectangular tunnel [39].

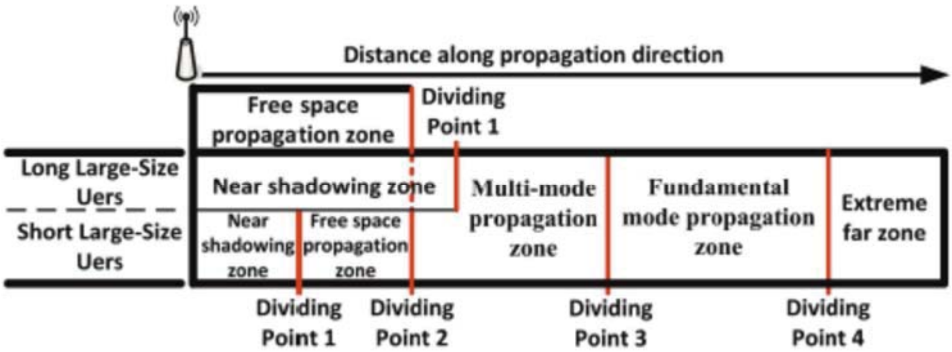


Figure 32: Propagation model for large vehicles inside tunnels [38]

Figure 32 illustrates a proposed five-slope model, where the different zones are defined as follows [38]:

- Near shadowing zone: In particular large vehicles will block parts of the first Fresnel zone between the vehicle mounted antenna and the roadside unit. This will lead to an attenuation larger than the free space path loss.
- Free space propagation loss: In this zone, the angles of incidence for the rays reflected off the walls are high resulting in high attenuation of reflected rays. Therefore, only the direct wave will significantly contribute to the received signal strength and the path loss will be similar to the free space path loss.
- Multi-mode propagation zone. In this zone, higher order modes are significant. This zone does however also correspond to the near region of the two-slope model.
- Fundamental mode propagation zone: In this zone, guided propagation is stabilized, and the propagation loss is significantly lower than for free space.
- Extreme far zone: In this zone, the waveguide effect vanishes because of the attenuation of each reflection. The path loss is then similar to the free space path loss. For lower frequencies, this zone may be significant for long tunnels. For frequencies used by mobile networks ant ITS G5, it is probably less relevant.

Figure 33 shows an example of the path loss curve for a tube-shaped tunnel linking Austria and Slovenia [37]. The operating frequency is 400 MHz and the height of the tunnel 4.70 meters. For the first 20 meters, the attenuation follows the free space path loss. Over the next 200 meters, the slope of the path loss is lower, but still steeper than that promised by the waveguide model. The deep fades are probably caused by reflections off vehicles. For distances longer than 200 meters, the slope is much slighter, and can be modelled as a waveguide where the path loss decreases linearly with distance between the transmitter and receiver [37].

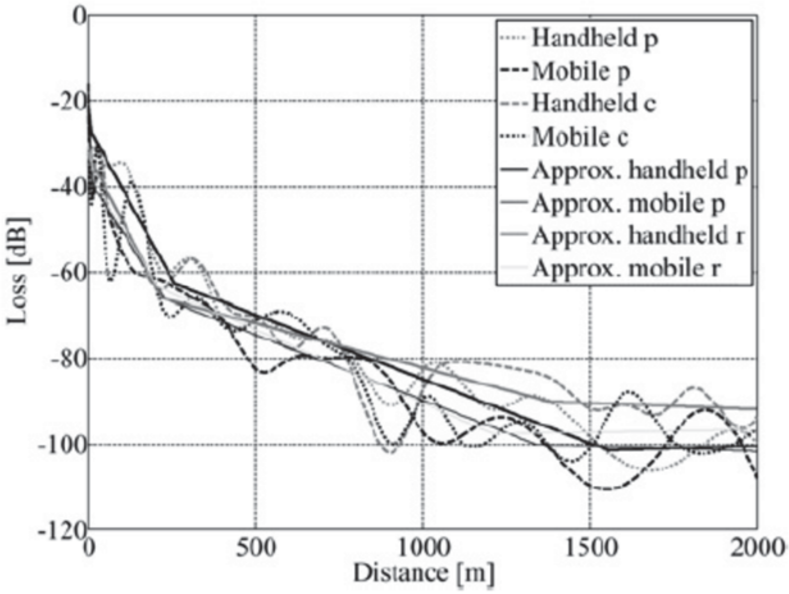


Figure 33: Measurement results in the straight part of the road tunnel [37]

Other vehicles in the tunnel between the transmitter and the receiver will have significant impact on the path loss. As could be expected, the size of the vehicles and the number of vehicles are the dominating factors. In [40], additional loss of 20 dB to 30 dB is reported for 5GHz measurements conducted in Pakistan. The size of the tunnel was 10.3 meter in width and 6 meters in height.

Curves in a tunnel will also lead to additional loss. The smaller the radius of curvature, the larger is the additional loss. In [32], measurements at three frequency bands are reported. Three zones are being defined, one up to 60 meters distance, one between 60 and 200 meters, and one over 200 meters. In zone 1, the additional loss is proportional to the frequency, while the relations in the other two zones are reversed.

4.5.2 Corner models

In urban environments, future ITS services will require reliable communication between vehicles, and also between vehicles and roadside equipment, around corners. A typical example of such applications is negotiations between vehicles crossing intersections without traffic lights. Urban propagation models can be used for such scenarios. Some models that address corners in particular have however been proposed.

In [41], a corner model is proposed that classifies each pair of vehicles into three possible cases: line of sight (LOS), non-line of sight (NLOS) with one corner along the path (NLOS1), and NLOS with two corners along the path (NLOS2. This is illustrated in Figure 34. The path loss for the three cases is modelled as:

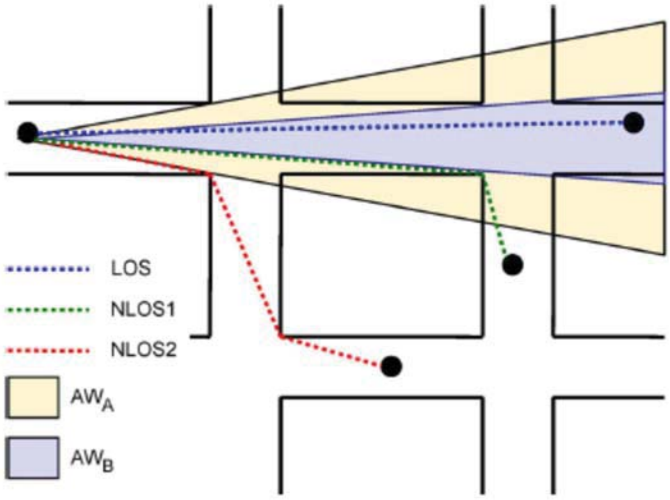


Figure 34: Propagation: graphical example of vehicles mapped on road segments separated by two crossroads [41]

- LOS: The path loss can be modelled as free space path loss.
- NLOS1: The received power is the sum of all rays that are either diffracted or reflected by the surrounding buildings. If the receiver is closer to the central point of the intersection than the transmitter, then the reflected components will dominate. Otherwise the diffracted components will dominate. Analytical formulas for the reflected and diffracted components are developed in [42].
- NLOS2: This case becomes more complicated. The received signal will be composed of four main components: rays reaching the receiver only through reflections, only through diffraction, and the two cases where the rays are diffracted around one corner and reflected by surrounding buildings around the other corner. Also in this case the formulas in [42] are used to predict the path loss.

It is claimed that the model accurately predicts the connectivity obtained from experiments [41].

While the model described above takes into account reflections and diffraction, others have considered models for signals penetrating obstructions. The model then put the number of walls the signal penetrates from the transmitter to the receiver as a parameter [43]. How dominant rays penetrating buildings will be compared to diffracted and reflected rays depends on the characteristics of the obstructions and on the carrier frequency.

In [44], a third approach is proposed. This is tested for blind corners, i.e. corners with no or very narrow sidewalk. The model introduces an estimated distance as:

$$Estimated\ Distance = (d_1 + d_2) \times \min(d_1, d2) \times \alpha \qquad (49)$$

The parameters d_1 and d_2 are the distances from the transmitters to the corner and from the corner to the receiver, respectively. The parameter α ($\alpha \geq 0.4$) represents the degree of obstruction. In the paper, values from 1.1 to 1.3 are used for different buildings. The path loss model included is the two-ray model coupled with the Nakagami model.

4.6 Path loss modelling based on machine-learning

The algorithms described in the previous sections are based on classical models. Recently, path loss prediction based on machine learning (ML) has received significant attention. The idea is however not new, as it was proposed to use neural networks for field strength prediction almost 30 years ago [45].

The task of ML algorithms is to find the best functional fit for a specified set of input features and corresponding path loss [46]. The model must be trained using a training set of measurements. The accuracy of the model is evaluated using a test set of measurements that is not part of the training set.

4.6.1 Important aspects for ML algorithms

4.6.1.1 Input features

The input features can be system-dependent and environmental-dependent parameters [47]. System-dependent parameters include distance between transmit and receive antenna, antenna height, angle between line-of-sight path and horizontal plane and carrier frequency. Environmental-dependent parameters are determined by the geographical environment such as terrain, buildings and other structures, and vegetation. Hence, models only including system-dependent parameters are analogous to the non-geometrical models described in Section 4.3, while models including both system-dependent and environmental-dependent features are analogous to the geographical models described in Section 4.4.

The selection of input features is important for the performance. Leaving out relevant features or including irrelevant features will both lead to reduced quality of the estimates. Several techniques for feature selection have been proposed. Feature weighting algorithms assign weights to features individually and rank them on their relevance to the parameter to estimate. A survey of feature selection methods are given in [48]. In [49], the importance for mean error and standard deviation of features for a 2.4GHz link is compared using the Random Forest algorithm. The path ground distance is the most important feature. Less important are terrain complexity, vegetation variability, mean percent canopy, path angle, source canopy, and finally receiver canopy.

4.6.1.2 Model selection and evaluation

Many different ML models have been applied to path loss prediction. In order to select the best model for a given case, several evaluation criteria related to prediction accuracy, generalisation and complexity are considered.

