Improving Information Dissemination in Sparse Vehicular Networks by Adding Satellite Communication

Master Thesis

by

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Abstract

Research in the field of Intelligent Transport Systems (ITS) is emerging, motivated by the need for improved road safety and environmental concerns. In Europe, many traffic fatalities occur each year and the transportation industry is one of the largest emitting industry of greenhouse gases. These problems can be mitigated by the use of vehicular networks, safety applications can directly affect road safety and indirectly improve traffic flow resulting in less emission.

Information dissemination in pure Vehicular Ad hoc NETworks (VANET) becomes problematic when the network is sparse. This is certainly the case in the early years of market introduction, because of the low market penetration. Moreover, in rural areas or during night-time the vehicular network can become sparse due to low traffic density. Sparse vehicular networks become fragmented, resulting in disconnected clusters of vehicles due to the limited communication range of Car-to-Car (C2C) technology. Therefore, information dissemination beyond these clusters is impossible or leads to massive delays by using techniques such as Store-Carry-Forward.

This thesis proposes the addition of Car-to-Satellite (C2S) communication to solve this issue. The large coverage of C2S complements C2C, this way the satellite can be used to bridge communication between clusters, hence information dissemination can be improved. The impact of supplementing C2C with C2S is quantified by simulating a realistic real-world scenario.

A rural area in the southern part of Germany has been simulated, by using OpenStreetMap and real traffic data from official traffic census. The simulation is executed using SUMO, for traffic simulation, in conjunction with ns-3, for simulating information dissemination. The information dissemination is evaluated with respect to the in-time reception of safety-related information, by means of a Road Hazard Warning (RHW) application. This application implies that a vehicle driving through a rural area detects a dangerous situation on the road and sends out a RHW to all vehicles in the vicinity. The RHW is kept alive within a certain area, called the area of validity, for some period of time, which is called the time of validity or Time to Live (TTL).

The results show that information dissemination can be significantly improved through a limited number of C2C vehicles which are additionally equipped with C2S. In fact, if the results are related to the prediction of C2C market introduction, it is shown that adding C2S can have the same effect as pushing forward the market introduction of C2C significantly by up to 12 years. Hence, combining C2C with C2S can have great impact on the future of cooperative ITS.

Acknowledgments

In March 2011 I started my work at the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany. After spending the first couple of months on my literature research, I started my thesis in June. This thesis is the product of almost a year of work, of which half of it in Germany. This was and will be an eventful year, with many changes!

My work in Germany was a great experience and DLR provided an inspiring work environment. This great experience was impossible without the support of Geert who helped me finding this project, Thomas who gave me this opportunity and Bernhard with whom I had a weekly discussion.

During the whole period Geert, Bernhard, Thomas and Hans provided me with useful feedback on my work, my thesis and my presentations. I learned many things, related to the content but also related to the approach, methods and writing. With the help of Bernhard, Thomas and Geert a paper about my work was accepted at the 2012 IEEE Intelligent Vehicles Symposium. For all this I am very grateful!

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Contents

CHAPTER 1

Introduction

For over decades road traffic injuries are seen as a major public health problem by the World Health Organization (WHO). The WHO even predicts that road injuries will rise to become the fifth leading cause of death by 2030. For this reason, the WHO encourages countries and governments to actively increase road safety [1, 2]. In the European Union (EU), for example, 35.0000 people died in traffic accidents and over 1.7 million were injured in 2009. Therefore new EU road safety guidelines aim to cut European road deaths by 50% by 2020 [3].

Besides vehicles being a danger to people, they are also a danger to the environment. The environment suffers from the emission of greenhouse gases of vehicles. The transportation industry is the second emitting industry, after the production of electricity, responsible for 22% of the total CO_2 emissions worldwide [4]. Hence, reducing the CO_2 emissions in the transport industry is of great importance to meet the goals set by the Kyoto Protocol in 1997 [5]. This can be done by directly looking at fuel and engine technologies, as done in [6]. However, increasing traffic flow by means of ITS applications is also a way to decrease CO_2 emissions, e.g. mitigating traffic jams [7].

Motivated mostly by these safety related and environmental issues, organizations from all over the world advocate for Intelligent Transport Systems (ITS). Project initiatives were already started in the late 80s incorporating many different organizations including research institutes, governments, universities and the automotive industry. After many years of intensive research in the field of ITS, there are still many open challenges. This thesis deals with one of these problems.

1.1 Problem Statement

In vehicular networks, vehicles equipped with wireless communication technology can communicate with each other. However, the wireless technology used in vehicular networks, as described in Section 2.2, has a limited communication range. Therefore, if the density of vehicles equipped with this technology is too low, information dissemination has poor quality, or in the worst case does not function at all. The reason for this, is that the network becomes fragmented, resulting in disconnected clusters of vehicles due to the limited communication range. Therefore, information dissemination beyond these clusters is impossible or leads to massive delays. If information dissemination fails, the applications that rely on information from other vehicles also fail. Therefore, it is important that the performance of information dissemination is reliable so safety applications are functional.

The main reasons for a low density of equipped vehicles are traffic density and market penetration. Of course a low traffic density implies a low density of equipped vehicles. Rural areas often have smaller roads with low traffic density. Also, during night time less people are traveling causing a low traffic density. The market penetration is another reason of low density of equipped vehicles, because in the early years of market introduction only a small portion will be equipped with this communication technology.

This problem is very relevant in the upcoming years. The problem of not having connectivity between vehicles in sparse vehicular networks may cause applications to malfunction. If applications are not functioning properly, the technology looses its added value, leading to a slow or stagnating market introduction. So there is a danger ending up in a vicious circle.

1.2 Research Questions

Starting from the hypothesis that the connectivity problems of ad hoc communication among vehicles, referred to as Car-to-Car (C2C) communication, may be solved by equipping vehicles with an additional satellite link, in this work referred to as Car-to-Satellite (C2S) communication, the main question of this thesis is:

How can C2C benefit from additional C2S to improve information dissemination in sparse vehicular networks?

By answering this question it is shown to what extent the problems of C2C in sparse vehicular networks can be solved by adding C2S. To answer this question the following subquestions are addressed:

1. *What are the advantages and disadvantages of both C2C and C2S technologies?*
   Both technologies have their own characteristics. By recognizing the strengths and weaknesses of each technology a synergy can be formed to get the best of both worlds.

2. *What are the scenarios and applications where both technologies can benefit from each other?*
   Not all scenarios or applications may be suitable for the combination of both technologies. Therefore it is investigated which situation is suitable regarding the characteristics of both technologies.

3. *What information dissemination strategy should be used when combining C2C with C2S?*
   The technologies impose certain restrictions on the information dissemination strategy. By examining existing strategies it is tried to find a suitable

strategy where C2S should be optional.

4. *Which evaluation metric should be used to fairly evaluate the simulation results?*
A simulation model, based on the outcome of the previous subquestions, is executed and the results evaluated. Choosing appropriate evaluation metrics that matches the scenario is key to make a fair objective evaluation.

5. *How does C2C supplemented with C2S perform compared to the performance of pure C2C?*
Based on performance evaluation, given the chosen evaluation metrics, the added value of supplementing C2C with C2S can be quantified. It will show whether adding satellite communication lead to a significant increase of performance.

The outline section indicates in which sections of this thesis the subquestions are answered.

1.3 Approach

This research examines the possibility to solve the connectivity issue by introducing an additional communication link. This work is carried out at the German Aerospace Center within the context of the SafeTRIP project. The concept of SafeTRIP is to promote innovative satellite technologies offering two-way communication in ITS. SafeTRIPs satellite technology is therefore used as a basis for this work.

A literature research lies at the basis of this thesis. Until now there is no general agreement on a worldwide standard for vehicular communication. Therefore, in this work the European standard ITS-G5 for C2C communication is used. For C2S communication the technology advocated by the SafeTRIP project is used as a starting point. The literature review forms the basis for answering the first three subquestions stated above.

Based on this literature research the advantages and disadvantages of both technologies are revealed (subquestion 1). Moreover, technologies advocate certain applications. Applications that match the characteristics of both technologies are selected and put into the context of a realistic scenario that meet the requirement of a sparse vehicular network (subquestion 2). Integrating both technologies may lead to adaptation of existing information dissemination strategies (subquestion 3). The scenario, application, and information dissemination strategy is implemented resulting in a simulation model consisting of a mobility model and network model.

The results used for performance evaluation are generated by running the simulation model. Simulation is a useful technique for performance analysis, especially if no real testbed is available making a real-world experiment impossible. For analysis a suitable performance metric is described, the effect of application is used as a starting point (subquestion 4). Based on analysis of the results, the remaining subquestion, whether information dissemination benefits from the combination of C2C with C2S, is answered (subquestion 5).

1.4 Outline

The remainder of this thesis is organized as follows: Chapter 2 gives a general overview of ITS and a detailed description of both technologies: C2C based on the standard ITS-G5 and C2S based on the SafeTRIP project. Each technology is described in terms of architecture, access technology, and applications.

After the state of the art in C2C and C2S technology, Chapter 3 describes the way the two technologies can be combined. This chapter starts with related work on this topic, describing what already has been done to overcome this problem. The next subsections tackle the first three research subquestions respectively: both technologies are compared, the scenario and applications that suit the combination of technologies are described, and an appropriate information dissemination strategy is given that can handle both technologies.

The performance evaluation by means of simulation is described in Chapter 4. The first subsection deals with the details of the simulation setup, discussing the underlying models and parameters. After that the performance metrics are described, with that subquestion 4 is answered. The last subsection describes the simulation results of the different simulation configurations, and with that answers the last subquestion, covering the difference between a centralized and decentralized satellite broadcast and the impact of changing the rebroadcast rate and communication range. Also, the behavior of information dissemination over time is addressed. The chapter concludes by describing the impact the addition of a satellite link can have, related to a figure describing a prediction of the C2C market introduction.

This thesis is concluded by Chapter 5 wrapping up the general ideas and results presented in previous chapters. The general conclusions are followed by the answers of the research questions presented in this chapter. Finally, future work related to this research is discussed.

CHAPTER 2

State of the Art

Research in the field of Intelligent Transport Systems (ITS) is experiencing enormous growth. A quick search for papers written about this topic results in thousands of papers for 2011 alone. This chapter gives an overview of the background of ITS and a detailed description of the two communication technologies that are the basis for this thesis: Car-to-Car (C2C) and Car-to-Satellite (C2S) communication.

2.1 Intelligent Transport Systems

ITS covers a broad spectrum of research. The large domain of ITS can be subdivided into several networking environments [8, 9]. An overview of the ITS system architecture, based on the draft reference architecture of the C2C Communication Consortium, is depicted in Figure 2.1. General descriptions of each communication mode, together with examples of their application, are given below.

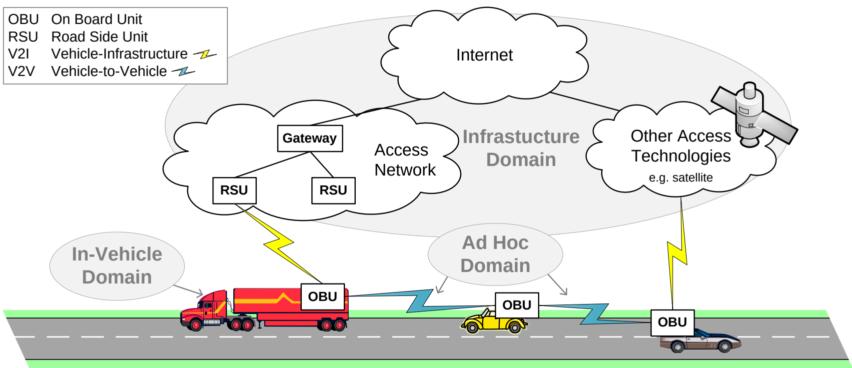


Figure 2.1: ITS System Architecture, based on the draft reference architecture in [10]

In-Vehicle (or 'intra-vehicle communication') is non-cooperative with its surrounding, its functionality lies entirely within the vehicle. The well known Controller Area Network (CAN), developed by Robert Bosch GmbH in

1983, is used extensively in automotive applications to connect the numerous Electronic Control Units (ECU) [11], in vehicular networks referred to as Application Units (AU). The network of AUs defines the domain known as In-Vehicle Domain. Applications, such as Anti-lock Braking System (ABS) and Adaptive Cruise Control (ACC), rely on these kind of networks. These are passive ITS applications since they do not interact with the outside world, they solely rely on intra-vehicle sensors.

Vehicle-to-Infrastructure (V2I) is communication from a vehicle to the infrastructure or vice versa in an ad hoc domain. Vehicles are equipped with devices, called On-Board Units (OBU), which implement the communication protocol and algorithms. The Infrastructure Domain, described as part of the architecture in [10, 12], includes many different access networks. Thus, it is not limited to only ad hoc communication between OBU and Roadside Unit (RSU), known as Vehicle-to-Roadside (V2R) communication. C2S is such an alternative using the satellite as an alternative access technology, this is used in this thesis and explained in Section 2.3. V2I can be, for example, used for Electronic Toll Collection (ETC) which is already widely used in many countries, for example in Europe. However, ETC is not interoperable due to many differences among the different implementations [13]. Therefore, standardization bodies like the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) published standards for ETC [8]. ETC offers a substantial greater amount of traffic capacity than any other form of toll collection available [14], hence reducing traffic jams.

Vehicle-to-Vehicle (V2V) is the ad hoc communication between vehicles, mostly referred to as Car-to-Car (C2C) communication. The term Inter-Vehicle communication (IVC), in contrast to intra-vehicle, is not often mentioned in literature. Most vehicular applications are cooperative in the sense that they exchange information with other vehicles in their vicinity, in order to have a better understanding of their environment. In [15], this cooperative information exchange is called Over-the-horizon Awareness and is used in the Congestion Assistant which, in concept, reduces the number and effects of traffic jams. Cooperative Adaptive Cruise Control (CACC) is ACC with an added notion of the situation on the road ahead. It is shown that vehicles with CACC achieve better traffic-flow than vehicles without it [16]. Another application to increase road safety is to send warning messages, so called Road Hazard Warnings (RHW), for security hazards, such as wrong-way drivers, traffic incidents, weather hazards, etc. The RHW application is used in this thesis to demonstrate the performance of information dissemination.

Infrastructure-to-Infrastructure (I2I) refers to communication between between infrastructure objects, such as RSUs. This can in principle be done by means of wired and wireless communication. Examples are variable message signs, traffic light control and data collection. In [17], data collection by means of a wireless sensor network is used for adaptive traffic light control. In this way, ITS assists traffic operators, who deal with traffic management, to increase traffic flow.

This overview briefly describes each category with limited application examples. An extended overview of possible applications for each category is given in [8].

In this thesis the focus is on vehicular networks, and information dissemination between vehicles in particular. The next section describes ITS-G5: the European C2C communication standard. Followed by a section explaining SafeTRIP, Car-to-Satellite (C2S) communication, i.e. a kind of V2I, using a satellite link to disseminate information.

2.2 Car-to-Car Communication

A Car-to-Car (C2C) communication network — a network of cars communicating with each other — is often described as a Vehicular Ad hoc Network (VANET). VANETs are a special type, or subset, of Mobile Ad hoc Networks (MANET) [18, 19].

A MANET shows great resemblance to a VANET. Both networks need to control energy consumption. Although vehicles have unlimited power supply, the increasing amount of electronics in cars will result in energy constraints. Due to limited channel bandwidth, both technologies need techniques to cope with bandwidth constraints [20]. Also both networks have limited physical security and suffer from eavesdropping, spoofing and denial of service (DoS) attacks [21].

Despite the similarities, mobility in VANETs exhibit characteristics that are quite different from MANETs. The topology more dynamic, it changes rapidly, due to the high speed of vehicles, but also due to driver behavior, which may be effected by the content of messages it receives. Although the network is highly mobile, the mobility patterns of VANETs can be exploited, since vehicles are restricted to specific paths and directions [20].

2.2.1 Architecture

In VANET communication there is no need for infrastructure. Communication is decentralized and ad hoc. As depicted in Figure 2.1, vehicles can communicate with other vehicles, i.e. communicate between OBUs, but also communication from OBU to RSU is possible, or vice versa. Note that communication with RSU is optional and dependent on the existence of infrastructure, because of high costs it is unlikely that RSUs are widely deployed, especially not in rural areas.

The standardization of architectures and frameworks for ITS is still an ongoing process. There are several standardization bodies involved, the main players are the Institute of Electrical and Electronics Engineers (IEEE), International Organization for Standardization (ISO) and European Telecommunications Standards Institute (ETSI). Although the focus of this work is on ETSI, a brief overview of other standardization progress is given next.

