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Verification of wireless communication performance and robustness for automotive applications

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Till dem som finns med oss,
och dem som inte gör det.

Sammanfattning

Från och med april i år är det lag på att alla nya bilar som säljs inom Europa måste vara uppkopplade. Vad menar man då med att bilen måste vara uppkopplad? Det innebär att bilen ska ha samma funktioner som en mobiltelefon, dvs man kan ringa och skicka data med den. Men vadå lag, ska det vara lag på att kunna ringa, surfa, eller kolla på ett YouTube-klipp i bilen? Nej inte riktigt, lagen som gäller ifrån 1:a april 2018 är att om bilen krockar och om krockkraften är så stor att krockkuddarna aktiveras och blåses upp så skall bilen automatiskt ringa upp larmcentralen i det land bilen befinner sig i. Det kommer upprättas ett telefonsamtal mellan bilen och larmcentralen så att larmcentralen kan prata med föraren eller passagerare i bilen. Personen eller personerna i bilen är kanske så pass allvarligt skadade att de inte kan prata, därför skickar bilen alltid automatiskt GPS-koordinaterna till larmcentralen så de kan skicka en ambulans till olycksplatsen ifall det behövs.

I och med att alla nya bilar kommer ha en inbyggd mobiltelefon kan biltillverkarna utöka funktionaliteten i bilen så att passagerarna kan surfa, lyssna på musik via Spotify, streama YouTube-klipp mm. Biltillverkarna kan även förbättra kvalitén på bilen under dess livslängd genom att ladda ner ny mjukvara till bilen när den står parkerad över natten. Varför ska man då göra detta via bilens inbyggda mobiltelefon istället ifrån sin egen smarttelefon? Anledningen är att bilen nästan kan ses som en jättestor skärmburk för radiosignalerna som sänds ifrån mobilmasterna och som ska leta sig fram till din smartmobil inne i bilen. De allra flesta bilar idag har en antenn på taket som är kopplad till bilens inbyggda mobiltelefon vilket innebär att radiosignalen som går den vägen är ca 100 gånger starkare än den radiosignal som når din egen smartmobil.

Ett annat spännande område inom trådlös fordonskommunikation är bilar, lastbilar och motorcyklar som pratar med varandra. Syftet är att fordonen på vägen ska informera varandra om vilken typ av fordon de är och vilken riktning, position, hastighet etc. de har, flera gånger i sekunden. Händer något specifikt, ex. en bil gör en panikbromsning längre fram i trafikkön så skickar denna bil ut ett meddelande: nu panikbromsar jag. Därmed kan alla fordon i dess

närhet, ca 500 m bort, få denna information och på så sätt kan bakomvarande fordon sänka hastigheten eller bromsa så att fler olyckor undviks. I stadsmiljö innebär denna fordon-till-fordonskommunikation att man kan “se”runt hörn i en korsning. Skulle t.ex. två bilar komma körandes på korsande vägar i hög fart och kollisionsrisk föreligger, kan fordon-till-fordonskommunikationen informera dessa två bilar tidigt att kollisionsrisk föreligger och uppmana dem att sänka farten. För att detta system ska fungera bra så måste det finnas andra bilar att kommunicera med, därför kommer det ta många år innan detta är ett heltäckande system. Men någon ska börja, och därför har man på den japanska marknaden börjat använda detta sedan några år tillbaka, i USA så har Cadillac introducerat tekniken på sin bilmodell CTS för modellår 2017 och VW-gruppen har i år meddelat att flera volymmodeller inom VW-gruppen kommer ha fordon-till-fordonskommunikation som standard från 2019 i Europa. Även Toyota har annonserat att de kommer införa tekniken från 2021 i USA.

Hur skall man då testa all trådlös kommunikation som finns i dagens bilar, och som det kommer bli ännu mer av i framtiden (med t.ex. 5G), så att den fungerar som den skall? Svaret på den frågan idag är att mycket mätningar görs i fält, dvs. man kör runt med bilen i t.ex. Europa för att testa kommunikationen till mobiltelefonnätet. En sådan mätning testar verkligen hela systemet men är väldigt tidskrävande och därmed kostsam. Dessutom är mätningarna inte repeterbara eftersom radio- och trafikmiljö ändras från ett mättillfälle till ett annat.

Telekomindustrin och akademin är oerhört duktiga på radiokommunikation och har genom åren tagit fram ypperliga provmetoder för att testa prestandan och tillförlitligheten på t.ex. smarta telefoner utan att behöva gör detta i fält. Dessa prov utförs i labbmiljö, närmare bestämt i ett skärmrum som avskärmar alla radiosignaler som kommer utifrån. I detta slutna skärmrum emulerar (genererar) man sedan radiosignaler som t.ex. motsvarar det en smarttelefon upplever när den åker i en bil på en motorväg eller upplever när en person håller den i handen och promenera runt i staden. Med dessa provmetoder kan man utföra samma typ av mätningar om och om igen för att testa olika konstruktioner av telefonen, och repeterbarhet är uppnådd. Men hur ser de radiosignaler ut som man emulerar i detta skärmrum? Det är inte så lätt att svara på, för radiomiljön i vår omgivning är väldigt komplex. Mycket forskning har gjorts inom området av telekomindustrin och akademin där de genom mätningar i fält har tagit fram ganska enkla matematiska modeller som beskriver hur radiosignalen utbreder sig ifrån mobilmasten till mobiltelefonen. Radiosignaler utbreder sig ifrån sändarantennen i en viss riktning men all energi gå inte rakt fram till mobiltelefonen utan viss energi utbreder sig åt sidorna och även uppåt och nedåt. Sidosignalerna kommer också ibland fram till smarttelefonen efter har studsat på någon byggnad eller något fordon. Sidosignalerna har då lägre energi än den direkta signalen, är fördröjda något och har ev. en liten annan frekvens p.g.a. dopplereffekten (jmäför när du hör en polisbil som kör emot dig eller ifrån dig, tonen ändras på ljudet ifrån sirenen). Det är väldigt viktigt att tidigt i utvecklingsprocessen kunna testa prestandan på en mobiltelefon under realistisk radiomiljö så att man vet att den kommer uppfylla de krav som konsumenterna kräver.

Min forskning, som sammanfattas i denna avhandling, har fokuserat på två områden. I det första har vi skalat upp en av de provmetoder som mobil- och telekomindustrin har utvecklat för att testa smarttelefoner i skärmrum, vi har placerat en bil i ett väldigt stort skärmrum och har på så sett kunna genomföra samma mätningar som mobil- och telefonindustrin gör, fast på en inbyggd telefon i en bil. Såvitt vi vet, så är vi de första i världen som har genomfört denna typ av mätningar på en hel bil. I det andra området har vi tagit fram matematiska modeller för hur radiomiljön ser ut för fordon-till-fordonskommunikation på frekvensen 5,9 GHz. Detta är ett område som inte har forskats tillräckligt på och där vi nu har bidragit till ökad förståelse. Vårt bidrag har främst fokuserat på att ta fram bättre matematiska modeller för hur radiosignalens energi dämpas i förhållande till avståndet mellan sändande och mottagande bil i motorvägsmiljö och för korsningar i stadsmiljö. Dessutom har vi undersökt om det finns någon korrelation ("ett mått på hur lika signalerna är") mellan flera olika fordon-till-fordonskommunikationslänkar och även tagit fram en matematisk modell för denna korrelation. Vetskap om denna korrelation kan hjälpa fordon-till-fordonskommunikationssystemet att vidarebefordra ett meddelande från ett fordon till ett annat via ett tredje fordon ifall kommunikationen mellan de två första är blockerad av en stor lastbil.

Abstract

Today's test methods used for verifying the performance and robustness of automotive applications using wireless communication are often based on field trails, which are time consuming, costly, and not repeatable. Therefore, there is an urgent need for new verification methods that can be performed in lab environment, where the realistic radio propagation environment can be emulated. The telecom industry is using standardized over-the-air (OTA) test methods for verification of their products, e.g., smartphones. In these OTA test methods, different standardized channel models are emulated to reflect different user scenarios, e.g., walking in a city or driving on a highway.

