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DEVELOPMENT, IMPLEMENTATION AND EVALUATION OF AN ARCHITECTURE FOR VEHICLE-TO-VEHICLE AND VEHICLE-TO-INFRASTRUCTURE NETWORKING

Timo Sukuvaara

Department of Communications Engineering

University of Oulu

Finland

DOCTORAL DISSERTATION

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Academic dissertation

Development, implementation and evaluation of an architecture for vehicle-to-vehicle and vehicle-to-infrastructure networking

Author	Timo Sukuvaara Arctic Research Centre Finnish Meteorological Institute
Supervisor	Prof. Marcos Katz Centre for Wireless Communications University of Oulu
Reviewers	Prof. Chai Keong Toh Tsing Hua honor Chair Professor of EECS Assistant Prof. Marina Petrova RWTH Aachen University
Opponents	Prof. Risto Kulmala Finnish Traffic Agency Prof. Chai Keong Toh Tsing Hua honor Chair Professor of EECS
Custos	Prof. Marcos Katz Centre for Wireless Communications University of Oulu

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Abstract

In this doctoral thesis the development, implementation and evaluation of the architecture for a vehicle-to-vehicle and vehicle-to-infrastructure access network have been presented. The work started in 2006, when the original concept of the intelligent hybrid wireless traffic service architecture between cars supported with wireless transceivers on the roadside was initially presented. The original communication architecture was based on traditional Wi-Fi communication between vehicles and infrastructure, supplemented with GPRS (General Packet Radio Service) communication within a cellular GSM network as the backbone access method.

The original wireless traffic service architecture developed in this work presented an innovative solution for hybrid vehicular networking, based on wireless networking and mobile communication solutions available at that time. The enhanced access network protocol standard and mobile access system with commercial equipment available allowed the further development of the architecture. The key objective was to provide an intelligent hybrid wireless traffic safety network between cars and infrastructure, relying now on a short-range (local wireless vehicular) access network, combined with the overlay cellular network. Furthermore, there was a set of example services concentrating on accident warnings (both critical and minor incidents) and road weather data, reflecting rather well the general type of vehicular networking services, and employing the platform resources, both in terms of capacity and reaction time. The IEEE 802.11p vehicular communication standard based platform was first tested in an extensive set of different kinds of vehicular networking scenarios. The communication capacity and connectivity was tested in vehicle-to-infrastructure, vehicle-to-vehicle, as well as vehicle-to-vehicle-to-vehicle communication entities. The field tests with a limited amount of vehicles were extended into simulation scenarios with a larger platoon of vehicles. The resulting communication platform was found to be appropriate for the preliminary example services, and finally the entire architecture, together with 3G backbone communication and embedded services, was pilot tested in the demonstration system. This communications architecture, particularly tailored for vehicular networking, is the main topic of this thesis.

The further development of the communication architecture focuses more and more on near-the-market services and multi-standard communication. Both of these goals are combined in the Finnish Meteorological Institute approach to employing a vehicular networking entity to provide route weather information for vehicles passing our combined Road Weather Station (RWS)/Road Side Unit (RSU). Route weather is a special type of weather service tailored for dedicated road stretches, based on a road weather model and data collected from local RWSs and from vehicles themselves.

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Ajoneuvojen ja infrastruktuurin välisen kommunikaatioverkkoarkkitehtuurin kehitys, implementaatio ja evaluaatio

Tiivistelmä

Tämä työ esittelee ajoneuvojen sekä ajoneuvojen ja infrastruktuurin välisen kommunikaatioverkkoarkkitehtuurin kehitys-, implementointi- ja evaluointityön. Työ aloitettiin vuonna 2006, jolloin alkuperäinen ajoneuvojen välisen tukiasema-avusteisen kommunikaatioverkon arkkitehtuuri esiteltiin. Alkuperäinen kommunikaatioarkkitehtuuri perustui langattomaan Wi-Fi -verkkoon ajoneuvojen sekä infrastruktuurin välillä, tuettuna kaupalliseen GPRS-pohjaiseen kommunikaatioon taustalla olevana kiinteänä verkkojärjestelmänä.

Alkuperäinen ajoneuvojen välisen tukiasema-avusteisen kommunikaatioverkon arkkitehtuuri esitteli uudenlaisen ratkaisun, jossa yhdistettiin lyhyen kantaman langaton verkko ja maantieteellisesti kattava mobiiliverkko sillä hetkellä käytössä olevilla ratkaisuilla. Kehittyneempi lyhyen kantaman langaton ajoneuvokommunikaatioprotokollastandardi sekä kehittyneempi mobiiliverkkoratkaisu tarjosivat mahdollisuuden toteuttaa arkkitehtuurista kehittyneempi versio. Tärkein tavoite oli toteuttaa älykäs langaton ajoneuvojen ja ajoneuvojen ja infrastruktuurin välinen kommunikaatioarkkitehtuuri, jossa lyhyen kantaman ajoneuvoverkko yhdistettiin maantieteellisesti kattavaan kehittyneeseen mobiilikommunikaatioverkkoon. Järjestelmään kehitettiin joukko esimerkkipalveluita keskittyen onnettomuusvaroituksiin (sekä kriittiset että informatiiviset) ja tiesäätietoon, jotka edustavat melko hyvin yleisimpiä ajoneuvoverkkopalveluita mutta samalla kuormittaen kommunikaatioalustaa niin kapasiteetilla kuin reaktioajalla mitaten. IEEE 802.11p ajoneuvokommunikaatiostandardiin perustuva kommunikaatioalustaa testattiin ensin laajasti moninaisilla ajoneuvokommunikaatioskenaarioilla. Kommunikaatiokapasiteetti ja yhteyden kattavuus testattiin sekä autojen ja infrastruktuurin, autojen keskinäisen sekä useamman auton muodostamissa kommunikaatioympäristöissä. Kenttätestit toteutettiin rajatuilla ajoneuvomäärillä, mutta nämä tulokset laajennettiin suurien automäärien simulaatioskenaarioihin. Tutkimustyön tuloksena syntynyt kommunikaatioalusta todennettiin toimivaksi kehitellyille esimerkkipalveluille, ja lopulta koko arkkitehtuurille, yhdessä rekursiivisuutta ja taustatukea tuovan 3G-verkon ja sisäänrakennettujen palvelujen kanssa, toteutettiin pilottitestaus erityisessä järjestelmädemonstraatiossa. Tämä kommunikaatioarkkitehtuuri, erityisesti räätälöity ajoneuvojen välistä tietoverkkoa varten, on tämän väitöskirjatyön keskeisin aihe.

Kommunikaatioarkkitehtuurin jatkokehitys keskittyy enenevässä määrin lähellä kaupallisia markkinoita oleviin palveluihin ja monia eri kommunikaatiomenetelmiä yhtä aikaa hyödyntävään nk. multi-standardikommunikaatioon. Molempia näistä tavoitteista viedään eteenpäin Ilmatieteen laitoksen yhdistetyn tiesääaseman ja älykkään tienvarsiaseman konseptissa autojen väliseen tietoverkkoon. Reittisää on erikoissääpalvelu, joka on räätälöity erikseen määritellyille tieosuuksille. Se perustuu tiesääennustemallille yhdistettynä tiesääasemilta ja suoraan ajoneuvoilta kerättyyn dataan.

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The research work of this thesis has been mainly conducted in Carlink (2006-2008), WiSafeCar (2009-2011) and CoMoSeF (2012-2015) projects, all of them hosted by EU Eureka Celtic and EU Eureka Celtic Plus initiatives. These three projects have been successive development steps towards the near-commercial vehicular communication architecture with an attractive set of pilot services. The interactive road weather station development work has been partially conducted also in the Northern Periphery Programme (NPP) project SNAPS and the EU Interreg project Intelligent Road. Closely related road weather service development has been partially conducted in the EU FP7 project ROADIDEA and EU FP7 project FOTsis, respectively. The thesis work has also been greatly supported by a grant from Henry Fordin Säätiö in Finland.

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This work is dedicated to Venla and Elisa. You are my precious ones, my pride and my delight.

Contents

List of original papers

This thesis is based on the following original publications, which are referred to in the text as P1-P5 and as part of the references. The publications are reproduced as appendices with the kind permission from the publishers.

[P1] Timo Sukuvaara and Pertti Nurmi, "Wireless traffic service platform for combined vehicle-to-vehicle and vehicle-to-infrastructure communications", IEEE Wireless Communications, Vol. 16, No 6, December 2009, pp 54 – 61.

[P2] Timo Sukuvaara and Carlos Pomalaza-Ráez, "Vehicular Networking Pilot System for Vehicle-to-Infrastructure and Vehicle-to-Vehicle Communications", International Journal of Communication Networks and Information Security, Vol 1, No 3, 2009.

[P3] Darya Stepanova and Timo Sukuvaara, "Simulation of IEEE 802.11p vehicular networking with real-life traffic scenario", in proceedings of 2011 IEEE 73rd Vehicular Technology Conference: VTC2011-Spring, 15-18 May 2011, Budapest, Hungary

[P4] Timo Sukuvaara, Riika Ylitalo and Marcos Katz, " IEEE 802.11p based vehicular networking operational pilot field measurement", IEEE Journal on Selected Areas in Communications, Vol. 31, No. 9, September 2013

[P5] Timo Sukuvaara, Kari Mäenpää, Riika Ylitalo, Pertti Nurmi and Evgeny Atlaskin, "Interactive Local Road Weather Services through VANET-capable Road Weather Station", in proceedings of 20th World Congress on ITS, October 14-18, 2013, Tokyo, Japan.

Author’s contributions

The author has had the main responsibility for writing Papers P1, P2, P4 and P5. The author has developed the original ideas of Papers P1, P2, P3, P4 and P5. In Papers P1 and P2, the author had the main responsibility for defining the wireless traffic service architecture and the operational model of key services, as well as defining and analyzing the field measurements validating the work. In Paper P3, the focus was on the simulation approval of the wireless traffic service platform. The simulating field environment system were designed by the author, and implemented together with Darya Stepanova. The simulation analysis was conducted mainly by the author, in co-operation with Darya Stepanova. In Paper P4, the author had the main responsibility of defining an enhanced version of the vehicular networking architecture. The pilot field measurements were designed and analyzed by the author, and conducted in co-operation with Riika Ylitalo and our research team. The enhanced set of pilot services and the final pilot system were designed in co-operation with the project research team. In Paper P5, the author had the main responsibility of defining the road weather station. The development of the services was conducted in co-operation with the research team.

Symbols and abbreviations

3G	Third Generation Mobile communication
CAN	Controller Area Network
CC	Cloud Computing
CCN	Content-Centric Networking
CCW	Cooperative Collision Warnings
CDS	Crash Detection Systems
CISS	Cooperative Intersection Safety Systems
C2C-CC	Car-2-Car Communication Consortium
Carlink	Wireless Traffic Service Platform for Linking Cars
CoMoSeF	Co-operative Mobility Services of the Future
DoT	Department of Transportation (in USA)
DSRC	Dedicated Short-Range Communication
ECU	Electronic Control Unit
EDCA	Enhanced Distributed Channel Access
EIRP	Effective Isotropic Radiated Power
FMI	Finnish Meteorological Institute
FP6	European Union EU IST 6th framework
FP7	European Union EU IST 7th framework
GPRS	General Packet Radio Service
HMI	Human-Machine Interface
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
LOS	Line Of Sight
MAC	Medium Access Control
MANET	Mobile Ad Hoc Networks

MEU	Mobile End User
MLIT	Japanese Ministry of Land, Infrastructure and Transport
M2M	Machine-to-Machine
OFDM	Orthogonal frequency-division multiplexing
QoS	Quality of Service
RSU	Road Side Unit
SMS	Short Message Service
SPAT	Signal Phase and Timing
STAR	Shortest-Path-Based Traffic-Light-Aware Routing
TSBS	Traffic Service Base Stations
TSCU	Traffic Service Central Unit
VANET	Vehicular Ad Hoc Network
VII	Vehicle Infrastructure Integration
VSC	Vehicle Safety Communication
V2I	Vehicle-to-Infrastructure communications
V2R	Vehicle-to-Roadside communications
V2V	Vehicle-to-Vehicle communications
V2V2V	Vehicle-to-Vehicle via Vehicle
V2X	Vehicle-to-Vehicle/Infrastructure communications
VLC	Visible Light Communication
WAVE	Wireless Access to Vehicular Environment
Wi-Fi	Wireless Fidelity
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WiSafeCar	Wireless traffic Safety network between Cars

1. Introduction

Improved safety on the road is one of the major advantages made possible by wireless communications and telecommunications. At the same time, road travel is growing more and more hectic, and roads are becoming increasingly crowded, and thus the probability of the occurrence of dangerous situations is increasing. On the other hand, the trend for road accidents has decreased in recent years, thanks to tailored regulations, developed road infrastructure, as well as advanced passive and active safety systems deployed on vehicles. However, at the same time, the absolute number of accidents has also grown enormously as the number of vehicles grows even faster. Traditional safety enhancements on the vehicle and road infrastructure can and will be developed to further improve the safety on the road, but with ever increasing costs. Employing wireless communication within the spectrum of traffic infrastructure creates a completely new era of safety and advisory applications for cost-effective and efficient improvements. The development of a general architecture for vehicle-oriented wireless communication is the key objective in this work. This will be instrumental for achieving the next level of road safety and operability.

1.1. Background

Going back to the 1950's, automobiles were basically mechanical systems. In the past few decades, electronics has become another major element of a vehicle's value, reaching a mean share of around one third of the total value of a modern car. The first generation of vehicle electronics was stand-alone in-vehicle systems, basically automating or supporting certain driving tasks. A typical example of such an achievement is anti-lock braking system. The number of such ECU (Electronic Control Unit) systems on each car has increased from only a few in the 1990's to around 50 and more by 2010. ECUs control almost every activity in a modern vehicle, aiming to improve travel safety and comfort, as well as reducing fuel consumption [1].

The next major step just emerging and happening is the adaptation and exploitation of wireless telecommunications. The main motivation for the applications of wireless networking to road traffic scenarios is to optimize driving with respect to safety and efficiency. While passive safety systems have proven to be effective in protecting passengers, they typically do not help in avoiding accidents in the first place. That is the key motivation for the development of active safety systems, often relying on wireless communications. Safety and efficiency in traffic, as well as travel convenience can be enhanced with wireless networking advantages [1].

The term wireless communication in this work refers to the different concepts developed in the area of wireless (local area) networking, cellular networking dominated by mobile phone systems and vehicular networking, respectively. The technological development of wireless communication is overviewed in the Figure 1, with particular emphasis on car communications.

Wireless networking started to gain more popularity during the late 1990's as the communication devices on the markets become more affordable and more attractive also for general use. The concept of wireless networking was originally developed for the office environment, typically between computers and communication devices with static or nearly-static characteristics (negligible mobility). Wireless communication range between devices was generally assumed, typically requiring also LOS (Line-of-Sight) between counterparts. However, LOS was not always expected, and a more appropriate definition is short-range communication, referring to a range of few hundred meters. The idea of ad-hoc networking connecting

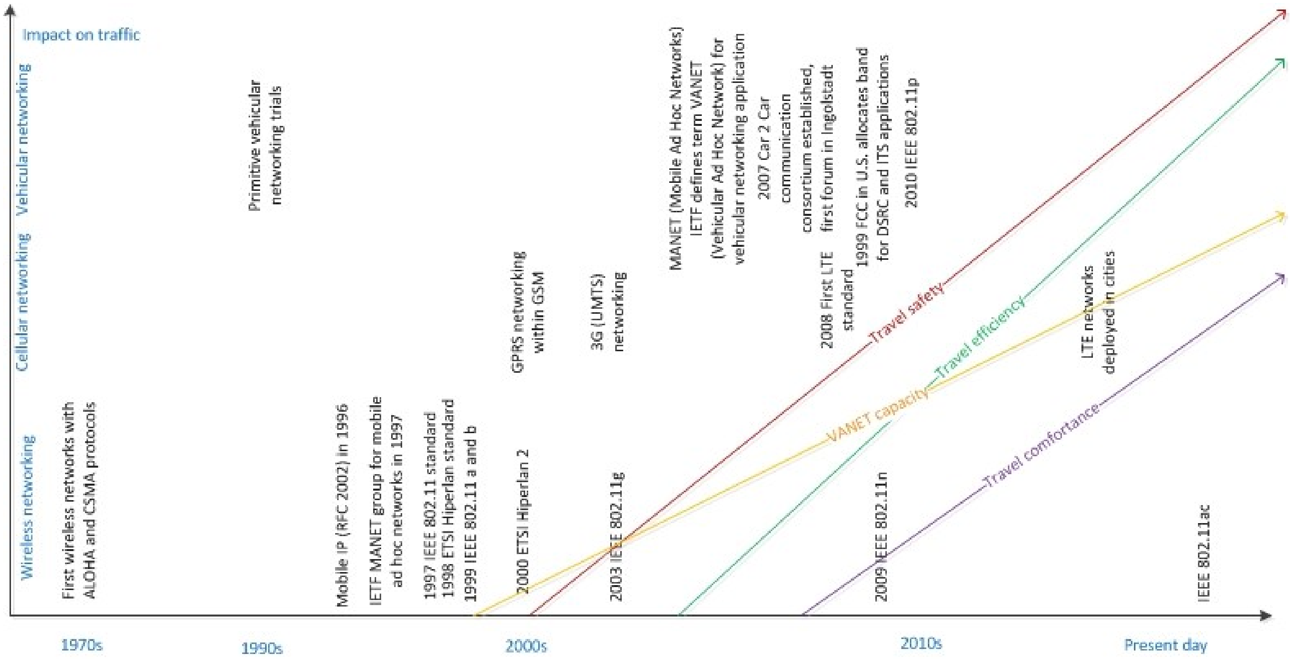


Figure 1: The technological development of vehicular networking related wireless communication

together independent computers located in the same office area, providing media for data exchange and communication with seemingly little effort. One step further was the concept of multi-hop networking, where the devices forwarded data packets from one partner to another. The range of wireless network was significantly enhanced, with the cost of an additional network load leading to a decreased performance. However, with enhanced ad-hoc routing methods, the performance of multi-hop access networks made it possible to optimize into the appropriate level for seamless use of network resources, as long as the network complexity, in terms of maximum hop-count and ad-hoc network members, remained low enough. When relatively stable and smooth operation in offices was reached, the interest in using wireless communication in more challenging environments grew. One of the ultimate wireless communication environments was the ad-hoc network between moving vehicles.

The vehicular ad-hoc networking concept introduces a completely different, much more challenging wireless network. The dynamics in the communication environment and supporting infrastructure availability is relatively high, depending on how essential the road stretch is. The vehicular networking is typically divided into three different types, namely rural, sub-urban and urban area networking. The main properties of these entities are overviewed in the Figure 2. In general, moving from a rural area towards the urban area decreases the traffic speed and increases the availability of a roadside infrastructure (roadside units, traffic lights etc.) and local communication entities. Vehicles are moving at extremely high velocities, in either the same or opposite directions, providing extreme challenges in terms of delay requirements (with the short time the nodes are exposed). In the case of communication with a roadside unit, and especially with an oncoming vehicle, the time window for communication is extremely short. In general, the vehicular access network availability varies a lot compared to a traditional wireless network. Also the line-of-sight link between the counterparts is often blocked by other vehicles and roadside installations like bridges and buildings, making the signal dynamic. The Doppler effect appearing in communicating modules moving towards each other also has a noticeable effect on the signal quality. Multi-hop communication can only be attempted between vehicles moving into the same direction, and even in that case traditional congestion avoidance methods are hard, or even impossible to implement due to the high variation in the network structure.