Examples of metrics that compare the predicted path loss with measured values during training are (root) mean square error ((R)MSE), mean absolute (percentage) error (MA(P)E), maximum prediction error (MaxPE), error standard deviation (ESD) and correlation factor (CF). The definition of these metrics can be found e.g. in [47].

The generalisation property indicates how well a model performs in other locations and in other environment types than the one used during training. Typically, a model has better generalisation performance when data collected in different environment types are used for training.

The computational complexity of a model is typically evaluated by monitoring processing time and memory usage. The time it takes to train a model, and the amount of training data required is often a key characteristic for selecting the model.

Once the model is selected, corresponding hyperparameters must be set. Examples of hyperparameters are number of layers in an artificial neural network, the kernel of SVR, tree depth in a decision tree and regularization parameters. The tuning of hyperparameters is important for the performance and effectiveness of the model. Methods to optimize hyperparameters include grid search, random search and Bayesian optimization.

Some models used for path loss prediction are described further down.

4.6.1.3 Data augmentation

ML algorithms depend on large volumes of training data. As doing measurements generally is expensive, strategies to use synthetic data or augmenting a limited amount of available data have been proposed.

Transfer learning is a way of data augmentation, and is described in [50]. The purpose is to transform data collected e.g. at one carrier frequency to generate data for another frequency band, or to transform data collected in one type of environment so that it can be used for training in another type of environment. In [51], both frequency-based transfer learning and scene-based transfer learning are proposed for path loss and delay spread prediction for UAV-to-ground millimetre-wave channels.

4.6.2 Artificial neural networks (ANNs)

Artificial neural networks have found applications in many areas, and there is a rich literature describing the concept and the various flavours of ANNs.

An ANN consists of one or several neuron layers. A challenge related to the design of ANNs is to optimise the number of layers, and the number of neurons per layer. This involves a trade-off between capturing the complexity of the underlying function given the training data and the model's ability to generalize to new inputs.

The neuron model is a feed-forward network. For training, backpropagation and gradient descent is most often applied. Hence, the weights are updated using the gradient vector. Algorithms allowing faster convergence such as the Levenberg-Marquardt algorithms may also be used. According to [46], the Levenberg-Marquardt algorithm is about 1000 times faster than the standard gradient descent algorithm.

A well-known problem related to ML algorithms is over-fitting, which means that the model fits very well to the training data but generalize poorly to other data sets. Several solutions to avoid over-fitting are therefore proposed. One of these is early stopping (ES). When applying ES, the measurement data are divided into three subsets; training, validation and evaluation. The training data set is used for computing the gradient and the neuron weights. As the training progresses the error (i.e. the difference between the modelled path loss and the measured path loss) for the training data decreases. At the same time, the error using the validation data set is monitored. When this error starts to increase, the algorithm stops.

Other approaches to mitigate overfitting are referred to as regularization methods. The most common approach is the use of *dropout*, where ANN parameters are randomly set to zero during training. This introduces noise, which has a regularizing effect, and breaks dependencies between parameters. Typically, 20-50% of the parameters are zeroed out every training iteration. The use of *weight decay*, where the absolute or square sum of the ANN parameters are added to the loss function, is also an option.

4.6.3 Support vector machine (SVM) based regression

SVR is an extension of Support vector machine (SVM) used in classification. In SVM, the basic idea is to nonlinearly map a set of data in a finite-dimensional space to a high- or even infinite-dimensional space so that the data set is linearly separable. The function used to map a lower dimensional data into higher dimensional data is called the kernel. Several kernels are proposed, such as linear kernel, polynomial kernel, Gaussian redial basis function, sigmoid kernel, and combinations.

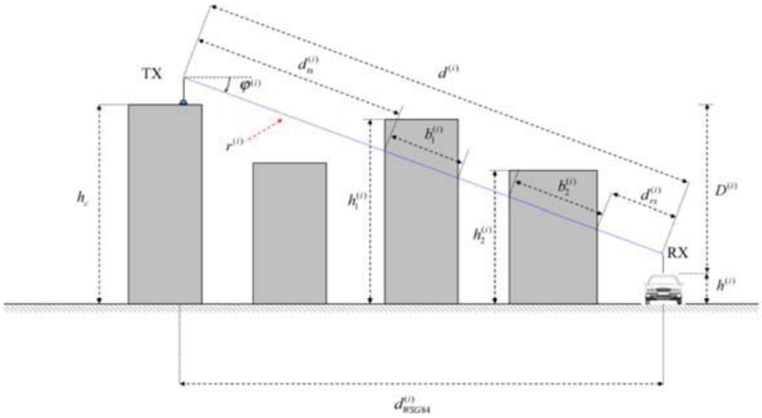


Figure 35: Schematic representation of an urban scenario in which the line-of-sight wireless link between a TX and a RX is blocked by multiple buildings [52]

SVR is used to predict system coverage and propagation loss at 169 MHz in [52]. Predicting the system coverage is a classification problem, while predicting the propagation loss is a regression problem. The features used are the positions of the transmitter and receiver and 3D geometrical representation of the considered propagation environment. The 3D geometrical representation is used to describe the size of the obstructions between the transmitter and the receiver, and the proximity of the transmitter and the receiver to such obstructions (see Figure 35). The accuracy of the model is evaluated using the RMSE metric. RMSE values in the order of 9-10 dB is reported, which is better than the typical values of the Hata model (10-14 dB).

4.6.4 Random forest regression (RFR)

Random forest regression is a so-called ensemble machine learning method. Ensemble methods are based on the hypothesis that combining the results from multiple models will give more accurate results than the result from one model.

In RFR, several decision trees are run in parallel. The decision tree algorithm breaks down the data set into smaller and smaller subsets while at the same time an associated decision tree is incrementally developed. A completed tree has decision nodes and leaf nodes. A decision node has two or more branches, each representing values of the attribute tested. Leaf nodes represent a decision on the numerical target. Decision trees are known to carry a big risk of overfitting, as the resulting decision tree and predications can be quite different if the training data is changed.

RFR is a bagging technique. Each individual tree draws a random sample from the original data set. The outputs are aggregated at the end without preference to any model. An alternative to bagging is boosting, where the individual models learn from the other models.

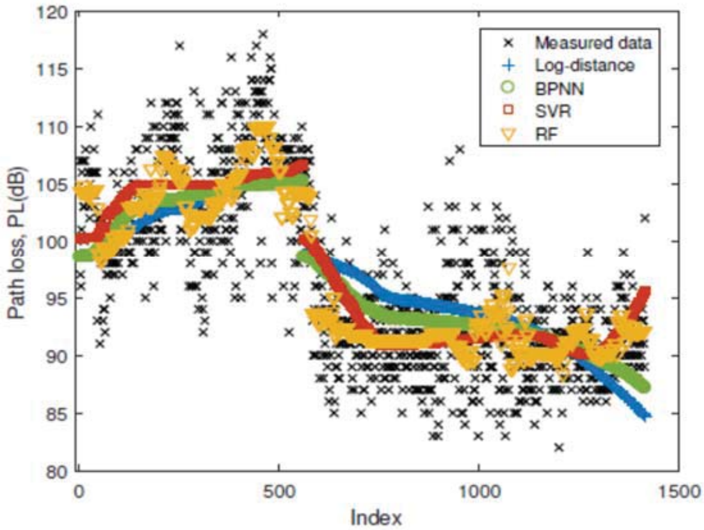


Figure 36: Prediction performance of different predictors on the test dataset. The samples are from TD-SCDMA BS, with 80% of the samples as training dataset and 20% of the samples as test dataset [47].

RF is known to provide good results when compared to other ML techniques. This is the case for many types of systems and also for path loss prediction. In [47], RFR is compared with ANN and SVR in urban areas with antenna separation as the only feature. The carrier frequency is 2 GHz, and base station antenna height 40 meter. The results are shown in Figure 36. From the figure it can be difficult to see which algorithm that is best, but metrics like RMSE indicates that RFR outperforms the other algorithms. In [49], RFR is compared to other ML algorithms and to classical algorithms for 2.4 GHz radio links deployed in a 2000 square km area with varying terrain and vegetation. The other ML algorithms are neural network, K-Nearest Neighbours and AdaBoost (another ensemble ML method). The classical algorithms are the empirical propagation models Weissberger, ITU-R and COST235. The random forest showed the lowest error. Similar results are obtained for UAVs in a 5G context [53], where ensemble methods are compared and bagging prediction method provides the best result. In [54], coverage of digital terrestrial television (DTT) is predicted using several ML algorithms (RFR, AdaBoost regression and K-nearest neighbours regression and others). RFR provides the best result.

4.7 Bibliography

[1] C. Phillips, D. Sicker, and D. Grunwald, "A Survey of Wireless Path Loss Prediction and Coverage Mapping Methods," IEEE Communications Surveys & Tutorials, vol. 15, no. 1, pp. 255-270, 2013.
[2] Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda, "Field strength and its variability in VHF and UHF land-mobile radio service," Review of the Electrical Communication Laboratory, vol. 16, no. 9-10, pp. 825-873, Sep-Oct 1968.
[3] M. Hata, "Empirical formula for propagation loss in land mobile radio services," IEEE Transactions on Vehicular Technology, vol. 29, no. 3, pp. 317-325, Aug 1980.
[4] J. Minseok and L. Bomson, "Comparison between path-loss prediction models for wireless telecommunication system design," in Antennas and Propagation Society International Symposium, 2001. IEEE, 2001, vol. 2, pp. 186-189 vol.2.