One topic in this thesis has been to see if it possible to scale up the used OTA verification methods for smartphones, to a setup where the device under test (DUT) is a car. Detailed studies have been performed on the OTA mutliprobe setup inside an anechoic chamber, using a complete car as the DUT. The measurements were performed on a single-input single-output (SISO) system at 5.9 GHz, a frequency band used for vehicle-to-vehicle (V2V) communication. The conclusions we present are that the repeatability is under control for a SISO system and that the desired channel can be emulated. For multiple-input multiple-output (MIMO) systems further research is needed.

Emulation of a V2V channel in the OTA test setups requires deep knowledge of the characteristics of the V2V channel, e.g., it could be gathered through measurement based analysis. In the other research topic, measurement campaigns have been preformed using IEEE 802.11p transceivers (standard for V2V communication) installed in several vehicles, both cars and trucks, a unique campaign in that sense. For the communication links cross all vehicles, estimation of the joint shadowing effects have been possible to make. A cross-correlation model of the large scale fading process is presented for a V2V scenario on a highway. In addition, improved path loss models for both highway and urban scenarios is presented, which consider antenna pattern and other vehicles obstructing the communication.

Preface

This thesis is the culmination of my work as an industrial Ph.D. student from Volvo Cars with the academic partner Lund University, Department of Electrical and Information Technology. It is a challenge two have “two”jobs at the same time so the work has taken almost seven years (2011-2018). The ambition with this Ph.D. project has been to gain knowledge from the university and transfer this knowledge to Volvo Cars to improve our development process and strategies within wireless communication. The thesis comprises of two parts. The first part gives an overview of the research field in which I have been working during my Ph.D. studies and a brief summary of my contribution to it. The second part is composed of five included papers that constitute my main scientific work:

[1] M. G. Nilsson, D. Vlastaras, T. Abbas, B. Bergqvist, and F. Tufvesson, ”On Multilink Shadowing Effects in Measured V2V Channels on Highway,” in *Proc. of the 9:th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, Apr. 2015.

Personal Contributions: This paper results from the Vinnova FFI project Wireless communication in automotive environment (WCAE), a collaboration between Volvo Cars, AB Volvo, Actia, Kapsch TraffiCom AB, RISE, and Lund University. WCAE was a large project with several work packages and one of them had the focus on channel characterization at the 5.9 GHz frequency band. In this work package a measurement campaign was conducted where I took the lead of the planning and was a driver during the test drive. In addition, I supported Taimoor Abbas with the coordination of all cars during the campaign. The post processing was done by me, extracting the log files, synchronizing the log files and the videos in time, and the most time consuming, watching the videos and identifying the transitions between line-of-sight (LOS) and obstructed LOS (OLOS) communication. I also performed the analysis of the experimental results and wrote the main parts of the paper.

[2] M. G. Nilsson, C. Gustafson, T. Abbas, and F. Tufvesson, "A Measurement-Based Multilink Shadowing Model for V2V Network Simulations of Highway Scenarios," in *IEEE Transactions on Vehicular Technology*, vol. 66, no. 10, pp. 8632-8643, Oct. 2017.

Personal Contributions: This paper is a follow up to Paper I, where deep investigations on path loss models and their implications on auto- and cross-correlation of the shadowing processes were studied. In deep discussions with Fredrik Tufvesson and Carl Gustafson, further improvements of the existing two-ray model for LOS communication have been performed. The analysis of all communication links and development of the cross-correlation model were performed by myself whereas the model implications was done by Carl Gustafson. I was the main author of the paper.

[3] M. G. Nilsson, C. Gustafson, T. Abbas, and F. Tufvesson, "A Path Loss and Shadowing Model for Multilink Vehicle-to-Vehicle Channels in Urban Intersections", to be submitted to *Sensors*, special issue on *Advances on Vehicular Networks: From Sensing to Autonomous Driving*.

Personal Contributions: A second measurement campaign was performed in the WCAE project, this time with four cars and two trucks driving different scenarios for a week. I was the project leader for this campaign and together with Fredrik Tufvesson we defined the test setups and test scenarios. In total 10 companies and more than 25 persons were involved during the test drives. A similar analysis as in Paper II was performed by me, now also the packet success ratio was analyzed for 25 simultaneous communication links. Carl Gustafson and myself developed our proposed path loss model. I performed all the analysis and comparison with the existing Magel model for non-LOS (NLOS) communication, as well, writing the main parts of the paper.

[4] M. Nilsson, P. Hallbjörner, N. Arabäck, B. Bergqvist, and F. Tufvesson, "Multipath Propagation Simulator for V2X Communication Tests on Cars," in *Proc. of the 7:th European Conference on Antennas and Propagation (EuCAP)*, Göteborg, Sweden, pp. 1342-1346, Apr. 2013.

Personal Contributions: This paper is also performed within the WCAE project, but under the work package Multipath propagation simulator (MPS). A work package with focus on verification methods for complete vehicle level testing of wireless communication systems used in cars. I am the main contributor of this paper, and I took the lead writing the paper. The design and manufacturing of the MPS box were mainly performed by Paul Hallbjörner and Niklas Arabäck. I planned and performed the design of experiments (DOE), analyzed the measurement results and together with

Björn Bergqvist made conclusions of the importance for different design parameters of the test setup. Fredrik Tufvesson supported with valuable knowledge within vehicle-to-vehicle (V2V) channel characteristics as input to the verification method.

[5] M. G. Nilsson, P. Hallbjörner, N. Arabäck, B. Bergqvist, T. Abbas, and F. Tufvesson, "Measurement Uncertainty, Channel Simulation, and Disturbance Characterization of an Over-the-Air Multiprobe Setup for Cars at 5.9 GHz," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 12, pp. 7859-7869, Dec. 2015.

Personal Contributions: This paper is a follow up to Paper IV, where I planned and analyzed the results from the measurement system analysis (MSA) experiments. The execution of the MSAs were performed by myself and colleagues since several operators were needed for the experiments. The channel sounder measurements were done mainly by myself, Taimoor Abbas and Fredrik Tufvesson, the analysis of the results was done by myself. The last part, the probe coupling measurements were done together with Paul Hallbjörner and also here I did the analytic part. I was the main author of this paper.

During my Ph.D. studies, I have also contributed to the following publications and presented research outcomes as temporary documents (TDs) in the European Cooperation in Science and Technology (COST) actions IC1004 and CA15104. However, these publications are not included in the thesis:

[6] D. Vlastaras, T. Abbas, M. Nilsson, R. Whiton, M. Olbäck, and F. Tufvesson, "Impact of a Truck as an Obstacle on Vehicle-to-Vehicle Communications in Rural and Highway Scenarios," in *Proc. IEEE 6:th International Symposium on Wireless Vehicular Communications (WiVeC 2014)*, Vancouver, Canada, Sept. 2014.

[7] M. Nilsson, P. Hallbjörner, N. Arabäck, B. Bergqvist, T. Abbas, and F. Tufvesson, "Experiments and Analysis of Measurement Uncertainty of an Over-the-Air Multi-Probe Setup for Cars at 5.9 GHz," in *COST IC1004 Technical Meeting*, TD(14)10029, Aalborg, Denmark, May 2014.

[8] M. G. Nilsson, D. Vlastaras, T. Abbas, B. Bergqvist, and F. Tufvesson, "On Multilink Shadowing Effects in Measured V2V Channels on Highway," in *COST IC1004 Technical Meeting*, TD(15)12042, Dublin, Ireland, Jan. 2015.

[9] M. G. Nilsson, C. Gustafson, T. Abbas, and F. Tufvesson, "A Measurement Based Multilink Shadowing Model for V2V Network Simulations of Highway Scenarios," in *COST CA15104 Technical Meeting*, TD(16)01040, Lille, France, May 2016.

[10] M. G. Nilsson, C. Gustafson, T. Abbas, and F. Tufvesson, "On Multilink Shadowing Effects in Measured Urban V2V Channels," in *COST CA15104 Technical Meeting*, TD(18)06043, Nicosia, Cyprus, Jan. 2018.