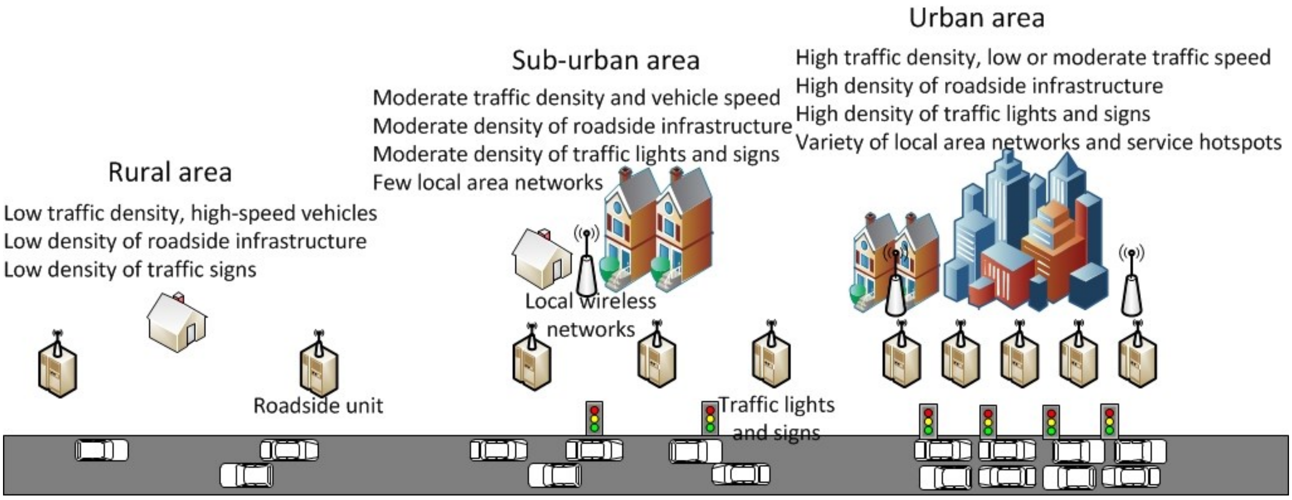


Figure 2: Different environments in vehicular networking

However, establishing an ad-hoc network between moving vehicles in close proximity has a number of important advantages. Vehicles can exchange their (environmental) observations and information about the traffic or weather conditions, and the anomalies in the road, depending on the sensors embedded in the vehicle. Ultimately, a vehicle in a traffic accident can broadcast a warning to other vehicles approaching, avoiding further accidents. With exploitation of roadside installments with a link to a fixed network, this data can be further forwarded, allowing vehicles to avoid road stretches occupied with accidents, queues or road construction works. In addition to this, an unlimited amount of commercial services like advertisements, guidance and general information can be delivered to and from the vehicles.

Furthermore, it is important also to classify different types of vehicular area networking, in terms of communication range. The taxonomy of vehicular networking is viewed in the Figure 3, based on the automotive network domain presented in [1]. The in-vehicle shortest range of communication emerges in in-vehicle communication, where the wireless devices inside the vehicle form the network. A typical application for this is a wireless link between a mobile smart phone and vehicle systems, allowing the use of the microphone and the speakers of the car for a mobile phone conversation. Vehicle-to-vehicle communication consist of data exchange with passing vehicle, networking between vehicles travelling in the same direction and emergency data broadcasting to the other vehicles nearby. Emergency data broadcasting is the most important application, from which the whole idea of vehicle networking is derived. Additionally, vehicle-to-infrastructure communications employs the roadside infrastructure for data exchange and networking with the car. The roadside infrastructure usually has a permanent link to the fixed network, hypothetically allowing Internet connectivity at least on a temporary basis. Both vehicle-to-vehicle and vehicle-to-infrastructure communications can be implemented with either radio or optical communications. However, wireless optical communication is an emerging technology, and has not been studied in this work. A vehicle can also have a direct connection to the fixed network infrastructure through cellular network systems (typically mobile phone networks) allowing continuous connectivity. Combining these different networking types (excluding in-car communication) into a single architecture is the main objective in this work.

It is obvious that the kind of stable operating wireless network expected in office environments is not possible in a vehicle networks environment, and numerous compromises need to be made. Truly continuous connectivity is one issue that is extremely hard to pull out, especially with low vehicle and roadside unit densities, and usually it is not expected to take place in vehicular networking. However, with the support of

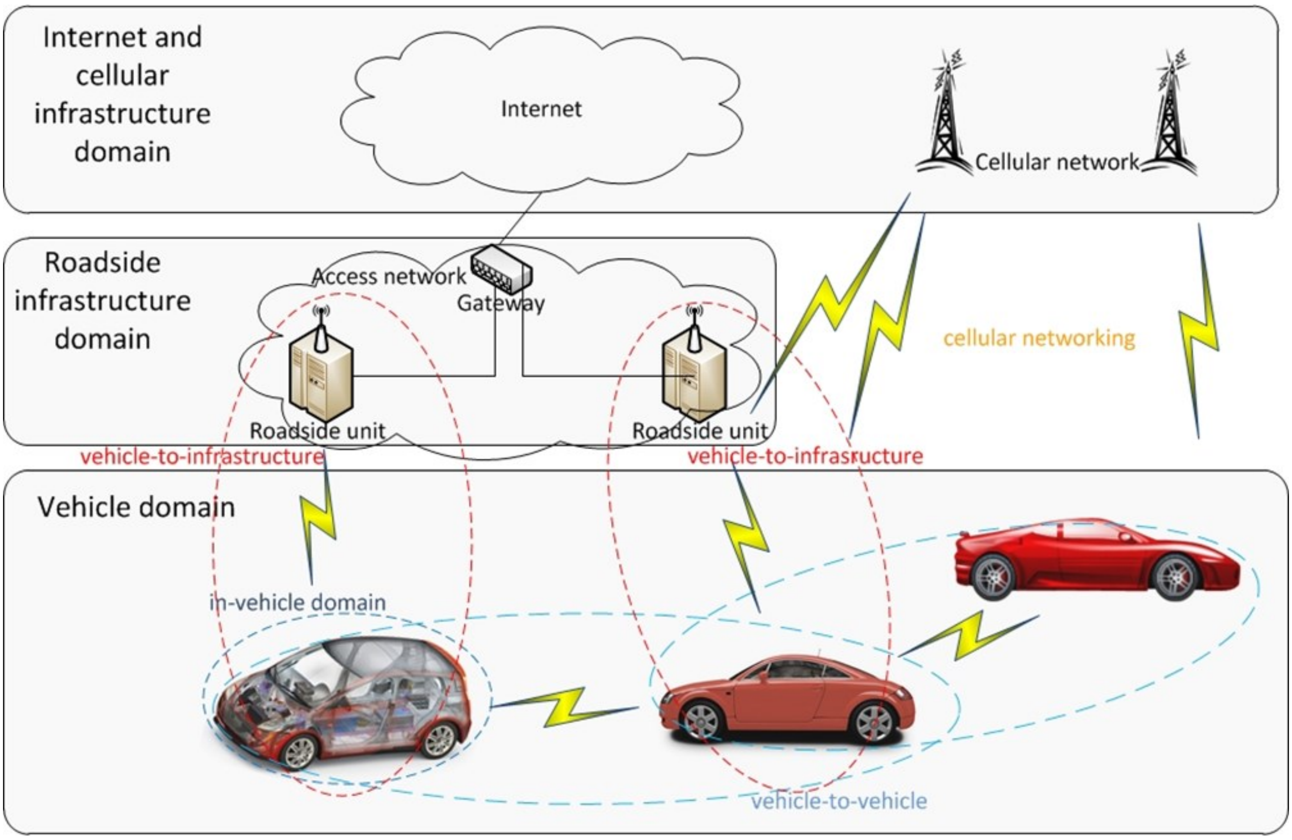


Figure 3: The taxonomy of vehicular networking

simultaneous cellular mobile communication, the connectivity can be significantly enhanced and sometimes even continuously supplemented. The price of this approach is the complexity of managing multiple communication systems simultaneously. The issues to be considered are smooth or even seamless handovers between the systems, adaptations to the high variations in the data throughput rates, and the quality of service (QoS), as well as the parallel maintenance of different systems. The main challenge in vehicular networking is to find a good engineering balance between conflicting requirements. The services developed for this environment must be tailored to cope with anything but a stable data channel. Highly probable communication blackouts must not significantly decrease the general performance.

For vehicular communication, there are generally two fundamental approaches, short-range wireless local area networking and wide-area cellular based communication. Wireless Local Area Networking (WLAN) is independent of any network operator, and is also more suitable for instantaneous data exchange between parties relatively near to each other. Cellular communication offers wide area coverage with a relatively small data rate, and requires a network operator to host the communication. The most advanced cellular networking systems, like LTE, provide the best data rates, comparable to WLAN data rates, but the coverage is lower due to the more limited cell size and lower density of service access points. However, as the LTE system is downward compatible to a 3G communication system and ultimately a GPRS system, it provides in practice complete coverage with different quality of services, depending of the location. The global trend in vehicular networking approaches has been to focus on WLAN type of solutions, but with advanced data rates, cellular systems are gaining more and more interest. Nowadays, even some advanced vehicular applications relying on a cellular networking system do exist. For example, the co-operative WAZE application [2] allows vehicles to either drive with the application open on their phone to passively contribute to traffic and other road data, or take a more active (co-operative) role by sharing road reports on accidents or any other hazards along the way. In this work, the approach has been to rely on short range communication, with supporting cellular communication wherever short range communication is not available. In general, this approach is an ultimate solution with all the benefits, as long as the handoff between different technologies does not cause prohibitive complexity and/or delays.

As the thesis work has been conducted in a meteorological institute, the role of road weather is fundamental. However, there are also other aspects supporting the focus on road weather services. Together with accident warnings, road weather services are commonly recognized as one of the key advantages available through vehicular networking, especially in communication between roadside infrastructure and vehicles. On the other hand, the road weather service justifies the use of bidirectional communication, as weather related data gathered from moving vehicles can clearly enhance the accuracy of local weather forecasting and related services. Finally, with a functional local road weather service partially based on vehicle data the whole vehicular networking architecture can be justified, and its operability in real-life usage verified.

The research work in this thesis started within the Carlink project (Wireless Traffic Service Platform for Linking Cars) [3], established in 2006. The architecture development basis combined both vehicular ad-hoc network and infrastructure-based networking with roadside fixed network stations inherited from the self-configurable heterogeneous radio network concept [4]. The conceptual idea of multiprotocol access networking was used for combining Wi-Fi (Wireless Fidelity) and GPRS networking. As a result, the Carlink project designed and piloted one of the first operating vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication architectures. The general state-of-the-art in the field of vehicular networking was composed of a number of somewhat separated component technologies. The first rudimentary vehicular services had already been launched, exploiting the mobile phone SMS-messaging (Short Message Service) system as the communication media. An example of such a service is the VARO-service designed by the Finnish Meteorological Institute (FMI), providing SMS weather warnings and route guidance to the end-user devices embedded into mobile phone in a car [5]. A variety of more general SMS services contained vehicle identification (based on registration plates) information request and primitive navigation services. On the other hand, few road side weather stations were already installed to gather up-to-date local weather information to be used to enhance weather forecasts and warnings in the road areas. Obviously, communication with passing vehicles was not an issue in the first five years of the 21st century, but those road weather stations were equipped with a power supply and some means of collect and deliver station data to the network host supervising the stations. The concept of wireless networking was already a hot topic in telecommunications research, and especially the ad hoc networking in self-configurable networks was gaining considerable interest. In the field of ad hoc networking a great deal of different routing methods were proposed and studied, but the communication media was usually assumed to be the same, the so called Wi-Fi based wireless networking based on the IEEE 802.11 family of standards.

The concept of hybrid vehicular access network architecture were successfully studied, developed and evaluated in the Carlink project. The general idea of the continuation project WiSafeCar (Wireless traffic Safety network between Cars) [6] was to overcome the limitations of communications by upgrading communication methodology, Wi-Fi with the special vehicular WAVE (Wireless Access in Vehicular Environments) system based on IEEE 802.11p standard amendment [7] and GPRS with 3G communication, respectively. The architecture was employed with a set of more sophisticated services, tailored for traffic safety and convenience. The set of example services was also adjusted to be compliant with services proposed by the Car-2-Car Communication Consortium (C2C-CC)[8] and ETSI standardization for the “day one set of services”[9]. Especially the newly-found IEEE 802.11p based vehicular access network system underwent an extensive set of test measurements, both with V2V and V2I communications, respectively. After careful analysis of several commercially available products (or systems) in 2009, the NEC LinkBird-MX equipment [10] was chosen to be used in the vehicular access network test measurements and pilot platform. The platform capacity and range were estimated and analyzed in the evaluation and field-testing of the system, presented in [5]. The project pilot platform was deployed with the example services in operation under realistic conditions. Based on the experience gained from both field measurements and pilot deployment, a realistic architecture deployment strategy for simple scenarios was presented also. The measurements demonstrated that the IEEE 802.11p has clearly better general performance and behavior in the vehicular networking environment, compared to the traditional Wi-Fi solutions used for this purpose. The peak performance in terms of data throughput was lower when using IEEE 802.11p, but still more than appropriate for the needs of vehicular access network. The pilot platform deployment proved that the new system operates also in practice, and we can provide defined pilot services properly. In the deployment, the overlay cellular network (3G) played an important role, and this hybrid method would be an attractive solution for the ultimate commercial architecture. One clear benefit was that exploiting 3G, the communication system would be available in a limited form already on day-one of the deployment process, and with low implementation costs. It was concluded that the solution had clear potential for the comprehensive heterogeneous vehicular communication architecture, aiming at decreasing the amount of accidents and lives lost on the roads. The system deployment could be initiated in a cost-effective manner, relying purely on existing 3G overlay network in the early deployment phase. As a result, the WiSafeCar project drew an outline for the commercially operating intelligent vehicular access network architecture, with a general deployment proposal.

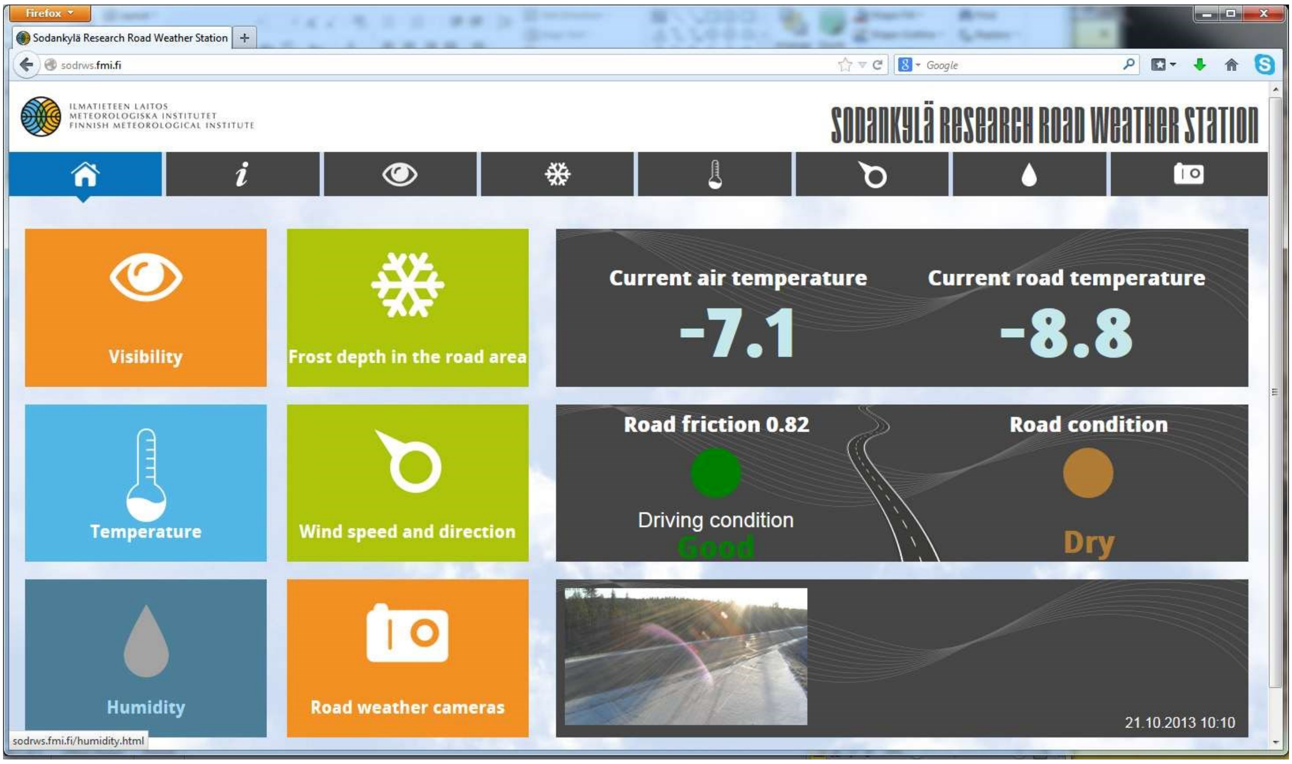
Even if the commercial deployment did not take place, the developed system served as the basis for a more advanced project, CoMoSeF (Co-operative Mobility Services of the Future) project [11], along with other intelligent traffic related research. The focus in the CoMoSeF project was on near-the-market services and multi-standard communication. The aim was to not only to service vehicles, but also exploit vehicle-originating data to ultimately enhance the very same services. Similarly, road-side units are not just serving the vehicles as connectivity points, but also host Road Weather Station (RWS) capabilities to provide additional data for the services. Both of these goals are combined in the Finnish Meteorological Institute approach to employing vehicular networking architecture to provide route weather information for vehicles passing our combined RWS/RSU. The station is equipped with up-to-date road weather measurement instrumentation, compatible with (but not limited to) the equipment expected to be available also in the demonstration sites own permanent and locally owned RWSs. The procedure is to design, develop and test both the local road weather service generation, and the service data delivery between RWS and vehicles. The vehicle passing the combined RWS/RSU is supplemented wirelessly and automatically with up-to-date road weather related data and services, and at the same time possible vehicle-oriented measurement data is delivered upwards. IEEE 802.11p is the primary communication protocol, but also traditional Wi-Fi communication is supported. The station, together with research vehicles, forms the pilot system in Sodankylä, Finland, acting as a real-life test bed for the demonstration systems yet to come.

Based on the presented research problem of common architecture, challenges and underlying goals, and considering defined assumptions, the approach of the hybrid wireless traffic service architecture between cars was presented. The enabling technologies are an IEEE 802.11p vehicular networking approach and a 3G mobile communications system. The system capacity and range was estimated and evaluated in the field tests, presented in detail later in this work. Partially based on the capacity estimate, the successful project pilot platform deployment was constructed, with the specially designed example services in operation under realistic conditions. In Figure 4, the user interface of the WiSafeCar pilot system is presented. Furthermore, in Figure 5 the FMIs operative combined RWS/ RSU is presented, with an up-to-date user interface of RWS (identical to both Internet and vehicular networking users) in Figure 6. Based on the experience gained from both the field measurements and the pilot deployment, a realistic system deployment strategy with simple scenarios has been proposed. The measurements proved that the IEEE 802.11p has clearly better

Figure 4: WiSafeCar pilot system in operation

general performance and behavior in the vehicular networking environment, compared to the traditional Wi-Fi solutions used for this purpose. The peak performance in terms of data throughput is lower with IEEE

Figure 5: FMI combined Road Weather Station and Road Side Unit



Current air temperature -7.1

Current road temperature -8.8

Road friction 0.82

Driving condition Good

Road condition Dry

21.10.2013 10:10

Figure 6: Road Weather Station user interface in the Internet (and vehicular networking)

802.11p, but still more than appropriate for the needs of vehicular networking. The pilot system deployment proved that the new system operates also in practice, and we can provide defined pilot services properly. However, in the deployment, the 3G network plays an important role, and such a hybrid method could be an attractive solution for the ultimate commercial system. It has been shown that the solution presented in this thesis work has a clear potential for a comprehensive heterogeneous vehicular communication entity, aiming at decreasing the amount of accidents and lives lost on the roads. The system deployment can be initiated in a cost-effective manner, relying purely on the existing 3G overlay network in the early deployment phase.

1.2. Motivation

Vehicular communication is nowadays an important and well established research topic. Safety advances leading to a reduced amount of traffic fatalities and accidents in general is a noble mission not only for telecommunication engineers, but also for the vehicle industry, traffic management and governance, as well as for ordinary people. Traffic safety enhancement is the key motivator in most of the approaches, typically exploiting sensor data from vehicles and roadside units for various incident warning services. Just as before, traffic observations and information are exploited with enhancement of road network usage. Exploiting and exploring internet capabilities are also an important goal, because they allow the experience of seamless mobility for smart phones to be extended into a vehicular environment, giving business opportunities and an enhanced set of services. As stated before, the combination of the somewhat conflicting goals of real-time safety warnings and bidirectional high capacity access is the challenge not yet satisfactorily completed. Even though the pieces of the puzzle are available, a respectable and globally acceptable strategy for putting the pieces together still remains to be seen. There is a need for a proof-of-concept type of architecture for vehicular networking, applicable for both commercial applications and governmental systems that enhance traffic safety. There should be an architecture for safety applications motivating both traffic agencies and the vehicle industry to provide added value, at the same time allowing service providers to develop commercial products for mobile users in vehicles. The development of such an architecture is the main goal of this work.