[5] A. Blomquist and L. Ladell, "Prediction and calculation of transmission loss in different types of terrain," in NATO AGARD Electromagnetic Wave Propagation Involving Irregular Surfaces and Inhomogeneous Media,, 1974, pp. 1-17.
[6] Prediction procedure for the evaluation of interference between stations on the surface of the Earth at frequencies above about 0.1 GHz, 2015.
[7] A. Lie and P. K. Remvik, "Performance efficient method for scattering reflection prediction in mobile cellular networks," in IEEE 47th Vehicular Technology Conference. Technology in Motion, Phoenix, Arizona, USA, 1997, vol. 2, pp. 1103-1107.
[8] J. Walfisch and H. L. Bertoni, "A theoretical model of UHF propagation in urban environments," Antennas and Propagation, IEEE Transactions on, vol. 36, no. 12, pp. 1788-1796, 1988.
[9] F. Ikegami, S. Yoshida, T. Takeuchi, and M. Umehira, "Propagation factors controlling mean field strength on urban streets," IEEE Transactions on Antennas and Propagation, vol. 32, no. 8, pp. 822-829, 1984.
[10] E. Damosso and L. M. Correia, "Digital Mobile radio Towards Future Generation Systems Communications, COST 231 Final Report," Brussels, Belgium, 1999, Available: http://www.lx.it.pt/cost231.
[11] W. C. Y. Lee, "Studies of base-station antenna height effects on mobile radio," IEEE Transactions on Vehicular Technology, vol. 29, no. 2, pp. 252-260, May 1980.
[12] Rec. ITU-R P.526-14, Propagation by diffraction, 2018.
[13] S. Topcu, P. Goktas, E. Karasan, and A. Altinas, "A new approach to diffraction modelling for line-of-sight (LOS) paths," presented at the 2015 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC) Torino, Italy, September 7-11, 2015.
[14] N. DeMinco and P. McKenna, "A Comparative Analysis of Multiple Knife-Edge Diffraction Methods," presented at the International Symposium on Advanced Radio Technologies/ClimDiff 2008, Boulder, Colorado, USA, 2-4 June, 2008.
[15] K. Bullington, "Radio propagation at frequencies above 30 megacycles," Proc. of IEEE, vol. 35, pp. 1122-1136, 1947.
[16] M. F. Levy, Parabolic Equation Methods for Electromagnetic Wave Propagation. London: Inst. Electr. Eng. Press, 2000.
[17] P. Valtr and P. Pechac, "Tropospheric refraction modeling using ray-tracing and parabolic equations," Radioeng., vol. 14, no. 4, pp. 98-104, 2005.
[18] J. B. Keller, "Geometrical Theory of Diffraction," Journal of the optical society of America, vol. 52, no. 2, pp. 116-130, 1962.
[19] R. J. Luebbers, "Propagation prediction for hilly terrain using GTD wedge diffraction," IEEE Transactions on Antennas and Propagation, vol. AP-32, no. 9, pp. 951-955, Sept. 1984.
[20] M. Kvicera et al., "Short-Term Terrain Diffraction Measurements From L- to Q-Band: Results and Analysis," IEEE Transactions on Antennas and Propagation, vol. 62, no. 7, pp. 3693-3701, July 2014.
[21] L. E. Vogler, "An attenuation function for multiple knife-edge diffraction," Radio Science, vol. 17, pp. 1541-1546, Dec. 1982.
[22] J. Epstein and D. W. Peterson, "An experimental study of wave propagation at 850 Mc/s," Proc. IEEE, vol. 41, pp. 595-611, May 1953.
[23] C. L. Giovanelli, "An analysis of simplified solutions for multiple knife-edge diffraction," IEEE Transactions on Antennas and Propagation, vol. 32, no. 3, pp. 297-301, March 1984.
[24] G. P. Ferreira, L. J. Matos, and J. M. M. Silva, "Improvement of Outdoor Signal Strength Prediction in UHF Band by Artificial Neural Network," IEEE Transactions on Antennas and Propagation, vol. 64, no. 12, pp. 5404-5409, December 2016.
[25] D. A. Bibb, J. Dang, Z. Yun, and F. Iskander, "Computational accuracy and speed of some knife-edge diffraction models," presented at the 2014 IEEE Antennas and Propagation Society International Symposium (APSURSI) Memphis, Tennessee, USA, 6-11 July, 2014.
[26] Rec. ITU-R P.1812-5 (08/2019) A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands, 2019.

[27] Rec. ITU-R P.1546-6 (08/2019) Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz, 2019.
[28] Rec. ITU-R P.2001 : A general purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz, 2019.
[29] Rec. ITU-R P.1411 : Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz, 2019.
[30] Rec. ITU-R P.833 : Attenuation in vegetation, 2016.
[31] S. E. Carpenter and M. L. Sichitiu, "Evaluating the Accuracy of Vehicular Channel Models in a Large-Scale DSRC Test," in 2017 IEEE 14th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), 2017, pp. 241-249.
[32] K. Guan et al., "Stochastic Modeling for Extra Propagation Loss of Tunnel Curve," in 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring), 2016, pp. 1-5.
[33] Z. Sun and I. F. Akyildiz, "Channel modeling and analysis for wireless networks in underground mines and road tunnels," IEEE Transactions on Communications, vol. 58, no. 6, pp. 1758-1768, 2010.
[34] A. Hrovat, G. Kandus, and T. Javornik, "A Survey of Radio Propagation Modeling for Tunnels," IEEE Communications Surveys & Tutorials, vol. 16, no. 2, pp. 658-669, 2014.
[35] Y. P. Zhang, "Novel model for propagation loss prediction in tunnels," IEEE Transactions on Vehicular Technology, vol. 52, no. 5, pp. 1308-1314, 2003.
[36] K. Guan et al., "Complete Propagation Model in Tunnels," IEEE Antennas and Wireless Propagation Letters, vol. 12, pp. 741-744, 2013.
[37] A. Hrovat, G. Kandus, and T. Javornik, "Four-slope channel model for path loss prediction in tunnels at 400 MHz," IET Microwaves, Antennas & Propagation, vol. 4, no. 5, pp. 571-582, 2010.
[38] K. Guan, Z. Zhong, b. ai, R. He, and C. Briso-Rodriguez, "Five-zone propagation model for large-size vehicles inside tunnels," Progress In Electromagnetics Research, vol. 138, pp. 389-405, 01/01 2013.
[39] C. Briso-Rodriguez, J. M. Cruz, and J. I. Alonso, "Measurements and Modeling of Distributed Antenna Systems in Railway Tunnels," IEEE Transactions on Vehicular Technology, vol. 56, no. 5, pp. 2870-2879, 2007.
[40] M. A. Qureshi, R. M. Noor, A. Shamim, S. Shamshirband, and K.-K. Raymond Choo, "A Lightweight Radio Propagation Model for Vehicular Communication in Road Tunnels," PLOS ONE, vol. 11, no. 3, p. e0152727, 2016.
[41] E. Giordano, R. Frank, G. Pau, and M. Gerla, "CORNER: A Radio Propagation Model for VANETs in Urban Scenarios," Proceedings of the IEEE, vol. 99, no. 7, pp. 1280-1294, 2011.
[42] Q. Sun, S. Y. Tan, and K. C. Teh, "Analytical formulae for path loss prediction in urban street grid microcellular environments," IEEE Transactions on Vehicular Technology, vol. 54, no. 4, pp. 1251-1258, 2005.
[43] C. Sommer, D. Eckhoff, R. German, and F. Dressler, "A computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments," in 2011 Eighth International Conference on Wireless On-Demand Network Systems and Services, 2011, pp. 84-90.
[44] S. Jaktheerangkoon, K. Nakorn, and K. Rojviboonchai, "Blind Corner Propagation Model for IEEE 802.11p Communication in Network Simulators," Journal of Advanced Transportation, vol. 2018, pp. 1-11, 07/18 2018.
[45] K. E. Stocker and F. M. Landstorfer, "Empirical prediction of radiowave propagation by neural network simulator," Electronics Letters, vol. 28, no. 8, pp. 724-726, 1992.
[46] E. Ostlin, H. Zepernick, and H. Suzuki, "Macrocell Path-Loss Prediction Using Artificial Neural Networks," IEEE Transactions on Vehicular Technology, vol. 59, no. 6, pp. 2735-2747, 2010.
[47] Y. Zhang, J. Wen, G. Yang, Z. He, and J. Wang, "Path Loss Prediction Based on Machine Learning: Principle, Method, and Data Expansion," Applied Sciences, vol. 9, no. 9, p. 1908, 2019.
[48] S. Khalid, T. Khalil, and S. Nasreen, "A survey of feature selection and feature extraction techniques in machine learning," in 2014 Science and Information Conference, 2014, pp. 372-378.

[49] C. A. Oroza, Z. Zhang, T. Watteyne, and S. D. Glaser, "A Machine-Learning-Based Connectivity Model for Complex Terrain Large-Scale Low-Power Wireless Deployments," IEEE Transactions on Cognitive Communications and Networking, vol. 3, no. 4, pp. 576-584, 2017.
[50] S. J. Pan and Q. Yang, "A Survey on Transfer Learning," IEEE Transactions on Knowledge and Data Engineering, vol. 22, no. 10, pp. 1345-1359, 2010.
[51] G. Yang, Y. Zhang, Z. He, J. Wen, Z. Ji, and Y. Li, "Machine-learning-based prediction methods for path loss and delay spread in air-to-ground millimetre-wave channels," IET Microwaves, Antennas & Propagation, vol. 13, no. 8, pp. 1113-1121, 2019.
[52] M. Uccellari et al., "On the application of support vector machines to the prediction of propagation losses at 169 MHz for smart metering applications," IET Microwaves, Antennas & Propagation, vol. 12, no. 3, pp. 302-312, 2018.
[53] S. K. Goudos, G. V. Tsoulos, and G. Athanasiadou, "Modelling Received Signal Power in Modern Mobile Communications with UAVs Using Ensemble Learning," in 2019 13th European Conference on Antennas and Propagation (EuCAP), 2019, pp. 1-4.
[54] C. E. G. Moreta, M. R. C. Acosta, and I. Koo, "Prediction of Digital Terrestrial Television Coverage Using Machine Learning Regression," IEEE Transactions on Broadcasting, pp. 1-11, 2019.

5 Communication requirements for the future road transport system

Petter Arnesen and Odd André Hjelkrem

5.1 Introduction

The future transport systems are believed to be heavily connected, as outlined by the EU commision (Figure 37). The stakeholders in the transport community are therefore currently debating and working tirelessly towards defining how the common future of connectivity will look like.