ISO provides Communications Access for Land Mobiles (CALM), standardized in ISO 21217. CALM is a communication architecture framework, based on the ISO Open Systems Interconnection (OSI) model. Each layer has various functionalities, each described in different ISO standards. CALM mainly tries to use (Mobile) IPv6, however it also offers CALM FAST for security messages, CALM Geo-routing, and Non-CALM aware services for the generic domain (i.e. Internet). For the network access, CALM supports multiple technologies on the physical and data link layer, such as cellular systems or Wireless LAN (WLAN) technology [8, 9].

IEEE 1609 is the family of standards for Wireless Access in Vehicular Environments (WAVE). It provides services and interfaces for V2V and V2I wireless communications [22]. WAVE is a suite of standards that are focused on MAC and network layers. WAVE is most often used together with the term Dedicated Short-Range Communications (DSRC). DSRC concentrates on the wireless bands and technologies, however it is also used as a more general ITS term [23].

In Europe, DSRC is used to provide a communication link between vehicles and roadside units. The DSRC band is located around 5.8 GHz in the Industrial, Scientific and Medical (ISM) frequency band defined by the International Telecommunication Union Radio (ITU-R) communication sector [24]. CEN uses DSRC in the standardization of the European Electronic Toll Service. Currently, many different systems for road tolling are in use in Europe, however they are not compatible [8, 13]. DSRC uses a reduced OSI communication stack, consisting of the physical, data link, and application layer, tailored for real-time systems. This reduced stack reduces protocol overhead and is able to meet stricter timing constraints. [25]

The ETSI Technical Committee (TC) specified an ITS station reference architecture for ITS communications [26]. This architecture is based on two domains: the ITS domain and the generic domain. As discussed before, CALM uses similar domains, the CALM aware and non-CALM aware domain respectively. Like CALM, it is a framework that supports a variety of new and existing access technologies and ITS applications.

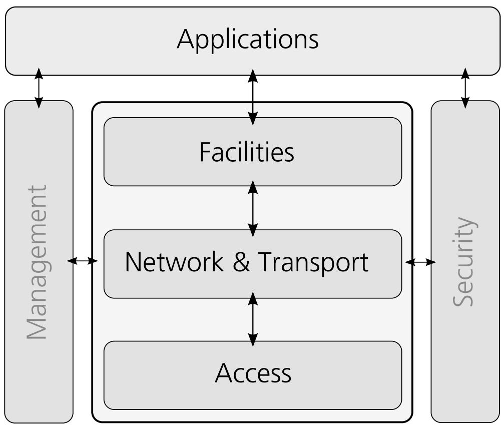


Figure 2.2: ETSI ITS Station Reference Architecture

The ITS station reference architecture, depicted in Figure 2.2, follows the OSI paradigm. Comparing it to the OSI model, the Access layer represent OSI layers 1 and 2, Networking & Transport represent OSI layers 3 and 4 and OSI layers 5 to 7 are represented by the Facilities layer. The Applications layer present the ITS station (ITS-S) applications using the underlying layers to connect to one or more other ITS-S applications [26].

Two ore more connected ITS-S applications together form an ITS application providing an ITS service to a user. The vertical layers Management and Security provide managing communications, access to the Management Information Base (MIB) and security services. The individual layers are interconnected via observable interfaces, depicted as arrows in Figure 2.2. Although the model is based on isolated layers, ITS communication also provides cross-layer functionality [26]. Distributed Congestion Control (DCC) is an example of cross-layer functionality essential to maintain network stability, throughput efficiency, and fair resource allocations [27].

2.2.2 Access Technology

The Access Layer (AL), shown in Figure 2.2, consists of two sub-layers, a physical layer (PHY) connecting physically to the communication medium and a data link layer (DLL) for end-to-end data transfer. The DLL in turn is subdivided in Medium Access Control (MAC), managing the access to the communication medium, and Link Layer Control (LLC), for multiplexing protocols transmitted over the MAC layer. A vertical management layer of the AL directly manages PHY and DLL. Communication channels are provided by an AL communication interface by means of Logical Channels (LCH). LCHs are mappings onto physical channels specified in standards on access technologies. Through LCHs the AL provides, in principle many, different access technologies, such as IEEE 802.11p, IEEE 802.11 WLAN or Bluetooth [26]. In the next subsections the PHY and MAC of ETSI ITS-G5, based on IEEE 802.11p, are discussed.

Physical Layer

In 1999, the Federal Communications Commission (FCC), responsible for outlining frequency band usage in the US, assigned 75 MHz (5.850–5.925 GHz) of spectrum to (DSRC) ITS; the first 5 MHz serve as guard space [28]. In 2008, the European Electronic Communications Committee (ECC) also decided to allocate 50 MHz (5.875–5.925 GHz) of spectrum dedicated to ITS [29] in the 5.9 GHz band. Furthermore, ECC recommends 25 MHz (5.855–5.875 GHz) of spectrum dedicated to non-safety ITS use [30]. The 5.470–5.725 GHz band can be used for Wireless Access System (WAS) or Radio LAN (RLAN), however this band is not dedicated to ITS. These bands partially overlap the 5.725–8.875 GHz ISM frequency band. An overview of these frequencies is given in Figure 2.3.

Standardization is needed to ensure cooperability between cars of different brands and from different countries. Furthermore, by having a band dedicated to ITS there is no interference from other systems. ECC studies showed that the needed bandwidth is between 30–50 MHz for road safety applications, including 20 MHz of bandwidth for time critical road safety applications [29].

The European profile standard for communications in the 5 GHz band is named

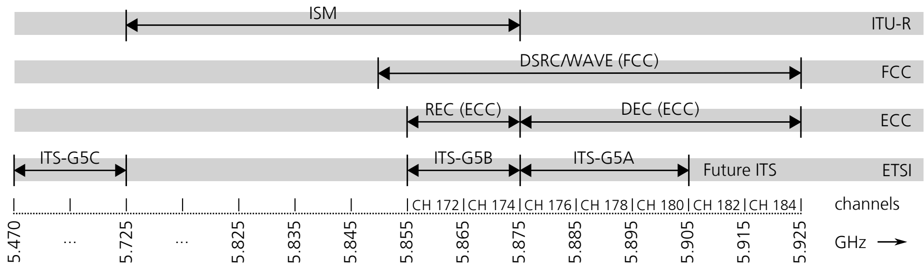


Figure 2.3: Overview frequency band allocations by different standardization bodies

ITS-G5 [27]. ITS-G5 is based on IEEE 802.11 [31] and amendment IEEE 802.11p [32]. It covers the following frequency ranges, as shown in Figure 2.3:

ITS-G5A 5.875–5.905 GHz, dedicated to ITS safety applications,

ITS-G5B 5.855–5.875 GHz, recommended for/dedicated to ITS non-safety applications,

ITS-G5C 5.470–5.725 GHz, non-dedicated to ITS non-safety applications.

The dedicated ITS band (5.855–5.925 GHz) is divided into 10 MHz physical channels. ETSI defined six Service Channels (SCH) and a special Control Channel (CCH). The ITS-G5 CCH (G5CC) is channel 180, depicted in Figure 2.3. In WAVE, channel 178 is the CCH. The reason for choosing channel 180 in ETSI instead of conforming to WAVE is not stated in the literature. G5CC shall be used for road safety and traffic efficiency applications and may be used for ITS service announcements of services on other ITS-G5 SCHs (G5SC) [27].

When not transmitting on ITS-G5A or ITS-G5B, ITS-G5 stations that support safety applications should be able to always receive on the G5CC. All ITS-G5 stations, also those not supporting safety applications, should be able to transmit on the G5CC. This implies that ITS-G5 stations, operating on both G5CC and one of the G5SCs, have to be able to simultaneously receive on both channels when not transmitting. This is referred to as the dual receiver concept. The ETSI dual receiver concept is different to WAVE where a single receiver is used together with a globally synchronized channel coordination scheme, using alternating fixed length intervals (50 ms) for CCH and SCH communication [10, 33, 34].

Since ITS-G5C, in contrary to ITS-G5A and ITS-G5B, is not in a dedicated band it has to cooperate with other systems in the same band, e.g. radar systems. Therefore, Dynamic Frequency Selection is used which implies a master and slave(s) environment. Consequently, the communication mode proposed in ITS-G5 is not possible in ITS-G5C, because it does not use a master as described later on [27].

As a transmission technology on the PHY layer, ITS-G5 uses Orthogonal Frequency Division Multiplexing (OFDM), similar as in IEEE 802.11a. The basic idea of OFDM is to divide the channel into narrower sub-channels. The high data rate stream is than split up into lower data (symbol) rate streams and transmitted over the sub-channels. The advantage is the ability to cope with severe channel conditions and mitigation of Inter-symbol Interference (ISI). Different transfer rates are possible, using different modulation and coding rates as shown in Table 2.1 [27]. For a detailed description of the different modulation schemes and coding rates, refer to [19]. Transmit Power Control (TPC) is a DCC mechanism at the PHY layer. Using TPC the transmission range can be changed and thereby the interference range. This way congestion can be mitigated.

Modulation	Coding rate (R)	Transfer rate (Mbps)
BPSK	1/2	3
BPSK	3/4	4.5
QPSK	1/2	6
QPSK	3/4	9
16-QAM	1/2	12
16-QAM	3/4	18
64-QAM	2/3	24
64-QAM	3/4	27

Table 2.1: OFDM Transfer Rates using different modulation schemes and coding rates

Medium Access Control

The Medium Access Control (MAC) layer is an important sub-layer of the DLL, and defines when a station is allowed to access the shared medium. There are many different ad hoc MAC protocols [35], which can be classified as being either contention based or contention-free (non-contention based) protocols. Examples of conflict-free protocols are, Time Division Multiple Access (TDMA), and Frequency Division Multiple Access (FDMA). In these protocols, stations are assigned time slots or sub-channels respectively to transmit data. Drawback of this technique is the need for a central allocation mechanism. Two well-known examples of contention based MAC protocols are, Aloha, and Carrier Sense Multiple Access (CSMA). Aloha has no coordination at all, i.e., a station can access the medium at any time for data transmission. It works fine for light loads and does not impose any overhead due to access mechanisms. However, when the loads get higher CSMA is preferred. With CSMA, the carrier is sensed before it is accessed: “listen before talk.” Obviously, transmitting while the channel is busy is useless because a collision will occur. Both Aloha and CSMA have the drawback of not being deterministic, and are not able to meet real-time requirements [36]. Another improved version of CSMA is CSMA with Collision Avoidance (CSMA/CA), which adds a back-off scheme in case of a busy medium to achieve fairness among competing stations, and to decrease the probability of a collision. If the medium is busy a random backoff time is chosen within a certain Contention Window (CW) bounding the chosen delay, because of this random delay the chance if two nodes transmitting at the same time is reduced.

ITS-G5 adopts the IEEE 802.11 standard and its amendment IEEE 802.11p [27]. For medium access ITS-G5 uses CSMA/CA with binary exponential back-off, also referred to as Distributed Coordination Function (DCF). Binary exponential back-off means that the CW is doubled after a collision, i.e., no acknowledgment (ACK) is received. DCF is contention-based in contrast to the contention-free Point Coordination Function (PCF) which needs an access point to control medium access. For controlling the waiting time before medium access, different Inter-frame Spacing (IFS) intervals are used. Before transmitting the sender senses the medium, if it is idle for a DCF IFS (DIFS) period, a station can access the medium at once. Otherwise, the station has to wait a DIFS period plus a random back-off time chosen from the CW. To provide fairness a back-off timer is used, this way deferred stations do not each time choose a new back-off time, but continue to count down the residual back-off time [19].

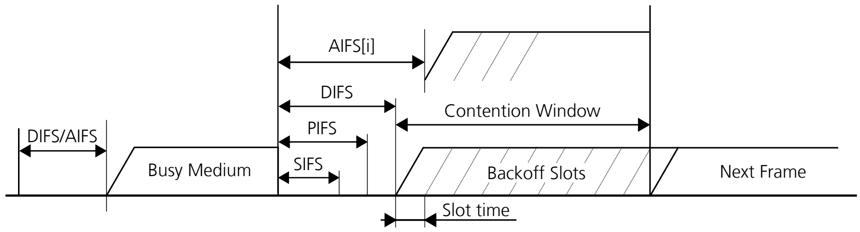


Figure 2.4: CSMA/CA IFS relationship [31]

To provide prioritization there are different IFSs. The different IFSs are depicted in Figure 2.4. The smallest IFS is the Short IFS (SIFS) and is used, for example, for sending an ACK after receiving unicast data correctly. PCF IFS (PIFS) is used with PCF, hence it is not used in ITS-G5. To provide different levels of priorities, IEEE 802.11e introduced the Hybrid Coordination Function (HCF) with a mechanism called Enhanced Distributed Channel Access (EDCA). EDCA provides different priority levels by adjusting the CW and using multiple Arbitration IFSs (AIFS), also for the first idle time, as shown in Figure 2.4 [37].

In the ad hoc mode of IEEE 802.11 an Independent Basic Service Set (IBSS) is used. An IBSS is a connected group of stations where mutual communication is possible. The group is advertised using beaconing. To join the group, authentication and association is needed using handshaking. Each member of an IBSS has a BSS Identification (BSSID). To restrict communication to members within the same IBSS, frame filtering is applied on the MAC layer. Because of the high mobility in VANETs the paradigm of groups of associated members is not feasible. Handshaking imposes too much overhead. Therefore, ITS-G5 stations shall transmit and receive data outside the context of a IBSS. Communication outside the context of a IBSS uses the wild card BSSID, so station will not discard the data [38].

Additional techniques like RTS/CTS [19], using Request To Send (RTS) and Clear To Send (CTS) control packets, for mitigating the hidden terminal problem, are not realistic for use in VANETs because of overhead, the highly dynamic environment [39], and because broadcast communication prevents the use of ACK messages [40].

2.2.3 Applications

Safety and safety related information for all kinds of cooperative ITS applications are encoded and transmitted predominantly in two different types of messages, standardized by ETSI in the application support facilities:

Cooperative Awareness Messages (CAM) [41] are periodically sent by vehicles to inform other vehicles in their vicinity about their status, such as current geographical position, speed and heading. CAMs are broadcasted as periodic beacons with a given frequency, also called the network heartbeat. This is typically between 1-10 Hz, satisfying both the road safety application and network and transport layer requirements, and can be adjusted to the current channel load. As CAMs are most relevant for other vehicles in the close vicinity and outdated after a short time, CAMs are usually not re-broadcasted by a receiver [42].

Decentralized Environmental Notification Messages (DENM) [43] are triggered by a vehicle to inform other vehicles, within a certain surrounding area, about a special event, such as a roadwork construction or an accident. The geographic target area of a DENM is often much larger than the communication range itself, and the information about the event is valid for a much longer time, e.g. up to hours. So, while the initiating vehicle is already outside the target area, the DENM has to be kept alive within for a certain amount of time, the so called time to live (TTL) of the DENM. This is done by periodic re-transmission by the receivers. The rebroadcast rate is dependent on the dissemination scheme.

An ITS application is by definition an association of two or more complementary ITS-S applications, e.g. server and client. ETSI standardized the different applications in the Basic Set of Applications (BSA), which is composed of applications that are considered as being deployable within three years time after the complete standardization of the system [44]. The applications are divided into the following four classes:

Active road safety includes, for example, cooperative awareness to assist the driver and sending road hazard warnings (RHW). Cooperative awareness uses CAMs to notify an approaching emergency vehicle or indicate the approach of a slow vehicle. DENMs are used in case a driver should be notified of a dangerous situation, such as a road accident or roadwork warnings.

Cooperative traffic efficiency is used to increase the traffic flow, and as a result mitigate pollution. Speed management, for example, is used to regulate speed limits and advise for the optimal speed to approach a traffic light. To enhance guidance and navigation, cooperative navigation can be used to notify drivers of changes, such as roadworks.

Cooperative local services are services that are only locally relevant, such as Point of Interest (POI) notification, or parking management. The latter is used to give information about pricing, number of available parking slots and assist the driver to the precise parking location, for example.

Global Internet services are provided to ITS stations for use with, for example, community services, or ITS station life cycle management.

All ITS applications associate to a priority value according to the functional and operational requirements of the application, this indicates the maximum possible value of the channel access priority as discussed in Section 2.2.2.

2.3 Car-to-Satellite Communication

Many different access technologies can be used to communicate between vehicles, or OBUs. Here, satellite communication is used, referred to with the term Car-to-Satellite (C2S). The SafeTRIP[1] project promotes two-way data communication via satellite to develop and demonstrate services to improve safety, security and environmental sustainability of road transport infrastructures [45]. Within the S-band, a short wave band from 2 to 4 GHz, the ECC granted 30 MHz (1.98–2.01 GHz) of spectrum exclusively for Mobile Satellite Services (MSS) [46], which is partially used by SafeTRIP. The company Eutelsat provides SafeTRIP with the S-band satellite service using their W2A satellite, positioned in geostationary orbit, launched in April 2009 [47].