In order to meet this challenge, several sub-goals must be fulfilled. First of all, the vehicles in the architecture must have instant communication access to nearby vehicles to avoid accidents (or further involvement in accidents that have already occurred). This communication link must be efficient enough to provide the necessary range for accident avoidance, but also enough data capacity to deliver sophisticated service data. Secondly, the architecture must also support wide-area communication. In this way the accident and incident data can be spread to a larger area, and vehicles approaching an accident site or traffic jam, for example, can avoid the site completely by choosing an alternative route. Wide area communication is also a requirement for (commercial) convenience services like advertisements, up-to-date route info and local road weather forecasts. This communication is not necessarily employed with a high data speed all the time, as long as there are some high-band service hot-spots available every once in a while. The architecture must allow reliable, low latency and high capacity (megabit-level, allowing modern applications) communication between vehicles, supplemented with communication between vehicles and a roadside infrastructure, allowing vehicles (partial) connectivity to the backbone network. A selective set of example services is needed also, in order to verify the architecture's operability and estimate the capacity. The main technical details are generally provided by global standards, such as IEEE 802, IEEE 1609 and ETSI, which provide major guidelines in practice. Compatibility with the standardized technical specifications is an essential element. Finally, the entire system must be constructed in a cost-effective manner. The vehicle devices must be based on equipment tailored for the mass-market (or expected to turn into mass-market products) so the deployment costs are not an issue for the vehicle owner, car manufacturer or roadside infrastructure provider. One aspect that is important especially for the road authorities, typically responsible of the roadside infrastructure, is that the communication architecture itself is also cost-effective, meaning in this case that the communication architecture/standard is expected to maintain its popularity also on a longer time-scale, decreasing the need of system upgrade costs. The possibility to exploit already existing infrastructure would be a huge advantage.

1.3. Outline of the thesis

In the first Chapter, the research problem has been stated, including an overview of the background, motivation and related matters. In Chapter two, related work and the state-of-the-art of vehicular networking is reviewed, with an overview for related wireless networking perspectives, as well vehicular networking with a detailed introduction of different types of vehicular networking. The third chapter presents the evolution of the communication architecture development of this work. Chapter four showcases the developed communication platform solution with related field measurements, pilot systems and simulation work. The conclusions are drawn in the fifth Chapter. Chapter six presents an overview to the original papers.

1.4. Contribution of this thesis

In this work, the architecture for a vehicle-to-vehicle and vehicle-to-infrastructure access network has been developed, implemented into demonstration platforms and finally evaluated. The original wireless traffic service architecture developed in this work presented an innovative solution for hybrid vehicular networking, based on wireless networking and mobile communication solutions available at that time. The developed access network protocol solution and mobile access system with available commercial equipment allowed the further development of the architecture. Furthermore, there was a set of example services concentrating on accident warnings and road weather data, reflecting rather well the general type of vehicular networking services, while employing the platform. The resulting IEEE 802.11p communication platform with 3G backbone communication and embedded services was found to be an appropriate communications architecture for vehicular networking. Even though the commercial deployment of the architecture presented in this work has not yet happened, the architecture introduces considerable estimation of hybrid communication architecture for the operative vehicular networking environment, to be used as a base of the future commercial architecture.

2. Related work

This Chapter presents an overview for the wireless communication methodologies applicable for the vehicular environments. The historical development process, shown in Figure 1 is presented considering the methodologies and standards related to the communication entities that can be seen in Figure 2. The main features of the communication methods within the entities are listed into Table I.

2.1. General wireless networking

Wireless networks refer to any type of network that does not have a physical connection using cables. The original motivation for wireless networks was to avoid the costly process of introducing cables into office buildings, or as a connection between various equipment locations. The commonly known term wireless local area network (WLAN) refers to a system that links two or more devices over a short distance using a wireless distribution method, usually providing a connection through an access point for Internet access.

The major contribution for WLAN development has been produced through the IEEE (Institute of Electrical and Electronics Engineers), and more specifically through its standardization process, known as the IEEE 802.11 standard. The original standard, published in 1997, defines the wireless LAN Medium Access Control (MAC) and physical layer (PHY) specifications. The fundamental access method for the MAC realization is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The IEEE 802.11 architecture defines three different propagation modes. These are the 2.4 GHz FHSS (Frequency-Hopping Spread Spectrum), the 2.4 GHz DSSS (Direct Sequence Spread Spectrum) and the infrared system [12]. The basic version of the standard supports only 1 Mbps and 2 Mbps data rates, but there has been numerous amendments published since the original standard to update the data speed as well as other properties of the standard [12].

The first amendments for the standard were IEEE 802.11b and IEEE 802.11a. There is a fundamental difference between these amendments; while the objective in 802.11b was to maintain compatibility with the original standard, the 802.11a was aiming to increase capacity and efficiency by upgrading modulation, operating frequency and bandwidth, respectively. One can say that all the following amendments are inherited from these two, and therefore they are presented with details.

Table I: The main features of the communication methods related to vehicular networking

Communication method	*Theoretical data rate*	*Mobility support*	*Architecture*	*Connection delays*	*Theoretical range*
Conventional WLAN; IEEE 802.11g	54 Mbps	Low	Local cells	Low	140 m
Conventional WLAN; IEEE 802.11n	600 Mbps	Very low [2]	Local cells	Low	250 m
V2V (vehicle-to-vehicle) [1]	3-54 Mbps	Good	Local cells	Very low	1 km
V2I (vehicle-to-infrastructure.) [1]	3-54 Mbps	Good	Local cells	Very low	1 km
GPRS cellular data	56–114 kbit/s	Good	Cellular	Moderate	unlimited [3]
3G cellular data	0.2 Mbps	Moderate	Cellular	Moderate	high [3]
LTE cellular data	300 Mbps	Moderate	Cellular	Moderate	low [3]
Hybrid	0.2-54 Mbps	Good	Hybrid	Very low	unlimited

1 based on IEEE 802.11p networking

2 with maximum data rate mode

3 commercial cellular systems range is not defined as the range of one cell, but the coverage of operational systems in 2013

IEEE 802.11b is quite similar to the original 802.11 standard architecture. With this amendment, the name Wireless Fidelity was adopted to refer IEEE 802.11b and its subsequent amendments. 802.11b is operating in the same 2.4 GHz frequency band, and has the same MAC, CSMA/CA. It is also backward compatible with the original standard, therefore supporting 1 Mbps and 2 Mbps data rates. As an extension to the original standard architecture, 802.11b also provides new data rates, 5.5 Mbps and 11 Mbps, respectively. The CCK (Complementary Code Keying) modulation method enables the possibility to achieve higher data rates. Otherwise, the IEEE 802.11b has only minor differences to the original standard architecture [13]. Basically IEEE 802.11b completely replaced the original 802.11 standard, due to the much higher capacity of extension b. 802.11b, which itself had the same destiny when it was later on replaced by IEEE 802.11g, and nowadays the de-facto standard for Wi-Fi communication is IEEE 802.11n [14].

IEEE 802.11a has very many differences compared to the original standard. The most significant differences are that the Physical Layer of 802.11a is based on OFDM (Orthogonal Frequency Division Multiplexing) modulation as the carrier system, and it uses 5.2 GHz frequency band. The underlying modulation schemes used are BPSK, QPSK (similar to the original standard) and different levels of QAM (Quadrature Amplitude Modulation). With these changes, 802.11a is able to achieve (from 6 Mbps) up to 54 Mbps data rates. Due to these major differences, 802.11a is not compatible with the original standard. However, the MAC architecture is the same CSMA/CA as in the original standard [15].

As stated before, the following Wi-Fi standard extension was IEEE 802.11g, providing an 802.11a type of architecture (with the same capacity, up to 54 Mbps), but operating still in the 2.4 GHz frequency [16]. The extension most commonly used nowadays is the IEEE 802.11n. Its purpose was to significantly improve network throughput by combining elements of 802.11a and 802.11g. With the use of four spatial streams at a channel width of 40 MHz with a significant increase in the maximum net data rate from 54 Mbit/s to 600 Mbit/s. This data rate can only be achieved when operating in the 5 GHz bandwidth, adapted from 802.11a. Therefore, IEEE 802.11n operates in two different bandwidths; in 2.4 GHz the downward compatibility is maintained with previous amendments but with relatively the same capacity, while in the 5 GHz band the ultimate improvements of capacity and efficiency are fully gained. Channels operating on a width of 40 MHz are the key feature incorporated into 802.11n; this doubles the channel width from the 20 MHz in the previous 802.11 to transmit data, providing a double data rate availability over a single 20 MHz channel. It can only be enabled in the 5 GHz mode, or within 2.4 GHz if there is knowledge that it will not interfere with any other 802.11 or non-802.11 (such as Bluetooth) system using the same frequencies [14],[17].

2.2. Vehicular ad-hoc networking

The main usage scenario in the Wi-Fi type of networking was originally the rather static office environment, with multiple communicating computers at a relatively small distance from each other, having only light physical walls and objects between them. Nowadays the concept has been expanded to the idea of a wireless home, with computers, printers, home multimedia entertainment systems, TVs, DVD players, tablet computers and mobile phones all connected to the same wireless network. The key concept in communications remains the same, communication units are located within rather short distances and are stationary or slowly moving. In this kind of scenario, the Wi-Fi works well; the capacity is high enough for even rather demanding usage scenarios, connection establishment time is not an issue, and even infrequent connection losses do not cause unbearable harm. This is not the case in a vehicular communication environment.

The first primitive experiments in vehicular networking were carried out already in 1989 [18], but more systematic research within the concept of vehicular networking was started in the early part of this millennium. Obviously, the starting point was Wi-Fi, as an existing and widely used wireless communication system. As expected, Wi-Fi networks were soon found to be rather inadequate for this purpose. Vehicular safety communication applications cannot tolerate long connection establishment delays before being enabled to communicate with centralized safety systems and /or other vehicles encountered on the road. Naturally, communication reliability all the time is also an important issue. Non-safety applications also require fast and efficient connection setups with roadside stations that provide services (e.g., weather and road data updates) because of the limited time a car spends within the station coverage area. Additionally, rapidly moving vehicles and a complex roadway environment present challenges on the physical level. These problems typically arise when using Wi-Fi. The IEEE 802.11 standard body has created a new amendment, IEEE 802.11p, to address these concerns [7], [19].

The primary purpose of IEEE 802.11p standard is to enhance public safety applications and to improve traffic flow by vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The underlying technology in this protocol is Dedicated Short-Range Communication (DSRC), which essentially uses the IEEE 802.11a standard OFDM-based physical layer and quality of service enhancements of IEEE 802.11e, adjusted for low overhead operations. The IEEE 802.11p uses an Enhanced Distributed Channel Access (EDCA) MAC sub-layer protocol designed into IEEE 802.11e, with some modifications to the transmission parameters. DSRC is a short-range communication service designed to support communication requirements for enhancing public safety applications, to save lives and to improve traffic flow by vehicle-to-vehicle and infrastructure-to-vehicle communications. Wireless Access to Vehicular Environment (WAVE) is the next generation technology, providing high-speed V2V and V2I data transmission. The WAVE system is built on IEEE 802.11p and IEEE 1609.x standards [20] operating at 5.850-5.9250 GHZ with data rates and supports between 3 and 27 Mbps with 10 MHz channel and 6-54 Mbps in 20 MHz channel, respectively. Up to 1000 m range in a variety of environments (e.g., urban, sub-urban, rural) is supported, with relative velocities of up to 110 km/h. Depending on usage needs, either 10 MHz or 20 MHz channel bandwidth can be chosen [7],[19],[20],[21],[22],[23].

The development of vehicular communication networks has created a variety of emergency services and applications. The major contributions so far have been provided within the European Union EU IST 6th framework (FP6) and EU 7th framework (FP7) projects (main projects listed in [24]), in the Vehicle Safety Communication (VSC) project and Vehicle Infrastructure Integration (VII) supported by US DoT (Department of Transportation) in the USA and in the activities supported by Japanese Ministry of Land, Infrastructure and Transport (MLIT) in Japan. The pilot services developed so far contain different types of Cooperative Collision Warnings (CCW), (Post- and Pre-) Crash Detection Systems (CDS) and Cooperative Intersection Safety Systems (CISS), among many others [24].

As stated above, a vehicular access network is often classified into vehicle-to-vehicle and vehicle-to-infrastructure communications. As viewed in Figure 3, there are more sub-categories of vehicular networking, but one can say that these two are the main sub-types, while the rest are some kind of special related cases. In this work, there are many special cases and scenarios dedicated purely to either V2I or V2V. Therefore it is important to consider the differences of these communication types in more detail. In the following subchapters V2I and V2V, as well as hybrid combinations of them, are considered one by one.

2.3. Vehicle-to-infrastructure communication

Vehicle-to-Infrastructure communication means a Vehicular ad-hoc network (VANET) created between moving vehicles and a static infrastructure beside the road. The communication architecture is centralized, the roadside infrastructure acting as a central for one or many vehicles. The communication is bidirectional, despite the fact that the term vehicle-to-infrastructure seems to refer to one direction only. However, in the vehicle-to-infrastructure direction the communication is of the unicast type, while in the opposite direction, the communication type is both broadcast (while delivering general data) and unicast (while responding to the vehicles requests). Roadside infrastructure, or simply RSU, is typically supplemented with a fixed power supply and a backbone network connection, therefore we are not required to consider the consumption of these resources in its operation. RSU can be equipped with multiple and/or directive antennas, making the downlink channel (from RSU) typically much stronger compared to uplink. In some V2I applications, the uplink channel is meaningless or not existent, making the service more like a broadcast type. Nevertheless, V2I must not be mixed with broadcasting systems, the existence or at least preparedness for deployment of an uplink being an essential element when considering V2I.

V2I communication is usually employed to deliver information from road operators or authorities to the vehicles. Roadworks warning is a typical example of a V2I service; vehicular access network transceivers are deployed into the roadworks area, informing the vehicles approaching the area about the exceptional road operability. One particularly important advance is the ability for traffic signal systems to communicate the signal phase and timing (SPAT) information to the vehicle in support of delivering active safety advisories and warnings to drivers. One approach for traffic-light optimizing is the Shortest-Path-Based Traffic-Light-Aware Routing (STAR) protocol for VANETs [25]. Both of these services are broadcast-type, lacking the use of an uplink channel. On the contrary, the RSU with a road weather station employed in [3] not only delivers the weather and warning data for the passing vehicles, but also gathers the weather and safety related observations from the vehicles to further update the data.

V2I communication has certain similarities to a wireless link between the mobile node and access point in a traditional wireless network. Just as an access point, RSU is a static element within moving vehicles, like the mobile nodes in a traditional wireless network. Due to its fixed nature, RSU possesses superior resources in terms of signal strength and therefore data capacity, just like access point. However, due to the temporary nature of V2I communication, RSU cannot provide continuous backbone network connectivity for the vehicles. Instead, RSU can merely act as service hotspot, delivering a pre-configured high-band service data exchange between the vehicle and fixed network whenever in the vicinity area of an RSU. One example of such a data dissemination network is introduced in [26].

In some related work, there is discussion about Vehicle-to-Roadside (V2R) communications. V2R is a special case of V2I communications, in which the focus is strictly limited to roadside infrastructure, like roadworks and SPAT mentioned above. Nevertheless, V2R is a special case of V2I, and in this work it is not considered separately.

2.4. Vehicle-to-vehicle communication

The V2V communication approach is mostly suited for short-range vehicular communications. The general idea is that moving vehicles create a wireless communication network between each other, in an ad-hoc networking manner and on a highly opportunistic basis. The communication architecture is distributed, as individual vehicles are communicating equally, in an ad-hoc manner. The data exchange between passing vehicles is typically of the unicast type, but also multicast (for example in case of a platoon of vehicles exchanging traffic information) and broadcast (in the case of accident warnings) transmissions are employed. A pure V2V network does not need any roadside infrastructure, making it fast and relatively reliable for sudden incidents requiring information distribution on the road. Therefore it is the primary communication candidate for real time safety applications in vehicles.

One of the key motivations for V2V communications is the opportunity to enable cooperative vehicle safety applications that will be able to prevent crashes. Such cooperative collision-avoidance applications that are envisioned for initial deployment would be 1) to identify other vehicles in the immediate vicinity, 2) to maintain a dynamic state map of other vehicles (location, speed, heading and acceleration), 3) to perform a continuous threat assessment based on this state map, 4) to identify potentially dangerous situations that require driver actions and 5) to notify the driver at the appropriate time and manner. In the long run, automatic vehicle intervention to avoid or mitigate crashes with these applications is envisioned, but it still needs much work on the validation of the required reliability in communications [1], [27].

A special case of V2V communications is multi-hop dissemination (including broadcasting) with specific multi-hop protocols. Especially in the case of a traffic accident the vehicle participating in or observing an accident will broadcast a warning message, which is forwarded by the vehicles receiving the message during a certain period of time, allowing others up to kilometers away to make smart driving decisions well ahead of time. In dense traffic conditions, there is a risk of a broadcast storm problem, where multiple vehicles are trying to transmit the message at the same time causing multiple packet collisions and in an extreme case total outage of the communication channel [28]. Several solutions exist to avoid the problem, most of them derived from the idea of forwarding the message with certain random, weighted or adjusted probability, instead of automatic “blind forward” [1], [27].

The V2V communications entity is very challenging. In V2V, the connectivity between the vehicles may not be possible all the time since the vehicles are moving at different velocities, due to which there might be quick network topology changes. Without any roadside infrastructure, multi-hop forwarding must be enabled to propagate the messages or signals. The addresses of vehicles on highways are mainly unknown to each other. Periodic broadcasts from each vehicle may inform direct neighbors about its address, but the address-position map will inevitably change frequently due to relative movements among vehicles. It is the receiver’s responsibility to decide on the relevance of emergency messages, and also decide on appropriate actions.

Due the crucial limitations presented above, V2V communications mainly focus on special cases of communications instead of a general “all-purpose” network. The most typical use cases are broadcasting of emergency or other critical data to all vehicles, exchanging data with bypassing vehicles and communication network between a platoon of vehicles moving into the same direction at the same speed. It is worth noting that a wireless ad-hoc network in trains can be seen as a special case of the last scenario. Furthermore, with location information gathered from for example a GPS device, it can be used to benefit V2V communication, allowing nearly continuous communication capabilities, especially when traffic is dense and multi-hop communications are used. Location based broadcast and multicast are also the proper communication methods for collision avoidance. In general, V2V communication is suitable for those roads with high vehicle density, and provides only small or even insignificant effort in rural areas.

2.5. Combined vehicle-to-vehicle and vehicle-to-infrastructure communication

Combined V2V and V2I networking can be seen as plain V2V supplemented with V2I capabilities. V2V is the starting point, with applications defined in the previous sub-chapter, and integrated V2I would enable an expanded range of vehicle crash-avoidance safety applications using the same wireless technology. One of the additional features enabled by V2I is intersection collision avoidance, whereby knowing the dynamic state map of all the vehicles, as well as the intersection geometry, the system could warn a driver about another potentially hazardous intersecting driver. From this perspective, hybrid V2V and V2I is often referred to as Vehicle-to-Vehicle/Infrastructure communications or simply V2X [27].

In this work, one of the essential issues has been to consider the combined V2V and V2I as its own special case of communications. A similar kind of approach has been presented in [31]. The RSU, infrastructure side of V2I usually has fixed power and can employ directive antennas especially tailored for the RSU, often making the downlink signal from the RSU to the vehicle dominant, compared to the uplink provided by the vehicle. Furthermore, RSU tends to communicate with all the vehicles, while the vehicle tries to optimize its use of communication resources by minimizing intervention with other vehicles. Finally, as the RSU usually has a fixed network connection, it can be seen also as an access point of the wireless network in a special kind of vehicular wireless network.