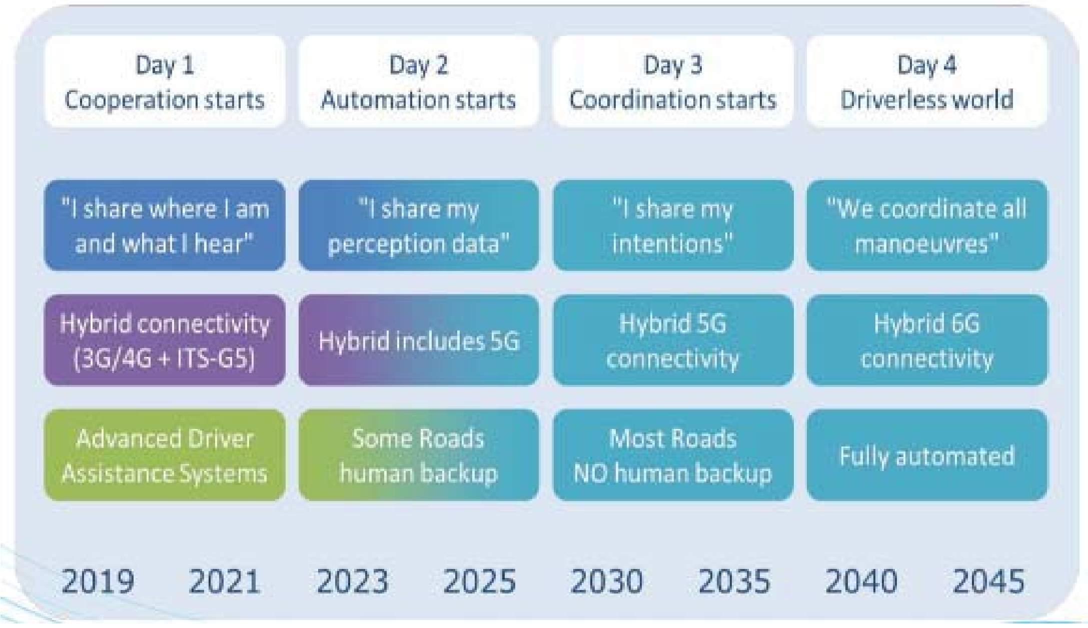


Figure 37: CCAM – Cooperative, Connected and Automated Mobility.

Meanwhile these discussions are taking place, millions of vehicles on the road are already connected using cellular technology. Ericsson expects this number to grow until 2024 and finally result in every new vehicle being connected after 2025 (Cerwall, 2019).

In the work with defining the future communication system for road transport, many stakeholders and interests are involved, reaching from road and communication authorities, network and service providers, telecom industry, car manufacturers, and providers of intelligent transport system (ITS) services. For many of these stakeholders, the discussions often focus on the communication technology or technologies to be applied, with cellular vehicle to everything (C-V2X), and in particular 5G technology, and the dedicated short-range communication (DSRC) ITS-G5 being debated. For instance, the recent proposed "Delegated Act on Deployment and Operational use of Cooperative Intelligent Transport Systems (C-ITS)" (European Commission, 2019) was rejected by the EU council, where the intention was to "establish specifications necessary to ensure compatibility, interoperability and continuity in the deployment and operational use of Union-wide C-ITS services based on trusted and secure communication" for V2V, V2I and I2I. Even though the proposal included telecommunication as taking part in a future hybrid communication system, the main criticism has been that future telecommunication solutions such as 5G would not be backwards compatible with ITS-G5 (GSM Association, 2019), in practice making ITS-G5 the only accepted technology. Despite this rejection, the work with C-ITS in line with the proposed delegated act has been carried forward, exemplified by Volkswagens recent rollout of VW Golf 8 equipped with ITS-G5 communication technology.

These developments and discussions of different technological solutions for communication within the road sector is of course important. However, one must not forget the true purpose(s) of enrolling connectivity onto the roads, namely increasing traffic safety, efficiency and reducing pollution. In the perspective of the individual, driving a future vehicle or living in a future city surrounded by road traffic, the choice of communication technology is not of importance. In this view, the quality of the services provided by the transport system is the important one. Of course, different communication technologies have different prerequisites for fulfilling the requirements for the future transport services, and it is of great importance to choose cost-efficient, sustainable and reliable solutions. However, to answer this question we argue that the following two clarifications must be made:

1) Which ITS-services and related contents are to be expected in the future?
2) What are the requirements in terms of communication for these services?

After answering these questions, the optimal deployment of different technologies can be answered. In this manuscript we focus for simplicity on V2I and I2V communication, excluding for instance V2V communication as these technologies would have slightly different requirements and be dependent on e.g. distance to other vehicles etc. As an introduction to the modelling and simulation of V2V for DSRC, the reader is referred to Islam et al. (2013) and the references therein.

When looking at data generation, much have been said about the autonomous vehicle. For instance, Intel projecting each car generating 4 TB of data every day (Krzanich, 2016), or 1215 EB per month for V2Cloud cruise assist (Automotive Edge Computing Consortium, 2018), but fewer embark on the journey to study how much of these data are necessary to upload, and also, how much data is needed to be downloaded into each vehicle, and at what rate and under what conditions. These questions are crucial when determining the looks of the electronic communication service for the future transport system.

5.2 Methodology

In this review, we focus on point 2) above, aiming to consider a future with CCAM fully implemented, i.e. all vehicles being connected, sending/retrieving data necessary for self-driving, i.e. Day 4 of Figure 37. A list of use case does emerge from such literature review, but we do not specify these ITS-services in more detail, and do not take the approach searching for use cases in the literature. We simply comment on literature where specifics about the content of CCAM and the need for connectivity is presented. Relevant information on this topic is scattered between sources such as academic papers, white papers, deliverable reports from large projects such as within EU, articles in media and so on. A strictly structured review is therefore not the preferred methodology in this case, increasing the risk of losing important manuscripts from alternative sources outside academic journals and topic-specific search engines such as TRiD. We do however perform both backward and forward snowballing where such information is available. A manuscript is firstly included or excluded from the review based on title and abstract/introduction, thereafter, included or not based on the content of the manuscript. If a manuscript is included, the snowballing approach is taken. Google and Google scholar are the search engines used for our review.

Based on the KPIs presented in the 5GCAR-project (5GCAR, 2017) and later confirmed as some of the most discussed KPIs by most of the manuscripts reviewed in this literature study, we identify four KPIs that are critical for the future of CCAM (in addition to the need for extrapolating communication services to operational traffic situation):

- **Data rate:**

Data rate is the number of bits sent per unit of time

- **Latency:**

As far as possible we focus on end-to-end latency.

- **Availability/Reliability:**

Availability: The probability that a system is declared available, which is dependent on e.g. reliability: The probability that the latency is less or equal to the required level of latency. We also consider coverage as a property of this KPI if found. See also Section 3.4.4 for an elaborated definition of availability.

- **Bottleneck and requirements for operative traffic situations:**

For the three first KPIs we identify requirements for a single vehicle with respect to communication. In addition, we also search the literature for possible bottlenecks with respect to a traffic situation, i.e. multiple communicating vehicles. A complex and large traffic flow would put stress on the communication network and its performance parameters, i.e. our last KPI is defined.

5.3 Review

Some of the manuscripts presented here are studying specific use cases to quantify a set of KPI for each service presented, including see-through, remote parking, etc. In this case, we identify all the presented use cases presented in each manuscript relevant for CCAM and extract the most extreme requirement for each of our KPIs.

5.3.1 Data rate

A review by Singh et al. (2019), with emphasis on the citation to Papadimitratos et al. (2009) within, is investigating the future communication system from a broad perspective and are dedicating a section to radio access technologies for autonomous vehicles. They point out that the fully automated vehicles tested today not are connected in terms of sharing data from their advanced sensor systems including LIDAR and visual cameras. The data rate for autonomous vehicles exchanging raw sensor data and processed data is assumed to be 100-700 Mbps for visual cameras, while high-resolution maps require low latency and throughput in Gbps, with high reliability and availability. These assumptions are largely based on Choi et al. (2016) where it is assumed that raw or compressed LIDAR data and data from vehicle cameras will play an important role with respect to providing other vehicles with a see through-service. Through specs and conversations with industrial partners they estimate a data rate of 100 Mbps for communicating each of these data sources to other vehicles or infrastructure.

For data rates in a future case of autonomous driving, at least for the use cases of remote driving for automated parking and see-through, it was envisioned by 5GCAR (2017) that a detailed video upload is necessary, projecting a data rate of maximum 29 Mbps per camera. This includes automated manoeuvring of the vehicle to available parking facilities.

In the white paper from AECC (Automotive Edge Computing Consortium, 2018), intelligent driving is presented through a use case where the drivers' physical conditions are monitored through in-vehicle sensors, cruising data etc. The required data rate for this service could be as much as 35 Mbps. They also presented high-definition map generation and distribution; however, the latency and availability are here assumed to be low, meaning that continuous data transfer from these services might not be necessary while driving.

In a white paper by 5G-PPP (2015), for the use case of bird's eye view, 40 Mbit/s is estimated, assuming four 10 Mbit/s pointing at an intersection. For one camera placed on a driving vehicle, 10 Mbit/s is necessary in the see-through use case. Similarly, Alieiev et al. (2015) describe requirements for vehicular communication for three use cases: Overtaking maneuver assistant system, platooning and cooperative sensing/see-through. They find that the required data rate is in the order of 220 Mbit/s, based on the most demanding use case (see-through).

All the above manuscripts present a future with a very high demand for data rates with respect to electronic communication for the future transport system. On the other hand, in a document prepared by ETSI TR (2019b) the use case of collective perception service (CPS) its presented. This work state that: "Simply broadcasting raw sensor data is not a viable solution, as this imposes very high requirements regarding data rates and transmission frequencies, especially with increasing number of sensors attached to vehicles or RSUs. Nevertheless, if the channel resource permits, the transmitting ITS-S may attach the raw data to the CPM in future releases". Here, the approach is that objects on and around the road segments are detected and classified internally in each ITS-station and only the list of objects with specific attributes are transmitted to the surroundings. In two simulation studies it is shown that messages below the size of 1100 bytes is generated typically with 10 Hz from each vehicle.