SafeTRIP presents several keys to success. Coverage, independent of terrestrial infrastructure and network density, is the first major difference to ITS-G5. It allows communication in sparse vehicular networks in rural areas or at night. This secondly implies quick and easy deployment, since it ensures full coverage as soon as the system is launched. Thirdly, the system is more energy-efficient than terrestrial repeaters. And last, the possibility of audio and video broadcasting could increase the popularity of the system and interest of manufacturers.

2.3.1 Architecture

SafeTRIP uses the S-band Mobile Interactive Multimedia (S-MIM) system in which a standardized S-band satellite mobile broadcast system is complemented by the addition of a return channel [48]. It provides an architecture that supports communication with speeds up to 150 km/h and velocity changes of up to 1.3 m/s^2. There are three different communication services defined: broadcasting, messaging and bi-directional communication services [49]. These services are also referred to as Service Segments (SS). In [50], three SS classes are defined, namely:

SS1 interactive mobile services,

SS2 messaging services for terminals,

SS3 real-time (emergency) services such as emergency calls, mainly for institutional users e.g. fire brigades or civil protections.

The network uses a satellite hub and an S-band satellite, together with optional Complementary Ground Components (CGC), for communication with the OBU as shown in Figure 2.5. The satellite hub and CGCs are connected with the S-band Satellite through a backhaul on the Ku-band, specified by the satellite operator. The S-Band satellite uses frequency conversion to switch between the Ku-band and S-band [48]. For the connection between the S-band satellite and OBU there is a distinction between the forward and return link. Both are using different air interfaces. Moreover, for the return link two different air interfaces are used. Broadcasting uses the forward link for streaming and data distribution services. The return link is used for messaging and bi-directional

[1] SafeTRIP: Satellite Applications For Emergency handling, Traffic alerts, Road safety and Incident Prevention

communication services. A more in depth overview of the different technologies is given in the next section.

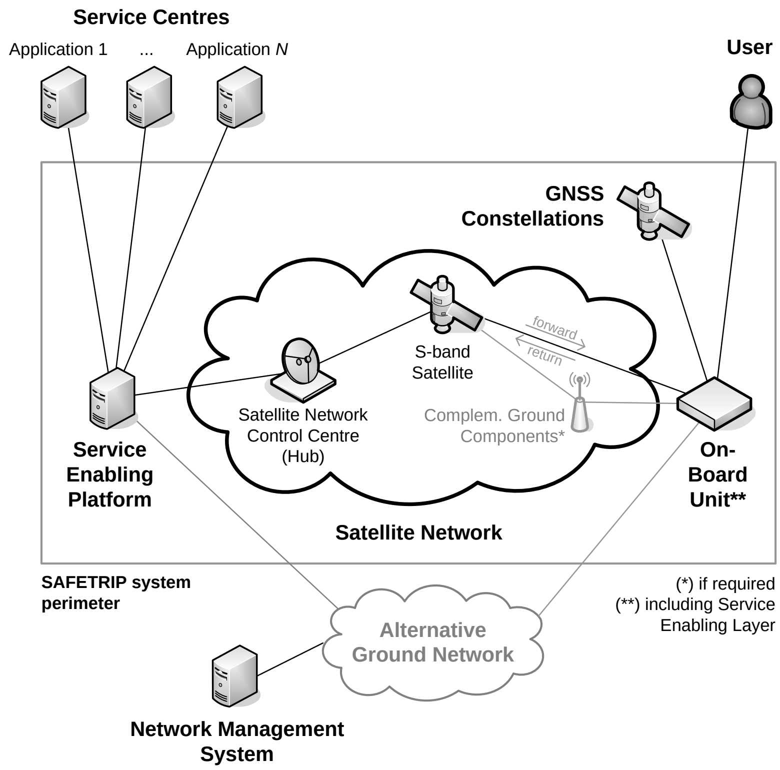


Figure 2.5: SafeTRIP system architecture [45]

While the SafeTRIP system is focused on satellite-based communication services, the SafeTRIP demonstrator can also receive position information using Global Navigation Satellite Systems (GNSS), supports Universal Mobile Telecommunications System (UMTS) and WLAN. It will also include an additional C2C modem [51]. In Figure 2.5 this is referred to as the GNSS constellation and the Alternative Ground Network.

SafeTRIP only defines the different air interfaces on a physical layer and convergence layer level. IP is used, together with the connection-less User Datagram Protocol (UDP), on top of the convergence layer.

2.3.2 Access Technology

The forward and return link are using different air interfaces. All service segments use the same broadcasting air interface over the forward link. On the return link however, two services are supported, messaging and bi-directional communication, both using a different air interface. The three different air interfaces, as specified in [52], are discussed next.

Broadcasting on the Forward Link using DVB-SH-LL

The forward link is used by all service segments to broadcast data to the terminals using one-to-many communication. The forward link provides audio/video streaming and data distribution services. The air interface is based on DVB-SH (Digital Video Broadcasting - Satellite to Handheld), supporting broadcasting to mobile terminals. DVB-SH is derived from the different DVB standards by ETSI [53, 54].

In addition to DVB-SH, a low latency extension is used, referred to as DVB-SH-LL (Low Latency). The low latency channel is integrated as a second logical channel embedded into the standard DVB-SH signal. The integration is done by a different way of interleaving, giving priority to low latency data. The regular and low latency throughput delays are given in Table 2.2. DVB-SH-LL is fully backward compatible and the support is optional for manufacturers [52].

Low latency on the forward channel is needed because of the services. The messaging service uses for example acknowledgments and congestion control. To provide the real-time service specified in SS3, a real-time forward link is also necessary.

DVB-SH describes two modulation schemes for the satellite: OFDM based on DVB-Terrestrial (DVB-T) referred to as SH-A, and Time Division Multiplexing (TDM) scheme, partially derived from DVB-S2 (DVB-Satellite 2$^{\text{nd}}$ Generation), referred to as SH-B. For SafeTRIP, SH-B is assumed in [55] and is also referred to in [52].

System Performance Requirements	
Maximum node speed	150 km/h
Maximum node acceleration/deceleration	1.3 m/s^2
Broadcasting Services	
FWD-Link throughput delay (low latency)	$\leq 1\,s$
FWD-Link throughput delay (normal)	$\leq 20\,s$
Messaging Services	
Delay Emergency Messages (low latency)	$\leq 1.5\,s$
Delay Normal Messages (normal)	$\leq 10.5\,s$
Bi-directional communication Services	
Data link setup time	$\leq 7\,s$
Connection jitter	$\leq 40\,ms$

Table 2.2: SafeTRIP System Requirements [49]

Messaging on the Return Link using E-SSA

The messaging communication service is asynchronous, one-to-one, and most often bursty. The asynchronous access is used for SS1 and SS2 [50]. Enhanced Spread Spectrum Aloha (E-SSA) is used for messaging services in the return link, first introduced by the European Space Agency (ESA).

E-SSA is based on the Aloha random access protocol allowing access without any coordination, thereby minimizing signaling overhead for access control.

The spread spectrum technique mitigate the problems of interference. High throughput is obtained by simple packet transmission control together with an enhanced design of spread spectrum Aloha with Serial Interference Cancellation (SIC) based on downlink signal quality observation. SIC enables the satellite hub to resolve collisions by first decoding bursts with higher received power and than sequentially cancel these from the received signal. However, the downside of applying SIC is that it imposes an extra delay [56].

Congestion Control is performed by the satellite hub to adapt the transmission rate of the terminals in case of congestion. If the satellite hub experiences congestion on the channel it adapts the transmission rate parameter, this information is sent to the terminals over the forward link.

Two priority types are used for the messages. There is a distinction between normal and emergency messages. Two Class of Services (CoS) are used indicating the priority of the message. The scheduler at the terminal gives priority to packets with higher priority CoS. The delay and loss ratio for both types of messages in Table 2.2 show that the messaging service is not suited for applications that require low delay.

Bi-directional communication on the Return Link using QS-CDMA

The bi-directional communication service provides continuous, connection-oriented, one-to-one communication for SS3. For bi-directional communication an adapted version of Code Division Multiple Access (CDMA) is used over the return link, referred to as Quasi Synchronous CDMA (QS-CDMA) [55]. QS-CDMA needs synchronization, this is done by the satellite hub using the forward link [52]. To setup a link a network synchronization procedure is performed first, the mobile terminal is assigned a spreading code after synchronization.

Real-time streaming applications use this bi-directional communication service, such as Emergency calls and Patrol with Eyes described in Section 2.3.3. Link setup time and jitter requirements are given in Table 2.2.

Co-existence of E-SSA and QS-CDMA

Two possible solutions are proposed in [52] for the co-existence of the two return link communication services. One is bandwidth sharing, where E-SSA and QS-CDMA use both the same frequency band of 5 MHz allocated for it. Secondly, bandwidth segregation can be used where each service is allocated its own 2.5 MHz band. The second option is used in SafeTRIP [52].

To cope with Multiple Access Interference (MAI), the following provisions are implemented. Firstly, QS-CDMA terminals transmit with a higher Equivalent Isotropically Radiated Power (EIRP) than E-SSA terminals. Secondly, the satellite hub implements a congestion control mechanism monitoring the level of interference of QS-CDMA as well as E-SSA, this will help the terminals to demodulate the signal. Thirdly, the QS-CDMA demodulator removes the QS-CDMA signals and delivers remaining “clear” signal to the E-SSA demodulator. Finally, the E-SSA performs SIC before demodulation.

2.3.3 Applications

The application architecture provides descriptions of applications which are being implemented and demonstrated within the SafeTRIP project, this is described in [45]. SafeTRIP defines four categories of end-user services based on their objectives: safety and security, entertainment, Advanced Driver Assistance System (ADAS), and monitoring and tracking. In the next section each category is explained including brief descriptions of the applications.

Safety and Security

To enhance general road safety and to guarantee security for passengers the objectives of these applications or services are mainly achieved by avoiding accidents or in case of an accident quickly alerting emergency services. This is done by improving the alert chain.

Emergency calls (or 'eCall') service, quickly disseminates alerts to rescue services and it is estimated that this could cut emergency response time by 50–60% [57]. A call is either initiated by a user or emergency situation and is handled by, for example, the motorway operations center or the local public emergency services. Even if no passenger is able to speak, e.g. due to injuries, available information, such as exact location of the crash site and impact, is sent to rescue services.

Road Safety Alerts are sent by a content provider which pushes information about certain events or hazards to OBUs. This information is displayed to the driver. The alerts contain a geo-location, OBUs can filter the events using their position.

Collaborative Road Alerts are sent based on information gathered from drivers who signal an accident, instead of a content provider. Alerts, such as road congestion or accidents, can be checked and validated by a road operator afterward.

HGV Tracking and Parking Guidance is a service for operators and managers to provide information regarding location, route, and cargo of Heavy Goods Vehicles (HGV).

Entertainment

These applications mainly provide broadcasting services to entertain the passengers on the road. Entertainment services can indirectly reduce stress of passengers and speed up the penetration of the SafeTRIP system in vehicles.

Live Radio/TV broadcasting provide entertainment to vehicle passengers.

Multimedia Datacast to deliver on demand, or preloaded, multimedia for entertainment of passengers, such as cartoons to amuse kids during a long ride.

SafeTRIP News pushes aggregated information from different sources to OBUs. The information can consist news, traffic information, alerts, weather forecasts, et cetera. The messages can be filtered using vehicle position.

Advanced Driver Assistance System

Advanced Driver Assistance System (ADAS) provides comfort to the driver by assistance during the driving process, which will also improve safety.

Driver Alertness Service warns the driver in case he tends to fall asleep while driving. Various sensors are used to analyze driver behavior. An alert is given when it recognizes tiredness-related changes to the driving style. According to different European studies, 25 to 30 percent of all fatal accidents are due to driving while being over-tired. While this seems like an in-vehicle application, it uses the messaging service to inform the fleet manager to inform about the sleepy driver.

Monitoring and Tracking

Third parties are provided by monitoring and tracking services to retrieve information from vehicles. The applications usually do not require interaction with the driver nor with other occupants of the vehicle.

Stolen Vehicle Tracking keeps track of a car when it is moving unauthorized. Authorization is carried out by the user who activates tracking when leaving the car and deactivates it when he enters the car again.

Real Time Tracking of Coaches allows coach companies to track their vehicles and communicate with the driver to supervise coach journeys.

Passenger Tracking for Coaches provides information about who is on the coach during the whole trip. In case of an accident the right information can be provided to the emergency services.

Patrol with Eyes is used to stream video information from patrol vehicles to road operators.

2.4 Information Dissemination: GeoNetworking

Information dissemination is the mechanism of distributing packets containing messages to nodes. The networking layer is responsible for routing packets through the network or establishing a connection between two stations via a route of other nodes. In VANETs the topology is changing rapidly and nodes cannot rely on infrastructure. Message propagation has to deal with sparse networks, which may be partitioned due to rural environments, night time, or low market penetration of vehicles equipped with OBUs. Another challenge are overload situations in dense networks, for example traffic jams. All these issues have to be solved to be able to broadcast safety messages in a reliable way. Therefore, the information dissemination protocol shall be robust and fault-tolerant, which implies a trade-off between redundancy and use of resources [42]. Mainly due to the highly mobile, and possibly partitioned environment, existing proactive and reactive routing protocols that maintain or build up routes to an end node, as used in MANETs, have poor performance or are not applicable at all [58].

For ITS, ETSI pointed out several different possible networking modes. Most used protocols are: Internet Protocol version 6 (IPv6) with mobility support [59], CALM FAST, and GeoNetworking [26]. Effort is also put into enabling the support of IPv6 in GeoNetworking, because a wide deployment of Internet access and services is only seemed possible with IPv6 [60, 61]. Therefore, ETSI provides a standard for IPv6 over GeoNetworking. These protocols are depicted in Figure 2.6, pointing out IPv6 over GeoNetworking. Because of the extra overhead, IPv6 is not applicable for safety applications [62]. GeoNetworking, standardized by ETSI in [63], provides a low-latency reliable communication protocol for safety messages. It shall be able to work in low and high density scenarios with low overhead and fairness among different nodes [64].

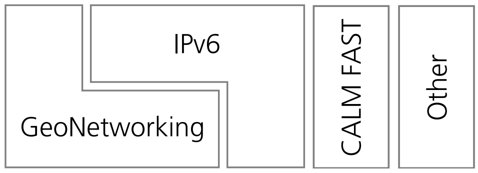


Figure 2.6: ITS-G5 Network Layer Architecture

Using short-range wireless technology, like ITS-G5, GeoNetworking provides ad hoc networking based on geographical addressing and routing. For GeoNetworking there are multiple communication modes between endpoints defined, depicted in Figure 2.7 [12, 65]. An endpoint can either be a vehicle or a roadside unit. ETSI defined the following modes [66, 67]:

GeoUnicast to communicate between two ITS station endpoints (Figure 2.7a),

GeoAnycast to communicate from one ITS station to a single arbitrary ITS station within a geographical target area, i.e., the packet is forwarded until it reaches one of the ITS stations within the geographic area (Figure 2.7b),

GeoBroadcast for flooding-like distribution of data packets from one ITS station to all ITS stations within a geographical target area (Figure 2.7c),

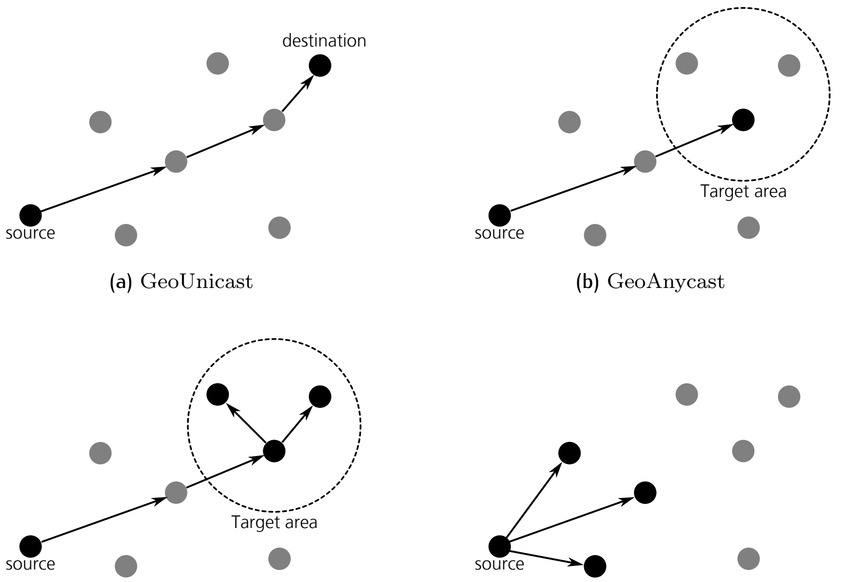
Topologically Scoped Broadcast (TSB) to broadcast a packet from an ITS source to an n-hop neighborhood (Figure 2.7d),

Single Hop Broadcast (SHB) similar to TSB but with a 1-hop neighborhood.