As stated above, the combined V2V and V2I communications access network consists of vehicles and RSUs, with relatively different objectives. Vehicles are communicating between each other in a V2V manner whenever in the vicinity area of each other, basically exchanging their observations from the traffic or forwarding/broadcasting multi-hop messages, or possible wide-area data received earlier from RSU. However, when entering the vicinity area of an RSU, vehicles not only exchange data with the RSU, but may also exchange data with services located in the fixed internet, through an access link provided by the RSU (if such operability is employed). As the interaction time with the RSU is very limited, such service hot-spot communication procedures must be pre-configured into the vehicle user profile, to be initiated automatically when entering into the RSU vicinity. The vehicle should therefore initiate different operational procedures for vehicle and RSU interaction. On the contrary, the RSU procedures are basically similar, regardless of whether the network is V2I or combined V2V and V2I.

2.6. Hybrid vehicular network

The concepts of V2V and V2I networking of VANET are based on local area networking, exploiting typically an IEEE 802.11p standard based access network, as stated above. Theoretically, an element of such a network can achieve up to a one kilometer communication range. In the field test measurements presented also in this work, this range is clearly smaller. In any case, it is not realistic to expect that such a local area networking system can be cost-effectively deployed to achieve complete coverage throughout the road network.

Mobile phone cellular networks provide (almost) complete geographical coverage, and nowadays they are also employed with a relatively high data capacity. A new and therefore very densely deployed LTE network goes up to a theoretical 100 Mbps throughput [32]. The widely deployed 3G cellular networking system allows data rates up to theoretical 2 Mbps with relatively good coverage, with underlying GPRS communication with very high coverage and typically around a 100 kbps data rate, [27]. However, the mobile phone network, as the name states, is merely designed for supporting on-demand phone connections rather than continuous connectivity. This fact evidently leads to an unbearable response time in the case of accident warnings and related safety services expected to be delivered instantly to the vehicles approaching a brand-new accident location. Upcoming enhancements of mobile networks provide increasingly higher data rates, but as they move to a higher spectrum, coverage areas are getting smaller and smaller. However, services like WAZE [2] can be adequately supported by cellular networks.

The solution for the coverage/response time problem is to bind VANET and cellular networking into a hybrid vehicular networking system. Referring to Figure 3, this means that all the concepts presented in the figure are combined together. One approach for combining Wi-Fi and GPRS into a hierarchical hybrid network has been presented in [29]. The concept of a self-configurable heterogeneous radio network presents another approach to this topic [4]. A kind of general approach from the cellular networking perspective is presented in [30], more related to cellular communication. All of these approaches have a continuous networking perspective to this issue, as do the majority of existing approaches in general. From the continuous connectivity perspective, the handing over of the connection from one protocol to another plays a crucial role. For example, [4] presents several approaches for a smooth handover within different types of ad-hoc IP networks. However, in vehicular networking, the primary perspective is different. The continuous connectivity is not the main concern, but clearly more important is to ensure instant delivery of local vehicular safety data delivery for the vicinity area nearby the sending vehicle. Therefore, the straightforward approach for the handover in hybrid vehicular networking entity is to always promote VANET networking whenever available, and whenever arriving into the range of another vehicular networking unit, with the price of breaking up the ongoing cellular network data transfer. This is the approach used also in the solution proposed in this work.

3. Vehicle-to-vehicle and vehicle-to-infrastructure architecture development

3.1. Overview

V2I communication is often seen as a special feature or enhancement of V2V VANET [27]. In this work, the combined V2V and V2I communications network is treated as a communications architecture of its own, rather than just a sub-domain of V2V. The aim was to build more comprehensive, flexible, effective and reliable architecture for V2V and V2I communication purposes. The main objectives in this work were to handle the communications environment between fast and independently moving vehicles, efficient and fast delivery of critical data regardless of the location or presence of other vehicles, and the generation of services. The special emphasis on services was not only to enhance traffic safety and efficiency, but also to exploit our architecture capabilities thoroughly.

Wide area connectivity must be ensured throughout the (road) network. Mobile cellular communication fulfills this requirement, but the data capacity (of solutions available) is not appropriate for all the services, and delivery time is not adequate for the critical safety services. On the other hand, capacity and delivery time are not a problem in the VANET type of local communication, as long as the transmission range is not exceeded. The obvious solution is the combination of these two communication approaches.

3.2. Basic Approach I: Hybrid IEEE 802.11g and a GPRS platform

The hybrid IEEE 802.11g and GPRS platform was developed as the first approach. The main objectives presented in the previous sub-chapter were already the framework, in which the most suitable approaches were selected from the solutions on hand at that time. IEEE 802.11g protocol was the most common version of Wi-Fi communications, so it was a rather straightforward candidate in the first place. Also the use of the WiMAX system [33] was studied in parallel during the project, but it was found to be more complicated and expensive, therefore less attractive considering the commercial perspective. When seeking the supplemental mobile communication system, GPRS was an obvious solution, being in wide commercial use and already possessing practically full coverage in mainland Finland and most parts of Europe.

The platform was designed to provide an infrastructure to a wide community of commercial and governmental traffic and safety services. The platform itself was the key element, but the services created for the platform also had a crucial role; on the one hand, they generated different ways of using and exploiting the architecture. But on the other hand, the services are the platform's showcase for consumers; in order to make consumers interested in purchasing the platform (and furthermore the vehicle industry to integrate the platform equipment into their vehicles) there had to be some key services attractive enough for consumers. Instead of an extensive package of services, just a couple of key services were defined to prove the applicability, usefulness and necessity of the architecture. The (hybrid) architecture, even with a low deployment rate, was envisioned as the so-called "killer-application" to raise public interest and therefore commercial success, leading to large scale deployment and generation of a wide spectrum of independent services.

The wireless traffic service platform was divided into three functional entities: the Traffic Service Central Unit (TSCU), the base station network with Traffic Service Base Stations (TSBS), and Mobile End Users (MEU) with ad-hoc connectivity and (non-continuous) backbone network connectivity.

The platform is presented in Figure 7. It consisted of MEU units embedded into vehicles, TSBS RSUs beside the road, and the host system TSCU beyond the base station network. The MEUs formed the V2V network. They did not have continuous connectivity, but operated in an ad hoc manner with each other whenever possible, typically when two cars were passing each other. Always when a vehicle with an MEU passed a TSBS, it received up-to-date traffic platform information stored in the TSBS. The TSBS received regular updates of the traffic platform information from the TSCU, located in the fixed network beyond the TSBS. The TSBS acted as an interface between the fixed and wireless networks. The MEU also transmitted received data to/from the TSCU over the GPRS alternative connection when critical weather, warning or accident information emerged.

The services designed for the architecture with specified pilot service applications are listed in Table II. The incident and emergency warning service used vehicle data to generate warnings considering exceptional traffic conditions or accidents. The local RWS collected observed weather data from comprehensive precise local road weather analysis and forecasts to be forwarded back to cars. The remaining services delivered the traffic congestion data for public authorities and travel data to users on the move.

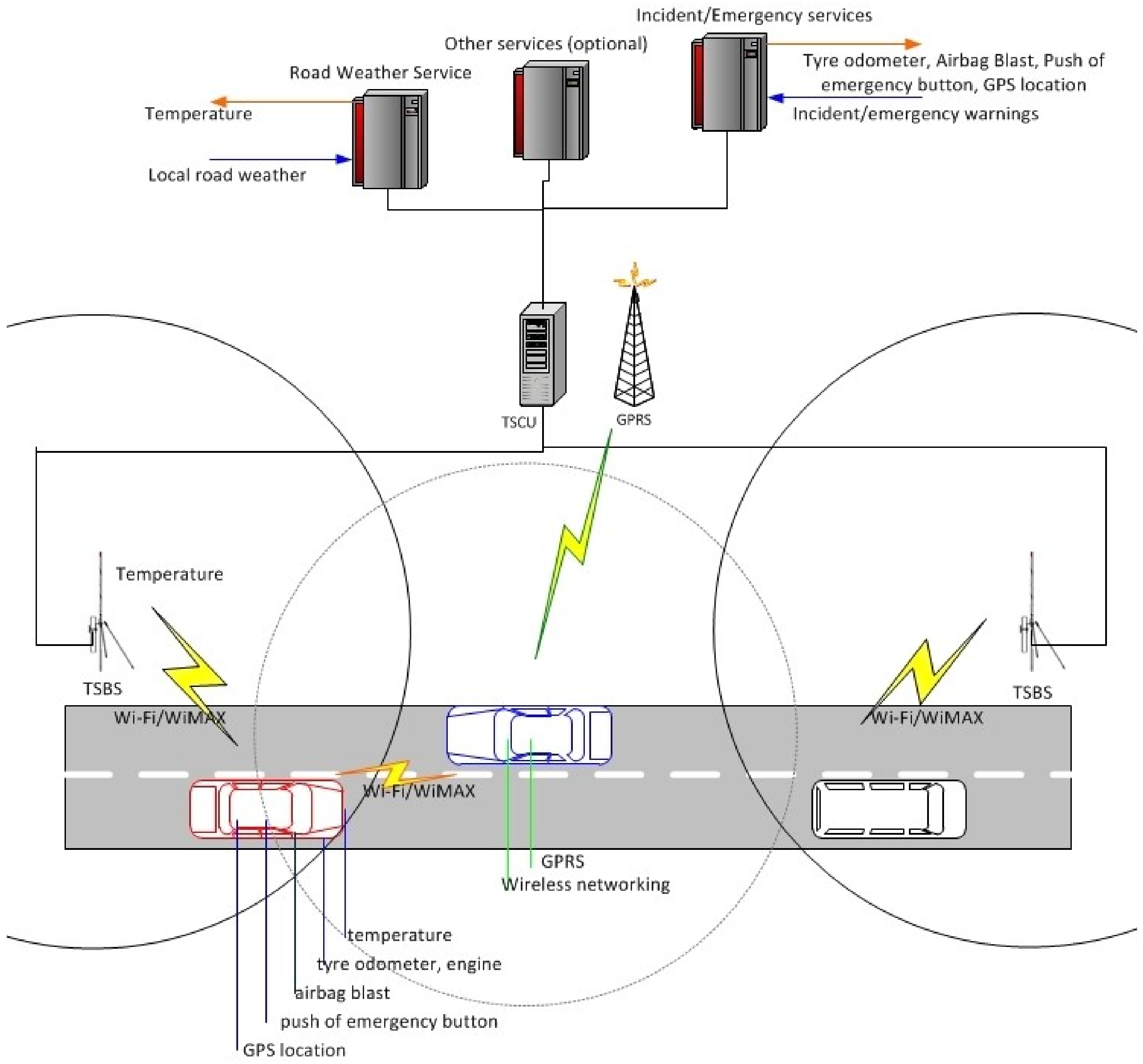


Figure 7: Hybrid IEEE 802.11g and GPRS platform

Table II: Services defined for the hybrid IEEE 802.11g and GPRS platform

General services	*Pilot system specific service*	*Brief Description*
Accident warning	Emergency button	Button pushed in vehicle, accident location distributed throughout the platform
	Airbag burst	When airbag burst in vehicle, accident location distributed throughout the platform
Incident warning	Vehicle throwing	When vehicle gyroscope registers lateral movement, incident location distributed throughout the platform
	Sudden break	When vehicle gyroscope registers rapid decrease of speed, incident location distributed throughout the platform
Local Road Weather	Current local road weather information	Weather data from TSBS and exceptional weather data from vehicles distributed throughout the platform
Positioning	Embedded to other services	Vehicle positioning
Transport	-	Transport guidance and real-time timetables
Traffic	-	Traffic logistics for traffic control centre
Route planner	-	Planning route to expected destination
Parking places	-	Real-time parking place availability info
Point of Interest	-	Guidance to point of interest
Geo-coding	-	Geometric data

The system operated as follows. In Figure 7, the TSCU is at the top of the Figure with connections to the fixed Internet services, the local traffic weather and the incident/emergency warning service. The TSCU took care of user management. As a central unit of the system, TSCU maintained the interdependencies of all the architecture elements. It also stored all the data gathered from the platform and forwarded the appropriate data to services.

The incident/emergency warning service parameters were an airbag blast, a push of the emergency button in the car, car throwing and sudden break, all of them including the GPS-location of the observed issue. The combined RWS and RSU core included a weather forecast model, generating local road weather outlook based on FMI's operational measurements. This model was supplemented with car measurements (temperature and GPS-location of observations) to complement the weather information. The resulting local road weather information was delivered to the TSCU, responsible for forwarding this data to the vehicles through the platform. Similarly, the incident/accident warning service collected vehicle data to build up warnings for exact locations, delivered back to the TSCU. Depending on the significance of the warning the TSCU selected the appropriate path for the warning data distribution. The most critical warnings (e.g., accident location) were delivered through the GPRS connection as rapidly as possible, while the more informative-like warnings were distributed through the RSUs. The network of TSBSs below the TSCU (Figure 7), mainly acted as a data transmitter from the TSCU to the MEUs and vice versa. The TSBS was also collecting weather data itself, delivering it to the TSCU.

The MEUs in vehicles were the users of the Carlink platform, gathering data along the roads they were driving, delivering it up to the TSCU and the underlying services and, finally, exploiting the weather and warning information derived from the vehicle based data. The parameters gathered from the vehicle were the temperature, car throwing indicator, car sudden breaking indicator, airbag blast notification, push of emergency button notification and the GPS location for each data source. The Wi-Fi and the GPRS interfaces were used for the communication with the TSBSs and the TSCU.

3.3. Basic Approach II: Hybrid IEEE 802.11p and a 3G platform

The IEEE 802.11p with supporting 3G were the main components of the second approach, operational intelligent hybrid wireless traffic safety network architecture pilot between cars and infrastructure. The possibility to exploit vehicle based sensor and observation data in order to generate intelligent real-time services and service architecture for vehicles was also considered. The NEC LinkBird-MX [10] equipment was selected from the state-of-the-art products into the vehicular access network test measurements and pilot platform. The main goal was to improve traffic safety with accident and weather condition related accurate services, but also to offer a platform for true bi-directional Internet-like networking experience tailored to vehicular environments.

A general view of the platform is presented in Figure 8. The platform consisted of an IEEE 802.11p based access network of vehicles, roadside units acting as system base stations, with the host systems as linking points connecting wirelessly the WiSafeCar network to the Internet. The vehicles did not have continuous connectivity, but were connected in an ad hoc manner with each other whenever possible, typically when two cars passed each other. Moreover, when a vehicle passed close to a roadside unit, it received up-to-date traffic platform service data from it, through the linking point located in the fixed network. The roadside unit acted as an interface between the fixed and wireless IEEE 802.11p networks. The vehicle could also transmit data to or receive from the linking point over the lower capacity 3G network, whenever the IEEE 802.11p-based connection to a roadside unit was not available. This alternative access over the cellular network

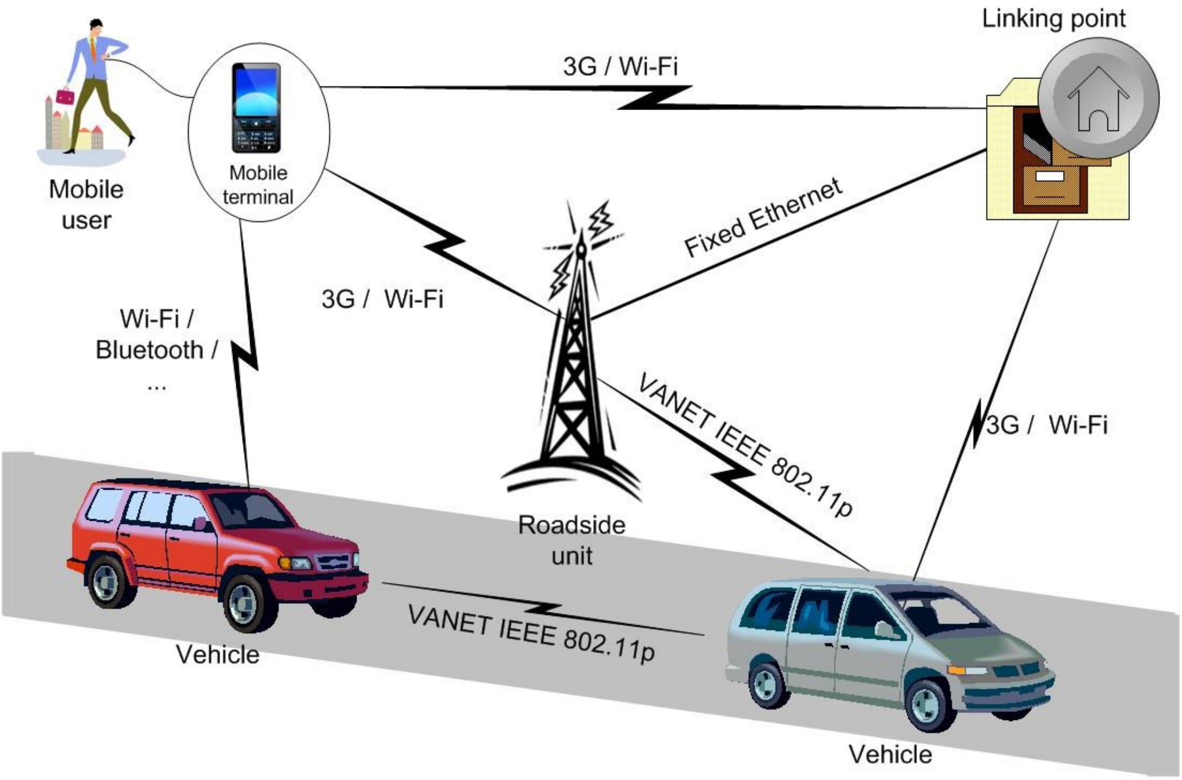


Figure 8: Hybrid IEEE 802.11p and 3G platform

provided robustness to the wireless connection. The communication platform had four main characteristics; the vehicle(s), the roadside unit, the linking point and a mobile user (not considered in detail here, as a project specific additional scenario). The linking point was one entity above the platform, hosting the vehicles through the roadside unit network. Vehicles used the IEEE 802.11p based access network to communicate with each other but mainly for communicating with a roadside unit, whenever in the vicinity of one. The vehicle received up- to-date real-time service data, but as an exchange it also delivered its own data gathered from the vehicle sensors and systems, to further update the services. The roadside unit delivered this data to the linking point through a fixed connection, together with its own advanced data set gathered from its own weather station and a variety of traffic sensors. 3G was used as an alternative option for critical data delivery in the position outside the range of the IEEE 802.11p network, providing complete coverage in urban areas.

Based on the architecture defined in the project and the results of field measurements, the set of pilot services was defined for the platform, and is listed in Table III. The services were collected indicating the data that formulated the concluding condition from one or multiple sources. The internal data sources originated from WiSafeCar, coming typically from either the vehicle or an advanced roadside unit. External data sources were independent of our system, and on the other hand, commonly used already in most cases. External data was provided through the linking point. By combining these different sources, the most effective reaction to different types of events and incidents was expected.

The research work showed that the solution has clear potential as a comprehensive heterogeneous vehicular communication entity, for decreasing the amount of accidents and lives lost on the roads. The system deployment can be initiated in a cost-effective manner, relying purely on an existing 3G overlay network in the early deployment phase.

3.4. Comparison of Approaches

Both of the approaches presented above were based on state-of-the-art mass-market products at the time of their development. The IEEE 802.11p based communication system (as well as 3G cellular networking system) was designed to enhance the deficiencies found from older solutions. When comparing these solutions, it becomes clear that the main objectives of the technology development have been successfully fulfilled.