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I'm also grateful to my co-supervisor Dr. Carl Gustafson at Lund University, my colleague Dr. Taimoor Abbas at Volvo Cars, and Dr. Katrin Sjöberg, a colleague in the automotive industry for their tremendous support. Carl, who has been my co-supervisor the second half, for his contribution to our papers, he never gives up and always would like to do that little extra. Taimoor, first as a colleague at Lund University and now a colleague at Volvo Cars, a more genuine person regarding helpfulness is difficult to find on this planet. He has always taken the time to explain things I did not understand. Katrin, so many long discussions we have had over phone about everything, it has been so fun. Together we were the two main authors of the Vinnova-project application that has funded my studies and it has been an honor to work with her.

I would like to thank my managers during the years at Volvo Cars, Susanne Rydén, Carolina Peters, Sofia Sköld, Karin Nordin, and Magnus Eek for their encouragement and willingness to let me try new things outside my comfort zone. I also want to thank all colleagues at the department of Electrical and Information Technology at Lund University for an interesting time together. In addition, I would like to thank all colleagues working with wireless communication within the automotive industry in Sweden and abroad that I have meet and worked with during these years as a student, let us continue with the great atmosphere we have. In Volvo Cars I have so many nice colleagues that it will fill many pages, so to you all, I'm glad working with you all. You are so professional.

My endless gratefulness goes to my family, for loving me and supporting me, whatever I do - my father Sven-Göran, my mother in heaven Kerstin, my sister Marina and her husband David, my brother in law Sten, and my cousin Jimmie, who always have been and will be a brother to me. To my friends, you know who you are.

Finally, I'm eternally grateful to my beloved wife Mariana for her tremendous support during all these years and being the mother to our two boys Melker and Malte. Without you, I would never being sitting here right now, writing this text.

Mikael Nilsson

List of Acronyms and Abbreviations

2G second generation of mobile telecommunications technology

3G third generation of mobile telecommunications technology

3GPP Third generation partnership project

4G fourth generation of mobile telecommunications technology

5G fifth generation of mobile telecommunications technology

AM amplitude modulation

AOA angle-of-arrival

AOD angle-of-departure

BLE Bluetooth low energy

BT Bluetooth

C2C-CC Car-to-car communication consortium

CDF cumulative distribution function

COST cooperation in science and technology

CSMA/CA carrier sense multiple access collision avoidance

CTIA Cellular telecommunications & internet association

C-V2X cellular-vehicle-to-everything

CW continuous wave

DAB digital audio broadcasting

DOE design of experiments

DSD Doppler spectral density

DSRC dedicated short range communication

DUT device under test

ECU electronic control unit

EMC electromagnetic compatibility

ETSI European telecommunication standards institute

FDTD finite-difference time-domain

FEM finite element method

FM frequency modulation

GLONASS global navigation satellite system

GLOSA green light optimal speed advisory

GNSS global navigation satellite system

GPS global positioning system

GSCM geometry based stochastic channel model

HIL hardware-in-the-loop

HSPA high-speed packet access

I2V infrastructure-to-vehicle

IEEE Institute of electrical and electronics engineers

IMA intersection movement assist

ISM industrial, scientific and medical

ITS intelligent transport system

LOS line-of-sight

LTA left turn assist

LTE long-term evolution

LTE D2D long-term evolution device-to-device

MAC medium access control

ML maximum likelihood

MIMO multiple-input multiple-output

MPC multi path components

MPS multipath propagation simulator

MSA measurement system analysis

NHTSA National highway traffic safety administration

NFC near field communication

NLOS non line-of-sight

OLOS obstructed line-of-sight

OLS ordinary least square

OTA over-the-air

P2N pedestrian-to-network

PDF probability distribution function

PDP power delay profile

PKI public key infrastructure

RKE remote keyless entry

RX receiver

SDARS satellite digital audio radio service

SISO single-input single-output

SNR signal-to-noise ratio

TD temporary document

TIS total isotropic sensitivity

TRP total radiated power

TRS total radiated sensitivity

TPMS tire pressure monitoring system

TV television

TX transmitter

UMTS universal mobile telecommunications system

V2I vehicle-to-infrastructure

V2N vehicle-to-network

V2P vehicle-to-pedestrian

V2V vehicle-to-vehicle

V2X vehicle-to-everything

VANET vehicle ad-hoc network

WCAE Wireless communication in automotive environment

WLAN wireless local area network

WMAN wireless metropolitan area network

WPAN wireless personal area network

WSSUS wide-sense-stationary uncorrelated-scattering

WWAN wireless wide area network

Contents

Part I

Overview of the Research Field

Chapter 1

Introduction

This chapter provides the background of different broadcasting and wireless communication technologies used in today's cars. In addition, it presents the verification and validation methods of the mentioned technologies used today in the automotive industry.

1.1 Infotainment

The mass introduction of wireless technology in cars took place during the 1930s; Galvin Manufacturing Corporation had a commercial success with their car radio in the U.S., the Motorola model 5T71 [1]. Every since, AM radio is used in the cars, even tough FM radio is the more common analog broadcasting technique today. The radio broadcasting has also taken the step into the digital world; 1995 the first broadcasting station using digital audio broadcasting (DAB) was launched in Norway [2], and 2001 the satellite digital audio radio service (SDARS) was launched in the U.S. [3]. Still, the analog FM is the dominating radio broadcasting technique world wide. It is not just radio that entertains drivers and passengers of today's cars but also television (TV). The TV is quite a rare feature of the modern car, since the driver is only allowed to watch TV when the car is standing still. Even tough, for luxury cars there are normally TV screens in the back seats, but these cars are less common.

The wireless technology not only entertains the drivers and passengers but also informs the driver about different things and lets the driver communicate with other people. As an information application, the global navigation satellite system (GNSS) is a good example, which informs the driver about the position the car has on the map. The dominating GNSS technology today is the global positioning system (GPS) developed by the U.S. department of defense but other systems have also been launched, e.g., global navigation satellite system (GLONASS) (Russia) and BeiDuo (China). The European union had in 2016 initial service of their system Galileo [4] and will reach final completion in 2020.

To let the driver communicate with other people using the smartphone directly is not safe and, due to that, not allowed in many countries within EU. Therefore many modern cars have a so called "handsfree" system, which enables drivers to control their smartphone via buttons on the steering wheel or dashboard, while making the phone call. The wirless connection between the car and the smartphone is normally Bluetooth (BT), both for the control of the smartphone as well for the voice. Since the reception of a signal from the base station is attenuated when having a smartphone inside a car compared to the outside, modern premium cars have inbuilt cellular modems using 2G, 3G, and 4G to improve performance and coverage of the cellular network. When having the cellular modem in the car, many premium car manufacturers have added a Wi-Fi hotspot to the car as well, giving the driver and passengers the same features as they have at home or at work. Wi-Fi is a trademark of the Wi-Fi Alliance and is a local area wireless computer networking (WLAN) technology using the standards IEEE 802.11a/b/g/n/ac. The entertainment applications radio and TV together with the information and communication applications such as GPS and 4G, is called *Infotainment* applications.

Wireless technology can also control today's cars, one example is the remote keyless entry (RKE) system which enables the driver to, e.g., lock and unlock the car remotely by using the key fob. There exists no standard for the RKE systems and therefore basically every car manufacturer is using their own propriety communication protocol at one of the industrial, scientific and medical (ISM) radio bands, 434 MHz is, e.g., a popular frequency band for RKE systems. Normally the RKE systems do not belong to the infotainment area, but since some car manufactures are looking into using a smartphone as a key, using near field communication (NFC) or Bluetooth Smart, also known as BT Low Energy (BLE), it can to some extent be seen as a part of the infotainment system.

1.2 Active Safety

Every year 1.25 million people are killed in road traffic accidents [5]. It is the leading cause of death globally, and the main cause of death among those aged 15 to 29 years. The number of killed people per year has plateaued since 2007. The sustainable development goals given by United Nation include a target of 50 % reduction in road traffic deaths and injuries by 2020. To achieve this, many actions need to be taken: 1) Changing road user behavior. 2) Enforcement of road safety laws. 3) Increase the attention to the vulnerable road users and make roads safer for this group. 4) Making cars safer. To make cars safer means different things in different countries. In low- and mid-income countries it is about making sure that the cars fulfill even the most basic international standards on vehicle safety e.g., to make sure that seat belts are mounted and used. In the high-income countries it is about improving the active safety features on the cars or to make it mandatory, electronic stability control is, e.g., highly effective and should be mandatory in all vehicles [5].