Requirements for CAM (Cooperative Awareness Message, information about vehicle dimensions, speed, direction etc.) and DENM (Decentralized Environmental Notification Message, information about vehicle surroundings) are found to be 100 to 600 Bytes for CAM and 300 to 800 Bytes for DENM, without security, and anyway below 1500 Bytes with security (Härri, 2016). In CAR 2 CAR Communication Consortium (2018), CAM are shown to be sent typically 3 times a second with an maximum size of 800 Bytes. A typical example of a service where CAM might be appropriate is cooperative adaptive cruise control (CACC) which is defined by ETSI TR (2019a) with a minimum of 30 Hz update frequency, giving a maximum of 192 kbps.

A study by Boban et al. (2018) quantified performance requirements for the use cases of cooperative awareness, -sensing and -manoeuvres, vulnerable road users, traffic efficiency and teleoperated driving. The required data rate for these use cases varies between 5 and >25 000 kb/s per vehicle.

5.3.2 Latency

The 5GCAR-project (5GCAR, 2017) cites an estimate from ETSI TR (2011) for end-to-end latency requirement of 5 ms in the future transport system and envision 5G to meet these requirements.

A review of current vehicular communication technologies was conducted by Papadimitratos (2009), focusing on past and then on-going projects, available wireless technology and some requirements for ITS-services, such as emergency electronic brake lights, pre-crash sensing and map upload/download. They estimated latency for these services in the range of 100-1000 ms. However, this paper is not considering intelligent driving / CCAM as use cases.

In 5G-PPP (2015), several of the use cases is assumed to require an end-to-end latency of 10 ms, including automated overtake and high density platooning. The aforementioned study by Boban et al. (2018) reports end-to-end latency in the range of 3 ms to >1s, depending on use case type, whilefor the use cases described by Alieiev et al. (2015), the required latency is 3.3 ms.

5.3.3 Availability/Reliability

In terms of availability, 5GCAR (2017) envisions 99.999 % for their use case of remote driving for automated parking. This includes automated manoeuvring of the vehicle to available parking facilities. Coverage is not treated specifically, but for the most advanced use case of automated remote driving to a parking facility, a coverage of several km is required with ultra-high availability and reliability (99.999 %), implying 100 % coverage of the area of this service the only option.

In 5G-PPP (2015), availability is quantified. Here as well, 99.999% is the number mentioned, in this case illustrated with automated takeover and cooperative collision avoidance services. They point out early in their white paper that connectivity is crucial for wide deployment of ITS services. Coverage will be necessary "along road and in low-density areas", and that data needs to be available practically everywhere, including device-to-device communication where network coverage might lack.

The study by Boban et al. (2018) estimate a required reliability of <90 % for the traffic efficiency use case, 90-95 % for cooperative awareness, and >95% for the other mentioned use cases, with teleoperated driving demanding the absolute highest reliability of approximately 100 %.

5.3.4 Bottleneck and requirements for operative traffic situations

Heineke et al. (2019) envision V2X both using "multitude of connected devices along the roadside", and C-V2X solutions. Connections to OEM clouds and common clouds will be key, in addition to direct communication. The latter will mainly rely on the ITS 5.9 GHz spectrum, but the "cellular network can assist" (5G in particular), especially with respect to none-line-of-sight systems. They emphasise that ubiquitous connectivity is key for autonomous driving, and that 5G will be key enabler for more reliable communication for vehicles, reducing latency (ten milliseconds end to end, one millisecond over air) and increasing reliability (targeting 99.999 %). However, they do not comment whether this will be a requirement for the future, but state that the increase in data from vehicles on the road will put significant stress on network capacity and latency.

The Automotive Edge Computing Consortium (2019) are studying solutions for the future high-volume data requirement of the future transport system, and build evaluating architecture and solutions focusing on the three key issues pertaining to data integration within Localized Networks; 1) Edge data offloading, 2) MSP Server Selection and 3) Vehicle System Reachability. The AECC also estimate that the related data traffic has the potential to exceed 10 exabytes per month by 2025 (Automotive Edge Computing Consortium, 2018)

The 5GCAR-project points out that the future road network must be able to "handle a very large density of connected vehicles", where in particular a specific reliability must be ensured for the whole fleet (5GCAR, 2017). Their estimate of vehicle density for urban environments is in the order of 1000 to 3000 vehicles/km^2. These requirements will have to be met for vehicles at a very high velocity, with 150 km/h being the upper speed limit in Europe. In the simulations performed in ETSI TR (2019b), 120 vehicles/km is used as high density traffic, citing the 3GPP guidelines for V2X simulations (3GPP TR, 2016).

A report from Ericsson expects data growth as a result of communication systems within the transport sector, pointing out that millions of vehicles already are connected through cellular network (Cerwall, 2019).

In the white paper from the 5G-PPP the KPI *Network density* (vehicles/km^2) is introduce, which defines the number of vehicles per unit area for which a specified reliability of a service must be achieved (5G-PPP, 2015). They estimate that in an urban environment a maximum of 3000 vehicles must be supported as the same time, i.e. that requirements for latency and reliability must be ensured for this number of vehicles at once. They also comment on the relative velocity between vehicles that the service must be operative under, see the white paper for details.

5.4 Summary of results and discussions

The quantified requirements found in the reviewed literature is presented in the Table 3 below.

Table 3: Summary of results from literature review, presented by use case.

Use case	Data rate	Latency	Availability/ Reliability	Bottleneck and requirements for operative traffic situations
Sensor data exchange	100-700 Mbps [1] [2]			
High-resolution maps	1 Gbps [1]	Low [1] [4] 100-1000 ms [3]	High [1] Low [6]	
Remote driving for automated parking	29 Mbps per camera [4]		99.999 % [4]	
See through	29 Mbps per camera [3] 10 Mbit/s per camera [5] 220 Mbit/s [5]			
Monitoring of drivers' physical conditions	35 Mbps [14]			
Bird's eye view	40 Mbit/s [7]			
CAM/DENM-message (ex. CACC)	<200 kbps [8] [9] [10]			
Collective Perception Service	88 kbps [11]			
Cooperative awareness, -sensing and -manoeuvres	5-25 000 kbps [12]	3-1000 ms[12]	90-95 % [12]	
Vulnerable road users	5-10 kbps [12]	100-1000 ms [12]	>95 % [12]	
Traffic efficiency	10-2000 kbps [12]	>1000 ms [12]	<90 % [12]	
Teleoperated driving	>25 000 kbps [12]	5-20 ms [12]	99.999 % [12]	
Emergency electronic brake lights		100-1000 ms [3]		
Pre-crash sensing		100-1000 ms [3]		
Automated overtake		10 ms [7] 3.3 ms [5]	99.999 % [7]	
High density platooning		10 ms[7] 3.3 ms [5]		
Cooperative collision avoidance			99.999 % [7]	
Vehicle density for urban environments				1000 to 3000 vehicles/km^2[4][7]
Simulation of high density traffic				120 vehicles/km [13]
General estimate		5 ms [3]		
Total data traffic				>10 exabytes bytes per month[6]

[1] Singh et al. (2019), [2] Choi et al. (2016), [3] Papadimitratos (2009), [4] 5GCAR (2017), [5] Alieiev (2015), [6] Automotive Edge Computing Consortium (2019), [7] 5G-PPP (2015), [8] Härri (2016), [9] CAR 2 CAR Communication Consortium (2018), [10] ETSI TR(2019a), [11] ETSI TR(2019b), [12] Boban et al. (2018), [13] 3GPP TR (2016), [14] Automotive Edge Computing Consortium (2018).

For use cases regarding cooperative driving, e.g. see through, cooperative awareness, sensing and traffic efficiency, the required data rate is on the Mbps to Gbps range. The current frequency allocations for V2X communications are not sufficient to support the high data rates required by some of the identified services even under idealistic conditions. The 10 MHz channel bandwidth used by the current IEEE802.11p-based DSRC and LTE-V2X in the 5.9 GHz band may support up to 20-30 Mbps under good conditions, but typically less. The emerging technologies IEEE802.11bd DSRC and NR-V2X are considering mmWave frequencies, e.g. in the 60GHz band, which may provide much higher bandwidth. However, communication in mmWave bands does require line-of-sight and conditions that may be difficult to obtain and maintain in a vehicular environment.

For use cases more specifically related to traffic safety, the focus is on latency and reliability and not necessarily data rate. The requirements for latency are in the magnitude of a few ms, while availability and reliability are close to 100 %. The use case of teleoperated driving require data rates in the range of cooperative awareness and latency and reliability conditions similar to the traffic safety use case. In terms of traffic, use cases need be able to handle densities up to 3000 vehicles/km2 or 120 vehicles/km (depending on the areas or road segments considered).

Our literature review also revealed the ongoing discussion between DSRC and C-V2X. Stakeholders affiliated to the telecommunication industry typically argue for high data rate requirements (up to 10-200 Mbps with low latency and high reliability), while ITS-G5 based infrastructure require much less (a few hundred kbps). Therefore, concluding this review with recommendations regarding future communication needs for CCAM is difficult, particularly since the requirements depend heavily on how CCAM is implemented (e.g. whether or not raw sensor data needs to be shared with the surroundings (Choi et al., 2016)).

5.5 Bibliography

3GPP TR. (2016). *36.885 V14.0.0; Study on LTE-based V2X Services;(Release 14)*.

5GCAR. (2017, August 31). *Deliverable D2.1 5GCAR Scenarios, Use Cases, Requirements and KPIs*. https://5gcar.eu/wp-content/uploads/2017/05/5GCAR_D2.1_v1.0.pdf

5G-PPP. (2015). *5G-PPP White Paper on Automotive Vertical Sectors.pdf*. https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White-Paper-on-Automotive-Vertical-Sectors.pdf

Alieiev, R., Kwoczek, A., & Hehn, T. (2015, April 6). *Automotive requirements for future mobile networks—IEEE Conference Publication*. https://ieeexplore.ieee.org/abstract/document/7117947

Automotive Edge Computing Consortium. (2018). *White Paper, General Principle and Vision, Version 2.1.0*.