Together with these communication types there are different routing algorithms defined. In [66], also other algorithms are mentioned, but since they are regarded informative they are not included here. The normative algorithms are:

Greedy Forwarding (GF) [66], also referred to as Position-Based Forwarding (PBF), can be used for GeoUnicast and GeoAnycast, but is also used for line forwarding in Simple Geobroadcast with line forwarding. Using GF packets are forwarded using the destinations' location information. At each hop the neighbor with the smallest geographical distance to the destination is chosen to forward the packet to. This process is repeated until the destination (geographical target area or address) is reached.

Contention-Based Forwarding (CBF), as published in [68], is an alternative to GF and can, like GF, be used for GeoUnicast and GeoAnycast. In CBF



(a) GeoUnicast

(b) GeoAnycast

(c) GeoBroadcast

(d) SHB or TSB with 1-hop neighborhood

Figure 2.7: Communication modes in GeoNetworking

data is broadcasted to all direct neighbors. Neighbors themselves decide to forward the packet or not. This is in contrary to GF where the sender determines the next hop. When a packet is received it is buffered, and a timer is started (inversely proportional to the distance from the receiver to the destination). When the timer expires and no duplicates are overheard from other neighbors the receiver forwards the packet.

Simple GeoBroadcast with line forwarding [66] broadcasts a packet, using the broadcast link layer address, within a geographical target area. In case the sender is outside the target area, GF is used to reach the area. An algorithm computes if the packet is inside or outside the area.

Topologically Scoped and Single Hop Broadcast [66] broadcasts a packet within an n-hop neighborhood, the location table (i.e. a table internally used to store neighbor information) is used to check if there are neighbors. If there are no neighbors the packet is buffered. The packet is forwarded if, it is not a duplicate, and the hop counter is not zero after decrementing it.

CHAPTER 3

Combining Technologies

Both C2C and C2S technologies, as described in the previous sections, come with their own advantages and disadvantages. This chapter first describes related work regarding the mitigation of connectivity issues in sparse vehicular networks. Then the differences between the two technologies and how they are combined to create synergy are explained. Not all scenarios and applications are suitable for combining the two technologies, therefore this chapter describes an example of where the synergy suits best. Also the information dissemination strategy should be adapted to make it work. How this can be implemented is shown in the last section of this chapter.

3.1 Related Work

The research area of ITS is very much alive. Numerous papers are written about vehicular networks. In [69], the problems of broadcasting in VANETs with changing traffic densities are addressed. If traffic is sparse a broadcast can, in the worst case, totally fail if there is no other vehicle within the transmission range of the source.

Mechanisms that deal with this problem have been proposed. Epidemic Routing [70] addresses the sparsely connected nature of mobile wireless networks. In [71] a similar approach is proposed in the context of VANETs. Both advocate the concept of Store-Carry-Forward. This technique allows vehicles to store received packets and rebroadcast them if new vehicles in the vicinity are recognized. Because this solution heavily depends on the movement and behavior of vehicles, it cannot be guaranteed, that information from one cluster reaches the vehicles in an other cluster in time.

Another option to mitigate the problem of disconnected VANETs is to use infrastructure points, known as Road Side Units (RSU). The effects of including RSUs as relay nodes is studied in [72] and a similar approach is proposed in [73]. Overall results show that the use of additional RSUs is indeed a promising technique to solve the problem of disconnected VANETs. However, for scenarios with low vehicle density, such as rural areas, the costs of deploying the required RSUs may be prohibitive.

A very interesting approach for overcoming the problem of disconnected VANETs is to integrate C2C with other complementary communication technologies, such as cellular systems, as proposed in [74]. In contrast to that, the approach in this thesis is to use a communication satellite as an additional complementary communication technology (C2S communication link) and quantify the potential gain of information dissemination performance by simulation.

The development of a concrete open platform for vehicles using the S-band satellite technology (DVB-SH) as the basis for its communication infrastructure is aimed in the SafeTRIP project [75]. The technological details were already presented in Section 2.3. One important task in SafeTRIP was to analyze the benefit of integrating C2S, in particular ITS-G5, with its satellite communication technology, which is re-described in the following sections.

3.2 Comparing C2C with C2S

The characteristics of both C2C and C2S are quite different, as described in the previous chapter. Both technologies have their own advantages and disadvantages. To successfully combine both technologies, this section describes their strengths and weaknesses. Table 3.1 gives an overview of some important aspects.

	C2C	C2S
Communication range	−	+
Communication delay	+	−
Flexibility	+	−
Scalability	+/−	+/−
Service costs	+	−

Table 3.1: C2C vs. C2S technology: a comparison of some important aspects

Key benefit of C2C technology is the ability of fast, dynamic and low cost communication. Communication between vehicles is fully distributed without any need for centralized coordination. Because of the decentralized ad-hoc nature, communication does not depend on infrastructure components. C2C provides low latency data dissemination compared to other wireless communication systems, such as satellite systems. Because no infrastructure is needed, with C2C technology the startup costs are low compared to the launch of a satellite. Moreover, in operation C2C communication is a free service.

In principle the decentralized structure of C2C communication offers a scalable solution. However, extreme situations regarding traffic density causes major technical challenges. In dense traffic situations, there is the problem of channel congestion, the total data traffic of all vehicles exceed the available bandwidth, resulting in an overloaded saturated network. In the other extreme, if traffic density is sparse, connectivity problems occur.

Connectivity is a major problem in sparse networks, not only because of low traffic density. Also the initial market introduction is problematic. Due to the limited communication range of C2C, information dissemination is obstructed.

Because vehicles are often out of communication range with other vehicles, no vehicle is able to forward information. Without any additional measures or mechanisms information dissemination is blocked, and in the worst case information gets lost without any vehicle receiving it.

Coverage is a key advantage of geostationary satellite communication, therefore C2C and C2S complement one another. Large coverage means efficient broadcasting of information to many receivers. Wide coverage also enables connectivity at remote places, such as mountainous areas, islands or developing countries. Three GEO satellites enable global coverage, i.e. complete coverage of almost any spot on earth, and in contrast to satellites operating in other earth orbits, geostationary earth orbit (GEO) satellites typically do not need a handover due to the large footprint [19].

Because GEO satellites have a distance of almost 36,000 kilometers to earth, propagation distance leads to high delay. Not all applications can deal with such high latencies, therefore satellite communication is not always suitable.

Where C2C communication is free, it is most likely that C2S communication is not free of transmission or service costs. Because it is very expensive to transfer a GEO satellite into orbit, commercial companies will charge money for offered services.

3.3 Information Dissemination Strategy

The scenario used in this thesis, as further described in Section 4.1.1, requires that safety related information is disseminated in a certain geographic area. Therefore, the information dissemination strategy is based on GeoBroadcasting as described in Section 2.4. GeoUnicast, GeoAnycast and TSB are not suitable for this purpose. In the implementation, discussed in the next chapter, the target area equals the simulation area. Therefore, no line forwarding is needed, since the vehicle initiating the broadcast is already within the target area. Flooding is used to disseminate the information throughout the target area and is kept alive as long as the TTL is not exceeded.

GeoBroadcasting works well if all vehicles within the geographic target area can be reached. However, if the traffic density is sparse, this can become problematic because information can not be disseminated beyond the communication range. On rural roads clusters of vehicles will appear [76], due to slow vehicles accumulating vehicles behind them. Within these clusters C2C works well, and information can be disseminated; this is depicted in Figure 3.1. With the introduction of an additional C2S link it is tried to overcome this problem.

3.3.1 Bridging clusters using C2S

As shown in Figure 3.1, communication between clusters might be impossible because of the limited communication range of C2C. Therefore, in this thesis the use of an additional complementary communication technology is advocated. In this case satellite communication is chosen, because it provides large coverage

Figure 3.1: Clustering of VANETs in case of low density of equipped vehicles. Information exchange is possible only between vehicles within one cluster (left), but not between different clusters (right).

and hence far communication range. Exploiting the large coverage, the satellite can be used as a bridge between clusters, as depicted in Figure 3.2.

Not every vehicle has to be equipped with C2S. If only some of the vehicles are able to disseminate the information over the satellite, each vehicle receiving the RHW over the satellite, can rebroadcast this information within its cluster. In the best case every cluster contains one vehicle equipped with C2S, as the example in Figure 3.2 shows. Vehicles that receive a RHW over C2C will disseminate this RHW further over satellite if they are equipped with C2S technology. Other vehicles receiving this RHW over the satellite link will start disseminating the RHW further to all vehicles they can reach over C2C.

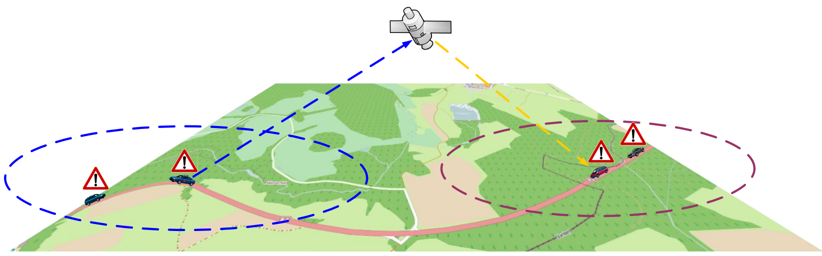


Figure 3.2: Despite of VANET clustering, transmission of safety related information between clusters is possible by using an additional satellite link.

Listing 3.1 shows the implementation of this information dissemination strategy. It assumes that the RHW is already initiated, although the same strategy applies for the initiating vehicle if you consider initiating the RHW being the same as receiving the RHW before. So, if a vehicle receives a RHW it checks whether it has already received the RHW before, i.e. it is already broadcasting the RHW. If it is a new RHW the vehicle starts a periodic broadcast. Broadcasting is done by sending the RHW over all available networking devices. This means that if a vehicle is solely equipped with C2C it will send it via C2C, but if a vehicle is additionally equipped with C2S it will also send it via the satellite. After broadcasting the vehicle will wait for the next time slot to rebroadcast the RHW again, based on the rebroadcast rate in place. Rebroadcasting will continue as long as the vehicle is within the geographic broadcasting area and as long as the TTL of the RHW is not exceeded.

```
if vehicle received RHW & did not receive RHW before
  //start periodic broadcast of RHW
  while within broadcast area & TTL is not exceeded
    foreach available networking device
      send RHW over networking device
    wait for next time slot //rebroadcast interval
```

Listing 3.1: Pseudo code for the information dissemination strategy combining C2C with C2S technology

Obviously, the approach of using the combination of C2C with C2S is particularly suitable with the application in the scenario sketched in Section 4.1.1. The RHW application uses DENMs which are more delay tolerant, in contrast to CAMs which are outdated very fast, as described in more detail in Section 2.2.3. Also, CAMs are important for vehicles in the vicinity of the sender and less relevant in far areas. Moreover, at a certain penetration rate of C2C disconnected clusters disappear, hence making the bridging function of C2S superfluous.

The next chapter describes the performance evaluation of this approach. It will be analyzed to which extent and under which conditions the serious disadvantage of C2C in sparse vehicular networks, as described above, can be eliminated by adding a satellite communication component to some of the vehicles.

3.3.2 Centralized/Decentralized Satellite Broadcast

Broadcasting via satellite can be done centralized or decentralized. Decentralized satellite broadcast is defined as using the satellite only as a relay. As opposed to the decentralized approach, centralized satellite broadcast is defined as using a satellite hub in between. This means that messages are first sent from the vehicle to the satellite hub via the satellite uplink. After that, the satellite hub is in control to periodically broadcast this message via the satellite downlink to all vehicles. The centralized approach is proposed by SafeTRIP and depicted in Figure 2.5.

The decentralized approach is used in the implementation described by Listing 3.1. However, if vehicles use flooding to disseminate information over the satellite link using a decentralized approach, the bandwidth usage will potentially grow exponentially with the number of vehicles, mainly because of the large coverage of the satellite. This results in an excessive use of the satellite link, something that should be avoided since it can affect the lifetime of the satellite. Therefore, adding a satellite hub makes broadcasting more efficient, whereas it might seem redundant. Vehicles inform the satellite hub over the satellite uplink. The satellite hub is then in charge of periodically broadcasting the information over the satellite downlink. By receiving the information from the satellite, vehicles know that the satellite hub is informed, so there is no need to send the information over the uplink again. This way the downlink usage is not dependent on the number of vehicles, but only on the rebroadcast interval and the uplink is only used to inform the satellite hub.

```
1 if vehicle received RHW & did not receive RHW before
2   //start periodic broadcast of RHW
3   while within broadcast area & TTL is not exceeded
4     foreach available networking device
5       if C2S networking device & satellite hub informed
6         continue //do not send to hub via C2S again
7       send RHW over networking device
8     wait for next time slot //rebroadcast interval
```

Listing 3.2: Pseudo code for the information dissemination strategy combining C2C with C2S technology using a centralized satellite hub

The pseudo code of the implementation of a centralized approach is given by Listing 3.2. Line 5 and 6 indicate the centralized approach using the notion of a satellite hub. This means that if a vehicle equipped with C2S technology receives a RHW, it will notify the satellite hub by sending the RHW via the return link to the satellite hub if it is not already notified. Receiving a RHW via C2S indicates that the satellite hub is already notified and is already periodically broadcasting this RHW. Therefore, vehicles equipped with C2S technology shall keep track for each RHW if they have received it via C2S.

The next chapter evaluates the performance of combining C2C with C2S technology. In Section 4.3.1 the performance of the decentralized approach is compared with the centralized approach.

CHAPTER 4

Performance Evaluation

In this chapter the impact of combining C2C with C2S technology is shown by means of simulation. The goal of the simulation is to quantify the performance of combining C2C with C2S improves information dissemination. Evaluation of the simulation results does give good insight in the opportunities and challenges of combining C2C and C2S.

Simulation is a useful technique for performance analysis, also in the field of computer networks. Especially when a real testbed is not available, or technology is still under development. Even if the system is available, a real testbed is often unfeasible, because of time, costs and logistic issues. In particular if the simulation spans a large area with many vehicles, such as in the scenario used here. Furthermore, simulation has the advantage of having a controlled environment and the possibility to get reproducible results.

While simulation is a useful technique for performance analysis and evaluation, it is merely a model, a representation of the real-world, and does not perfectly reflect and replace real testbed experiments. In addition, flaws in the model can exist and there is no proof of correctness. This can lead to useless or even misleading results. Therefore, it is necessary to take care of what and how to simulate. Increasing complexity often raises the chance of errors, moreover actually running the simulation might be too time consuming.

Assumptions are made to reduce complexity, while trying to represent the real scenario as close as possible. These assumptions are described throughout this chapter. The next sections give an overview of how the simulation is implemented, how performance is measured, what the results of the simulation runs are and what they mean.

4.1 Simulation Setup

For the simulation setup multiple parameters are used, the main parameters are listed in Table 4.1. The simulation of each configuration, i.e. set of parameter values to be simulated, is repeated 30 times. Since the simulation relies on random number generation, one run is not representative. Therefore, it is necessary to repeat the simulation several times. Pseudo random number generation is used in combination with different seeds, resulting in non-overlapping streams. Hence, the results are reproducible and independent.

FIXED PARAMETERS	VALUE
Number of runs	30
Delay C2C (s)	0
Delay C2S (s)	1
Range C2S (m)	∞
Average number of vehicles on the L218 (veh/hr)	155
Maximum vehicle velocity (km/hr)	100
Transient simulation period (hr)	1
RHW time to live (hr)	2
Total simulation time (hr)	4
VARIED PARAMETERS	VALUES
Penetration rate C2C	$0, 2.5, 5, \ldots, 50\%$
Penetration rate C2S	$0, 20, 40, \ldots 100\%$
Range C2C (m)	250, 1000
Rebroadcast interval (s)	$4, 10, 25$

Table 4.1: Parameters used for the simulation setup

Most important in the performance evaluation are the effects of varying penetration rates. Each combination of penetration rates is simulated. This results in 120 different configurations, if other parameters remain unchanged. Multiplied by the number of iterations 3600 simulation runs are needed. If for example each simulation run takes two minutes, this results in a total execution time of five days if it were run without parallelization. Hence, reducing time complexity of the simulation is key for containing the simulation run time. Together with running multiple simulations in parallel, the total simulation time becomes practicable for the duration of this thesis.