To further increase passenger safety of cars, messages between cars can be exchanged wirelessly to inform each other about potential hazards, e.g., if one car is making an emergency brake, it is important that the cars behind, which have no visual line-of-sight (LOS) to the emergency braking car, also get the information with low latency. Messages like this, are standardized within ETSI [6] for the EU market and within SAE [7] for the U.S. market. This wireless technology is called vehicle-to-vehicle (V2V) communication and both EU and the U.S. markets are using the IEEE 802.11p standard [8] for the lower part of the communication stack. In Japan they are using a standard from ARIB, which is similar to 802.11p. The standard [8] describes an ad-hoc network architecture and is using the dedicated 5.9 GHz frequency band both in EU and in the U.S. Unfortunately the upper part of the communication stack is different, EU uses ITS-G5 [9] and the U.S. uses WAVE [10]. In parallel, there are on-going activities within 3:rd generation partnership project (3GPP) to standardize long term evolution device-to-device (LTE D2D) communication as well for V2V applications [11], called cellular-vehicle-to-everything (C-V2X). In the future this will be a part of the 5G standard. Regardless which wireless communication standard that will be used in the future, the wireless technology will be an enabler to increase road safety and contribute to the *Active safety* applications in the cars.

In addition to the V2V systems above, wireless technology will be mandatory in post-crash scenarios from April 2018 in EU [12]. By then, eCall will be a legal requirement on all new cars sold within EU. In the event of a serious accident, eCall automatically dials 112 - Europe's single emergency number, using the cellular network. Even if no passenger is able to speak, e.g., due to injuries, a minimum set of data is sent, which includes the exact location of the crash site. This active safety application is expected to save hundreds of lives in the EU every year [12].

1.3 After Market

Smartphones have had the possibility to update the firmware wirelessly, or as it is called in the industry "over-the-air"(OTA), since they entered the market. For cars the Tesla Model S, which was launched in 2012, has also had the possibility to update the firmware via OTA [13]. Today's cars, with their complex electrical architecture can each have up to 100 or more electronic control units (ECUs) installed. The possibility to update these ECUs with new firmware via OTA will save a lot of money for the automotive manufacturers and time for the owner of the car, since the car does not need to visit the workshop for firmware updates. Another possibility with OTA is remote diagnostics and remote data collection, which means that the manufacturers with permission from the car owner, can remotely investigate errors reported by the car itself and collect data to improve functionality for future firmware versions. The OTA possibilities will reduce the maintenance cost of the vehicles, which is beneficial for the *Aftermarket* application area.

1.4 Environmental Care

With transport contributing to 23 % of global CO_2 emissions [14], the sector holds the key to reducing the emissions. One way to reduce the emissions is to do like the U.S., making tire pressure monitoring system mandatory (TPMS) on light duty vehicles. Low tire pressure increases the rolling resistance, resulting in increased fuel consumption and more CO_2 emissions to move the vehicle. In a report from the U.S. department of transportation, national highway traffic safety administration, during 2011 TPMS is estimated to have saved $511 million across the vehicle fleet in USA through reduced fuel consumption [15]. TPMS can be implemented in two ways, indirect TPMS and direct TPMS. Indirect TPMS uses the anti-lock braking system sensors to estimate the tire pressure by monitoring the wheel rotational speed and by performing a spectrum analysis of the anti-lock braking signal. Direct TPMS employ pressure sensors on each tire, reporting the pressure wirelessly to a receiver on the car. TPMS uses the ISM-bands, also for this application 434 MHz is a popular frequency band since then the same receiver on the car can be used for both RKE and direct TPMS.

Another way to reduce the CO_2 emissions is to implement intelligent transport systems (ITS), by applying information and communication technologies to vehicles and transport systems as stated in the report from ERTICO [16]. Implementing the function, green light optimal speed advisory (GLOSA), in traffic lights by using infrastructure-to-vehicle (I2V) communication in urban

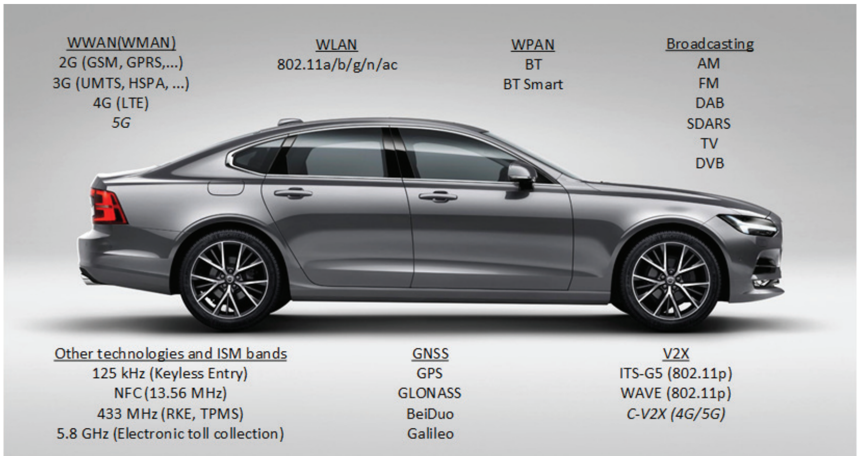


Figure 1.1: Examples of wireless technologies used in a modern premium car today and on-going standardization activities (italic font), grouped into the areas: Wireless wide area network (WWAN)/Wireless metropolitan area network (WMAN), Wireless local area network (WLAN), Wireless personal area network (WPAN), Broadcasting, Other technologies and ISM bands, Global Navigation Satellite System (GNSS) and, Vehicle-to-everything (V2X).

surroundings, has the potential to reduce the CO_2 emissions with more than 10 % [16]. The I2V communication can either be based on the wireless technology IEEE 802.11p or 3G/4G. Both the TPMS and GLOSA functions are good examples that belongs to the *Environmental Care* application area.

The wireless technologies used in a modern car within the areas of *Infotainment, Active Safety, Aftermarket, and Environmental Care* as well other systems are shown in Fig. 1.1.

1.5 Verification and Validation

Testing wireless technology for different applications with regards to functional[1] and non-functional[2] requirements is done in different ways. Functional require-

[1] A functional requirement define the specific behavior of a function.
[2] A non-functional requirement define the specific quality of a function.

ments are first modeled and simulated to test the behavior of the functions and second when physical parts are available the behavior of the electrical system is tested in a hardware-in-the-loop (HIL) platform.

A traditional system design of a wireless communication system in cars contains three main parts, the transceiver, the antenna, and the coaxial cable between these two parts. The non-functional requirements of the transceiver are tested on a test bench and typical parameters that are measured are, e.g., packet rate vs. received signal power and transmitted output power. For the antenna gain, an advanced measurement setup needs to be used to be able to measure the antenna gain when the antenna is mounted on the car [17]. The mentioned verification[3] methods measure the performance under ideal propagation conditions i.e., no reflections from, e.g., buildings are present and fed into the transceiver and the antenna gain measurement is only a passive measurement (only a continuous wave (CW) signal is used). To measure the influence of the radio propagation on the wireless communication system today, testing is performed by field trails, which is rather validation[4] because the system is tested under normal customer circumstances. Using validation and trying to measure the parameters required by the verification test plan is very time consuming and costly, nor repeatable due to the fact that the environment cannot be controlled. Therefore with this background, new verification methods are needed in the automotive industry.

1.6 Problem Description and Thesis Structure

This thesis focuses on two research topics within verification of wireless communication performance and robustness for automotive applications. In the first part, the V2V communication channel at 5.9 GHz is measured and characterized, with the aim of addressing the following two research topics:

- Path loss models, that are essential for predicting the V2V communication range between different vehicles. Even though research has been performed to model the path loss, still there are gaps where further research is needed for highway and urban scenarios, and especially for multilink scenarios.

[3] "Verification: The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with *validation*." [18]

[4] "Validation: The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers. Contrast with *verification*." [18]

- Further developments are needed to be able to fully understand the joint multilink shadowing process in vehicular ad-hoc networks (VANETs). Models for the joint path loss and correlated large scale fading process between different V2X links need to be developed. This allows for an improved design of VANETs in general, and for relaying and multi-hop techniques in particular.