A comparison between IEEE 802.11g and IEEE 802.11p communication platform measurements has been presented by the author of this thesis work in [34]. The main results are gathered into Table IV. Although the measurement platforms were slightly different, several observations could be made from the comparison. First of all, in IEEE 802.11p based platform measurements, the data speed during the connection remains approximately the same, regardless of the vehicle speed. On the contrary, in the IEEE 802.11g measurements based platform, the successful connection time varied significantly between different measurements. However, after the connection was ultimately established, the average data speed was better with IEEE 802.11g. Therefore, the peak performance in terms of data throughput is lower with IEEE 802.11p, but still more than appropriate for the needs of vehicular access network. The IEEE 802.11p has clearly better general performance and behavior in the vehicular networking environment. The price of balanced operation and range seems to be decreased peak performance, but this cost is clearly tolerable when considering the advantages. The typical services in vehicular communication do not usually require high

Table III: Services defined for hybrid IEEE 802.11p and 3G platform

Service	*Overview*	*Internal Data Sources*		*External Data Sources (via Linking Point)*
		Vehicle	*Roadside Unit*	
Accident warning	Accident in road interpreted	Airbag burst, GPS, emergency lights on	-	Accident info from authorities
Incident warning (BCW)	Exceptionally bad weather conditions interpreted or observed	Temperature, GPS	Road surface condition sensors, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc., authorities
Incident warning (SRW)	Slippery road conditions observed in specific spot	Road surface condition sensors, gyroscope, GPS	Road surface condition sensors, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc., authoritities
Incident warning (AOV)	Indication of approaching emergency vehicle	Vehicle-to-vehicle information through VANET	-	-
Incident warning (RWW)	Indication of roadwork ahead	-	Infrastructure-to-vehicle information through VANET	-
Local road weather (RWS)	Local weather information and forecast to the location of vehicle	Temperature, road surface condition sensors, GPS	Road surface condition sensors, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc.
Route weather (RW)	Weather information and forecast to the vehicle route options	Temperature, road surface condition, GPS	Road surface condition sensors, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc.

capacity, but rather rapid message delivery. The general performance and especially the data rate of IEEE 802.11p allow the most appropriate operation.

The comparison between 3G and GPRS is more straightforward. 3G is the downward compatible enhancement of GPRS. In general 3G has only one deficiency against GPRS with a shorter communication range, but even that is overcome with the dense deployment rate and ultimately with downward compatibility to GPRS. Therefore, 3G is clearly a superior networking system compared to GPRS.

Table IV: Comparison between IEEE 802.11g and IEEE 802.11p

IEEE Standard version	*802.11g*	*802.11p*
Maximum data rate in theory	54 Mbps	6-54 Mbps
Average measured data rate (V2V, 90 km/h)	2.45 Mbps	1.46 Mbps
Range of basic installation, in theory	140 m	1 km
Average range in measurements (V2V, 90 km/h)	248 m	235 m
Mutual stability between each measurement	Poor	Good
Mobility	Limited	Supported
Operating bandwidth	2.4 GHz	5.8-5.9 GHz

Summing it all up, the combined IEEE 802.11p and 3G provide an efficient and relatively stable communication platform. The former approach of combined IEEE 802.11g and GPRS had some critical deficiencies in vehicular safety access network delivery, mostly solved in the new approach. Especially during the original introduction of the pilot system, the approach of combined IEEE 802.11p and 3G communications for advanced vehicular networking represented a state-of-the-art approach for vehicular safety access network and general communication.

4. Proposed communication architecture for Vehicle-to-Vehicle and Vehicle-to-infrastructure networking

4.1. Introduction

Vehicular wireless communications and vehicular ad hoc networks are nowadays widely identified enablers for improving traffic safety and convenience. Minimization of traffic fatalities and human injuries is a major objective for both national and international authorities, but it also allows vehicle manufacturers, as well as vehicle equipment and service providers, to develop added value for their products. A large number of suggestions for vehicle-to-vehicle and vehicle-to-infrastructure communication and related devices and services has already been presented by the vehicle industry, as well as research communities and universities. The focus is typically on bilateral communication between two vehicles or on broadcasting information from one vehicle or infrastructure to vehicles in the surrounding area. Roadside infrastructure is also employed in many approaches, typically providing some local information related to traffic lights or road works to passing vehicles. Another approach is to connect a group of vehicles travelling to the same direction into the same ad hoc network. A typical example is vehicle platooning, in which the leading vehicle is coordinating the travel, while the rest of the participants can have somewhat easier driving with the system maintaining mutual distances and receiving traffic related guiding information from the lead vehicle. The ultimate case is Internet communication in the vehicle. With short-range communication systems this is not easy to arrange, the only way being basically the support of a dense roadside access point network. However, with new cellular mobile communications systems, with relatively large communications capacity, an Internet-like communication experience can be achieved to some extent. A variety of applications exists in each of the scenarios presented above. A typical application or solution focuses on one or a few of the challenges, while ignoring the other somewhat contradictory ones. A widely approved common communications platform supporting all of them has not been presented yet.

In this work, the focus is on a communications architecture which could adequately support all the scenarios and demands of vehicular networking. Communication between cars is arranged in an ad hoc manner, supported by a wireless base station connection to the backbone network whenever possible. The architecture employs a specific set of services (e.g., a local road weather service and an incident warning service), but a variety of services can be integrated to this kind of architecture, on an on-demand basis. Moreover, a common architecture integrated to the majority of vehicles and roadside infrastructure would ultimately allow vehicle manufacturers, commercial service providers and road authorities to develop more and more sophisticated and accurate services, based on market and policy demands. Furthermore, the approach of this work also pays attention to the possibilities of bidirectional communication. Instead of providing "static" services for the vehicles from other vehicles or roadside infrastructures, the vehicle data is collected and archived to be exploited in more accurate and localized services than general wide area services, based on fusion data of all possible sources. Road weather forecast is a perfect example of such kind of data. It is generated and provided based on variety of weather measurement systems with certain accuracy, but with supplemental localized support data from vehicles, ultimately even the smallest changes in local conditions can be observed and further exploited in the updated forecast.

The communication platform of this work has been developed in the research projects of the author and in the original papers of this thesis. It is the result of research conducted in this thesis.

4.2. Objectives

The main objective of this thesis was to develop a communication architecture supporting all the networking requirements in the fields of vehicle-to-vehicle and vehicle-to-infrastructure communication. The most obvious communication to be supported is V2V instant messaging. In the communication range of another vehicle, the vehicle needs to have a possibility to exchange data. A typical case occurs when passing vehicles exchange information related to the traffic or some particular service. However, the most important case is when the vehicle observes or faces an accident. On such an occasion, all the approaching vehicles must be warned. In this particular case, the vehicle must broadcast the warning information to all the vehicles in the range, but also the vehicles receiving this information need to forward this notification further, vehicle by vehicle. Another broadcast type of communication example is an emergency vehicle informing about its presence. Yet another type of communication is data exchange between a roadside unit and a vehicle, as the vehicle passes the station. Usually this kind of V2I communication has been treated as infrastructure delivering information to vehicles, but in the case of Internet communication or vehicle observation data gathering, data needs to be delivered also in the opposite direction. In the case of V2V broadcasting there is no need for recognition or verification of identity with a partner, but in V2I and bilateral V2V communication, also some level of counterpart identification is usually required before data exchange. This is realized with a conventional handshake procedure which has to be really fast. In general, the IEEE 802.11p communication system contains all the required capabilities to support all the cases of V2V and V2I communication.

For vehicular communication, there are generally two fundamental approaches, short-range wireless local area networking (Wi-Fi) and relying on wide-area cellular based communication. In this thesis, the approach has been to rely on short-range communication, with supporting cellular communication wherever short-range communication is not available. In general, this approach is an ultimate approach with all the benefits, as long as the handoff between different technologies does not cause unbearable complexity and/or delays.

The last objective in this work is the support of weather related services. As the thesis has been conducted in a meteorological institute, road weather services play an essential role. However, there are also other aspects supporting the focus on the road weather services, considered more closely in the first chapter. In a nutshell, road weather services are commonly recognized as one of the key advantages available through vehicular networking, especially in communication between roadside infrastructure and vehicles. With a functional local road weather service partially based on vehicle data, the whole vehicular networking architecture can be justified and its operability verified.

4.3. Operational procedure

Based on the objectives defined for this work, a vehicular networking architecture has been designed. The generalized view of the architecture is presented in Figure 9. The operational procedure is as follows: Vehicles A and B are passing each other, and as they pass, they exchange service data with IEEE 802.11p based V2V communication. If the queued vehicles A and C are within a mutual communication range, they can exchange service data as well. If vehicle A runs into an accident, or it observes some critical information (e.g., icy, slippery road, or precaution due to stray/wild animals), it will immediately broadcast warning information to all the vehicles in the surrounding area with IEEE 802.11p

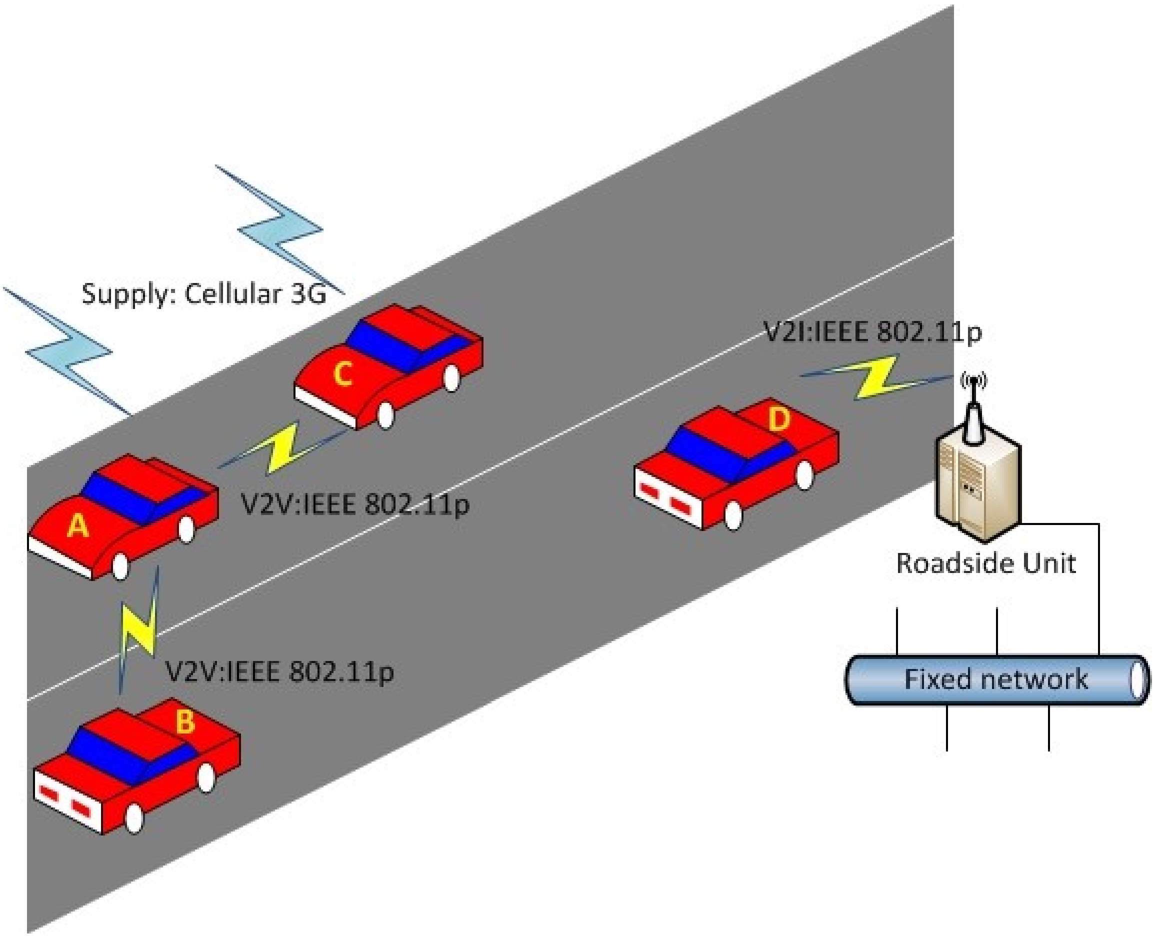


Figure 9: Generalized view of the architecture

based V2V communication, and ultimately vehicles B and C can avoid accidents. Similarly, if vehicle B has received such a broadcast warning from behind, it re-broadcasts the warning to vehicle A, to be re-broadcasted to vehicle C, allowing B and C to avoid an accident. The accident information is also delivered to the cellular network via 3G communication. A service center will receive the data and forward it with location data to the whole network. With a certain delay, vehicle D also receives this information, either through IEEE 802.11p based V2I communication with RSU, or via periodical critical information transmission via 3G communication.

As vehicle D is passing the RSU, it exchanges also other architecture data with it, through an IEEE 802.11p based V2I link. The observations (e.g., weather data) gathered by vehicle D during its travel are delivered to the RSU, to be further delivered via a fixed network connection into the service center(s), to be further analyzed and exploited in the local services. Up-to-date architecture service data is delivered to vehicle D in return. If the RSU possesses optional road weather station facilities, the weather measurements of vehicle D in the location of the RSU will be compared to the road weather station calibrated measurements, and the service center will be supplemented with quality estimation embedded in the weather observation data of the vehicle D. Naturally vehicle D will receive relevant up-to-date road weather station data, based on its user profile preferences. Finally, as it passes, vehicle D can also gain temporary Internet access through the fixed network connection of the RSU. As the link is accessible only as it passes by, the vehicular application using Internet access has to work in an offline mode for the rest of the time, or exploit a lower capacity cellular data link during those periods.

In general, the denser the RSU network beside the road, the more up-to-date services and more regular Internet connectivity can be delivered to the vehicles. However, the density of the RSUs is heavily limited by their deployment costs. Ultimately, regardless of the costs, on day one of system deployment there will be none or very few RSUs available in any case. However, in this hybrid communication architecture, the supplementary communication link via a 3G overlay cellular network is in operational use with high coverage, and therefore the system is available in limited form already on day one of the deployment process, with really low implementation costs.

4.4. Services supported by the proposed architecture

The communication architecture and the operational platform presented above support generally a variety of services envisioned for the vehicular networking entity. It is expected that after such architecture has been deployed and is in operative use, the commercial markets as well as national and international regulations will eventually supplement the architecture with the services required and the services will be commercially competitive. However, it is important to define the preliminary set of services to start with, showcasing the architectural efficiency and operability, as well as providing important safety advances to justify system deployment. Such an example service set has been defined in each evolution phase of this work presented earlier. Each set of services represented the envisioned set of necessary safety and convenience services at that moment. Based on the earlier service definitions and current evolution status of the architecture, an ultimate set of preliminary services is presented in Table V, tailored for the current evolution phase and expected needs. In general, the set of services is very similar to the service set presented in Table III, with some important additions for data sources and one additional service is now included.

The services are constructed from collected data from one or multiple sources. Internal data sources originate in the platform, coming from either the vehicle or the RSU. External data sources are platform independent, but commonly used. External data is typically provided through the RSUs, but they can also be achieved via 3G communication in periodical critical information packages.

The set of services consists of accident warning, four different incident warnings and a specific request regarding driving, road weather information and route weather information. The accident warning service indicates an observed accident. The service is initiated when a vehicle airbag bursts or emergency lights are activated, or externally from traffic authorities. Incident warnings are notifications about different kind of conditions that endanger travel. These conditions are exceptionally bad weather, a slippery road, an approaching emergency vehicle and roadworks. Exceptionally bad weather, as well as slippery road warning are constructed from data gathered from every possible source, vehicle sensors, RSU sensors (mainly RSUs with combined RWS) and externally from traffic authorities. Information about an approaching emergency vehicle is broadcasted by the emergency vehicle itself. A roadworks warning is broadcasted from the roadworks site. Naturally this information can be delivered through RSUs or 3G directly from the road authorities.

Both an approaching emergency vehicle and a roadworks warning are also defined by C2C-CC and ETSI as vehicular ITS services [9]. The request regarding driving is very similar to an exceptionally bad weather warning, only this time the driver is supplemented with a simple request of reduce speed or stop driving, in the case of local weather conditions seriously endanger driving. This particular service has been designed in the FOTsis research project, by the specific demand of local road authorities in Spain. Justification for such kind of separate service is the fact that local conditions in the mountain roads of Spain can change rapidly,

Table V: Services defined for proposed architecture

Service	*Overview*	*Internal Data Sources*		*External Data Sources*
		Vehicle	*RSU*	
Accident warning	Accident in road interpreted	Airbag burst, GPS, emergency lights on	-	Accident info from authorities
Incident warning bad weather	Exceptionally bad weather conditions interpreted or observed	Temperature, GPS	Road surface condition sensors, friction data, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc., authorities
Incident warning slippery road	Slippery road conditions observed in specific spot	Road surface condition sensors, friction measurement, gyroscope, GPS	Road surface condition sensors, friction data, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc., authorities
Incident warning emergency vehicle	Indication of approaching emergency vehicle	Vehicle-to-vehicle information through V2V	-	-
Incident warning roadwork	Indication of roadwork ahead	-	Infrastructure-to-vehicle information through V2I	Authorities
Beware driving request	Request of reducing speed or stop driving due to very bad local driving conditions	Road surface condition sensors, friction measurement, gyroscope, GPS	Road surface condition sensors, friction data, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc.
Local road weather	Local weather and friction forecast to the location of vehicle	Temperature, road surface condition sensors, friction measurement, GPS	Road surface condition sensors, friction data, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc.
Route weather	Weather information and forecast to the vehicle route options	Temperature, road surface condition, GPS	Road surface condition sensors, temperature, rain intensity, humidity, wind	Weather radars, weather stations etc.

and the fact that winter tires are not in regular use makes the critical weather conditions extremely dangerous [11]. Local road weather information and route weather information services are supplemented from all data sources available, vehicles, RSU sensors (mainly RSUs with combined RWS) and externally from traffic authorities. These particular services are expected to be presented as a “live” Internet service, the lack of continuous connectivity not being crucial as long as the services can be updated from time to time.

4.5. Field measurements and simulations

In order to verify the system operability and efficiency we have conducted an extensive set of field measurements and simulations. These measurements were focusing on IEEE 802.11p vehicular ad-hoc network evaluation, while the supplemental 3G was generally tested only in the pilot system, as it was expected to be a “well-known operative commercial system”. The field tests were conducted with only up to 3 vehicles and one RSU, the supporting simulations were designed to evaluate the operation with more vehicles and RSUs. The vehicular networking communication field measurements with IEEE 802.11p compatible units were conducted in the vicinity of Sodankylä, Finland, in a 2.5 km section of a public highway, over the years 2010 and 2011. These measurements were continued with exploitation of combined RSU and RWS in 2012 and 2013. The focus on the original field measurements was the capacity estimation of vehicular networking, with special scenarios of V2V and V2I communications. The test network consisted of On Board Units (OBU) installed into vehicles, communicating between each other and the RSU. Both the RSU and OBU equipment were identical, consisting of Windows (XP/7) computers, NEC LinkBird-MX version 3 transceiver devices with dual Larsen mobile antennas adjusted for 5.35-5.925 GHz operation. LinkBird-MX units were configured to use a 20 MHz channel width (optional width 10 MHz). The measured parameters were successful communication time while vehicles/RSU pass and an average throughput.

For the measurements, we prepared three different scenarios, seen in Figure 10. In V2I scenario 1, a vehicle carrying an OBU passing an RSU at a pre-defined speed of 70, 80, 90 and 100 km/h was considered. The RSU sent data to the vehicle, and successful data transmission was captured with special capture software for further analysis. In the scenario 2 (V2V), two vehicles (OBUs) passed each other at the pre-defined speed of 70, 80, 90 and 100 km/h, one of them transmitting data and the other receiving and capturing the successful data resection. Finally in scenario 3 (V2V2V), called the multi-hop scenario, three vehicles (a sender, a transmitter in the middle and a receiver) were driving in the same direction at a constant 80 km/h speed, maintaining equal distances of roughly 100 meters (clearly less than the communication range), sender being forced to deliver data to the receiver only through the transmitter in the middle. In each scenario, the transmitter sent UDP packets of 1202 bytes with 1 ms delay, leading to a 9.17 Mbps estimated maximum data rate. 76 measurement drives were conducted in the V2I scenario, 46 measurement drives in the V2V scenario and 2 measurement sessions (consisting of 44 separate connection establishments) in scenario 3. All the measurements were conducted in similar weather conditions.