The penetration rate prescribes the chance a vehicle will be equipped with a particular network technology. Each simulation run, random vehicles are equipped with C2C. Additionally, some of these vehicles are also equipped with a C2S communication link, i.e. no vehicles are solely equipped with C2S. E.g. assume a simulation of 100 vehicles and consider a penetration rate of 50% for both C2C and C2S. This means that on average 50 vehicles are equipped with C2C technology. From these 50 vehicles equipped with C2C, on average half of them is also equipped with an additional C2S communication link, so 25 vehicles are C2C and C2S equipped.

The effects on different range and rebroadcast interval values are described in Section 4.3. The simulation setup consists of two separate models. For simulating the scenario and the traffic driving through the scenario a traffic model is used. Network communication is simulated by a network simulator using mobility of the nodes provided by the traffic model. The remainder of this section first describes the scenario and applications followed by a detailed description of the traffic and network model.

4.1.1 Scenario and Applications

The scenario of interest in this thesis is in the context of sparse vehicular networks, caused by either a low traffic volume or low penetration rate of some communication technology. Therefore, the focus is on a vast rural area with a usual low traffic density, such as the “Obere Donau” shown in Figure 4.1. The selected area is a 20 times 20 kilometer rural part of the German province Baden-Württemberg located south of Stuttgart.

Figure 4.1: “Obere Donau” vast rural area located south of Stuttgart, in the province Baden-Württemberg of Germany.

This scenario is chosen because it is one of the challenging network situations. And in the context of market introduction it is the most important situation to deal with right now. Channel saturation is not an issue in sparse VANETs, in contrast to a dense vehicular scenario. Worse, vehicles are most likely not always in reach of each other, so it is more challenging to disseminate information to all interested vehicles. Moreover, improving road safety is key in a scenario like this, since half of the traffic fatalities occur on rural roads [3].

Of course improving road safety can be done in different ways, for example by better organizing traffic situations by means of landscaping, i.e. cutting down trees very close to the road. Another potential solution could be, exploiting navigation software to warn about dangerous traffic situations, e.g. warning drivers about sharp bends. For this scenario, ITS is exploited to improve road safety.

One of the applications to improve road safety is notifying vehicles or drivers about imminent danger on the road ahead. These notifications are compiled into messages, called Road Hazard Warnings (RHW). In order to inform other vehicles, the RHW is disseminated within a certain area over some period of time. Therefore, a safety hazard is associated with a geographical area and a time duration to indicate where and how long the information is valid. Hence, safety information must be kept alive by vehicles passing through this area, as already mentioned, this is a challenging task if traffic density is low.

Because of the high frequency, CAMs are inapplicable to be sent using C2S, due to the delay of the satellite link. For the RHW application, the DENM facility can be used to disseminate the information about potential road hazards to other vehicles, and keep this information alive within the geographic area for a certain time, indicated by the TTL.

Potential road hazards include, but are not limited to, crashed or stopped vehicles, roadway damage such as potholes, objects on the road such as animals or fallen trees, or slippery roads due to ice, mud or pools of water. These hazards may be detected by vehicle on-board sensors, such as suspension sensors or feedback from Electronic Stability Program (ESP) systems. Also drivers may report a hazard to warn about their vehicle that they have stopped, because of a breakdown. However, the emphasis of this research is on the information dissemination and not on the information itself. Hence, it is assumed a general road hazard is being reported and other vehicles must be warned about the imminent danger.

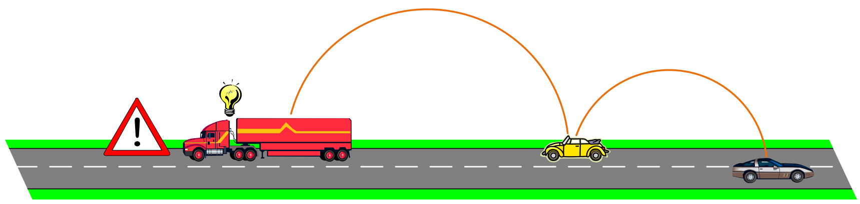


Figure 4.2: Brief overview of the scenario: the truck detects a dangerous situation and initiates the notification of other vehicles, information is disseminated via other vehicles. Communication between vehicles, indicated with orange arcs, is achieved through arbitrary communication links.

To recapitulate, the scenario is as follows. A vehicle driving through a rural area detects a dangerous situation on the road and sends out a RHW to all vehicles in the vicinity. The RHW is kept alive within a certain area, called the area of validity, for some period of time, which is called the time of validity or TTL. This scenario is depicted in Figure 4.2.

4.1.2 Traffic Model

A traffic model is a representation of the behavior of traffic, in order to simulate a realistic VANET scenario it is essential for the traffic model to reflect real behavior of vehicles. This model can be described at different scales of observation. A macroscopic scale model considers traffic flows, whereas a microscopic scale model describes the behavior of each individual vehicle. For this simulation setup a microscopic scale is used because the focus is on the behavior of individual vehicles and their communication [77].

In this thesis a traffic simulator based model is used. The simulator of choice is SUMO, which is a mature open source microscopic traffic simulator and able to generate a real-world traffic topology from OpenStreetMap[1] [78]. For the simulation setup a large rural area of the German province Baden-Württemberg is chosen. The selected area is called the "Obere Donau" a 20 times 20 kilometer rural part of the province south of Stuttgart. Realistic traffic is generated according to traffic census of the province Baden-Württemberg in 2005 [79].

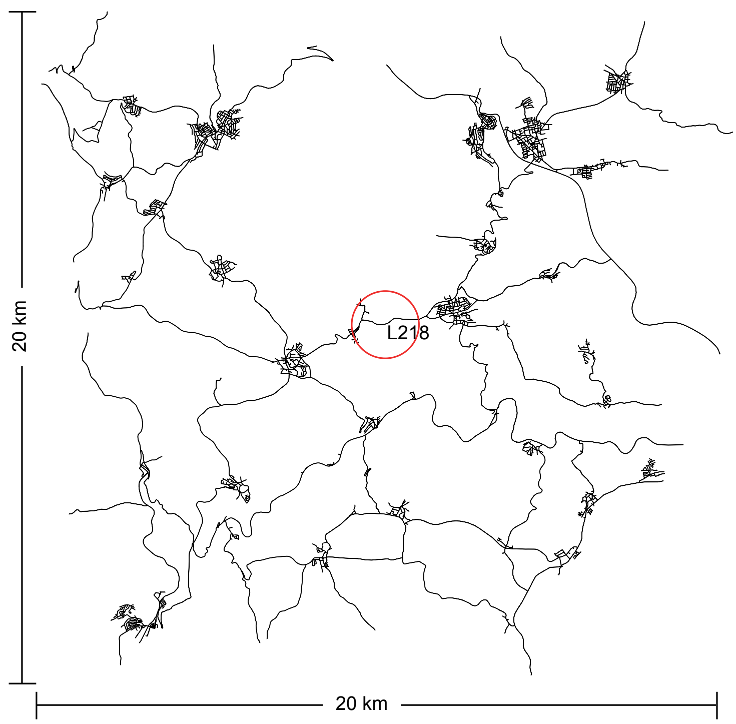


Figure 4.3: "Obere Donau" rural road topology distilled from OpenStreetMap and used by the traffic model. The red circle indicates the assumed location of the road hazard on the road L218.

The time between two successive vehicles passing a certain point on the road is called the inter-arrival time. This can be modeled by a certain distribution based on the traffic characteristics, e.g. traffic density. It is shown that in rural areas, the inter-arrival time of vehicles can be modeled by an exponential

[1] www.openstreetmap.org

distribution, if traffic density is low, i.e. less than 1000 vehicles per hour at a certain road [80]. This assumption is used for generating traffic based on the given traffic census. The inter-arrival time distribution, $f(x)$, with parameter λ, plotted in Figure 4.4, is given by

$$f(x) = \lambda e^{-\lambda x}$$

where λ, the number of vehicles per second, can be derived from the average traffic volume per hour, T_v, provided by the traffic census

$$\lambda \approx \frac{T_v}{3600}.$$

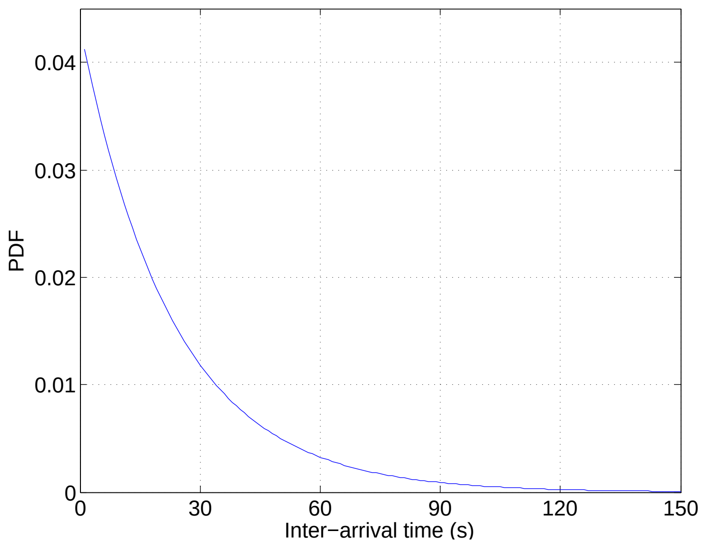


Figure 4.4: Inter-arrival time distribution, $f(x)$, based on average traffic volume, T_v, of 155 vehicles per hour.

Traffic is generated for the L218 according to traffic census of Baden-Württemberg in 2005. From the traffic census, the traffic volume on the L218 approximates to 155 vehicles per hour. Therefore, generation of traffic should result in the same number of vehicles per hour on average on the central road of the simulation area, the L218 as depicted in Figure 4.3.

Generation of traffic itself is done by SUMO based on trip definitions. The syntax of the trip definition is given in Listing 4.1. Each trip is given a unique identifier and consists of a departure time, a starting point and end point. The origin and destination are edges from the topology graph, as shown in Figure 4.3. SUMO uses the trip definitions to generate individual vehicles and routes each vehicle at a specific departure time (based on the inter-arrival time distribution) from origin to destination using Dijkstra's shortest path algorithm [81].

Trip definitions, as used as input for SUMO, can be formulated manually. Of course this is very time consuming. Therefore, here is opted for automatic generation of trip definitions. A correlation exists between the type of road and its amount of traffic, hence generation of traffic is dependent on the road types. Three different road types are distinguished. First type are the national and state roads, in German called ‘Bundesstraße’ and ‘Landesstraße’ respectively. Second type are the district roads, connecting roads between villages and towns, in German called ‘Kreisstraße’. Third type are residential roads, i.e. roads within towns and villages.

```
<tripdef
    id="<ID>"
    depart="<TIME>"
    from="<ORIGIN_EDGE_ID>"
    to="<DESTINATION_EDGE_ID>"
/>
```

Listing 4.1: SUMO Trip Definition Syntax

To match the amount of traffic generated, for each road type a different mean value for the exponential inter-arrival time distribution is used (the mean of an exponential distribution is given by λ^{-1}). Not only should λ^{-1} match the amount of traffic on a certain road type, most of all it should match the data given by the traffic census. The goal is to meet the same average number of vehicles on the L218 and surrounding roads as stated for each particular road in the traffic census. The selection of the three mean values for the distribution function to generate traffic for each road type is based on heuristics.

Pseudo code of the generation method is given in Listing 4.2. Each road type has a mean inter-arrival time and corresponding input edges. Based on the mean an exponential variable object is created where values can be drawn from. For each of the input edges, corresponding to the road type, vehicles are generated with a random inter-arrival time, based on the exponential distribution, until the departure time exceeds the simulation time. Each vehicle leaves the simulation area via an arbitrary output edge, where the major roads are given a higher priority because they are added twice to the set of output edges.

```
foreach RoadType in RoadTypes do
  create ExponentialVariable expVar(RoadType.getMean())
  foreach InputEdge in RoadType.getInputEdges() do
    departTime = expVar.GetValue()
    while departTime < simulationTime do
      from = InputEdge.getId()
      to   = OutputEdges.getRandomEdge() //to!=from
      create TripDefinition trip(departTime,from,to)
      write trip //write trip definition to file
      departTime += expVar.GetValue()
    end
  end
end
```

Listing 4.2: Pseudo code for generating trip definitions

Given the trip definitions, SUMO is able to route the vehicles through the network topology for a predefined simulation duration, as indicated in Listing 4.2 as simulation time. The vehicle speed is regulated by SUMO, the speed is maximized based on the maximum speed that applies on a certain road type and other vehicles on the road. On rural roads in Germany this is 100 km/h by default. SUMO uses the routes of all vehicles to generate a network state dump of the simulation. Eventually, the state dump can be converted to a trace file. The traces describe the speed and heading of each vehicle during the simulation and is compatible with the network model in ns-3.

Proper initialization of the simulation area is important. Because the road topology starts empty and vehicles are mainly generated at the border of the simulation area, it takes some time before the simulation area is populated with vehicles. Consequently, the transient period is taken into account and after this period network simulation starts to avoid initialization bias.

4.1.3 Network Model

Communication between vehicles is represented by a network model in order to simulate and afterwards analyze the behavior of information dissemination over time. Numerous network simulators and models are available, free open source as well as closed source commercial software. To be confident in the results of a simulation, choosing a widely used and highly regarded network simulation core is key. In this thesis ns-3 [82] is chosen. The network simulator ns-3 is a discrete-event simulator, written from scratch and intended as a replacement for the popular ns-2. An important feature is the possibility to import traces generated by SUMO and by that couple ns-3 with the traffic model.

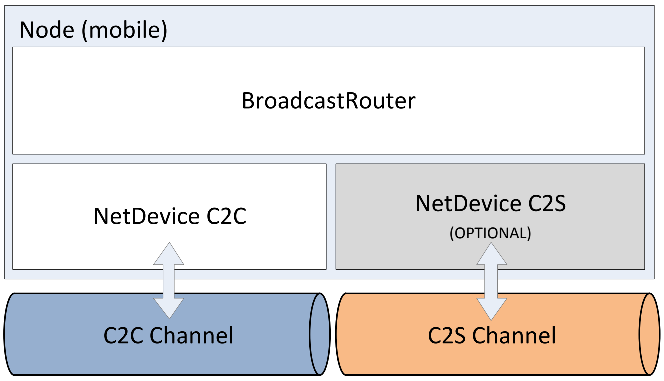


Figure 4.5: Implementation of networking layers installed on the nodes in ns-3. Nodes communicate through the NetDevice via a common shared channel.

Entities in the ns-3 network are called nodes, which are connection points in a network topology. In this case a node represents a vehicle. Mobility of nodes is taken care of by an existing ns-3 mobility model, which is fed by the trace file generated by SUMO. Hence, nodes are moving in a realistic manner over a virtual road topology. This links the traffic model, as described in the previous section, with the network model.

Nodes communicate via common shared channels, as shown in Figure 4.5. For this work, two different channels are defined. The different channels have different propagation characteristics, described by a propagation delay model and a propagation loss model. A constant propagation delay model is used to simulate communication with a constant time delay. Delay values of both channels are given in Table 4.1. To be able to simulate a fixed range and analyze the effect on performance, a range propagation loss model is used. The communication range is therefore fixed, meaning that if a node is within the communication range it will receive the signal, while if the node is just outside range it will receive no signal. Reason for these relatively simple channel models is to reduce time complexity of the simulation and focus on the effects to get an impression of the possibilities and bounds of combining both technologies.

As Figure 4.5 shows, each node uses a NetDevice for C2C to communicate through the C2C Channel and optionally also a C2S NetDevice for communication over the C2S Channel. Through the NetDevice a node can send to and receive from a corresponding channel. In this setup it is assumed that no collisions occur, therefore no medium access control is implemented. This assumption is justified for the reason that a sparse VANET is considered. Because of the low number of vehicles, the medium is virtually always free, so we omit the chance of a busy medium and collision.

The BroadcastRouter layer in Figure 4.5 is responsible for the information dissemination. Flooding is used as a broadcasting mechanism for information dissemination. Despite the bandwidth inefficiency, flooding is reliable and robust because it does not need any information about the underlying network topology. Every vehicle receiving a packet checks whether or not it is already broadcasting the packet, if not the vehicle starts broadcasting this packet periodically, according to a given rebroadcast rate. Broadcast messages are sent over all available NetDevices and passed on to the corresponding channel.

In case a centralized satellite broadcast approach is taken, an extra node is added to the network denoted as the satellite hub. The satellite hub is then responsible for (re-)broadcasting over the C2S channel to all C2S NetDevices. This means, the satellite hub is informed by receiving a particular RHW over the satellite uplink. From that time on, the satellite hub rebroadcasts the RHW periodically. All nodes receiving the RHW over the C2S channel know the satellite hub is informed and refrain from informing the satellite hub again.