The second part investigates whether the OTA verification methods used by the telecom industry are also applicable in the automotive industry.

- Standardized OTA verification methods of smartphones exist, where the phone is placed inside a small anechoic chamber. Is it possible to replace the smartphone as the device under test (DUT) with a car, simply by scaling up the anechoic chamber?

- Are there other alternative verification methods?

- Is it possible to achieve the desired repeatability, measurement time and cost of these measurements? To what extent can V2V OTA measurements replace time consuming and costly field trials?

The remaining chapters of part I are written with these research topics in mind. In chapter 2, we first give an overview of the vehicular channel, including some fundamentals on V2V channel measurements, modeling and characterization. Chapter 3 provides a description of different verification methods developed by the telecom and the automotive industry. Chapter 4 presents an overview of the V2V communication. Finally, chapter 5 summarizes the contributions of my work and future research topics are suggested.

Chapter 2

The Vehicular Channel

Many of the wireless communication technologies mentioned in chapter 1 are part of the acronym V2X, which is a collection of vehicle-to-network (V2N), vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) communications. Since more than a decade, the standardization organization IEEE has been working on, and standardized, the 802.11p system for V2V and V2I communication. Also in the telecom industry, there is an increased interest in V2X communication. One of the so called vertical sectors in 5G, is the automotive sector [19]. In Fig. 2.1, definitions of the different communication links used in this thesis are shown.

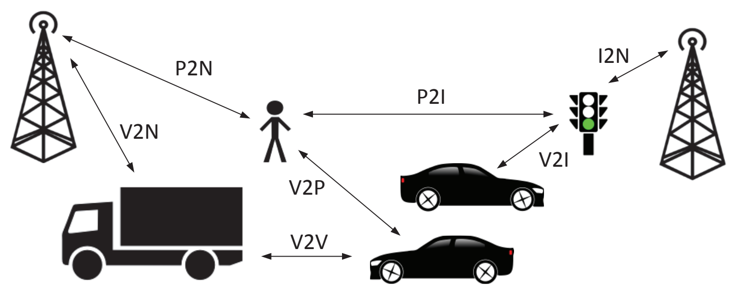


Figure 2.1: The different communication links in a vehicular context.

The propagation mechanisms, transmission, reflection, diffraction, scattering, and wave-guiding, is similar for V2X communication as for other wireless communication system using the air as the transmission media between a transmitter (TX) and a receiver (RX). However, the impact of the different mechanisms are quite different within V2X, e.g., in V2V there are typically strong reflections around both the TX and the RX since they both are close to ground, compared to V2N where there are usually very few significant interactions close to the elevated base station. The propagation of the electromagnetic field between the TX and the RX is usually referred to as the propagation channel and when including the TX and the RX antenna properties we refer to this as the radio channel. Knowledge of the channel is very important in many aspects, examples in different industries include: mobile operators need the information to make proper and efficient cell planning, manufacturers of smartphones need the information in the design phase, and the automotive sector would like to predict the communication range between two vehicles. In addition, all of three industries would like to emulate the channel during the verification of the different products, see chapter 3 for details. This chapter gives an introduction and the purpose of channel measurements, modeling, and its characteristics, with the focus on V2X communication and our contributions in these areas, see Fig. 2.2 for an overview.

2.1 Channel Measurements

The wireless channel can be characterized and modeled based on channel measurements. Several measurement campaigns have been performed within telecom industry and academia in the past. The focus has mainly been on the conventional communication between, e.g., a pedestrian and the base station (P2N) or between a vehicle and a base station (V2N). Recently, there has been an increased interest in V2V communication and thus several measurement campaigns have been performed, see, e.g., [20, 21] and the references therein.

By using a so called channel sounder during a measurement, large amounts of channel data can be recorded. By analyzing and post processing the data, it is possible to characterize and model many different channel properties, see Fig. 2.2 for some examples. A wide variety of channel sounders exist, some can only measure SISO channels and others can measure MIMO channels. The sounders are very sophisticated instruments which either can perform the measurements in the time domain or in the frequency domain and the recorded data can either be the channel impulse response $h(\tau, t)$ or the channel transfer function $H(f, t)$. When sounding the V2V channel, a common setup is to use a channel sounder and measure the channel transfer function, as with the case of the RUSK-LUND channel sounder [22]. Channel sounders are typically quite costly, and usually only one TX and one RX exist in the setup. Therefore, only measurements between two vehicles are normally performed.

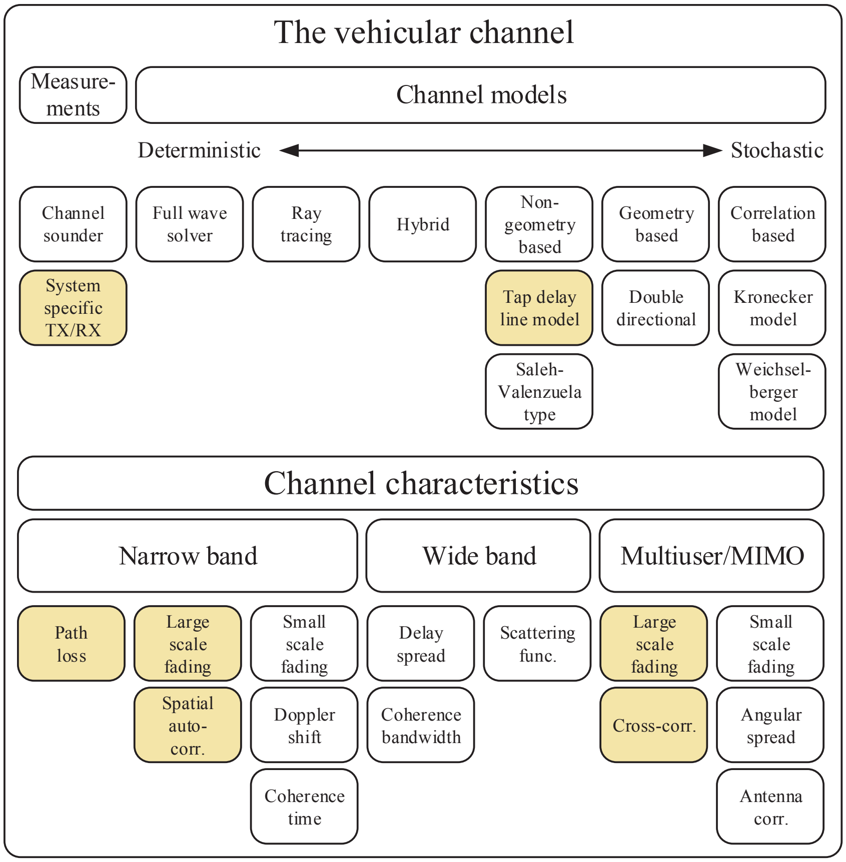


Figure 2.2: An overview of channel measurements, channel models, and its characteristics. The boxes marked in beige color is the focus of this thesis.

Using system specific transceivers intended for the communication system in the measurement campaigns, makes it possible to extract some of the channel parameters in Fig. 2.2, but not so many compared to the case when using a channel sounder. The reason is that the system specific transceivers often have limited capabilities in terms of measuring or storing data: 1) wide bandwidths, 2) MIMO channels, and 3) the phase of the received signal. This means that, for instance, the delay and angular spread cannot be derived. In addition, the sampling rate could also be an issue, with too low sampling rate it is not possible to characterize the Doppler spread or the autocorrelation. However, the advantages of system specific transceivers are the low costs and the scalability, and therefore several transceivers can be used during a measurement campaign. This makes it possible to characterize simultaneous channel properties, e.g., joint multilink shadowing effects. It has been shown in P2N scenarios [23, 24] that there is a cross-correlation of the large scale parameters and that this cross-correlation can have a significant effect on the system performance [25, 26].

In peer-to-peer systems, like LTE device-to-device (LTE D2D) or in VANETs, the correlation of the channel between different devices are of interest. The importance of the shadowing correlation between communication links in mesh networks is shown in [27] and an extensive feasibility study regarding correlation models of shadowing are summarized in [28]. In ITS-G5, there is a multi-hop feature, i.e., a message can be transmitted from one unit to another via a third unit, in this case the cross-correlation of the different channels is one important characteristic parameter. To our knowledge, no measurement based analysis has been performed to characterize and model the joint multilink shadowing effects in VANETs, this is one topic presented in Paper I to III. There are parameters in Fig. 2.2 that we have not focused on due to the limitations of our system specific transceivers that have been used. However, several studies are found in the literature that have already characterized these, hence we have quite a good knowledge about them already.