Automotive Edge Computing Consortium. (2019, September 19). *AECC Publishes Technical Report, "Driving Data to the Edge: The Challenge of Traffic Distribution."* https://www.businesswire.com/news/home/20190919005890/en/AECC-Publishes-Technical-Report-Driving-Data-Edge

Boban, M., Kousaridas, A., Manolakis, K., Eichinger, J., & Xu, W. (2018). Connected Roads of the Future: Use Cases, Requirements, and Design Considerations for Vehicle-to-Everything Communications. *IEEE Vehicular Technology Magazine*, *13*(3), 110–123. https://doi.org/10.1109/MVT.2017.2777259

CAR 2 CAR Communication Consortium. (2018). *Survey on ITS-G5 CAM statistics* (C2CCC_TR_2052).

Cerwall, P. (Ed.). (2019). *Ericsson Mobility Report June 2019*.

Choi, J., Va, V., Gonzalez-Prelcic, N., Daniels, R., Bhat, C. R., & Heath Jr, R. W. (2016). Millimeter Wave Vehicular Communication to Support Massive Automotive Sensing. *ArXiv:1602.06456 [Cs, Math]*. http://arxiv.org/abs/1602.06456

ETSI TR. (2019a). *ETSI TR 103 299 V2.1.1; Intelligent Transport System (ITS); Cooperative Adaptive Cruise Control (CACC); Pre-standardization study*.

ETSI TR. (2019b). *ETSI TR 103 562 V2.1.1; Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective-Perception Service (CPS); Release 2*. https://www.etsi.org/deliver/etsi_tr/103500_103599/103562/02.01.01_60/tr_103562v020101p.pdf

ETSI TR. (2011). *ETSI TR 102 889-2 V1. 1.1; Electromagnetic Compatibility and Radio Spectrum Matters (ERM)*.

European Commission. (2019). *Commission Delegated Regulation (EU) of 13.3.2019 supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the deployment and operational use of cooperative intelligent transport systems*. European Commision.

GSM Association. (2019, April 9). GSMA letter to the European Parliament on Delegated Act C-ITS. *GSMA Europe*. https://www.gsma.com/gsmaeurope/news/gsma-letter-to-the-ep-on-delegated-act-c-its/

Härri, J. (2016, July 27). *MTU and size of a typical CAM / DENM / ITS messages*. https://mailarchive.ietf.org/arch/msg/its/ulRAN2Am8OrILKtNBrQ4otM8Pu0

Heineke, K., Ménard, A., Södergren, F., & Wrulich, M. (2019). *Development in the mobility technology ecosystem—How can 5G help?* (p. 10).

Islam, T., Hu, Y., Onur, E., Boltjes, B., & de Jongh, J. F. C. M. (2013). Realistic simulation of IEEE 802.11p channel in mobile Vehicle to Vehicle communication. *2013 Conference on Microwave Techniques (COMITE)*, 156–161. https://doi.org/10.1109/COMITE.2013.6545061

Krzanich, B. (2016, November 15). *Data is the New Oil in the Future of Automated Driving*. Intel Newsroom. https://newsroom.intel.com/editorials/krzanich-the-future-of-automated-driving/

Papadimitratos, P., La Fortelle, A., Evenssen, K., Brignolo, R., & Cosenza, S. (2009). Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation. *IEEE Communications Magazine*, *47*(11), 84–95. https://doi.org/10.1109/MCOM.2009.5307471

Singh, P. K., Nandi, S. K., & Nandi, S. (2019). A tutorial survey on vehicular communication state of the art, and future research directions. *Vehicular Communications*, *18*, 100164. https://doi.org/10.1016/j.vehcom.2019.100164

6 Requirements and needs – planning tool LambdaRoad

Randi Ann Fagerholt and Odd André Hjelkrem

6.1 Introduction

As a part of WP1 in LambdaRoad, a specification of needs and requirements for the planning tool is needed. The suggested purpose of this planning tool is to provide information about the signal strength of 4G/5G or ITS-G5 along the road and further give relevant information for planning new system components (such as deployment or modification of ITS-stations) and recommendations for additional supportive infrastructure. This chapter maps up the requirements and needs of actors potentially using a planning tool for hybrid digital communication infrastructure. We use ARKTRANS as a framework to define the scope of the planning tool. ARKTRANS use a top-down approach to define requirements (Foss, 2015). By using actors from the LambdaRoad project, we can evaluate the accuracy and applicability of this general model. The ARKTRANS-model consists of a variety of abstract roles with associated responsibilities. An actor is a specific person, department, organisation or company that undertakes to fulfil one or more of the role's responsibilities. Figure 38 shows a model of abstract roles and their connection to each other. Brief descriptions of the different roles are presented below.

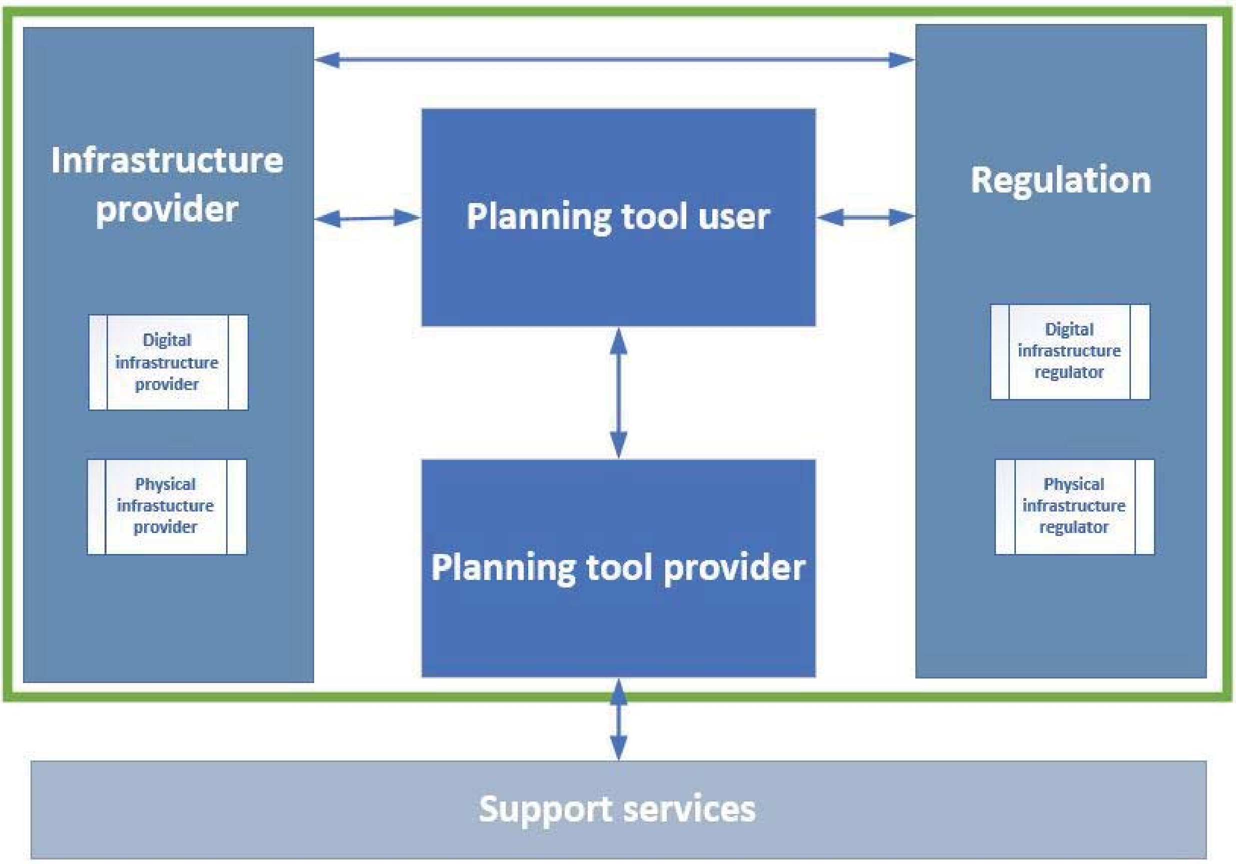


Figure 38: Theoretical model of actors involved in the planning tool

6.1.1 Planning tool user

The first role is the planning tool user, and this role includes:
- defining the need for a planning tool, safety, and functionality demands
- entering a contract with planning tool provider

- control that the planning tool works properly and give expected results

6.1.2 Planning tool service provision

The second role is the planning tool providers. This role includes:

- develop, maintain, and hold ownership of the planning tool
- enter contract with the planning tool users regarding any payment for and delivery and use of the tool
- schedule data harvest based on user requirements and available services
- schedule the implementation of the planning tool delivery.
- conduct and control the execution of the planning tool

6.1.3 Infrastructure provider

The third role includes providing infrastructure on which the planning tool depends. This is a role that involves two types of infrastructure:

Physical infrastructure provider

- Plan, builds, manages, operates, and maintain a physical infrastructure
- Adhere to the regulations and licenses issued by the regulators

Digital communication infrastructure provider

- Plan, builds, manages, operates, and maintain a digital communication infrastructure, e.g. the infrastructure for e-communication such as telecom (3G/4G/5G) or ITS-G5 communication
- Adhere to the regulations and licenses issued by the regulators

6.1.4 Regulation

The fourth role includes regulation of the planning tool, involving both road and communication authorities, thus two subcategories of regulation:

Digital communication infrastructure regulation

- Draw up regulations and manage authorizations schemes.
- Controlling the compliance of actors with the issued regulations, and concessions.
- Interventions and sanctions, e.g. fines in those cases where an actor does not fulfil instructions given as a part of the monitoring services.

Physical infrastructure regulation

- Develop laws, regulations, and guidelines, and ensure that the planning tool comply with other regulations such as privacy, universal design, and social security.