Networking of a node can be activated and deactivated and is triggered by the mobility model, i.e. the trace provided by the traffic model. All nodes are created at the beginning of the simulation and inactive by default. When the node enters the simulation area, i.e. starts driving from an edge, the node is automatically activated. The node is active until it leaves the simulation area by reaching its destination edge.

If the simulation is run, after initialization phase to populate the simulation area with vehicles, broadcast of the RHW is initiated by the the first vehicle equipped with a NetDevice — one or more — passing the predefined hazardous location. It is assumed that the vehicle detects the hazard, by means of some sensor, and constructs a RHW accordingly. This packet is tagged with a certain time to live (TTL), as given in Table 4.1, which indicates how long the message should be kept alive. If the TTL is expired the RHW is discarded and it is assumed that the hazard is remedied. At this point, all data is gathered and the performance can be evaluated according to the performance metrics.

4.2 Performance Metrics

For analysis and evaluation of the simulation, which performance metric is chosen is of utmost importance. Different metrics can be chosen and for each the performance can be evaluated and compared to other results, however not all metrics are suitable. For example, one could measure delay, however if the scenario is delay tolerant, delay might be not the performance metric of choice.

This thesis uses the *In Time Reception Ratio* and *Number of Received Duplicates* as performance metrics to evaluate the simulation results. These performance metrics are explained in detail in the following subsections.

4.2.1 In Time Reception Ratio

Section 4.1.1 describes the scenario where C2C is combined with C2S together with its applications. The application of warning a user about imminent danger is only useful if users are warned in time, i.e. the warning is received after passing the hazardous location or is not received at all. Users should receive information about hazardous locations early enough to be able to avert danger, otherwise a road accident might be inevitable. Therefore, the in time reception is an important performance metric to analyze the effect in terms of road safety.

Whether or not a vehicle is informed in time, is determined by two criteria. First a vehicle should have received a message containing the information. If no such message is received the vehicle is not informed at all, so definitely not in time. Second, if a vehicle did receive the information, the driver should be able to avert danger. At the point the vehicle receives the message we assume the driver is informed immediately. From this point the driver needs time to bring the vehicle to a standstill, which means covering a certain distance. Using the current velocity and deceleration speed of the vehicle the braking distance is determined. The total braking distance is given by,

$$d_{brake} = \frac{v^2}{2 \cdot b} + v$$

which is the braking distance of the vehicle, with velocity v at the point it is informed and an assumed deceleration b of $5\,m/s^2$, comparable to deceleration on wet asphalt [83]. Additionally a one second delay ($1 \cdot v$, therefore v) is added to reflect the reaction time of the driver.

Evaluation of this metric is done by comparing the total braking distance to the actual distance of the vehicle to the hazardous location at the point the vehicle receives the message. If the total braking distance is shorter than or equal to the actual distance to the hazardous location it is assumed that the vehicle received the message in time. An example is given in Figure 4.6.

Each vehicle in the simulation equipped with communication technology is evaluated, resulting in the *In Time Reception Ratio*. This ratio tells us how many of all vehicles, that could have been informed about the road hazard, actually did receive the message and were able to avert danger. That is, the higher the ratio, the better the performance.

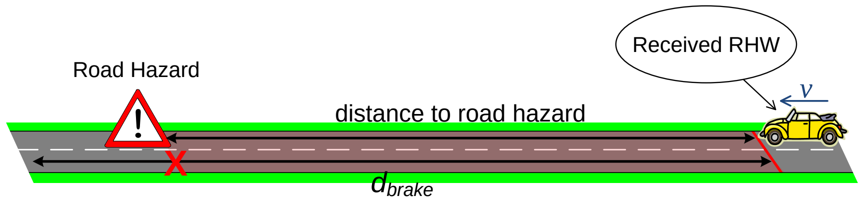


Figure 4.6: Evaluation of the *In Time Reception* of the RHW. In this example, the RHW is not received in time, since the braking distance d_{brake} is larger than the distance to the hazardous location, indicated by the warning triangle. The velocity, v, of the vehicle is used in the calculation of the braking distance.

4.2.2 Number of Received Duplicates

Because information dissemination is based on broadcasting, vehicles could receive a particular message more than once. Obviously, the most efficient way vehicles can be informed is by receiving the message only once.

During the simulation the number of duplicates each vehicle receives is counted. The performance metric *Number of Received Duplicates* denotes the sum of all received duplicates.

The way information is disseminated to other vehicles clearly influences the *Number of Received Duplicates*, however it also affects other performance metrics. If only the number of received duplicates is taken into account, other performance metrics could drop. Hence, this performance metric should be used together with other performance metrics, such as the *In Time Reception Ratio*. While other performance metrics stay at least the same, the number of duplicates should decrease. For this performance metric, less is better applies.

4.3 Simulation Results

As described in the previous sections, the simulation consists of a traffic and a network model. One mobility pattern is generated using the traffic model described in Section 4.1.2. This mobility pattern is used for each simulation run, while for each run different vehicles are randomly selected to be equipped with communication technology. Each data point, describing a particular configuration (see Table 4.1), is the average of 30 independent iterations.

For an individual run it could be the case that the initiating vehicle is unable to forward the RHW to other vehicles such that passing vehicles will not be informed, resulting in a ratio of zero. This has a relatively large effect on a particular data point, which leads to a drop of the data point together with higher uncertainty for this data point. This uncertainty is indicated by error bars in the graphs based on a computation of the 95% bootstrap confidence interval using MATLAB with a bootstrap re-sample size of 10,000. The bootstrap method [84] is used because standard assumptions are invalid due to the non-normal distributed data. Hence, this may lead to drops and peaks in a graph, when it might be unexpected with an increasing penetration rate.

4.3.1 Centralized or Decentralized Satellite Broadcast

Section 3.3.2 described the possible information dissemination using a centralized and a decentralized approach. The performance of a decentralized approach is given in Figure 4.7 and that of the centralized approach in Figure 4.8.

The performance of different configurations is shown based on the *In Time Reception Ratio*, as described in the previous section. Each data point describes the average of the number of runs, according the number of runs in Table 4.1. The y-axis describes the portion of vehicles, with respect to the total number of vehicles equipped with one or more communication devices, that receive the RHW in time. E.g. if the *In Time Reception Ratio* is 0.5, this means that half of the vehicles received the RHW early enough to react in time to avoid danger. The other half of the vehicles did not receive the RHW or where unable to react on it in time. Vehicles without communication capabilities are not taken into account, since they never receive the RHW at all. On the x-axis the C2C penetration rate is shown, indicating the percentage of vehicles equipped with C2C technology. The different curves show the performance with a different percentage of vehicles equipped with an additional satellite link.

To give a concrete example of how to read the graphs, take for example Figure 4.8. If one out of ten vehicles (10 % C2C penetration) is equipped only with C2C technology (0 % C2S penetration), the graph indicates that slightly more than 20 % of the equipped vehicles passing the hazardous location were informed in time. If the same C2C penetration rate of 10 % is considered, but now with a C2S penetration rate of 60 %, more than 80 % of the vehicles are informed in time.

As expected, the centralized and decentralized satellite approach show quite similar results. Only if the C2C penetration rate is low (< 10 %) and vehicles are also equipped with an additional satellite link, the graphs show different results. This is due to an artifact in the simulation, because the simulation area is finite and vehicles that reach the border of the simulation area stop broadcasting over the satellite. Hence, information dissemination stalls because of the small amount of vehicles equipped with an additional satellite link, i.e. at some point there is no vehicle within the simulation area equipped with a satellite link to forward the message to. This is not the case if a centralized satellite hub is broadcasting the message, because it is always within the simulation area. Therefore, both simulations would show exact similar results if vehicles continued broadcasting the message over the satellite after leaving the simulation area.

Using a centralized satellite approach the *Number of Received Duplicates* is constant with respect to the penetration rate, as opposed to the decentralized satellite approach where this relation is linear, as depicted in Figure 4.9. With a centralized satellite approach and a C2S penetration of 2.5 % the *Number of Received Duplicates* was already reduced by 67 %. Given the linear rate of change of a decentralized satellite approach the impact gets even higher if the C2S penetration rate increases.

It can be concluded that information dissemination itself is not improved by taking a centralized satellite approach. However, this approach is more bandwidth efficient, in fact this way there is no congestion at the satellite link which

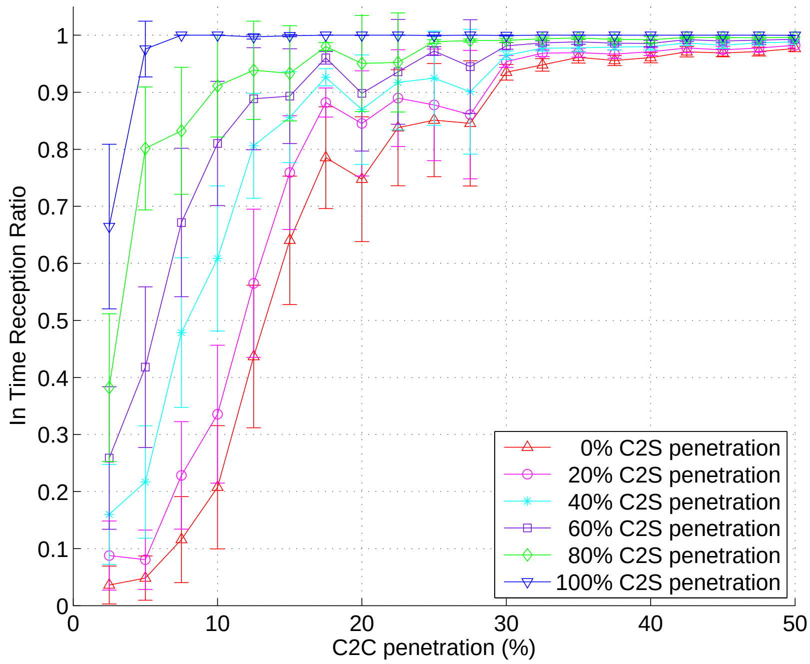


Figure 4.7: Performance of using a Decentralized Satellite approach, with rebroadcast rate of 0.1 Hz (10 seconds interval) and communication range of 250 m

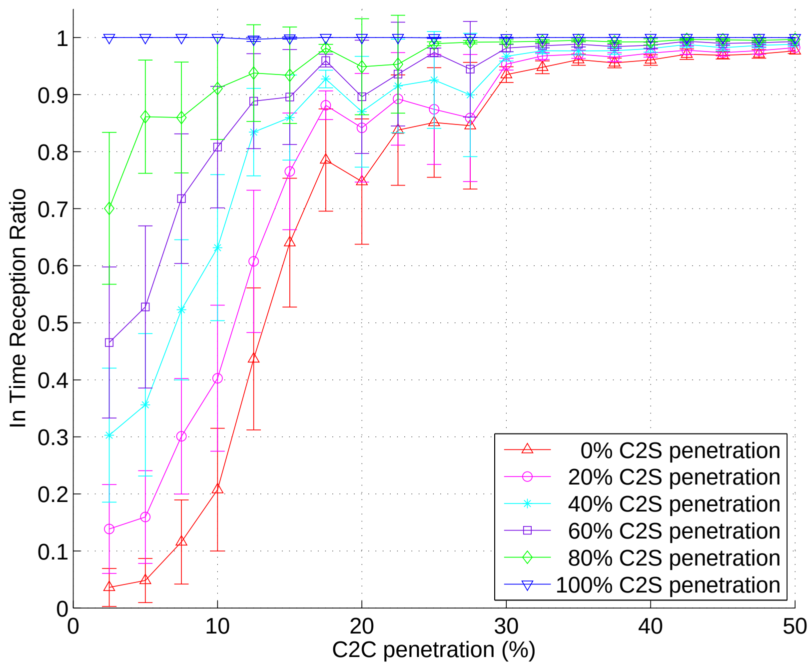


Figure 4.8: Performance of using a Centralized Satellite approach, with rebroadcast rate of 0.1 Hz (10 seconds interval) and communication range of 250 m

all the more justifies the assumption of a simplified channel access model. Moreover, since the SafeTRIP architecture assumes the use of a satellite hub, this approach is more realistic too. Hence, in the following simulations a centralized satellite approach is assumed.

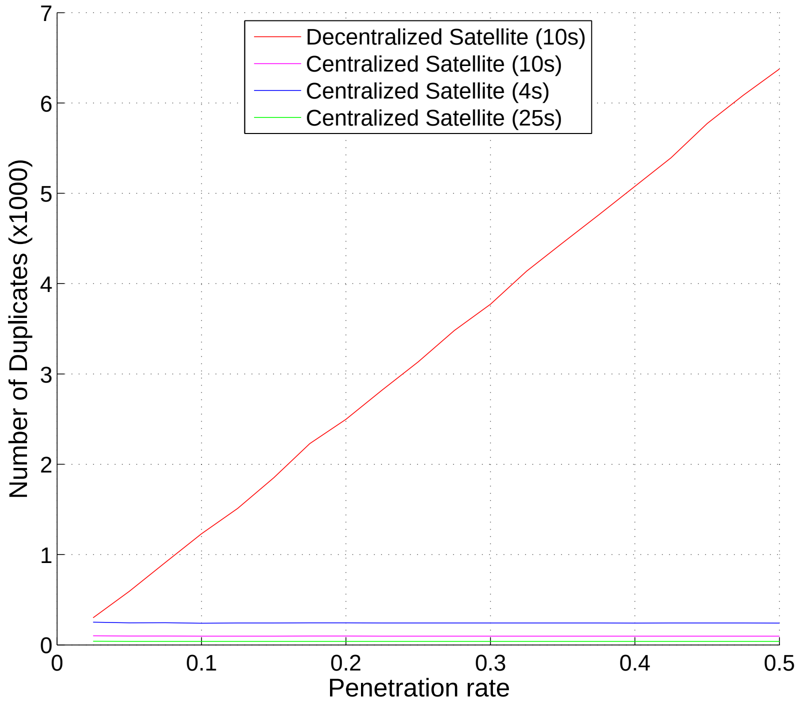


Figure 4.9: Average number of duplicates received per vehicle for varying penetration rates. The decentralized approach shows a linear relation between number of duplicates and penetration rate, in contrast to that of the centralized approach which is constant. Different rebroadcast intervals, indicated between parentheses, show that increasing the interval leads to less number of duplicates.

4.3.2 Trade-off Rebroadcast Rate and Performance

The performance of information dissemination depends on the interval between two consecutive broadcasts, i.e. rebroadcast rate. If the interval is too large and a vehicle wants to forward information to passing vehicles via C2C, those vehicles might be already outside the communication range by the time the vehicle broadcasts the information. Obviously this problem does not apply to C2S, because the communication range is relatively large compared to the communication range of C2C.

To show the performance impact of increasing the rebroadcast rate, an interval of 4 seconds is simulated and depicted in Figure 4.10. Increase in performance is visible if the penetration rate is low ($< 30\,\%$). If the penetration rate exceeds $30\,\%$ there are enough vehicles to forward the information to, hence there is no extra gain in performance. The impact on performance is higher if the vehicles equipped with C2C only are dominant, because with higher C2S penetration rates the information dissemination depends less on the dissemination via C2C. Increasing the rebroadcast rate improves the *In Time Reception Ratio* by up to 0.05, however the *Number of Received Duplicates* is 2.5 times higher, as shown in Figure 4.9. The performance gain is too insignificant in relation to the significant decline of efficiency, therefore increasing the rebroadcast rate to 0.25 Hz is not justified.

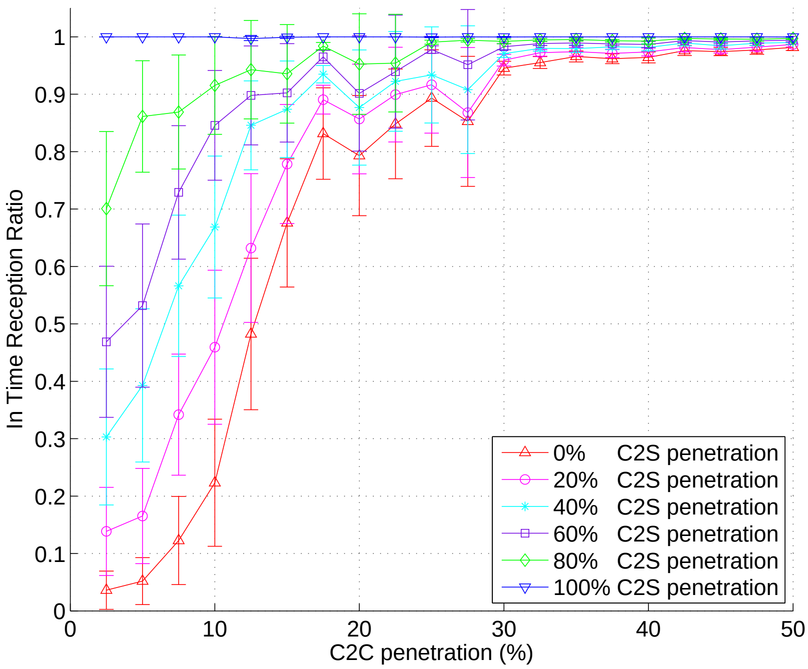


Figure 4.10: Performance of increasing the rebroadcast rate to 0.25 Hz (4 seconds interval) and communication range of $250\,m$

Figure 4.11 shows a dramatic decrease in performance if the rebroadcast interval is changed from 10 to 25 seconds, although Figure 4.9 shows a decreased *Number of Received Duplicates*. It shows that if the rebroadcast interval is too large, vehicles are unable to disseminate information to other vehicles via the C2C link. Obviously the influence is higher if the number of vehicles only equipped with C2C is dominant. Even if a large number of vehicles is also equipped with a satellite link the performance is poor, since by the time the vehicle receives the RHW it may already have passed the hazardous location.