2.2 Channel Modeling

Measurement campaigns are time consuming and expensive. To increase the knowledge of the channel, it is also possible to perform numerical calculations of the field propagation. For instance, full wave numerical solvers can be used to solve Maxwell's equations for a particular scenario, and the results can be used to model the channel. Such full wave solvers can be based on for instance the finite-element-method (FEM) [29] or finite-difference time-domain (FDTD) techniques [30]. These techniques need detailed information about the propagation environment, including the location of the TX and RX, and the locations, shapes and permittivities of the different scattering objects in the environment. The outcome of a full wave simulation is a detailed description of the channel but only for that specific case. Two other deterministic modeling methods, which are relatively less complicated than the full wave numerical solvers, are the ray-tracing and ray-launching methods [31]. These also require a detailed description of the surrounding, and exploits geometry such as 3D map and exact locations of the TX and the RX. Anyhow, the complexity of the simulations is high and the simulations take time, making extensive simulations of real world scenarios difficult to perform.

A goal when deriving channel models is to summarize large amount of measured data into mathematical or statistical expressions. The models shall be rather simple, i.e., easy to use and to implement in different simulation software or in lab instruments, such as fading emulators. The channel modeling process is a balance between simplicity and accuracy, an accurate model which is too complex will seldom be used. Opposite to deterministic models are the stochastic models. They are rather simple and they describe the properties of the channel statistically, e.g., path loss, the delay distribution of the different multi path components (MPCs), the correlation properties, instead of modeling a specific case. The stochastic models can be classified into three sub-classes: correlation based models, non-geometry based models, and geometry based models [32].

For MIMO systems, correlation based models are popular because of their simplicity. In the correlative models the wireless channels are often represented by a Gaussian distribution with specific correlation properties at the TX and the RX. The narrowband Kronecker model [33] is a simple and a popular correlation based model, assuming that there is no coupling between the scatterers at the TX and the RX. A more sophisticated model is the Weichselberger model [34], which does consider the coupling of the scatterers at the TX and the RX, and by that, it gives a more accurate description of the properties in the spatial domain.

The most commonly used non-geometry based and wide band model is the tapped delay line model, where the impulse response of the channel is modeled with components at certain delays (taps). It is written as [31],

$$h(t,\tau) = \sum_{i=1}^{N} a_i(t)\delta(\tau - \tau_i), \tag{2.1}$$

where $a_i(t)$ is the time-varying complex amplitude of the i:th tap arriving at the delay τ_i. With only non-LOS (NLOS) components, the distribution of the amplitudes is often described by a Rayleigh distribution, and with a strong LOS component the amplitudes of the received signal is often described by a Ricean distribution, see 2.3.5 for details. The average power of the taps is typically assumed to decay exponentially in delay and each tap may feature an individual Doppler spectrum, as proposed [35] for 802.11p. For a vehicular channel, the tapped delay line model may not be suitable due to the non-stationary nature of the wireless vehicular channel [36], see 2.3.7, although workarounds have been suggested by [37]. However, also for V2X communication the tapped delay line model is a common model used in verification setups to test the performance of the DUT, see chapter 3. To further increase the accuracy of the tapped delay line model, Saleh and Valenzuela proposed a cluster based model [38], where a cluster is composed of a group of MPCs with similar delay characteristics. Each tap or cluster is modeled by an exponential decaying profile, with its own arrival time and decay factor.

In geometry-based stochastic channel models (GSCMs) the position and properties of the scatterers or clusters are stochastically distributed around the TX and the RX and then a simplified ray-tracing of the MPCs between the two nodes is performed. There are well-established GSCMs such as COST 273 [39], COST 2100 [40], etc., with reasonable complexity, high accuracy, and spatial consistency. Another advantage for GSCMs, is that they are well suited for vehicular channels, since the movements of the TX, the RX, and the scatterers can be described by a GSCM model as shown in [36].

The last channel model from Fig. 2.2 that is not mentioned yet is the hybrid channel, which are based on both deterministic and stochastic parts. For example, a GSCM might employ ray-tracing to determine the delay and angular properties.

2.3 Channel Characteristics

From measurements or deterministic channel models, a number of different channel characteristics can be extracted in order to describe certain aspects of the channel in a simplified way, using a metric or model parameter. Channel characteristics that are often used have been summarized in 2.2, and the highlighted boxes indicate the areas which have been the focus for the research performed in this thesis.

2.3.1 Path loss

In free space, an isotropic antenna radiates the electromagnetic energy equally in all directions. A receiving antenna will absorb energy according to its effective area, which is $A_{eff} = \lambda^2/4\pi$ for an isotropic antenna. Since the effective area is proportional to λ, the effective area decreases with increased frequency. To define the free space path loss one can consider the area of a sphere $A_s = 4\pi d^2$, where d is the distance between the TX and the RX (the radius of the sphere). The received power at a distance d is the ratio A_{eff}/A_s, i.e., the attenuation between two isotropic antennas in free space, also known

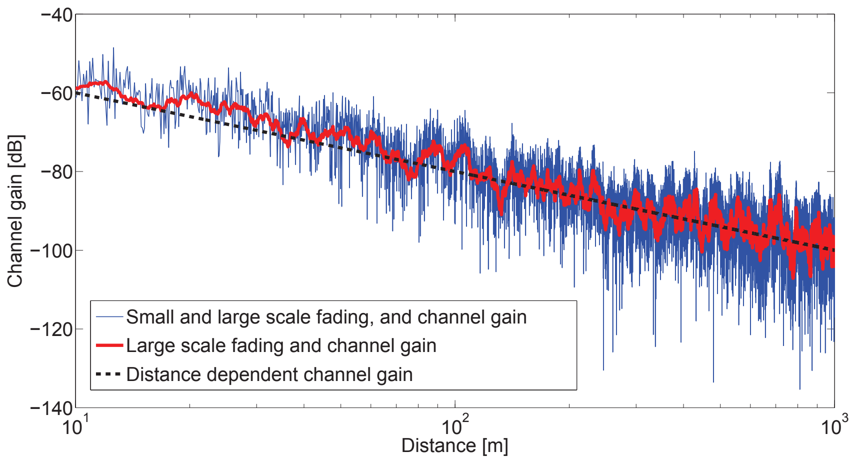


Figure 2.3: Propagation effects, distance dependent channel gain (inverse of pathloss), large scale fading, and small scale fading.

as the free space loss, is

$$PL_{free}(d) = \left(\frac{4\pi d}{\lambda}\right)^2. \quad (2.2)$$

As a comparison, a GSM system at 900 MHz has a free space path loss of 91.5 dB at 1000 m, a 802.11p system at 5.9 GHz has free space path loss of 107.9 dB at the same distance. This gives a difference of 16.4 dB, which is not negligible when designing transceivers and antennas mounted on the vehicles for the 802.11p system.

A classical model used when estimating the path loss from measured or simulated data from a specific environment, is the log-distance power law model with a single slope. In units of dB, the single slope model can be written as

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) \quad d \geq d_0, \quad (2.3)$$

where d is the distance, n is the pathloss exponent, and $PL(d_0)$ is the pathloss at a reference distance d_0. In Fig. 2.3 an example of the single slope model is shown, black dotted line.