In each measurement of the V2I scenario, the vehicle passed the RSU, maintaining the connection with RSU for as long as possible and at highest possible data rate. The resulting average connection time and throughput with different speeds are presented in Figure 11 and Figure 12, respectively. As the vehicle speed increased, the connection window decreased, as expected. With the highest speed used, 100 km/h, the connection window was still (on average) 30.3 seconds and even in the worst case 22.8 seconds. From the figures one can also see that in the measurements the vehicle speed change did not affect the average throughput speed. A similar type of measurement was conducted earlier with IEEE 802.11g based networking,

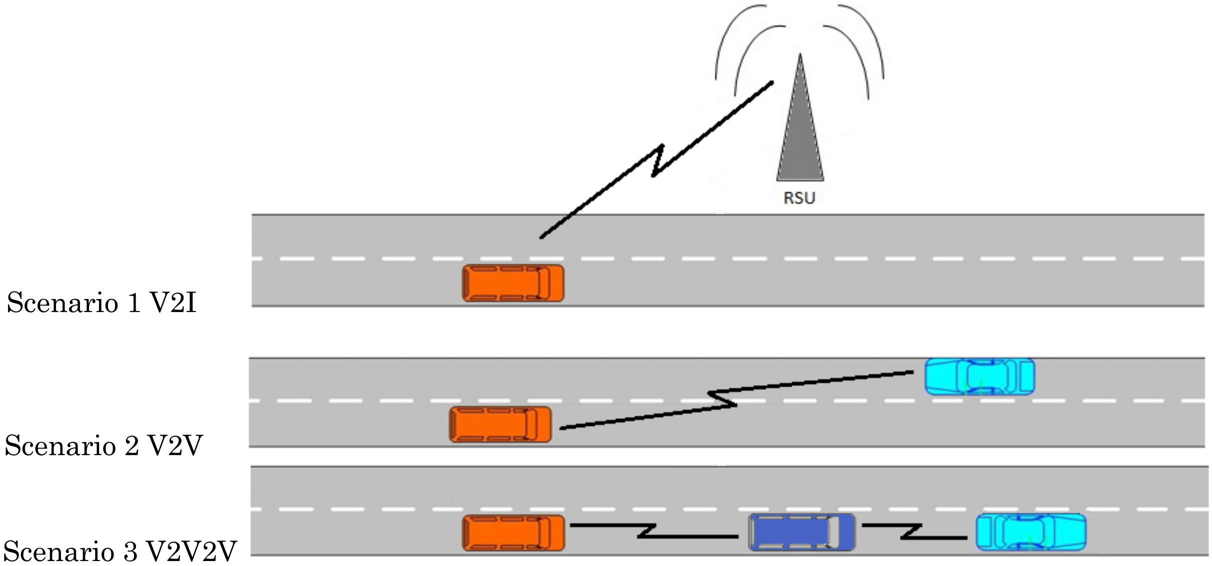


Figure 10: WiSafeCar field measurement scenarios

and this is presented in detail in [33]. In these measurements, much better antenna systems were used, but some conclusions can be drawn. First of all, the overall behavior of the IEEE 802.11p based system seems to be more stable. Where the results of IEEE 802.11g were varying greatly in terms of a successful connection window and general behavior, the IEEE 802.11p measurements were clearly more in line with each other. This was especially noticable when changing the speed; the IEEE 802.11p performance (in terms of the communication window) clearly decreased when the vehicle speed increased, while with IEEE 802.11g

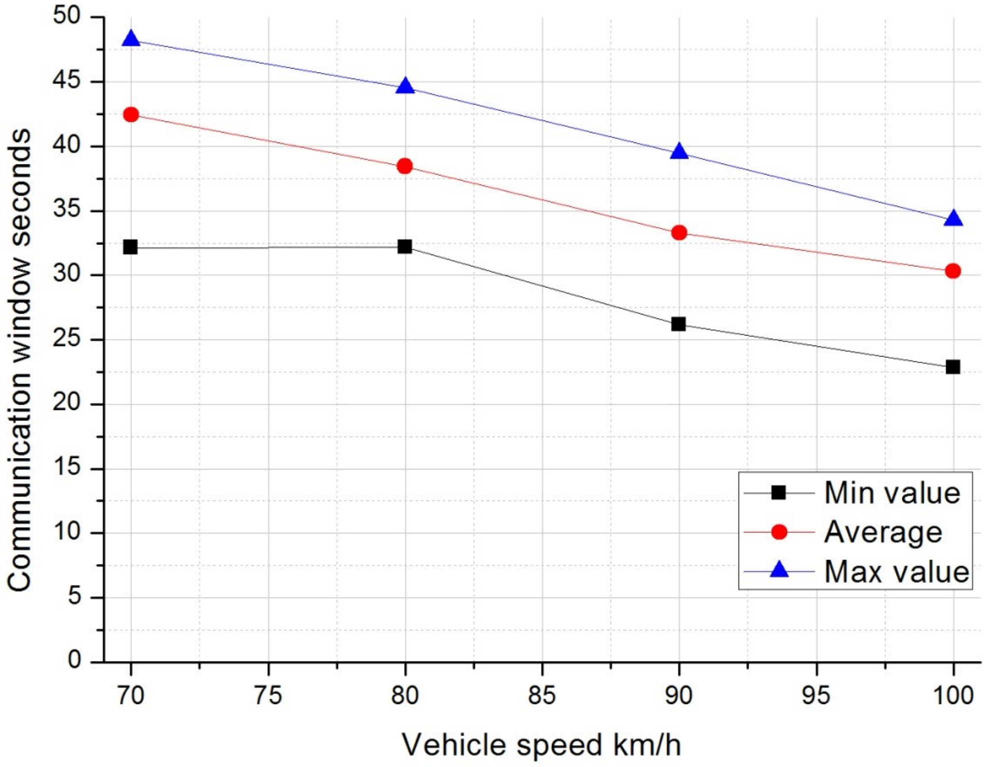


Figure 11: V2I scenario, average connection time

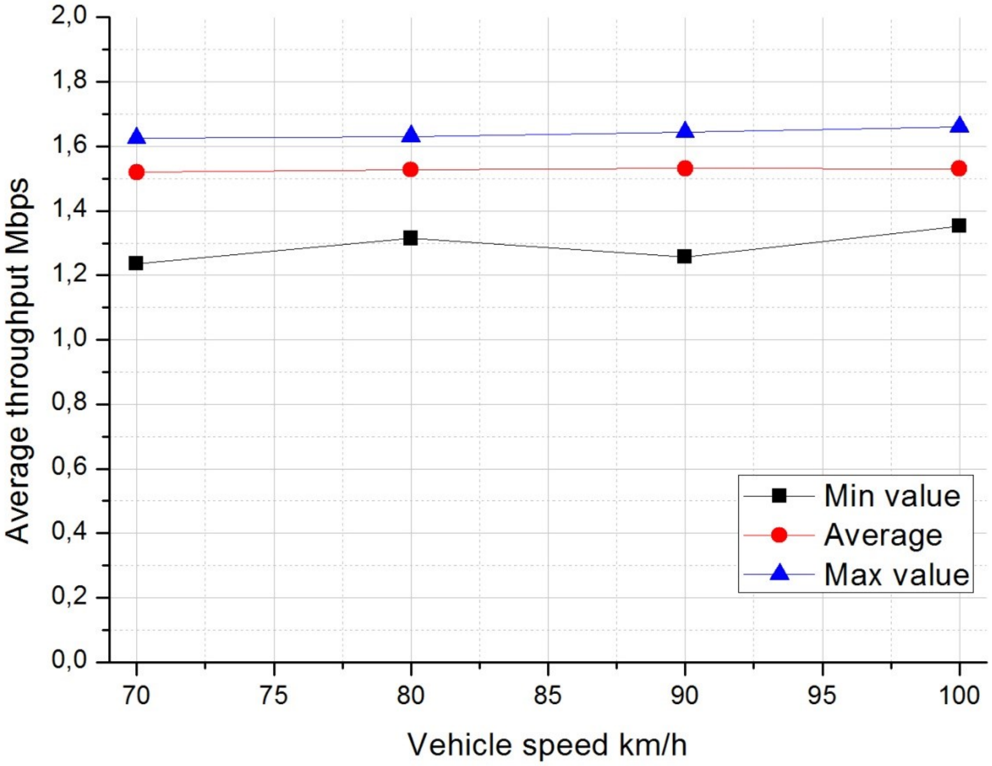


Figure 12: V2I scenario, average throughput

similar stability was not present all the time.

Secondly, the connection establishing process with IEEE 802.11p was clearly more stable between the measurements, compared to IEEE 802.11g. With IEEE 802.11p the connection was always created approximately at the same distance before the RSU, but with IEEE802.11g there was high variation. The blackouts in communication were caused by the traffic between the transceivers, but IEEE 802.11p recovered from the blackout much more sharper. The third point noted was the average data speed during the connection, which was clearly better with IEEE 802.11g (regularly around 5 Mbps in IEEE 802.11g measurements).

In the plot presented in Figure 11 there is a clear anomalous behavior in the minimum value result, the shortest communication window in 70 km/h speed is not in line with the other results. When analyzing the measurement data, it turned out that a single measurement with 70 km/h speed was not in line with the other measurements, suddenly cutting off the communication link without visible reason, clearly earlier than expected. Most likely there has been a car in between the transceivers exactly at the critical moment, blocking the link particularly effectively at the last part of communication window, and as a result the measured window is shortened. The risk for this kind event is always present when doing the field measurements in open streets, even if the measurements were attempted to conduct in homogeneous conditions. Especially when driving slower than other traffic (in our test road the speed limit was 100 km/h) these problems tends to emphasize. Therefore one should pay more attention to the average communication window size, and let the difference between minimum and maximum value represent a rough estimate of deviation. The same anomaly problem can be seen in Figure 12 minimum value results. In general, it would be better to have clearly larger amount of measurements within each scenario, and use standard deviation for scale visualization instead of minimum and maximum values. However, the amount of measurements was limited in our measurement campaign, and then again the presented results are also reflecting the imbalance always present in a difficult communication environment like vehicular network.

In 46 measurements in the V2V scenario, the vehicle passed another vehicle, maintaining the connection with it as long as possible at the highest possible data rate. The resulting average connection window and throughput at different speeds are presented in Figure 13 and Figure 14, respectively. Again, as the vehicle speed increases, the connection window decreases. With the highest speed used, 100 km/h, the average connection time is still 16.9 seconds and even in the worst case 7.7 seconds, allowing remarkable information exchange as the vehicles pass each other.

The average throughput in the V2V scenario is presented in Figure 13. Again, the data speed during the connection remained approximately same, regardless of the vehicle speed. Similar V2V networking measurements with IEEE 802.1g based networking [30] were available for the reference, and in this type of communication a more visible difference in performance between the IEEE standards 802.11g and 802.11p was found. Where the results of IEEE 802.11g were varying considerably in terms of a successful connection window, the IEEE 802.11p measurements were again clearly more in line with each other. The average data speed after connection establishment was clearly better with IEEE 802.11g (around 3 Mbps in IEEE 802.11g measurements, with speeds lower than 90 km/h). The traces of similar kind of anomaly like in V2I measurements are also present in these results, especially in the maximum values of average throughput and communication time. Again, they can be seen as anomaly behavior, but merely they should be seen as normal variation in very difficult communication environment.

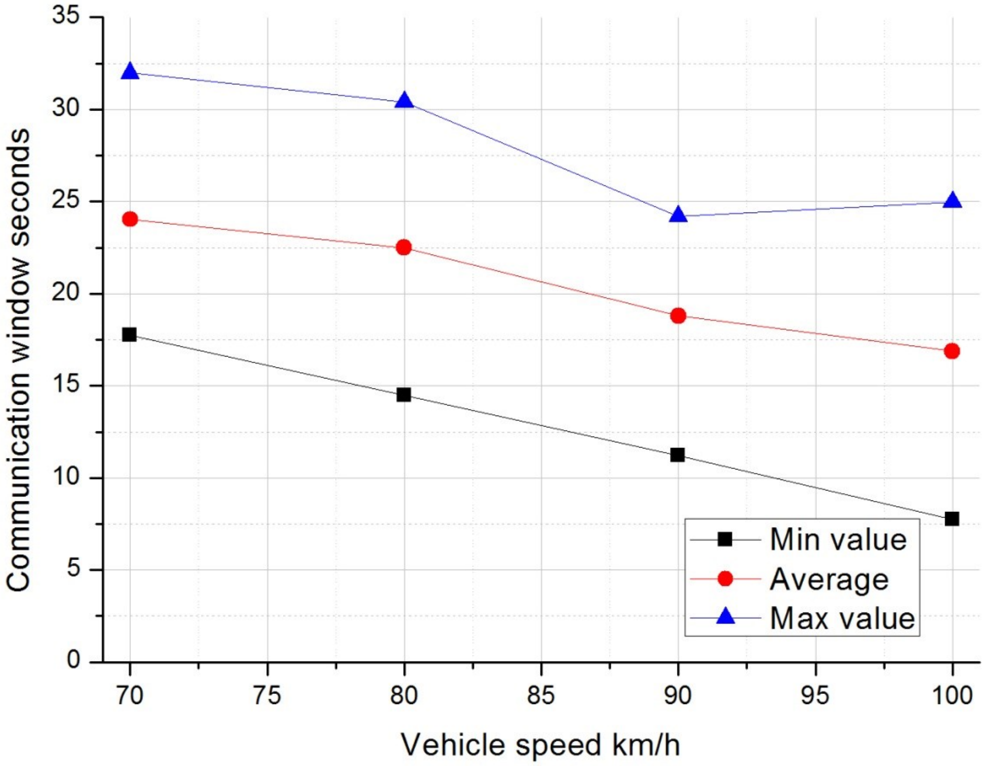


Figure 13: V2V scenario, average connection time

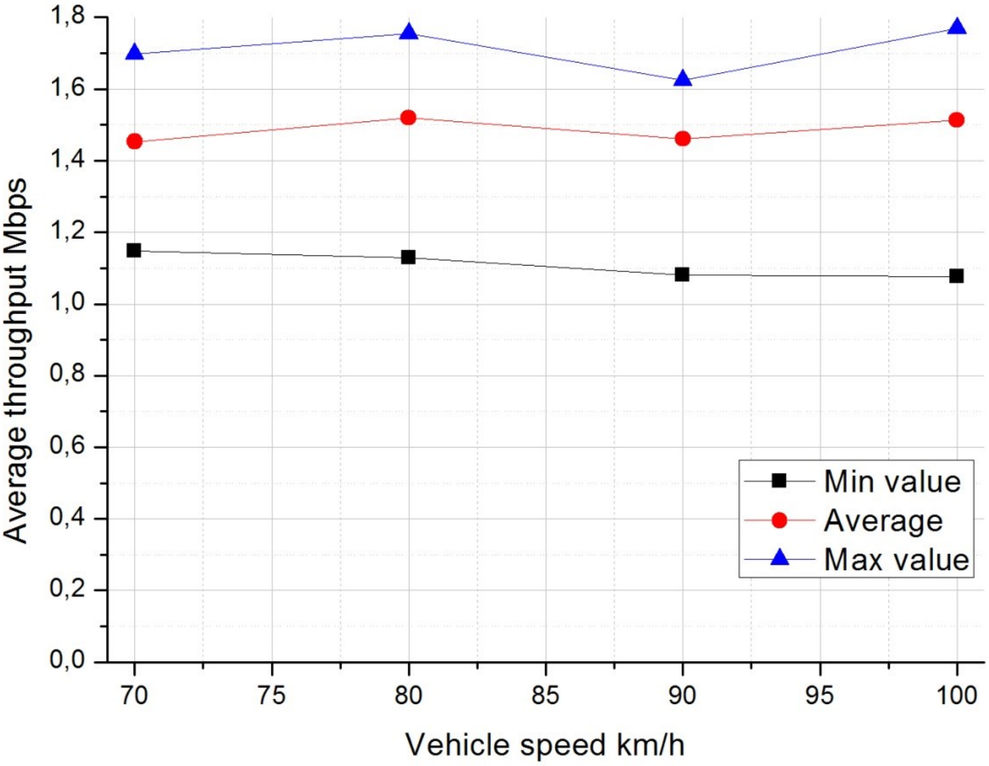


Figure 14: V2V scenario, average throughput

all the received packets were delivered through the vehicle in the middle to achieve the multi-hop communication.

The whole communication episodes consisted of relatively short communication sessions, the connection breaking relatively soon, but also re-initiating rather fast. One of the measurement sets is presented in Figure 15, all the connection sessions separated, and instead of a continuous data flow, we have 32 data bursts. Therefore, we concentrated our analysis to these data bursts.

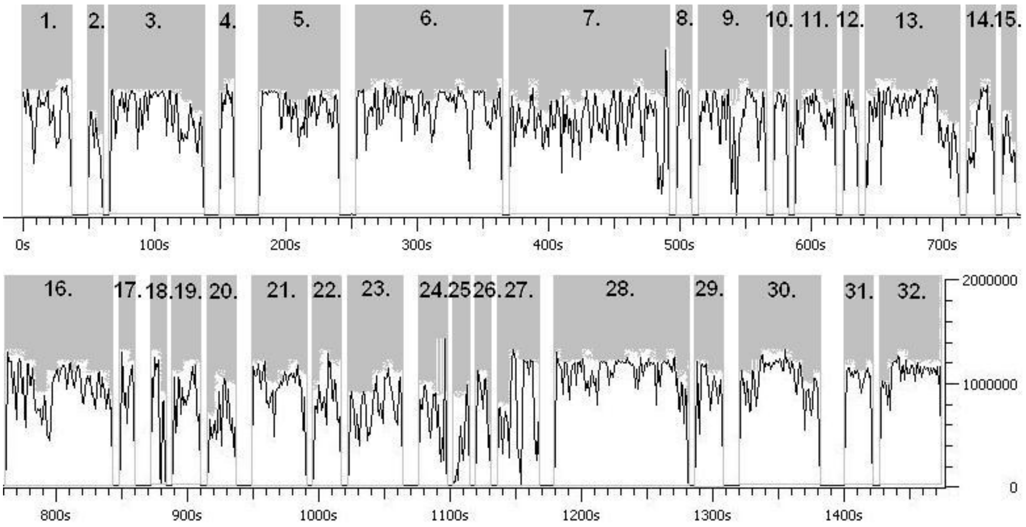


Figure 15: Example of vehicular multi-hop measurements (vertical scale bps)

A summary of the field measurement results from every scenario is gathered in Table VI. In the IEEE 802.11p standard, the theoretical range of the system is 1000 meters, which has been used to define the connection availability percentage. IEEE 802.11p does its job as expected, having clearly better general performance and behavior in the vehicular networking environment. Although the connection breaks up in our multi-hop scenario, the average connection availability of 81 % and decent average communication speed 0.86 Mbps (the corresponding speed in single-hop communication in the same area was around 1.6 Mbps) allows data delivery also in a multi-hop manner. The price of the balanced operation and range seems to be the decreased peak performance, but the cost is clearly tolerable, compared to the advantages. The typical services in vehicular communication do not usually require high capacity, but rather rapid message delivery and connection availability.

The NS-2 tool [36] with the SUMO traffic generator [37] were chosen to be the base of the numerical analysis, as it provided substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks, and was clearly the most common simulation platform used in related simulations. The SUMO tool provides a straightforward approach to generating scenarios for NS-2, based on real traffic material. The challenge in using NS-2 is that it is a freeware software simulation environment, originally designed for different types of wireless networking simulations, not perfectly appropriate for the vehicular simulations. It is a C++ based software entity, providing a real-time traffic model from a series of discrete events, allowing the implementing external features for the main process. The different routing protocols, interference models and other such features crucial for tailoring special purpose simulations (like our vehicular networking scenario) are employed as separate software libraries designed by mutually independent parties. This obviously means that the underlying protocol elements, physical phenomena approximations and behavior models are not perfectly harmonized. As an example, signal fading was not originally considered, but we have installed Rayleigh and Ricean fading model elements designed separately by a third party. All such cases should be traced and solved by the simulator users themselves, in order to ensure realistic results.