The performance of information dissemination is clearly affected by the rebroadcast rate. To a certain extent the performance increases by increasing the rebroadcast rate, i.e. decreasing the rebroadcast interval. If two vehicles approach each other, with a maximum speed of $100\,km/h$, the relative speed of these opposing vehicles is approximately $56\,m/s$. If assumed that the communication range is $250\,m$ and communication is instant, i.e. sending a message takes zero

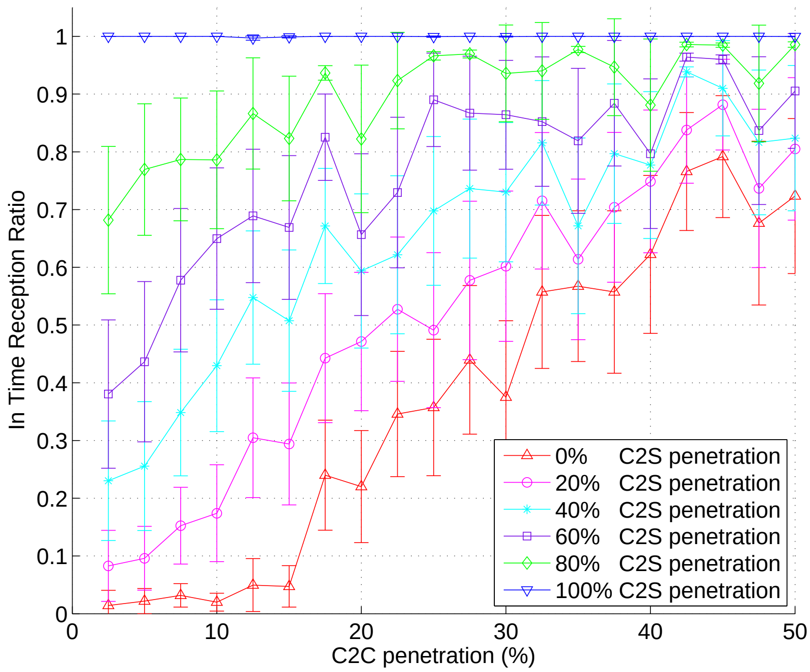


Figure 4.11: Performance of decreasing the rebroadcast rate to 0.04 Hz (25 seconds interval) and communication range of 250 m

time, the optimal interval between consecutive broadcasts would be approximately 8 seconds. This means that rebroadcasting at a higher frequency does not lead to informing more vehicles and is, therefore, useless. Based on the results shown in Figure 4.9, it is expected that with an interval of 8 seconds the *Number of Received Duplicates* will be 25 % higher than in case of a 10 seconds interval, while achieving the same performance as in Figure 4.10. Of course, this only holds for the assumptions regarding vehicle velocity and communication range as stated above. Since the 8 seconds interval is not simulated within this work, the validation of this theory is left for future work.

4.3.3 Influence of Car-to-Car Communication Range

Electromagnetic waves, used in wireless communications, are subject to signal attenuation, caused by multiple factors. In optimal environmental conditions, a signal propagating via a line-of-sight path through free space is subject to path loss, i.e. reduction in power density as it propagates through air.

While IEEE 802.11p was designed to support a communication range of 1000 meter [85], results in [86] show that this might not be realistic. On the other hand real world experiments have shown that communication is possible over 1000 meters and more [87]. However, many papers assume a communication range between 250 and 500 meter.

To show the effect of the C2C communication range in the scenario of this thesis, two extremes are simulated. In general a pessimistic C2C communication range

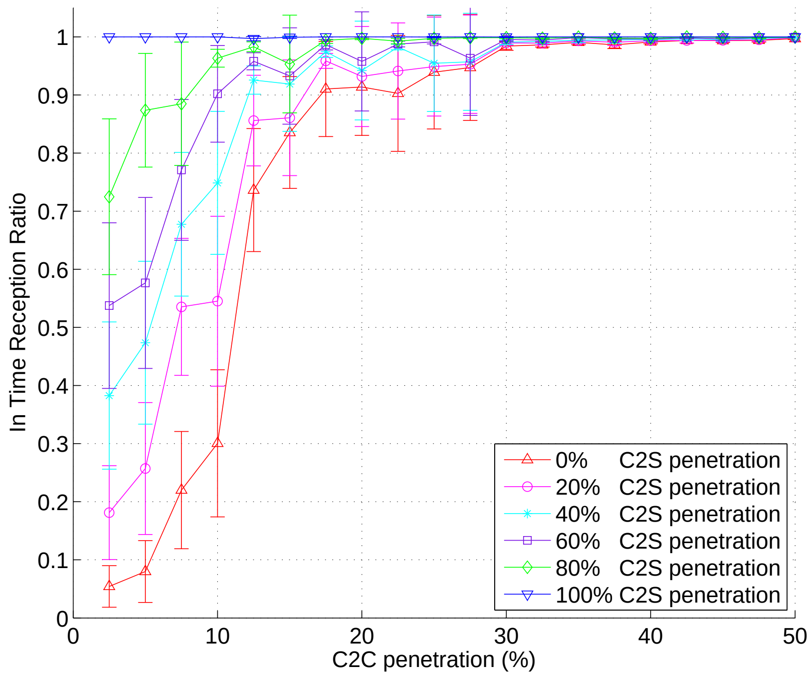


Figure 4.12: Performance of increased C2C communication range (1000 meter), with rebroadcast rate of 0.1 Hz (10 seconds interval), compare to Figure 4.8

of 250 meter is assumed, results of these simulations are already shown in Figure 4.7 until 4.11. The impact of increasing the C2C communication range to 1000 meter is shown in Figure 4.12. It shows little performance gain if the C2C penetration rate is low, up to 5%, and without an additional satellite link. Apparently, the distance between vehicles is still too large to overcome the gaps and disseminate the information by forwarding. The lines in the graph are more skewed to the left, indicating a better performance with lower penetration rates, especially with a C2C penetration rate between 5–10%. Adding C2S to vehicles also has a larger impact, with 2.5% C2C penetration rate together with a C2S penetration rate of 60% the *In Time Reception Ratio* improves from 0.46 to 0.54. This indicates that, because of the increased C2C communication range, the clusters of connected vehicles become larger and with that increase performance. Moreover, the effect of adding C2S becomes larger, because by bridging communication from one cluster to another via satellite more vehicles are notified.

In general the graphs, as discussed until now, show that without an additional satellite link the application performs poor if the C2C penetration is less than 30 %. On the other hand, if C2C penetration is higher than 30 % increasing the C2C penetration rate has no significant extra gain in performance and there is also no significant impact anymore in adding a satellite communication link. Therefore, it can be concluded that in this scenario a major benefit from an additional satellite link can be achieved if the C2C penetration rate is low.

4.3.4 Behavior of Information Dissemination over Time

Apart from looking at the overall performance while changing parameter values, it is also interesting to see how information dissemination behaves over time. The most interesting case is if vehicles are only equipped with C2C technology, because keeping information dissemination alive over time then relies on other vehicles, in contrast to C2S where a satellite hub is responsible for this task.

Figure 4.13 shows the performance over time for the duration of the time to live of the RHW. In this case the scenario is simulated with a C2C penetration rate of 2.5 % and none of the vehicles are equipped with an additional satellite link. Each data point is, as discussed before, the average of 30 iterations. In this case, as mentioned before, fluctuations in the results are because of the single mobility pattern used. It shows the inability to keep the RHW alive with such a small amount of vehicles equipped with C2C technology. After 50 minutes, none of the following vehicles passing the hazardous did receive the RHW in time. Of course, the results based on a TTL of 2 hours, however, it is clearly shown that it is hard to keep the RHW alive if the penetration rate is low.

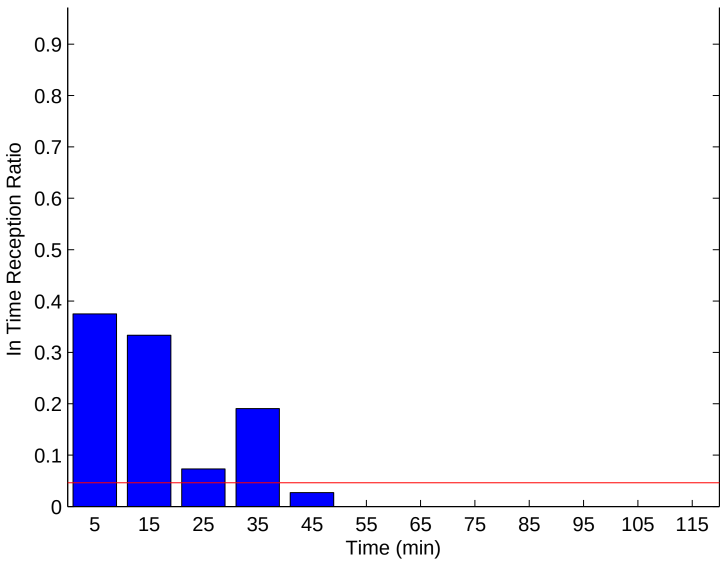


Figure 4.13: Information Dissemination stalls with the lapse of time. In this simulation 2.5 % of the vehicles are equipped only with C2C technology, with rebroadcast rate of 0.1 Hz (10 seconds interval) and communication range of 250 m.

The reason for the information dissemination to stall is the inability to forward information to vehicles because of the low penetration rate or because the inability to forward the information in the right direction, therefore vehicles passing the hazardous location are not informed while vehicles going a different route are. Of course, to some extent this has also to do with the finite broadcast area, which is restricted by the simulation area, however this area is already 400 kilometer squared.

A possible solution for this problem is the re-initiation of the RHW, as shown in Figure 4.14. The scenario is the same: 2.5 % of the vehicles are equipped with only ITS-G5 technology, so without an additional C2S communication link. The difference is that a vehicle that pass the road hazard, will initiate a new RHW broadcast if not being notified by means of a RHW. As Figure 4.14 shows, this way the RHW does not get lost after some time. The red line indicates the average, which is increased by more than 40 % compared to Figure 4.13. However, on average still half of the vehicles do not receive the RHW in time.

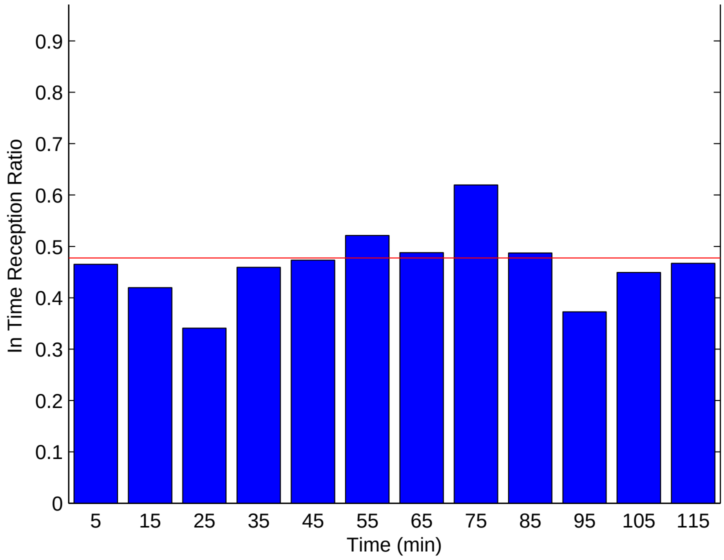


Figure 4.14: Information is kept alive if the RHW is re-initiated. In this simulation 2.5 % of the vehicles are equipped only with C2C technology, with rebroadcast rate of 0.1 Hz (10 seconds interval) and communication range of 250 m.

This reactive approach only mitigates the stalling effect. Adding a satellite link to some or all of the vehicles effectively solves the problem. Because of the centralized satellite hub, the RHW can be kept alive during its time to live period, solving the root cause, without having to rely on the number of C2C equipped vehicles within the area, i.e. the C2C penetration rate. The performance increase is then related to C2S penetration rate.

4.3.5 Accelerating C2C market introduction

One of the major problems recognized by others is the initial phase of C2C market introduction [88]. As already shown, performance of the RHW application in sparse vehicular networks with only C2C technology is poor. This has a negative effect on the acceptance of this new technology by investors and end users. Therefore, introducing a satellite component to overcome some of the limits in VANETs is not only a gain in performance, but also the market introduction of C2C technology itself can benefit significantly. This is illustrated by combining the results as shown earlier with the market introduction forecast shown in Figure 4.15. The figure shows an estimation by Volkswagen and others of the penetration rate of C2C equipped vehicles in Germany over several years for different introduction strategies. It indicates that the market introduction takes ages if only high class vehicles are equipped, i.e. after 10 years only 5% of the vehicles are equipped. If all vehicles belonging to middle class and above are equipped, it still takes 9 years to reach a 30% penetration rate, the penetration rate needed in the sparse scenario where only C2C is considered, see Figure 4.8.

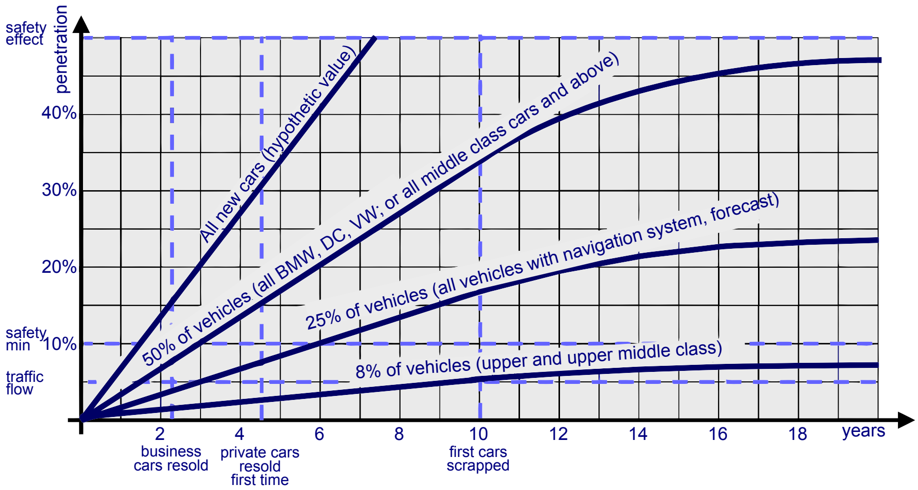


Figure 4.15: Market introduction estimation by Volkswagen and others [89], showing the C2C penetration in Germany over the years for different introduction strategies.

To show how the addition of satellite technology can accelerate C2C market introduction, the results of the performance analysis for the scenario presented in this thesis are mapped to the market introduction forecast. The resulting Figure 4.16 highlights two examples on how to interpret this mapping.

The first example considers the situation in a very early stage of market introduction where only 2.5% of the vehicles are equipped with C2C technology, in addition 20% of those vehicles is equipped with C2S. In other words, every 40th vehicle is equipped with C2C and every 200th also with C2S. The performance achieved in this situation equals the performance in case 7.5% of pure C2C penetration, so this actually means a kind of boost by C2S. The impact seems insignificant, however, if related to the market introduction where only high class vehicles are getting equipped, this means about 12 years advance in market introduction!

As a second example, consider another situation in the early stage of market introduction where 5% of the vehicles are equipped with C2C technology. Of these vehicles now 80% are additionally equipped with C2S technology. This means one out of 20 vehicles is equipped with C2C and one out of 25 is also equipped with C2S. In this case, the same performance is achieved with a penetration rate of 28% with pure C2C. Again, if this is related to the market introduction forecast and an optimistic market introduction is considered, in which 50% of all new vehicles are getting equipped, a leap in time of approximately 7 years is achieved.