In V2V communication an important path loss model is the two-ray model, see Fig. 4. In this case, the complex amplitudes of the two rays sum up either

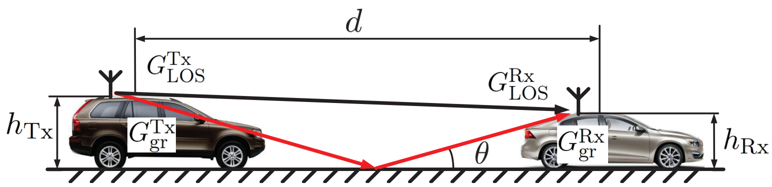


Figure 2.4: The two-ray model.

constructively, destructively, or something in between, depending on the phases of the two rays at the receiver, as shown in Fig. 2.5. As seen from the figure, there are distances that have deep dips in the channel gain at distances that very often occur in V2V communication. The path loss for the two-ray model, aka the ground model, is presented in Paper II, which is based on [41]. An approximation of the two-ray model is defined as [41],

$$PL_{two-ray}(d) \approx \left(\frac{4\pi d}{\lambda}\right)^2 \left(\frac{\lambda d}{4\pi h_{TX} h_{RX}}\right)^2 = \frac{d^4}{h_{TX}^2 h_{RX}^2}, \tag{2.4}$$

where an approximation of the phase difference is applied. However, the approximation is not that feasible for V2V communication, since (2.4) is only valid beyond $d_{break} \geq 4h_{TX}h_{RX}/\lambda$, quite a large distance between two vehicles driving on a road. In addition, after the break point the channel gain reduces with the factor d^{-4}, which actually is good since the congestion of messages in the air will then be less. In paper II we provide further analysis of the two-ray model to account for the permittivity of the road as well as for differences between different car bodies and antenna patterns.

2.3.2 Large Scale Fading

Large scale shadow fading typical causes "slow"changes of the received signal over many wave lengths due to movements of either the TX, the RX, the scatter points in between or that the signal path is blocked by an object. The received power is described in dB as,

$$P_{RX|dBm} = P_{TX|dBm} + G_{TX|dBi} + G_{RX|dBi} - PL_{|dB} + \Psi_{\sigma|dB} + \nu_{|dB}, \tag{2.5}$$

where, $P_{TX|dBm}$ is the transmitted power, $G_{XX|dBi}$ is the antenna gain at the two sides, $PL_{|dB}$ the distance dependent path loss, $\Psi_{\sigma|dB}$ is the large scale fading effects, and $\nu_{|dB}$ is the small scale fading effects, see 2.3.5. The large scale fading effects are commonly modeled using a log-normal Gaussian distribution

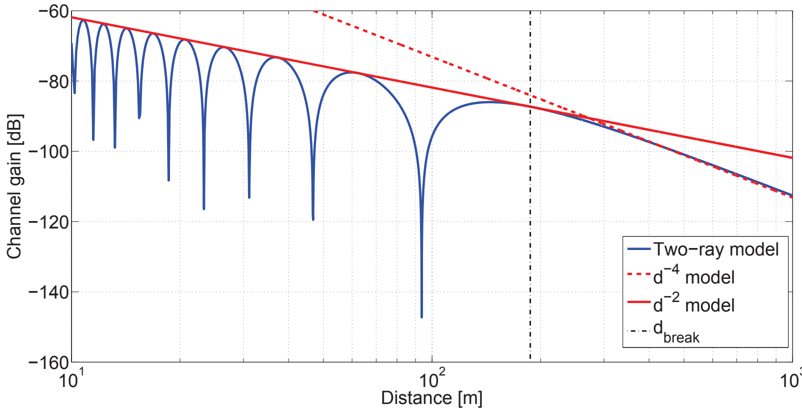


Figure 2.5: Channel gain vs. distance according to the classical two-ray model presented in [41], the approximated two-ray model (2.4), and the single slope model with d^{-2}. The following inputs to the models are used, f=5.9 GHz, h_{TX}=1.7 m, h_{RX}=1.4 m, and the ground reflection coefficient is set to -1.

$(\Psi_\sigma \sim \mathcal{N}(0,\sigma)|_{dB})$. The "slow" effects of the shadowing are shown in Fig. 2.3 with a red line.

To explicitly characterize the path loss and large scale effects in V2X communication, the following categorization is used according to Paper II:

- Line-of-sight (LOS) is the situation when there is an optical LOS between the TX and the RX antennas.
- Obstructed-LOS (OLOS) is the situation when the optical LOS between the TX and the RX antennas is obstructed by another vehicle.
- Non-LOS (NLOS) is the situation when a building between the TX and the RX completely block the LOS (as well as many other significant MPCs).

With these categories, estimation of different path loss models is possible, and the influence of different shadowing effects can be studied. An advantage of this categorization is presented in Paper II, where the standard deviation of the large scale fading is lower when estimating parameters for the two-ray model in a LOS scenario, compared to when parameters were estimated for the single slope model. The path loss model with lowest value of the standard deviation of the large scale fading fits better to the measured data.

The last category, the NLOS scenario, is an important scenario for safety applications in urban environments. It is a scenario where V2V communication really can help, since the on-board sensors (radar, camera, lidar) cannot “see””around corners as V2V communication can. Limited research has been done on this scenario for V2V communication, with an exception of the work by Mangel et. al. [42]. Even though the Mangel model is the most used one for NLOS scenarios in urban intersections, it has some limitations, e.g., the model is not reciprocal and does not consider other vehicle obstructing the communication, issues that we are addressing in Paper III.

2.3.3 Path loss and Large Sacle Fading Estimation

When estimating parameters for a specific path loss model, the following possible issues should be considered: 1) is the samples size large enough? 2) are the sample distances large enough? 3) is the dynamic range good enough?

The answer to the first question is that the needed sample size depends on the desired confidence interval that is wanted for the estimated parameters. In addition, the samples shall be uncorrelated and rather evenly distributed within the measured distances [43]. To the second question the answer is that the distances should fulfill $d_{max}/d_{min} \geq 10$, a rule of thumb presented in Paper II. Regarding the last question, the dynamic range is often an issue due to the noise floor of the channel sounder or the system specific transceivers used during the measurements. The ordinary least square (OLS) estimation method, which is the most common approach, does not consider the effect the noise floor has on the estimated parameters. The aim of OLS is to minimize the variance of the modeled values against the measured values. The single slope model can be expressed as a linear function,

$$y_i = a + bx_i + \epsilon_i, \tag{2.6}$$

where a is the path loss at the reference distance $PL(d_0)$, b is the path loss exponent n, and ϵ_i is the large scale fading Ψ_σ. To minimize the variance, with N number of samples, the expression is written in matrix form as [44],

$$\mathbf{y} = \mathbf{X}\mathbf{b} + \boldsymbol{\varepsilon}, \text{where,} \tag{2.7}$$

$$\begin{aligned}
\mathbf{y} =& [PL(\mathbf{d}/d_0)]_{N\times1}\\
\mathbf{X} =& [\mathbf{1} \;\; 10\log_{10}(\mathbf{d}/d_0)]_{N\times2}\\
\mathbf{b} =& [PL_(d_0) \;\; n]^T.
\end{aligned}$$

The OLS estimation is then given by,

$$\hat{\mathbf{b}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{y}$$
$$\hat{\sigma}^2 = \frac{1}{N-1}(\mathbf{y} - \mathbf{X}\hat{\mathbf{b}})^T(\mathbf{y} - \mathbf{X}\hat{\mathbf{b}})$$

A method that do consider the noise floor and uses the information of the censored samples is the maximum likelihood (ML) method presented in [44], see Fig. 2.6. For the samples were no signal were received by the RX, still the distances between the TX and the RX might be available. With this information the probability of observing a censored path loss sample $y \geq c$, at a distance d, is given by [44],

$$P(y_i \geq c) = 1 - \Phi\left(\frac{c - \mathbf{x}_i\mathbf{b}}{\sigma}\right), \tag{2.8}$$

where Φ is the cumulative distribution function (CDF) of the standard normal distribution. The censored samples are set to c, where $-c$ is a channel gain value located a few dB above the noise floor, so that a limited number of samples dominated by the noise floor are included in the measured data. Using an indicator function I, where I=0 for censored data, otherwise I=1, the likelihood function of the model is given by [44],

$$l(\sigma, \mathbf{b}) = \prod_{i=1}^{N} \underbrace{\left[\frac{1}{\sigma}\phi\left(\frac{y_i - \mathbf{x}_i\mathbf{b}}{\sigma}\right)\right]^{I_i}}_{\text{Uncensored}} \underbrace{\left[1 - \Phi\left(\frac{c - \mathbf{x}_i\mathbf{b}}{\sigma}\right)\right]^{1-I_i}}_{\text{Censored}}, \tag{2.9}$$

where ϕ is the standard normal probability density function (PDF). Using the log-likelihood, the parameters σ and $\mathbf{b}$ are estimated using

$$[\hat{\sigma}, \hat{\mathbf{b}}] = \arg\min_{\sigma,\mathbf{b}}\{-L(\sigma, \mathbf{b})\}. \tag{2.10}$$

In Fig. 2.7 the difference is shown between the two estimation methods for a single slope channel gain model on measured V2V communication in a highway scenario.