6.1.5 Support services

The fifth role includes support services to the planning tool, e.g. provide input data to the planning tool on the following areas: surface, elevation, terrain, base stations, and traffic data.

6.2 Methodology

We based our data collection on in-depth qualitative interviews. In the data collection, we have obtained data from actors that will have different roles, responsibilities, and demands for the tool. We conducted semi-structured interviews to acquire in-depth knowledge of how both private and public actors perceive their roles, needs, and responsibilities for the planning tool, how business and management models can be developed and preferred technical features of the planning tool. We conducted six interviews and interviewed ten people in total. Two interviews with representatives from NPRA, two interviews from representatives from Telenor, and one interview with respectively Q-Free and NKOM. We based our selection of respondents on a strategic selection where the companies and organizations themselves appointed the most suited candidates based on the main topics in the interview guide.

Semi-structured interviews were preferred as a method of initial data collection since there is not much pre-existing knowledge on the issue. The model in Figure 38 was used as a starting point in the interviews. The information collected from interviews is suited for answering the main subjects because we are interested in the subjective opinions and experiences of the respondents (Tjora, 2010). Although the opinions of the respondents are to some extent subjective, we have written the analysis as though the information represents their employer, for simplicity. We acknowledge that this may not always be true, although we believe that the respondents chosen in this study holds positions within their organization that make them capable of representing their organization and not just their subjective opinion. In addition, the information gathered through the interviews is supplemented with relevant literature and other documents.

We based all the interviews on an interview guide developed in advance (see appendix A). Not all the prepared questions were relevant for all the informants we interviewed, so we tailored the question to each interview. The main themes that were addressed in the interviews were overall needs the planning tool will cover, ownership and any forms of collaboration, what barriers and opportunities the different actors describe, as well as features, input, and output data.

6.3 Roles

In the following chapter, we will introduce the actors that may be relevant for the various roles based on both the theoretical model and the interviews. Some actors will have a sense of belonging in several roles. Considering the organisation and responsibilities of the service, the theoretical model is approved by all actors. Nevertheless, this is at an early stage, and critical parts of the organisational aspects are still to be determined.

6.3.1 Planning tool user

The role of planning tool user may involve several actors. A typical actor in need of this planning tool is equipment providers (e.g. Q-Free, Aventi, etc.) responsible for building, operate and maintain equipment and in the need for planning ITS stations along the road. As well as road authorities (e.g. NPRA) by being road owner and responsible for the road network and how this should be instrumented physically to ensure sufficient support for future ITS services. The regulator of digital communication infrastructure (NKOM) is also a potential user of the planning tool by needing information about infrastructure, roads, and deficiencies, especially when frequency resources are put out for tender by NKOM and a mobile coverage requirement is also set. The municipalities and county councils may also be potential planning tool users, both for planning ITS stations and for planning base stations.

6.3.2 Planning tool service provision

In this case, the actor responsible for providing the planning tool can be NPRA and/or NKOM. As of today, the two actors do not agree on who should be responsible for the provision of such a service. Neither NPRA nor NKOM is designated as the planning tool service provider (owner) in the interviews. The informants see both the potential benefits and challenges by having either NPRA or NKOM as an owner of the tool. It is stressed that NKOM has a role and a connection with the mobile operators already, while NPRA lacks this knowledge and experience. In addition to this, NPRA has trouble identifying ownership of such a planning tool in their mandate. Furthermore, the challenges of ownership among both actors are linked to resources related to operations and maintenance. For NKOM, ownership will require large in-house resources for operation and maintenance, and their IT departments do not have the resources nor capacity as of today. NPRA also stress this, specific funding from a governmental level is required for them to undertake ownership of the planning tool.

Lack of agreement on ownership of the planning tool is expected because these two sectors have not previously cooperated to a large extent. This means that these two actors need to coordinate and discuss such issues. Furthermore, considerable effort is also needed by the actor that becomes responsible for the tool, for instance in terms of recruiting new expertise and dedicating time and money.

6.3.3 Infrastructure provider

NPRA, the counties, and municipalities have sector responsibility for road traffic and are currently responsible for physical infrastructure on the road, e.g. roadside equipment, while the telecom operators (Telenor, Telia, and Ice) has responsibility for providing the digital communication infrastructure, mobile coverage, along the road. Another digital communication infrastructure is ITS-G5, and NPRA, the counties, or the municipalities as road owners are considered the provider of roadside ITS stations. This is explained by the fact that the road owner should also be the owner and responsible for all roadside equipment.

6.3.4 Regulation

When it comes to regulation of digital communication infrastructure, NKOM is responsible for, and sets requirements for coverage of licenses for mobile communications. In addition, they set requirements for transmitted signals such as maximum effect in all frequency bands to prevent interference problems and ensure coexistence between systems. NKOM is also responsible for managing the frequency resources in Norway, thus an obvious actor in the role as regulator for digital communication infrastructure. Frequency resources are needed to provide wireless communication services such as ITS-G5 and mobile communication, and e.g. telecom operators pay for access to these frequencies. The Ministry of Transport, the Ministry of Local Government and Modernisation, and the Norwegian Data Protection Authority are actors that also can hold the role of regulator for digital communication infrastructure. The Ministry of Transport by having overall responsibility for the framework conditions for public roads, and The Norwegian Data Protection Authority is a public authority on The Personal Data Act which may be relevant considering that data on future vehicles can be sensitive and require regulations concerning data protection.

NPRA is responsible for and must set requirements for roads and vehicles, i.e. physical infrastructure regulation. Other departments may be relevant for the role as the regulator of physical infrastructure, e.g. authorities responsible for that the deployment of base stations/equipment does not unnecessarily intervene in natural areas (e.g. The Norwegian Environment Agency).

6.3.5 Support services

The actors responsible for the data input for support services are The Norwegian Mapping Authority (geonorge.no), registers operated by NKOM (finnsenderen.no), and the NPRA (providing e.g. traffic data).

6.4 Requirements and need for the planning tool

At a general level, we find a significant need for the planning tool. Potential users describe a need for proper infrastructure for ITS and the realisation of this concept. The tool can help reduce the uncertainty surrounding the C-ITS concept. A planning tool can also shed light on what is required to realize future transport by pointing out needs and requirements and initiate processes of what is needed for development and responsibilities for the various parts of the tool and how it can be budgeted. In addition to this, we find a need for the tool to set requirements for further development of the e-communication networks, to set precise mobile coverage requirements through the information of infrastructure and equipment along the road, and as an input to the international work on harmonising frequency use for ITS.

However, Telenor has difficulties embracing a need for the planning tool as it is presented at an early stage. They have their own tools to predict mobile coverage and see little benefit in creating a new tool nor be a potential user of this tool unless this is better and more advanced compared to their current prediction tools. The enabling parts of the planning tool as Telenor sees it is 1) to improve own models by capturing cuts on roads where there is no coverage, and 2) to create an interactive map that conveys coverage quality in real-time (e.g. useful in storms and harsh weather).

We find a distinction between the actors belonging to the road sector and the communication sector. As mentioned earlier, these two sectors have not cooperated previously, and their relations may be characterized by limited insight into the other sector and their priorities. This is evident in various thoughts about utility, and how the planning tool should and should not work. The interviews were done at an early stage where no specifications were made for the tool, which has led to the need for additional data on the need for the planning tool, and how a collaborative platform should be developed. In this work, it is particularly important to specify future scenarios where there may be increased demands for e-communication related to the future transport system.

6.5 Forms of collaboration

The role as the regulator of the digital infrastructure (NKOM) is highlighted as a critical role by both Telenor and NKOM when it comes to collecting data for calculating mobile coverage. The goal of the planning tool is not to control the coverage given by different telecom operators, but rather to predict roadside coverage when installing new communication infrastructure. Each telecom operator has their own tools to do coverage estimations and may have different coverage thresholds when they do predictions. Telenor stresses the importance of a consensus of what the coverage threshold should be, completely independent of which operator is responsible for the mobile coverage in different areas. NKOM is considered a neutral party for all providers of digital communication infrastructure (telecom infrastructure operators), especially with regards to setting the threshold values that indicate mobile coverage. NKOM also points to this as a potential challenge and recommends that they are given the authority to do the calculation for all three telecom infrastructure operators, on equal demands with equal adjustments for all three operators, as they already do this through market regulation to ensure that operators compete under equal terms and to provide reliable electronic communication services with adequate capacity and functionality. There is particularly one challenge with this solution. NKOM collects data from the three operators quarterly, and the question is whether the telecom operators accept that the planning tool service is updated with coverage data a maximum of four times each year or if they demand a more frequent update. Both Telenor and NKOM point out that the alternative calculation, which is that each telecom operator predicts mobile coverage themselves using different prediction tools, is a less favourable solution, risking the coverage threshold being set differently among the three telecom operators and may result in lower and uneven capacity, quality and functionality.

NKOM has experience calculating mobile coverage, but no experience calculating coverage for ITS-G5. If they are to make calculations of the total coverage (both mobile coverage and ITS-G5) along the road, NKOM must increase its expertise in this field.

6.6 Specific requirements for the planning tool

The second part of the interviews focused on technical requirements for the planning tool. Here, we based the questions on the Open Distributed Processing (ODP)-model (ISO/IEC 10746), which defines standards for a system architecture, based on concepts, definitions and rules. It consists of five viewpoints:

- **Enterprise** viewpoint, which is about roles of various agents defines in the system, and the environment around the system. This viewpoint relates mainly to the material presented before chapter 6.6.

- **Computational** viewpoint, which focus on the functionality of the planning tool. This viewpoint describes what the planning tool should do on a general level.
- **Technology** viewpoint, which describe the physical architecture of the system.
- **Information** viewpoint. This viewpoint is about data flow in the planning tool, i.e. input data, output data and data format.
- **Engineering** viewpoint, which relates to how the planning tool should be designed programmatically and especially concerning the user interface.

The data from the interviews were used as an input for describing the requirements for the planning tool and is sorted into subchapters relating to the viewpoints.