The underlying real-life traffic scenario was taken from San Francisco, as there is public traffic data available, generated by TrafficPredict.com. In order to estimate the upper capacity limits of the architecture, we needed clearly higher traffic density than in Sodankylä, Finland, and for that purpose San Francisco public data was found to be highly suitable. TrafficPredict.com [38] is a website that shows the past week's freeway traffic reports for some cities of California (San Francisco, Los Angeles, San Diego and others). This site is intended to help to predict what the traffic is going to be like for driving during a specific time and day of the week. The data is grabbed in 30 second time loops posted out in 5 minute averages, and finally grabbed and plotted on a map. For our simulation, we chose a small area in the "tourist center" of San

Table VI: Summary of field measurement results

Scenario	*Bypass speed (km/h)*	*Communication window (sec)*	*Avg. Throughput when connection (Mbps)*	*Avg. Throughput during session (Mbps)*	*Connection availability % (vs. theoretical)*
1	70	42.437	1.519	0.627	41.257
1	80	38.442	1.527	0.652	42.713
1	90	33.280	1.531	0.637	41.600
1	100	30.320	1.530	0.644	42.111
2	70	24.044	1.453	0.679	46.751
2	80	22.508	1.519	0.760	50.018
2	90	18.793	1.461	0.686	46.983
2	100	16.875	1.513	0.709	46.875
3	80	36.121	0.950	0.860	81.379

Francisco. The traffic model was generated for a “rush hour”, Friday afternoon between 2pm and 3pm on November 20, 2009. The image capture of the traffic model map is viewed in Figure 16, with the red square (sized around 3.3 x 4.0 kilometers) bounding our study area. Based on the traffic data, the simulation environment for the research area was generated, and can be viewed in Figure 17. Two main routes were defined, from point I to II and from point III to IV. There were four different scenarios, with 4, 8, 12 and 16 RSUs, respectively. In each scenario, there were 20 vehicles, all of them moving at a speed of 100 km/h. The RSU range was limited to 500 meters. In all communication, the bidirectional traffic with TCP protocol was used, with the target data speed 27 Mbps and a packet size of 1500 bits. The entire simulation time is 250 seconds, but in order to capture a snapshot from an ongoing traffic scenario, the communication starting point of each vehicle was set to be their simulation starting moment. In Figure 17, the RSUs for the four different scenarios (4, 8, 12 and 16 RSUs) are A, B, C and D, respectively. The distance between RSUs varies between 1300 and 2000 meters in the 4 RSU scenario, between 500 and 1000 meters in the 8 RSU scenario, about 600 meters in the 12 RSU scenario and between 300 and 700 meters in the 16 RSU scenario.

Vehicles did not start movement at the same time. The first one started at 0.1 seconds and last one at 47 seconds. Some vehicles started to move from intermediate points. During the simulation, all RSUs were trying to set up a connection with vehicles coming within their range, and to send data packets to them. As soon as vehicle went out of RSUs range, the connection broke down.

As stated before, in the simulation run, vehicles started the movement and communication at different times (depending on their counterpart location in the underlying real-life scenario), making it hard to combine the vehicles. As a solution to this problem, the data of each vehicle was adjusted to start from the moment when its communication was initiated for first time, and this way brought every vehicle to the “same starting line”.

Figure 16: Real-life traffic scenario from San Francisco, the focus area on red square

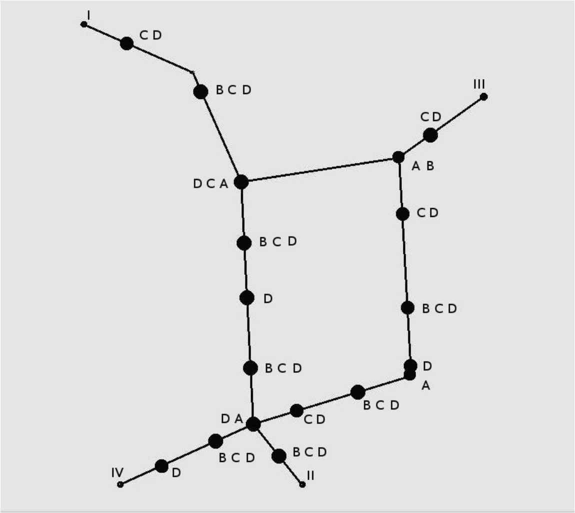


Figure 17: Simulation area captured from simulation view

The results of all the scenes are plotted into graphs and gathered together into Figure 18. From the figure it can be seen that an increase in RSUs dramatically enhances the data throughput of vehicles, especially in the cases of four and eight RSUs. This result is verified in Table VII, where the average throughput and percentage of average vehicle connection time are calculated from the results. Studying the trends in the table, it seems like the connection availability time is already saturated with 16 vehicles to a level of 50 %. However, this result may not be reliable, as the break times (visible in Figure 18) are sometimes longer than

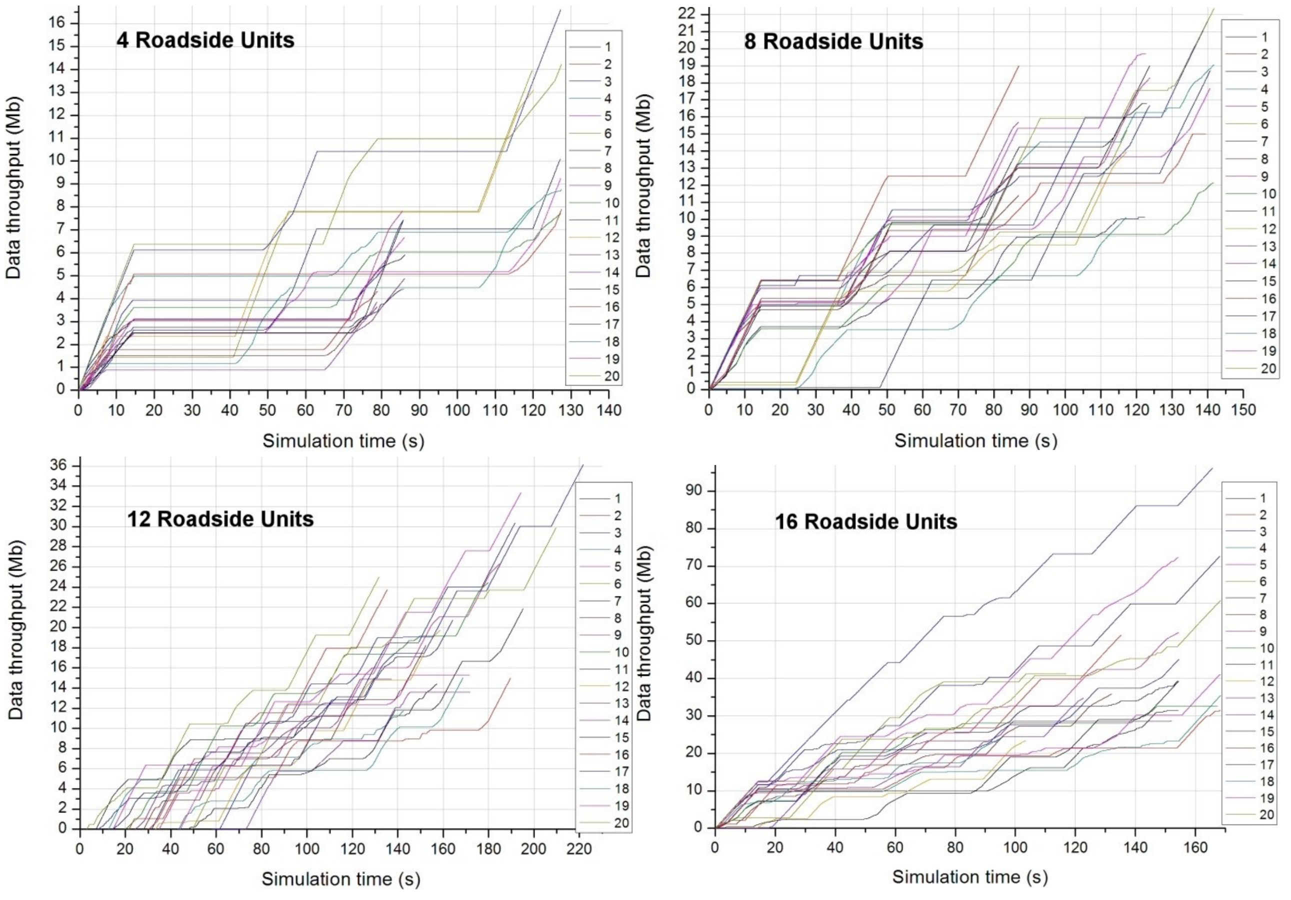


Figure 18: Combined results of all four simulation scenarios

Table VII: Vehicle connection percentage and average throughput during the simulations

Number of Roadside Units	*Avg. vehicle connection time %*	*Avg. throughput (incl.breaks) Mbps*
4	29	0.08
8	45	0.14
12	48	0.15
16	49	0.32

expected, and sometimes too regular to be independent. The average throughput of vehicles clearly benefits from the increased amount of RSUs, and the best performance in this parameter is likely to be achieved with even more than 16 RSUs. However, the results show that the observation area is likely to be best supported with around 20 RSUs, with optimal geographic locations. The results with 16 RSUs, with the average vehicle having a connection 49 % of the time and on average a 0.32 Mbps data speed, are already on the level of easily supporting services which are not time-critical. With time critical services like accident warning, the performance is not at an appropriate level, and there must be some way of increasing performance or overcoming this problem. The solution in this work is supplementary data links with 3G to fill the connection gaps coming from IEEE 802.11p vehicular networking.

4.6. Deployment estimation

In order to install the vehicular networking platform of this work, a detailed installation strategy is required. For this purpose, a deployment estimation is generated, based on the field measurement results presented in Table VI. By calculating the average range from the connection times of all V2I measurements conducted, one ends up in the 420 m range observed in the measurements. Furthermore, the average range of all V2V measurements is similarly calculated to be in the 475 m range observed in the measurements.

One can now draw an approximation of the vehicular networking communication architecture based on these results, combined together with the capacity data achieved presented in Table VI graphs. The resulting communication architecture is presented in Figure 19. RSUs are the service hotspots; in general, all the communication systems are available with maximum capacity, and the preferable solution in that case is vehicular networking with IEEE 802.11p. When travelling outside the RSU range, multiple options are available; the vehicle passing the RSU data directly, vehicle-to-vehicle communication with almost-up-to-date data just recently received from the RSU, or plain 3G data. The first option is the most efficient in a way that especially the critical safety data will be delivered instantly and the capacity is relatively good. However there is again a range limitation; the maximum range of two-hop communication being in this case around 900 meters. True multi-hop communication could also be used, but as stated in [39] the system will quickly have heavy congestion problems and an aggregation system would be needed. For simplicity, the estimation is limited to a two-hop range here. Furthermore, when travelling outside the “secondary range” of the RSU, the system is forced to rely on 3G in the case of network data. Even a few seconds delivery time may be inadequate with critical accident data, but otherwise the services operate properly. There is still an option to receive accident related critical data directly from the other vehicles in the area, meaning that vehicular networking provides improved safety also in areas where it is not connected with a roadside infrastructure.

Let us now consider the cost-effective vehicular networking platform deployment operation in practice and take an example of a straight highway section of 100 km length. If the highway area needs to be fully

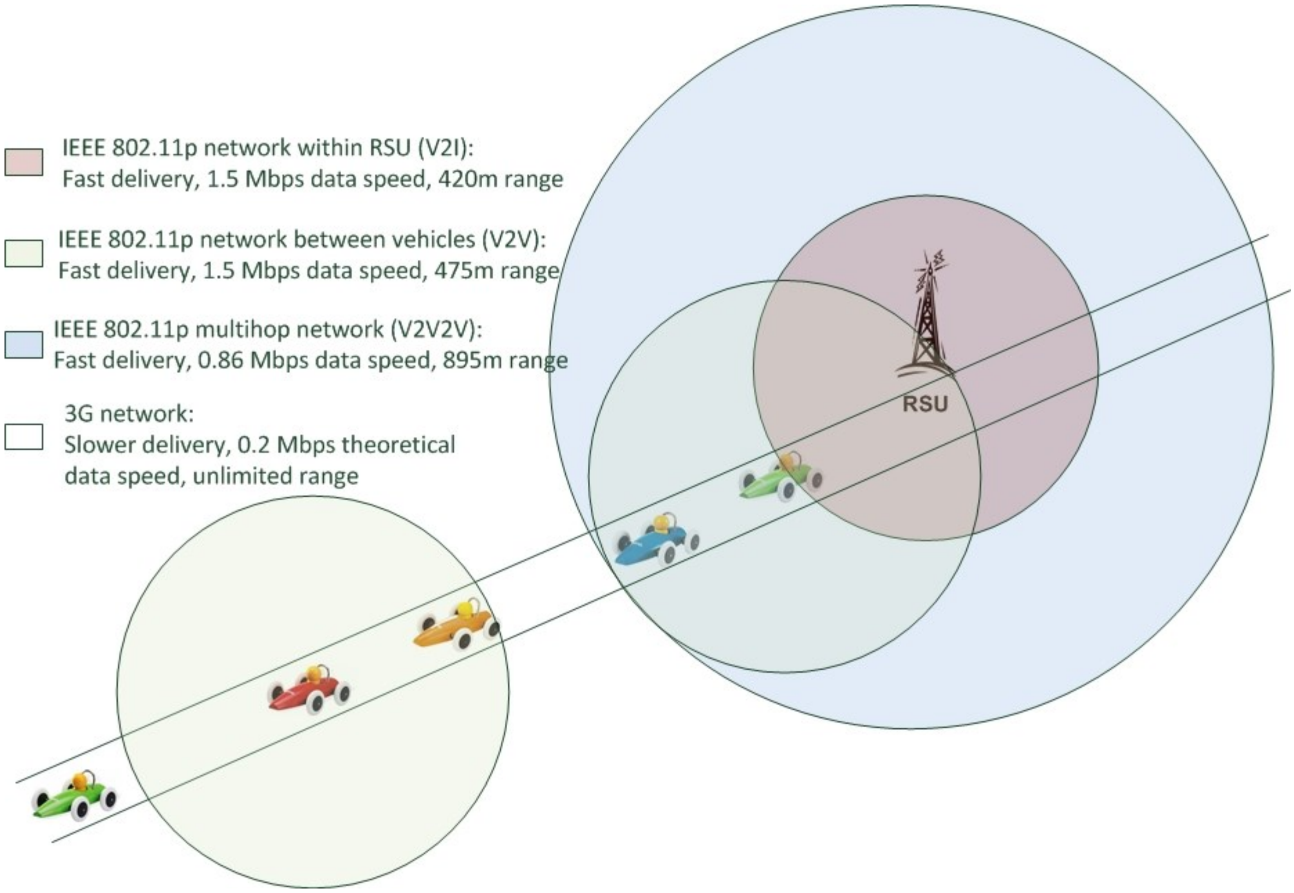


Figure 19: WiSafeCar geographical communication system

covered with RSUs, some 120 units are needed, which is obviously prohibitively expensive. However, if dense traffic is expected on the highway, the amount of RSUs can be scaled by relying on the multi-hop communication possibility, and this way duplicate the range of RSUs. In this case, 56 units are required, which still represents a rather heavy investment. A more realistic option would be to start the deployment with 10 RSUs. In this case, a vehicle travelling on the highway will have a direct RSU connection 8.4 % of the time of travel, a multi-hop link to RSU up to 9,5 % of time of travel, and the rest of the time near-real time data coming through 3G, supplemented with instant accident warnings about local accidents coming from vehicles witnessing or being involved in a particular event. This approach has relatively low installation costs, still offering clear improvements to the traffic safety and convenience. The minimum cost approach is to start without a single RSU unit. This approach would be clearly the easiest one; for example, the road administrator or a governmental agency could issue such a network by itself and without any pre-installations, just with an agreement with mobile network operator. Even in this case, services can be offered at an acceptable level, only the advantage of instantaneous accident and incident warnings, and higher capacity benefits are lost. Ultimately, the decision on the deployment strategy will be taken by the deploying organization, based on juridical restrictions and commercial demands, respectively.

4.7. Ongoing and future work

The platform development work is continuing in several research projects at the FMI, mainly in the European Eureka/Celtic Plus project CoMoSeF [11], aiming to create co-operative mobility solutions, devices and applications that are feasible for large scale deployment and that support the ITS Action Plan COM (2008) 886 and national ITS strategies. The project objective is to create co-operative mobility solutions (including devices and applications) feasible for large scale deployment that support the objectives of the European Commission's ITS Action Plan and national ITS strategies. The CoMoSef is a project on interactive local road weather services exchanged and enabled through an FMI combined Road Weather Station/Road Side Unit. The idea is to develop and deploy "Road Weather Testbeds" with advanced communication applications in interesting environments to test wireless networks and communications for the public.

FMI has constructed a combined Road Weather Station (RWS)/Road Side Unit (RSU), with an extensive set of road weather measurements, in Sodankylä, Finland. Together with research vehicles in Sodankylä, this station forms a pilot system in Sodankylä which acts as a real-life test-bed for the future demonstration systems. An extensive set of local weather data is offered to vehicles capable of operating with IEEE 802.11p or traditional Wi-Fi communication. The vehicles possessing compatible measurements (in practice our research vehicles) also deliver their own measurement data to the RWS. The multi-standard communication system will be analyzed and tested entirely, in order to be tailored appropriately for the demonstration systems [11].

The various new trends that are emerging in wireless networking, also to be considered in the future work of vehicular networking. Visible light communication (VLC) utilizes modulated optical radiation in the visible light spectrum. In [40], VLC is proposed to replace DSRC in V2V communication, in the deployment of collision warning and avoidance applications. VLC communication is enabled with photo-detectors and transmitters embedded into the vehicle headlamps and tail-lights. This kind of communication could be embedded also in the FMI's combined RWS/RSU, by installing street lights in the station and implementing VLC receivers and transmitters into them. The possibilities of this approach will be studied in the future work.

The Internet of Things (IoT) concept studies application scenarios where heterogeneous devices, spanning from smartphones and wireless sensors up to network-enabled physical objects (e.g. smart visual price tags) can seamlessly interoperate [41]. Machine-to-machine (M2M) technology can be seen as one aspect in IoT, focusing on communication between sensors and devices of the same type, without any particular need for Human-Machine interfacing (HMI). Article [42] discusses the possibility of exchanging vehicular telematics data in an M2M manner. M2M type of communication is indeed very interesting aspect in the future work. However, the essential element in this communication is the access to vehicle-oriented data systems within a CAN-bus (Controller Area Network) in a car. At the moment, the contents of the CAN-bus are restricted (except when considering heavy traffic), and only the general level information is available for research purposes. As soon as access to the CAN-bus information of passenger cars (or even just some of it) is allowed, the M2M applications will become a very important part of the future work. Nevertheless, even in the current circumstances IoT and M2M scenarios are considered from this perspective.

Cloud computing (CC) refers to a shared pool of configurable computing resources (e.g. storage, networks and services) that can be rapidly provisioned and released with minimal management effort. In [43], the authors envision huge vehicular fleets with embedded computer systems on our roadways and in parking lots will be recognized as available computational resources, to be exploited in third party or community services. This kind of scenario is not applicable for this particular combined V2V and V2I networking architecture on a short-term basis. However, the sophisticated road weather forecasting based on vehicular measurement data processed immediately by the shared computing resources of the very same vehicles would be a huge innovation. Indeed, this aspect must be recognized as one possible target in the future work.

Content-centric networking (CCN) is an alternative approach to the architecture of computer networks. Its founding principle is that a communication network should allow a user to browse and locate the data needed by referring to the data itself, rather than having to reference a specific, physical location where that data is to be retrieved from. Device mobility management by employing CCN is one possible application, studied in X. In the WiSafeCar project, the employing of CCN in V2V networking was studied also by the Technical Research Centre of Finland, VTT. The publication related to this work is pending. From this perspective, CCN is also an interesting topic for future work.

Clearly there are many options to promote the development of V2V and V2I architecture in the future. It is clear that the combined RWS/RSU has an important role in the future work, as well as enhanced exploitation of vehicle-oriented data. In addition to these things, all the research trends listed above are interesting, but eventually the focus in the research projects in which FMI participates will eventually determine the major topics of the future work.

5. Overview of the papers

In this Chapter, the original papers are briefly overviewed. The categorized contents of each paper are presented in Table VIII.

5.1. [P1]

In Publication [P1], the wireless traffic service platform developed in the Carlink project is presented. The aim was to build a more comprehensive solution for V2I and V2V communication purposes. The objective was to tackle the communication environment between fast and independently moving vehicles. The critical service data needed to be delivered efficiently and quickly regardless of the location or presence of other vehicles. The special cases of the commercial platform deployment phase and operation in rural areas where there is no high density base station network in use were also considered in order to provide an (almost) equal level of services.