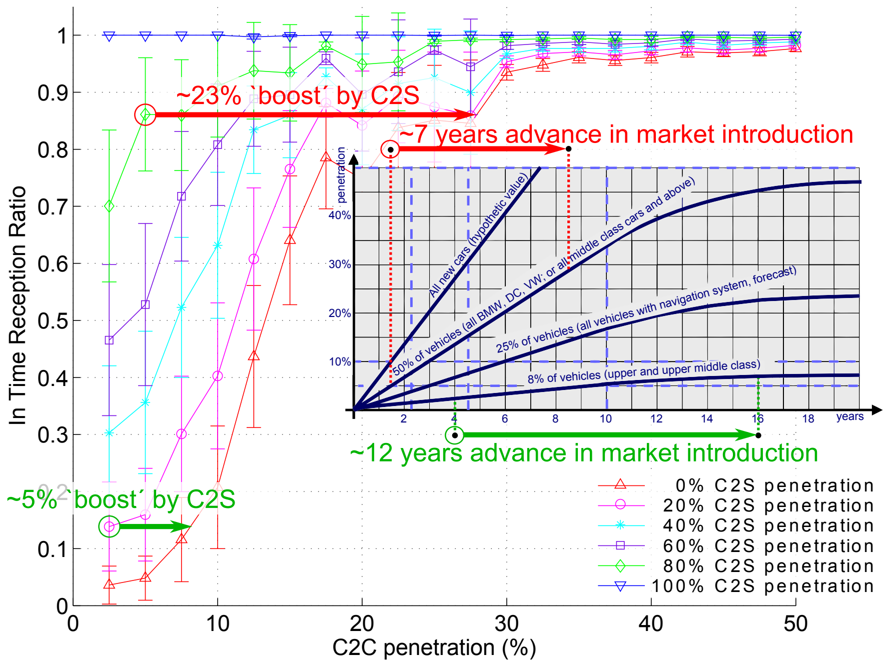


Figure 4.16: Accelerating C2C market introduction by adding satellite communication. Two examples are highlighted in red and green, these show that equipping a certain percentage of vehicles with an additional satellite link causes a leap in time compared to the market introduction of C2C only.

These examples show that the use of satellite in combination with C2C technology can have a tremendous impact in the early years of market introduction and with this synergy the problems in the early years can be prevented. Of course this applies only to this scenario and application. The satellite link is superfluous for information dissemination if in this case the penetration rate exceeds 30%, because almost the same results are achieved by C2C only. The satellite may still be useful as a data provider, though, providing for example information from road operators. Also, whereas security is an important and challenging issue in VANETs, the satellite can be used for the distribution of security certificates. However, this is out of scope of this thesis, albeit very interesting for future work.

CHAPTER 5

Conclusions

This thesis quantified the possible improvement of information dissemination in sparse vehicular networks by adding satellite communication. This final chapter describes the general conclusions, answers to research questions and future work.

5.1 General Conclusions

This thesis presented the connectivity problem in sparse vehicular networks where vehicles are equipped with C2C technology only. This problem can lead to fragmentation within the network, resulting in disconnected clusters of vehicles. The reason for this is the limited C2C communication range.

To overcome this problem, a complementary communication technology is introduced, this work uses C2S technology for this. Because of the large footprint of a satellite, C2S can be used to bridge communication between disconnected clusters. This solves fragmentation and with that the issue of information dissemination in sparse vehicular networks.

The performance gain of information dissemination in sparse vehicular networks by adding an additional satellite link is quantified by means of simulation. To get a realistic sparse vehicular network scenario, a rural area in the southern part of Germany has been simulated. The network topology is taken from OpenStreetMap and official traffic census provided realistic traffic data. The traffic model based on this data was fed to the traffic simulator SUMO providing a mobility model for the network simulation in ns-3. The network simulation implements a model of the C2C and C2S communication technologies.

Different parameters have been simulated. By varying the penetration rate of both C2C and C2S the impact of different rates were shown. The penetration rate tells how many vehicles are equipped with a particular communication technology. The results have shown, that information dissemination in sparse vehicular networks can be improved significantly by using an additional C2S communication link.

The impact on other parameters have also been tested. Three different broadcast intervals were simulated: 4, 10 and 25 seconds. It is a trade-off between performance, in terms of the *In Time Reception Ratio*, and efficiency, in terms of the *Number of Received Duplicates*. The results show that the simulated optimum is a rebroadcast rate of 0.1 Hz (10 seconds interval). Decreasing the rebroadcast rate to 0.04 Hz (25 seconds interval) performs badly. If the rebroadcast rate is increased to 0.25 Hz (4 seconds interval) the channel load is increased significantly while there is only a slight increase of performance. Based on theory the presumed optimal rebroadcast interval is approximately 8 seconds, under the assumptions of a communication range of 250 m and maximum vehicle velocity of 100 km/h. It is assumed that decreasing the interval even more will not lead to better performance, but only increases channel load.

A larger communication range has impact on the size of the clusters, hence there is less chance of fragmentation. Naturally this leads to better performance with lower penetration rates, however still a certain level of penetration is needed to disseminate the information if only C2C is considered. The impact of the additional satellite link increases in case the network is still fragmented, because the clusters are larger more vehicles are reached.

Furthermore, it is shown that in pure C2C vehicular networks, the network is unable to keep the information alive over time. Because vehicles, at some point, are unable to forward the information to other vehicles the dissemination stalls, leading to poor performance. Obviously, this problem becomes less severe with higher penetration rates. By re-initiating the RHW, the information is revived by other vehicles passing the hazardous location, this partially solves the issue. By adding satellite technology, the satellite hub is able to keep alive the information, thereby the performance is determined by the C2S penetration rate.

If the results are related to the prediction of C2C market introduction, it is shown that adding C2S can have the same effect as pushing forward the market introduction of C2C significantly by up to 12 years. Hence, the combination of C2C with C2S can have great impact on the near future of cooperative ITS systems.

5.2 Answers to Research Questions

In Chapter 1 the problem statement was presented together with the research questions that arose from it. Here the questions are answered based on the findings in previous chapters. First the subquestions are discussed, after that an answer to the main question is formulated.

1. *What are the advantages and disadvantages of both C2C and C2S technologies?*
   The main advantages of C2C communication are the low delay and decentralized ad hoc nature. In sparse vehicular networks the main problem of C2C is connectivity if the network is fragmented, due to the limited communication range of C2C. Coverage is one of the main advantages of C2S, so also in sparse vehicular networks information can be disseminated efficiently. The downside of C2S is the large propagation delay when a GEO satellite is used. If these technologies are combined a synergy is formed, C2C solves partially latency problems for vehicles in the vicinity

and C2S solves the connectivity problems in sparse vehicular networks if the network is fragmented. Of course, this solution leads to higher costs in hardware but also in service costs, since satellite operation expenses may be charged to the customer.

2. *What are the scenarios and applications where both technologies can benefit from each other?*
   The scenario of sparse vehicular networks are considered, since in this case the network starts to build clusters and gets fragmented. This in contrast to a dense scenario where fragmentation is not an issue, although in this case other problems arise, such as channel congestion. Low latency is one of the advantages of C2C communication, this can be exploited by the application to quickly inform vehicles in the vicinity. On the other hand, communication from one cluster to another using C2S should be delay tolerant because of the high latency of the satellite link. Hence, C2S is not suitable for sending volatile information, such as CAMs which are typically outdated in less then one second. Therefore, applications that use the DENM facility are considered, because this information is typically valid for a longer period. The RHW is chosen to notify vehicles about imminent dangers ahead, because this improves road safety and this application is also suited for C2C, in contrast to applications such as emergency calls.

3. *What information dissemination strategy should be used when combining C2C with C2S?*
   The RHW should be disseminated in a certain area in the vicinity of the road hazard for a specific period of time. Therefore, GeoBroadcasting is used as a dissemination strategy over C2C. Vehicles equipped with C2S technology inform the satellite hub once, the satellite hub in turn starts the periodic broadcast of the RHW. If a fragmented network is considered, the RHW can be promptly disseminated to vehicles within the cluster. Using C2S the satellite hub can be informed and vehicles equipped with C2S in other clusters receive this information and can disseminate the RHW over C2C to other vehicles within their cluster not equipped with C2S.

4. *Which evaluation metric should be used to fairly evaluate the simulation results?*
   Most important about the RHW application is that vehicles receive a warning of a road hazard they approach, such that they are able to react in time to avoid imminent danger. Therefore, the *In Time Reception Ratio* is chosen as the major evaluation metric. This metric describes how many of the total amount of vehicles passing the hazardous location, that could have received the RHW (i.e. are equipped with communication technology), actually received the RHW in time. In time reception means first of all receiving the RHW, second the vehicle should be able to halt before passing the hazardous location. This way information dissemination is evaluated at the application level.

   Another evaluation metric is chosen to measure the efficiency of information dissemination. Because information dissemination is based on broadcasting, vehicles could receive a particular message more than once. Obviously, the most efficient way vehicles can be informed is by receiving the message only once. During the simulation the number of duplicates each vehicle receives is counted. The performance metric *Number of Received Duplicates* denotes the sum of all received duplicates. It can be said that information dissemination is efficient, if the *Number of Received Duplicates* is minimized while maximizing other performance metrics, like the *In Time Reception Ratio*.

5. *How does C2C supplemented with C2S perform compared to the performance of pure C2C?*
   The results in terms of the *In Time Reception Ratio*, as presented in chapter 4, show that supplementing C2C with C2S can lead to significantly higher performance compared to pure C2C. If the penetration rate is low, i.e. less than 30%, the performance is poor in case of pure C2C which can be solved by adding a C2S link. The increase of performance by adding C2S depends on the C2S penetration rate. For example, in case of a C2C penetration rate of 5%, having 20% additionally equipped with C2S the *In Time Reception Ratio* increases from approximately 0.05 to 0.16, and if the C2S penetration is increased from 20% to 80% the performance increases even more to approximately 0.86. However, if the C2C penetration reaches a certain level, for this scenario this is around 30%, the extra gain in performance by adding C2S is less significant. This indicates that C2C penetration is high enough to bridge the gaps between clusters.

How can C2C benefit from additional C2S to improve information dissemination in sparse vehicular networks?

In sparse vehicular networks information dissemination with pure C2C is problematic because of network fragmentation due to a limited communication range. The large satellite coverage can bridge the gaps between clusters, therefore supplementing C2C with C2S can solve the problem of fragmentation. Together with the low delay of C2C and high latencies over the satellite link both technologies can achieve complementarity.

To quantify the benefit of combining both technologies a realistic sparse vehicular network scenario is simulated. The measurement of the performance is based on the in time reception of a specific RHW generated by one of the vehicles within the simulation. Efficiency is also taken into account by measuring the number of received duplicates.

The results have shown, that the information dissemination in sparse vehicular networks can be improved significantly if C2C is complemented with an additional C2S link, because the C2S indeed acts like a bridge between disconnected clusters solving the fragmentation in pure C2C networks. The scenario, as presented in this work, shows that if the penetration rate is higher than 30%, pure C2C performs almost as good as with the addition of C2S. Therefore, the benefit of C2S in addition to C2C to improve information dissemination is most relevant in the early years of market introduction. Related to the prospects of C2C market introduction, C2S can help accelerating the adoption of ITS and with that can have a positive effect the future of cooperative driving.

5.3 Future Work

Satellite communication makes data broadcasting over a large area possible. Besides improving information dissemination in sparse vehicular networks, the satellite may also be used to solve other issues in the field of ITS. One of the possibilities is to use the satellite for the dissemination of security certificates, instead of using RSUs as assumed in [90] and [91]. Another interesting question is whether C2S could be used to overcome issues in dense scenarios as well, perhaps to support congestion control. Moreover, the adoption of C2S and ITS in general might be stimulated by offering additional services, such as digital audio and video broadcasting.

The satellite link has limited capacity which can be a bottleneck if many vehicles make use of C2S communication at the same time. Therefore, it is important to recognize this limitation and investigate if and when this becomes a problem. This will also increase the need for more realistic channel models and medium access control mechanisms.

Besides satellite communication, there might be other communication technologies that could fulfill the the same task. Future work can take other communication technologies in consideration and compare them with each other. Related to this is that satellite services are most likely not free of costs. The financial aspect was out of scope of this thesis, but it also is an important acceptance criterion. So, future work may shed light on the costs of using satellite services.

The information dissemination strategy can be improved to increase bandwidth efficiency, something that is especially important for satellite communication. Using more advanced information dissemination strategies should not influence performance, i.e. result in the same *In Time Reception Ratios.* Key trade-off is between efficiency and reliability, a challenge if the information dissemination at the same time has to cope with extremes in network density. It is a big challenge to design an information dissemination strategy that will perfectly adapt to each of the many scenarios and applications present in vehicular networks.

Linked to the information dissemination strategy is the rebroadcast rate. In this work already various values are simulated and the results were shown. Also, an optimum is assumed based on theory. Future work should show if this theoretic optimum really is the optimum value for getting the best performance in this scenario.

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Acronyms

ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
ACK	Acknowledgment
ADAS	Advanced Driver Assistance System
AIFS	Arbitration IFS
AL	Access Layer
AU	Application Unit
BPSK	Binary Phase Shift Keying
BSA	Basic Set of Applications
BSS	Basic Service Set
BSSID	BSS Identification
C2C	Car-to-Car
C2S	Car-to-Satellite
CACC	Cooperative Adaptive Cruise Control
CALM	Communications Access for Land Mobiles
CAM	Cooperative Awareness Message
CAN	Controller Area Network
CBF	Contention-Based Forwarding
CCH	Control Channel
CDMA	Code Division Multiple Access
CEN	European Committee for Standardization
CGC	Complementary Ground Components
CO_2	Carbon Dioxide
CoS	Class of Services
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance

CTS	Clear To Send
CW	Contention Window
DCC	Distributed Congestion Control
DCF	Distributed Coordination Function
DENM	Decentralized Environmental Notification Message
DIFS	DCF IFS
DLL	Data Link Layer
DoS	Denial of Service
DSRC	Dedicated Short-Range Communications
DVB-S2	DVB-Satellite 2nd Generation
DVB-SH	Digital Video Broadcasting - Satellite to Hand-held
DVB-SH-LL	DVB-SH Low Latency
DVB-T	Digital Video Broadcasting - Terrestrial
E-SSA	Enhanced Spread Spectrum Aloha
ECC	Electronic Communications Committee
ECU	Electronic Control Unit
EDCA	Enhanced Distributed Channel Access
EIRP	Equivalent Isotropically Radiated Power
ESA	European Space Agency
ESP	Electronic Stability Program
ETC	Electronic Toll Collection
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FWD	Forward
G5CC	ITS-G5 Control Channel
G5SC	ITS-G5 Service Channel
GEO	Geostationary (or Geosynchronous) Earth Orbit
GF	Greedy Forwarding, same as PBF
GNSS	Global Navigation Satellite Systems
HCF	Hybrid Coordination Function
HGV	Heavy Goods Vehicle
I2I	Infrastructure-to-Infrastructure

IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IFS	Inter-Frame Spacing
IPv6	Internet Protocol version 6
ISI	Inter-Symbol Interference
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
ISO	Open Systems Interconnection
ITS	Intelligent Transport Systems
ITS-G5	European C2C communication standard
ITS-S	ITS station
ITU-R	International Telecommunication Union - Radio communication sector
IVC	Inter-Vehicle Communication
LCH	Logical Channel
LLC	Link Layer Control
MAC	Medium Access Control
MAI	Multiple Access Interference
MANET	Mobile Ad hoc NETwork
MIB	Management Information Base
MSS	Mobile Satellite Services
OBU	On-Board Unit
OFDM	Orthogonal Frequency Division Multiplexing
PBF	Position-Based Forwarding, same as GF
PCF	Point Coordination Function
PHY	Physical Layer
PIFS	PCF IFS
POI	Point Of Interest
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QS-CDMA	Quasi Synchronous CDMA
RHW	Road Hazard Warning
RLAN	Radio Local Area Network
RSU	RoadSide Unit
RTS	Request To Send

S-MIM	S-band Mobile Interactive Multimedia
SafeTRIP	Satellite Applications For Emergency handling, Traffic alerts, Road safety and Incident Prevention
SCH	Service Channel
SHB	Single Hop Broadcast
SIC	Serial Interference Cancellation
SIFS	Short IFS
SS	Service Segment
TC	Technical Committee
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TPC	Transmit Power Control
TSB	Topologically Scoped Broadcast
TTL	Time To Live
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
V2I	Vehicle-to-Infrastructure
V2R	Vehicle-to-Roadside
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad hoc NETwork
WAS	Wireless Access System
WAVE	Wireless Access in Vehicular Environments
WHO	World Health Organization
WLAN	Wireless Local Area Network