6.6.1 Functionality – computational viewpoint

When it comes to the functionality of the planning tool, the actors point to three main functions –

1) **Visualize** background data. The visualization of background data such as terrain surface, road network, traffic volume and mobile coverage.
2) **Plan ITS stations**. As of today, there is no dedicated tool for planning ITS-stations, to our knowledge. However, it might be possible to use existing tools for general network planning for this purpose, but it is unclear if this will work as intended. A functional tool will help the user to quantify and visualize the impact of new infrastructure.
3) **Plan mobile base stations**. This functionality is very similar to the previous bullet point, but with one important difference. Because the mobile operators already use other tools for estimating coverage for mobile networks, they do not see the need for another tool. However, this functionality will have some added value to existing mobile coverage. First, other project partners and users do not have direct access to other similar tools. Second, the mobile coverage calculated by other tools can be used as an input in the planning tool, to be used when planning a combination of ITS- and mobile base stations.

6.6.2 Use cases – computational viewpoint

A suggestion made in the interviews was the opportunity to choose different modules in the planning tool with the possibility to plan for different types of road sections. In this way, the modules can meet the requirements and needs of different road segments, such as urban roads, highways, or tunnels.

There are various arguments among the actors on what use cases are most relevant for the planning tool. Some point out that flat areas without obstacles in the roadway are not in the need for this tool. The problematic areas are road sections with high accident risk or with an extensive need for information, such as roads with rocky hills, slopes, mountain crossings, bewildering intersections, winding roads and hilly terrain, or areas where road work is carried out. Others focus on that the C-ITS services will be established on the most trafficable areas first and therefore points to these routes (mainly highways) as most relevant as a use case. In addition to this, several informants mention especially areas consisting of many tunnels and submarine tunnels as potential use cases due to limited coverage in tunnels. Hålogalandsbrua was mentioned as a specific use case.

6.6.3 Input data – information viewpoint

Several informants suggest that map bases with terrain models is necessary, which allows planning along the specific road and to find the best location on mobile communication such as 4G/5G, and which areas need to be supplemented with G5 along the road to get complete coverage.

Other suggestions for input data to the planning tool are information about power sources, annual average daily traffic, tunnels, and information on where the Mapping Authority's base stations for GPS are placed, which is important for autonomous vehicles that depend on both communication and accurate GPS signals.

Others call attention to a need for information concerning the surroundings that may interfere with the construction of physical infrastructures, such as military installations, nature conservation, or archaeological sites.

It was also mentioned that map sources from other countries are needed to use the tool in an international market. NKOM points out that information about passive infrastructures such as cableways, access points, and info on where to place equipment is advantageous for developing not only for C-ITS but e-communication in general along the road.

6.6.4 Output data – information viewpoint

The main result of the planning tool should be a quantification and visualization of the quality of e-communication, e.g. coverage.

One informant from NPRA suggested that the tool could provide a "to-do-list" showing what needs to be done to establish coverage on the given road section and how much it costs (e.g. x NOK for building a base station, x NOK for building a transformer, x NOK for power, x NOK for building high voltage power, and x NOK for building an ITS station). In this way, the tool could give an overview of the total cost of establishing coverage on a specific road section. This is also mentioned by NKOM, which needs such information in its role as regulator and as a part of tendering processes. As of today, NKOM lacks information on what it cost telecom operators to provide mobile coverage on specific road segments, e.g. the total cost of building a base station, with all the additional costs this entails (electricity, fibre, etc.).

6.6.5 Data format – information viewpoint

It was suggested that the tool should not rely too much on manual user input, especially regarding the input data. Therefore, the tool should mainly be based on APIs for the main components needed for the functionality. One important distinction in the input data is to separate between background data and infrastructure information, where the latter depends on specific user input. This user input could be either entered through the graphical user interface (GUI) or in a well-defined file format.

Regarding the output data, the visualization is regarded the most valuable. However, the results must also be available for export. This could be a textfile for generic use, or other formats to use the results for specific purposes, e.g. BIM.

6.6.6 User interface - engineering viewpoint

There are three main choices for the user interfaces when the main requirement for the tool is to have a graphical user interface:

1. A software product, which is considered out of the scope of the project.
2. In a GIS-software, which include the ability and functionality to visualize, edit and process geographical data.
3. As a web service. Although some of the flexibility of a GIS-based interface will be lost, a web-based tool will not require any knowledge about GIS-software.

6.7 Potential barriers and opportunities

The interviews revealed potential barriers for the planning tool, as well as potential opportunities that may arise in the development of this service.

SINTEF

6.7.1 Electricity and fiber

To realize the future transport system in general, NPRA stresses that when new roads are built, the regulator for digital infrastructure must have explicit requirements for building infrastructure that provides total coverage or at least the possibility for total coverage along the entire road section being built (e.g. by having fiber along the road). This to ensure the future use of what C-ITS solutions may come. Telenor draws attention to especially electricity as well and emphasizes that new roads must have cable conduits with the ability to draw electricity, as the mobile coverage depends on access to electricity. NPRA suggests that it is relevant to look at the experiences made in the Borealis project, where a 40-kilometer road in northern Norway has become a national test laboratory for new technology. Here, NPRA tests and develops intelligent transport systems (ITS). NPRA experienced that it in terms of getting a sufficient infrastructure for ITS, it was important to get information on who could supply fiber and who could supply the electricity in the local areas. The experience of the Borealis project showed that electricity is a huge cost because the power companies must calculate for each order that is made, based on length, the size of the transformer and if others need access to electricity in the area. However, the power companies often miscalculate the costs of establishing electricity along a road section, making it difficult to include these costs in the planning tool. In addition to this, NPRA saw great advantages to cooperate and have continuous communication with contacts within the telecom operators' companies that specialize in coverage on mobile communication.

6.7.2 Permissions from the telecom operators

NKOM is responsible for the register which provides information on the position of the base stations, but not the frequencies transmitted. NKOM emphasizes that data collected is given trough special permission from the telecom operators to use the data for this purpose. NKOM does not want to challenge the position they have or risk the cooperation with the telecom infrastructure operators. A new agreement with the operators must be developed to use this data for other purposes than the service www.finnsenderen.no.

6.7.3 Data safety and use of data

Data safety is a critical factor in the development of the planning tool. The overall database for mobile operators' base stations is defined as unclassified shielding worthy information. Both Telenor and NKOM emphasizes that the planning tool must be developed in such a way that safety-critical services are considered. The tool has the option of being open, but there must be restrictions on how to download information from the system. Potential actors that need access to this data (e.g. SINTEF) must attend an authorization conversation with NKOM, and an agreement must be made on how to receive data, which persons will be responsible for the data that is received, and that data is stored properly and not shared.

Furthermore, one informant points out that, they have faced challenges with too severe restrictions on the use of data, resulting in not being able to access data for the use of C-ITS.

6.7.4 Economy and funding

As mentioned in 6.3.2, the potential owners stress that operating and maintaining the planning tool will demand external funding.

6.7.5 Map data limitations

A challenge that is mentioned is that the municipalities and others who provide input to the Norwegian Mapping Authority do not report regularly, which results in inaccurate maps that may interfere with the mobile coverage. E.g. when reporting forests, the maps may say that the forest is measured at 10 meters, but the forest is measured to 30 meters because the map basis is not updated. Telenor has discussed this challenge with the Mapping Authority several times.

6.7.6 International market

Q-free emphasizes that the planning tool should be able to be used in other countries and that the tool is not limited to Norway by either practical or legal reasons. By using open source maps that are available to other countries instead of basing the map sources entirely on the National Road Database, will make it possible to use the planning tool internationally. Ownership may affect legal issues that may give restrictions in terms of international use, e.g. license-based use that applies only to Norwegian roads.

6.7.7 Crowd sourcing

An informant points to the possibility of using crowd sourcing, and whether this is an opportunity to get real measures of coverage instead of predictions. This may be a better solution than predictions, especially in areas where base stations are located in urban areas where many obstacles can get in the way (e.g. signs, neighbouring buildings, roofs, etc.). By using crowd sourcing, each device must accept and consent to the use of data, and where measurement data is reported back, such as signal strength as function and time, and signal quality as function and time.

6.8 Bibliography

Foss, Trond (2015). Fra ARKTRANS til kravspesifikasjoner for ITS applikasjoner. SINTEF-rapport. Trondheim: SINTEF Teknologi og samfunn

Tjora, Aksel (2010). *Kvalitative forskningsmetoder i praksis.* Oslo: Gyldendal akademisk

A Appendix

A.1 Interview guide

1) Identification of roles and needs

Roles, needs and responsibilities

- Needs for the planning tool in the role as … (give a priority)
- Views on the model – is this a role you can recognise? What are your thoughts on the other roles in this model?
- What is clear today regarding this/these role(s)?

- What do you need to change inside your own organization for the tool to be used?
- Do you have sufficient knowledge of the "other" sector (transport/communication)?
- Do you need any new form of expertise internally?
- Do you have to organize different internally compared to how the organization is today?
- Any new collaborations needed in order for the tool to be used?

- Who should be the owner of the planning tool?

- Any experiences gained in the past through collaboration on the development of innovative services in the public/private sector?

Barriers

- Any obvious barriers associated with roles and responsibilities as presented here?
- How to organize cooperation in an efficient and profitable way?
- How should collaboration be organized to realize communication for road transport?

2) The planning tool

The planning tool (ODP: Computational viewpoint)

- What features should the tool have? (be as specific as possible – prioritize if many features)
- What area of use is needed? (Give a specific use case)
- What results should the tool give? (As specific as possible)
- What quality should the results have?
  - Accuracy – how detailed?
  - Data security and access control

Technical features, result format, and data (ODP: Informational viewpoint)

- How should the User Interface be?
- What result format should the planning tool provide?
- Any standard for presenting signal strength or coverage?
- What condition for sharing data, and with whom?
- Which programming language should be used? (ODP: Engineering viewpoint)
- Do you see any problems with large amounts of data?
- Do you see any technical barriers that should be considered?

Barriers

What do you think are the biggest barriers to the successful realisation of digital communications for road transport and what can possibly be done to prevent the barriers becoming so large that the ITS service cannot be introduced.

Technology for a better society

www.sintef.no