The V2I and V2V communication was based on Wi-Fi networking through an IEEE 802.11g access network. During the Carlink project, IEEE 802.11g was the most efficient Wi-Fi system commercially available. The IEEE 802.11 working group was already designing the specialized vehicular solution IEEE 802.11p, but no hardware was available yet. Also WiMAX communication was considered, but ultimately IEEE 802.11g was the chosen approach. The aim was to provide a solution with a decent level of operability with only minor installations (coarse base station network) and therefore the system could not rely only on short range Wi-Fi access. For this purpose, hybrid communication with a General Packet Radio Service (GPRS) was employed in parallel with wireless local area networking.

The platform itself was the key element, but the services created for the platform also had a crucial role. On one hand, they generated different ways of using and exploiting the platform, proving its efficiency. But on the other hand, the services are the platform's showcase toward consumers; in order to interest consumers in purchasing the platform, there had to be some key services interesting enough for consumers. Instead of an extensive package of services, there were just a couple of key services to prove the applicability, usefulness, and necessity of the platform. The incident and emergency warning service used vehicle data to generate warnings considering exceptional traffic conditions or accidents. The local road weather service collected observed weather data from vehicles and RSUs, and together with weather information from other sources it was used to generate comprehensive precise local road weather analysis and forecasts to be forwarded back to vehicles.

Table VIII: Categorized contents of the original papers

Publication	V2V	V2I	Hybrid IEEE 802.11g and GPRS	Hybrid IEEE 802.11p and 3G	Performance evaluation	
					Field measurements	Simulations
P1	x	x	x		x	x
P2	x	x	x		x	
P3		x		x		x
P4	x	x		x	x	
P5	x	x		x		

The Publication presents an overview of the approach, with an operational model of key services. The schematics of the underlying road weather model are also covered. The platform's operability has been analyzed in simulations with the NS-2 tool and parallel field measurements, which are briefly overviewed in the Publication. Finally, the Publications presents an estimation of the operational system effect on traffic fatalities in Finland, based on accident statistics.

5.2. [P2]

Publication [P2] focuses more on the Carlink system field measurements and pilot system. The field measurements were focusing on evaluation of the IEEE 802.11g based wireless access system in V2V and V2I communication. From this perspective, the technical requirements of the Carlink system were analyzed, and the technical details of available access systems studied in detail. Both IEEE 802.11p and WiMAX based on IEEE 802.16e lacked the availability of commercial systems, making IEEE 802.11g the most appropriate system for our platform and field tests.

The field tests consisted of V2V and V2I connectivity measurements at different driving speeds. In the first scenario, we emulated a typical Carlink platform operation of a vehicle passing by a base station and exchanging platform data. On the second scenario, we had two vehicles passing by each other with pre-defined speeds, one of the vehicles sending data in a pre-defined pattern, and the other one capturing the successfully received data. The aim was to deliver as much data as possible, but especially two packet sizes (in separate measurements) were used in order to find the optimal delivery type. A small 315 byte packet is the standard size of a weather station report, while the larger packets of 1202 bytes represented the maximal offered network load. The effect of the packet transmission interval to delivery rate was studied by using two clearly different delays between consecutive packets, The transmission intervals were not necessary the optimal ones, but rather pointed to the parameter space where the optimal values are likely to be found.

Neither the size of data packets nor the packet delay were affecting too much the connection availability. The same share of time during passing was available for actual communication, regardless of the packet size. Based on this result, it was obvious that the average throughput is better with larger data packets delivered with a short delay between them. Relatively good throughput capacity was achieved in both of the field measurement scenarios, although the deficiencies of the Wi-Fi system employed in vehicular environment were clearly evident.

The field tests were purely focusing on Wi-Fi communication, while in the pilot system also GPRS communication was employed. In the pilot system, we deployed the specific services into a simple pilot platform, consisting on a traffic service central with two RSUs and two operating vehicles. The main data channel was Wi-Fi, but due to the extremely low density of the base stations, the system was relying on GPRS data communication most of the time. For communication between vehicles, we used GPRS communication only, as we were concentrating on showing the pilot services' operability in general. The specific pilot services were tested one by one, and were found to be operating adequately. We defined the service operation as being "adequate" when a) the service response to "impulse" (e.g., vehicle throwing is noted when the driver turns wheel suddenly) is reliable (at least a 90% success rate can be expected) and b) service data (incident/accident warning, weather data) is delivered to all vehicles/devices in the network within 5 seconds. Wi-Fi communication clearly speeded up the data delivery to be a "nearly instant" response. In the end, the pilot system was proved to have satisfactory performance in this limited scale. The

Publication concluded that the approach presents a noteworthy candidate solution for a comprehensive vehicular communication entity, with clear potential of avoiding traffic accidents and saving lives.

5.3. [P3]

Publication [P3] presents the simulation work related to the WiSafeCar project. The field measurements and pilot tests in both the Carlink- and WiSafeCar project were conducted with a limited amount of vehicles, so it was necessary to prove the wide scale operability with larger-scale simulations. Unlike Publications [P1] and [P2], this and the subsequent Publications are based on an IEEE 802.11p access network.

The NS-2 tool with a SUMO traffic generator were chosen to be the base of the simulations, as it provided substantial support for the simulation of TCP, routing, and multicast protocols over wired and wireless networks, and as it was clearly the most common simulation platform used in related simulations. The SUMO tool provided a straightforward approach to generating a scenario for NS-2, based on real traffic material. The underlying real-life traffic scenario was taken from San Francisco, as there is public traffic data available, generated byTrafficPredict.com. The data was grabbed in a 30 second time loops posted out in 5 minute averages, and finally grabbed and plotted on the map.

For the simulation, a small area in the "tourist center" of San Francisco was chosen. The traffic model was generated for a "rush hour", Friday afternoon between 2pm and 3pm on November 20, 2009. Based on the traffic data, the simulation environment for the research area was constructed. 4 different scenarios were defined, with 4, 8, 12 and 16 Roadside units (RSU). In each scenario, there were 20 vehicles, all of them moving at a speed of 100 km/h. The RSU range was limited to 500 meters. In all communication, there was the same bidirectional traffic with TCP protocol, and the target data speed of 27Mbps, with the packet size of 1500 bits. During the simulation, all RSUs try to establish connection with vehicles coming within their range, and to send data packets to them. As soon as the vehicle is coming out of the RSU's range, the connection breaks.

In the simulation run, vehicles start movement and communication at different times (depending on their counterpart location in the underlying real-life scenario), making it hard to combine the vehicles. As a solution to this problem, each vehicle's data was adjusted to start from the moment its communication was initiated for the first time and in this way we brought every vehicle to the same "starting line".

The results of all the scenes were plotted into graphs and gathered together. From the results, it can be seen that the average throughput of vehicles clearly benefits from the increased amount of RSUs, and the best performance in this parameter is likely to be achieved with even more than 16 RSUs. However, the results show that our observation area is likely to be best supported with around 20 RSUs, with optimal geographic locations. The results with 16 RSUs show the average vehicle having a connection 49 % of the time with on average a 0.32 Mbps data speed, which is already at a level easily supporting services which are not time-critical. With time critical services, like accident warning, the performance was not at an appropriate level, and there must be some way of increasing performance or overcoming this problem. In the WiSafeCar project, the solution was supplementary data links with 3G to fill the connection gaps coming from IEEE 802.11p vehicular networking.

The Publication concludes that in the urban area simulations presented, it can be seen that in a study area of few square-kilometers, an appropriate level of performance for the less time-critical vehicle services is achieved. For time-critical services such as accident warnings, there must be some way to ensure instant data delivery in all conditions and places. The solution for this in the WiSafeCar project was hybrid communication with IEEE 802.11p and 3G.

5.4. [P4]

In the Publication [P4], an intelligent heterogeneous traffic safety network between cars and infrastructure is presented. This safety network generated in the WiSafeCar project is an evolution from the Carlink solution, based on IEEE 802.11p vehicular access network combined with 3G mobile communication. It offered the possibility to exploit vehicle based sensor and observation data in order to generate intelligent real-time services and a service platform for vehicles. The main goal was to improve traffic safety with accident and weather condition related accurate services, but also to offer a platform for a true bi-directional Internet-like networking experience tailored cost-effectively to vehicular environments. The Publication presents the field test results for IEEE 802.11p vehicular networking measurements.

The platform consisted of an IEEE 802.11p based network of vehicles, RSUs acting as system base stations, with the host systems as linking points connecting the WiSafeCar network wirelessly to Internet. The vehicles did not have continuous connectivity, but connected in an ad hoc manner with each other whenever possible, typically when two cars passed each other. Moreover, when a vehicle passed close to an RSU, it received up-to-date traffic platform service data from it, through the linking point located in the fixed network. The RSU acted as an interface between the fixed and wireless IEEE 802.11p networks. The vehicle could also transmit data to or receive from the linking point over the lower capacity 3G network, whenever the IEEE 802.11p based connection to an RSU was not available. The communication entity had four main characteristics; vehicle(s), the RSU, the linking point and a mobile user (not considered in detail in this Publication). The linking point was one entity above the platform, hosting the vehicles through the roadside unit network. Vehicles used IEEE 802.11p based networking to communicate with each other, but mainly for communicating with an RSU, whenever one was in the vicinity. The vehicle received up-to-date real-time service data, but in exchange it also delivered its own data gathered from the vehicle sensors and systems, to further update the services. The RSU delivered this data to the linking point through a fixed connection, together with its own advanced data set gathered from its own weather station and a variety of traffic sensors. As an alternative option for critical data delivery in a position outside the range of the IEEE 802.11p network, 3G was used, providing complete coverage in urban areas.

Based on the architecture defined in the project and the results of the field measurements, the set of pilot services was defined for the platform. Similarly to the Carlink services, these services were focusing on traffic accident and incident warnings, together with road weather related services. The services collected the indicative data, formulating the concluding condition from one or multiple sources. The internal data sources originated from WiSafeCar, coming typically from either a vehicle or an RSU. External data sources were independent of our system, yet, on the other hand, commonly used already in most cases. External data was provided through the linking point. By combining these different sources, the most effective reaction for different types of events and incidents was expected.

The vehicular networking field measurements with IEEE 802.11p compatible units focused on estimation of the capacity of the vehicular networks, with special scenarios of V2V and V2I communications, and preparing for the final pilot measurements. The test network consisted of the On Board Units (OBU) installed onto vehicles, communicating between each other and RSUs. Three different scenarios were investigated. In the V2I scenario, there was a vehicle carrying an OBU passing an RSU at pre-defined speeds. The RSU sent data to the vehicle, and successful data transmission was captured with special capture software for further analysis. In the V2V scenario, two vehicles (OBUs) were driving in opposite directions and encountered each other at pre-defined speeds, one of them transmitting data and the other receiving and capturing the successful data resection. Finally, in the V2V2V (Vehicle-to-Vehicle via Vehicle) scenario, or multi-hop scenario, three roughly equidistant vehicles (a sender, a transmitter in the middle and a receiver) were driving in the same direction at a constant speed, with equal distance between them (clearly less than communication range). The sender delivered data to receiver only through the transmitter in the middle.

In the V2I scenario results, as the vehicle speed increases, the connection time decreases, as expected. The vehicle speed change did not have a direct impact on the average throughput speed (altogether 1.5 Mbps). The calculated communication availability is the relation between the achieved result and the ideal case. In this scenario, the connection availability remained at around 41%, meaning that the true range is clearly smaller than the theoretical one. The calculated average range of all V2I measurements conducted was 420 meters.

Also in the measurements of the V2V scenario, as the vehicle speed increased, the connection time decreased. The average throughput (altogether 1.5 Mbps) in the V2V scenario also remained approximately the same during the connection, regardless of the vehicle speed. In this scenario the connection availability remained around 46 % in most of the cases, meaning that the true range is again far from the theoretical one. By calculating the average range of all V2V measurements conducted we end up at 475 meters.

In the V2V2V measurement scenario, the aim was to analyze communication quality during the communication session when using a relaying station, this being slightly different approach to the previous two cases. The communication sessions were sets of relatively short communication periods. The data bursts had a relatively similar pattern, the average data rate of all sessions together being 0.95 Mbps, varying between 0.455 Mbps and 1.184 Mbps. The average connection availability was 81 % and the decent average communication speed of 0.86 Mbps (the corresponding speed in single-hop communication in the same area was around 1.6 Mbps) allows data delivery also in a multi-hop manner. The price to be paid for a balanced operation and range seems to be the decreased peak performance, but the cost is clearly acceptable compared to the achievable advantages. The typical services in vehicular communication do not normally require high capacity, but rather rapid message delivery and connection availability, which is the case also with the WiSafeCar pilot services. The field measurements support proper operation of such services.

The separate pilot system was at a low-level of operation for several months, ending up with a one-day public pilot in Tampere, Finland. Five pilot vehicles were equipped with measurements for temperature, wipers on/off, emergency lights on/off, fog lights on/off, ABS (Anti-lock Braking System)/ESC (Electronic Stability Control), high beam on/off and 3D-accelerations, respectively. The online services of road weather warnings, accident and incident warnings, and approaching emergency vehicle warning were offered to four pilot vehicles and one RSU. The services were provided both in short range (IEEE 802.11p) and long range (3G) communication, in such manner that the short range IEEE 802.11p network was used whenever available, and at other times the system relied on the overlay 3G network. The services of the pilot system operated as expected. The service data was observed to reach vehicles instantly with IEEE 802.11p and within seconds when using 3G, when data is traveling through the network oriented service core. All in all, the pilot measurements were successful, showing the service sketch in real-life operation, with decent response times. It was concluded that there are no visible obstacles for large scale operational use of the system, and with that comes the improvement of traffic safety and convenience.

The Publication also contained the deployment estimation based on the results. In the range of 420 meters from an RSU, the system offers a data speed of up to 1.5 Mbps with V2I, with the same speed for V2V communication at a 475m range. As a combination of these, V2V2V multi-hop communication allows up to a 0.86 Mbps data speed in an 895m combined range from the RSU. The Publication concludes with the statement that the WiSafeCar solution has clear potential for a comprehensive heterogeneous vehicular communication entity, aiming at decreasing the amount of accidents and lives lost on the roads. Furthermore, the system deployment can be initiated in a cost-effective manner, relying purely on an existing 3G overlay network in the early deployment phase.

5.5. [P5]

Publication [P5] presents the final concept of heterogeneous traffic safety architecture between cars and infrastructure, developed in the CoMoSeF project. The special focus is on an approach to employing the CoMoSef vehicular networking entity to provide route weather information for vehicles passing a combined Road Weather Station (RWS)/Road Side Unit (RSU).

CoMoSeF creates co-operative communication system between vehicles (V2V), and vehicles and infrastructure (V2I), employing interactive example services related to safety and weather information exchange. The combined RWS/RSU presents two major objectives; the development of local road and route weather services based on local data, and the development of communication methodology for the delivery of both source data from users/RWS and service data for users, relying on standardized protocols. The combined RWS/RSU has an IEEE 802.11p primary communication access system, supplemented with parallel Wi-Fi communication and alternative 3G communication.

In the RWS/RSU scenario the focus is on V2I communication. The vehicle passing the combined RWS/RSU is supplemented wirelessly and automatically with up-to-date road weather related data and services, and at the same time possible vehicle-oriented measurement data is delivered upwards. IEEE 802.11p is the primary communication protocol, but also the traditional Wi-Fi communication is supported. The local server in the RWS/RSU hosts the station operations. It is linked with the NEC Linkbird-MX modem for attempting IEEE 802.11p communication, but it has also an internal Wi-Fi modem, and both of these communication channels actively seek the passing vehicle communication systems. The local server also gathers measurement data from two different measurement entities, the Vaisala Rosa road weather measurement system and the FMI weather station measurements. The data from these sources, together with possible vehicle-oriented data is sorted and further delivered to FMI local facilities through a 3G communication link. The advanced weather services are developed in FMI facilities and delivered back to the RWS/RSU, to be further delivered to vehicles. The messaging system and operational procedure is overviewed in the Publication. The same software entity maintains the data delivery between the RWS and vehicles, and the RWS and the FMI site, while gathering and updating the local weather data of the combined RWS/RSU.

6. Conclusions

This thesis work has studied the evolution of a platform for a vehicle-to-vehicle and vehicle-to-infrastructure access network, covering the development, implementation and evaluation of the system. The original concept of the wireless traffic service platform was based on traditional Wi-Fi communication between vehicles and an infrastructure, supplemented with GPRS communication as the backbone access method. Even if it adequately fulfilled its objectives of advanced traffic safety support, it contained clear deficiencies to be fixed in further work. The key objective in follow-up evolution work was to provide an intelligent hybrid wireless traffic safety network, relying now on a more advanced short-range access network combined with the higher-capacity overlay cellular network. A set of example services concentrated on accident warnings, somewhat milder incident warnings and road weather data, reflecting the general type of vehicular networking services, and employing the platform resources. The 802.11p communication system was first tested in an extensive set of different kinds of vehicular networking scenarios. The communication capacity and connectivity was tested in vehicle-to-infrastructure, vehicle-to-vehicle, as well as vehicle-to-vehicle-to-vehicle communication entities. The field tests with a limited amount of vehicles were extended into simulation scenarios with a larger platoon of vehicles. The resulting communication system was found to be appropriate for the preliminary example services, and finally the entire system, together with 3G backbone communication and embedded services was pilot tested in the demonstration system. This communication system is the main topic of the thesis.

Although the communication platform of this work has been completed, the communication system development is continuing. Therefore it is important also to present and envisage the further development of the communication platform. The focus is more and more on near-the-market services and multi-standard communication. Both of these goals are combined in the Finnish Meteorological Institute approach to employing a vehicular networking entity to provide route weather information for vehicles passing our combined RWS/RSU. Route weather is a special type of weather service tailored for dedicated road stretches, based on a road weather model and data collected from local RWSs and from the vehicles themselves.

Even if the platform for the vehicle-to-vehicle and vehicle-to-infrastructure access network of this work has been defined, there are some deficiencies that need to be considered in the future. The current system combines the IEEE 802.11p access network operation with 3G mobile communication, but only one of them is active. Basically, the 3G network is used whenever the IEEE 802.11p access network is not available. Obviously, there are minor gaps in operation whenever the change of communication methodology occurs. A specified handover between the communication protocol, or merely an overlapping operation of underlying systems would slightly improve the general performance. The most critical data intervention of an imminent accident warning proceeding from car to car with high priority IEEE 802.11p vehicular communication is ensured all the time, but there can be some special cases when overlapping IEEE 802.11p and 3G may turn out to be crucial. Another issue to be solved is the adaptation of solid security and authentication of platform users. The security issues are not considered in this work, but without fully trustworthy security and authentication, this platform cannot be fully integrated to vehicular computer systems, and can therefore act as additional advisory system in the vehicle, in a similar manner as external GPS devices. The appropriate security system, however, is not at all a trivial task. For example, the C2C communication consortium has been heavily involved with this issue for years, and the ultimate solution for the problem is still pending.

Nevertheless, the solution presented in this work has clear potential for a comprehensive vehicular communication entity, with firm promise of decreasing the amount of accidents and lives lost in traffic, as well as bringing vehicles to be part of the networked modern world. Time will only tell what parts of this approach, if not entire solution, will be found in future intelligent traffic systems.

In this work, the architecture for a V2V and V2I access network has been developed. The architecture has been implemented into demonstration platforms and finally evaluated. The original wireless traffic service architecture developed in this work presented an innovative solution for hybrid vehicular networking, based on wireless networking and mobile communication solutions available at that time. The developed access network protocol solution and mobile access system, with commercial equipment available, allowed the further development of the architecture. A set of example services concentrating on accident warnings and road weather data reflect the general type of vehicular networking services, and employ the platform. The resulting IEEE 802.11p communication architecture with 3G backbone communication and embedded services is the main innovation of this thesis, and the main contribution to vehicular networking. Even if the commercial deployment of the architecture presented in this work does not yet exist, the architecture introduces considerable estimation of hybrid communication architecture for the operative vehicular networking environment.

The future work aspects are considered more carefully in the Chapter 4.7. Combined Vehicle-to-Vehicle and Vehicle-to-Infrastructure networking, Visible light communications, Internet of Things, Machine-to-Machine communications, Cloud Networking and Content-Centric Networking allow many interesting topics for the future work. At the moment the work continues within the CoMoSeF project, and combined RWS/RSU concept development. In the near future, combined RWS/RSU further development and employing third party commercial fleets as vehicle-oriented observation data sources, and consumers are the major research objectives.

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