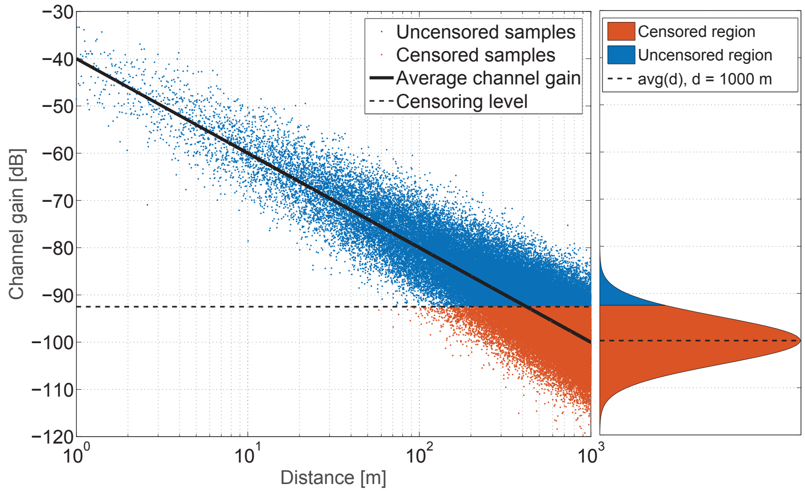


Figure 2.6: The figure shows the concept of censored and uncensored data samples.

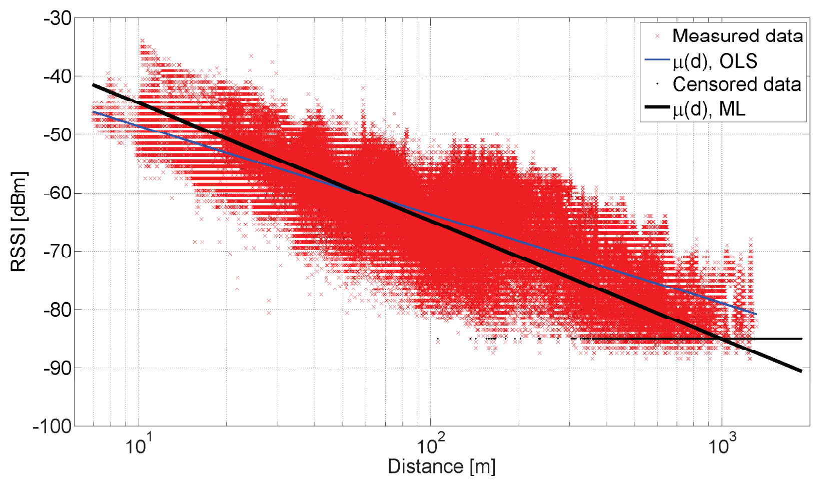


Figure 2.7: Received signal strength vs distance from a measurement between two cars driving on a highway. The two lines show the expected distance dependent received power using two different estimation techniques.

2.3.4 Spatial Autocorrelation

In vehicular channels, the autocorrelation of the shadowing process is normally a function of distance, which can be written as,

$$r(\Delta d_i) = E\{\Psi_\sigma(d_i)\Psi_\sigma(d_i + \Delta d_i)\}, \tag{2.11}$$

where d_i, is the distance between the TX and the RX, and Ψ_σ is the zero mean large scale fading process. In V2X measurement campaigns the channel is often sampled irregularly, as the test vehicles need to adapt their speed to the surrounding traffic. This issue is addressed in paper II.

The autocorrelation of the shadowing process can be approximated by a well-known model proposed by Gudmundson [45], based on a negative exponential function,

$$r(\Delta d_i) = \sigma^2 e^{-|\Delta d_i|/d_c} = \sigma^2 \rho(\Delta d_i). \tag{2.12}$$

In the Gudmundson model the de-correlation distance, d_c is defined as the value of Δd_i, at which the value of the autocorrelation function $\rho(\Delta d_i)$ has decreased to $1/e$. Once a vehicle is shadowed, it will stay shadowed during a distance roughly equal to the de-correlation distance. Another model of the spatial autocorrelation proposed by Mawira [46] and applied by us in Paper II, is the sum of two negative exponential functions,

$$\rho_D(\Delta d) = re^{-|\Delta d|/d_{c1}} + (1-r)e^{-|\Delta d|/d_{c2}}. \tag{2.13}$$

This model is not so common but in our case it actually fits the measured autocorrelation better than the Gudmundson model.

Table 2.1 summarizes spatial autocorrelation distances from the literature and our measurement results. As seen in Table 2.1 the de-correlation distance

Table 2.1: Reported de-correlation distances from measurements.

Scenario	**Highway**		**Urban**	
Paper	LOS	OLOS	LOS	OLOS
Paper II & III	43-78 m	89-177	2-4 m	2-4 m
Abbas et al. [47]	23.3 m	32.5 m	4.25 m	4.5 m
Roivainen et al. [48]	-	-	6.8-9.7	-

can be a significantly large distance for V2V communication on highways, but in urban environments, it is rather small.

2.3.5 Small Scale Fading

Small scale fading is "fast" changes of the received signal on the scale of a wave length due constructive or destructive superposition of the incoming electromagnetic waves at the receiver. The behavior is illustrated in Fig. 2.3. There are many propagation paths that connect the TX and the RX, there could be a LOS component, but also several other components, so called multi path components (MPCs). These MPCs occur due to interactions with different scattering objects. This includes specular reflection, diffraction around a corner, and even diffuse scattering to some extent, all with different amplitudes and phases. It is the movement, on a scale of the wavelength, of the TX, the RX or the scattering objects in between, that causes the small scale fading. The summation of the MPCs results in fast fluctuation of the received power represented by $\nu_{|dB}$ in

$$P_{RX|dBm} = P_{TX|dBm} + G_{TX|dBi} + G_{RX|dBi} - PL_{|dB} + \Psi_{\sigma|dB} + \nu_{|dB}. \quad (2.14)$$

Several distributions have been proposed to describe the small scale *amplitude* variations of the signal envelope, r. The by far most used one for NLOS scenarios, i.e., with no LOS or dominant MPC, is the Rayleigh distribution, whose PDF is [31],

$$p(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right), \quad (2.15)$$

where σ is the standard deviation of the in-phase and quadrature signals. In LOS or scenarios where few MPCs are dominant, it has been shown that the distribution of the small-scale fading can often be described by a Rice distribution with PDF [31]

$$p(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{rA}{\sigma^2}\right), \quad (2.16)$$

where A is the amplitude of the dominant component and I_0 is the zero-order modified Bessel function of first kind. The Rice distribution is characterized by the Ricean K-factor, $K = A^2/2\sigma^2$. The K-factor describes the shape of the PDF, with large values on K, i.e., in situations of a strong LOS component, the shape of the PDF will tend to a Gaussian distribution when $K{=}{\to}\infty$. When no dominant MPC exists, $K = 0$, and the PDF becomes a Rayleigh distribution.

2.3.6 Doppler Shift and Coherence Time

As mentioned in the previous section, it is the movement of the TX, the RX or the scattering objects in between that causes the small scale fading. A metric that describes the fading is the Doppler shift f_D. The effect it has on the received frequency is given by,

$$f = f_c\left(1 - \frac{\mathbf{u}\cdot\mathbf{v}_{RX} - \mathbf{u}\cdot\mathbf{v}_{TX}}{c}\right) = f_c - f_D, \tag{2.17}$$

where $\mathbf{u}$ is the propagation unit vector of the wave. The variable $\mathbf{v}$ is the velocity vectors of the TX and the RX, respectively. An intersection scenario is shown in Fig. 2.8. In case of moving scatterers these can either be seen as a virtual TX or RX depending on the particular contribution to be estimated, an example of a V2V communication scenario is shown i Fig. 2.9.

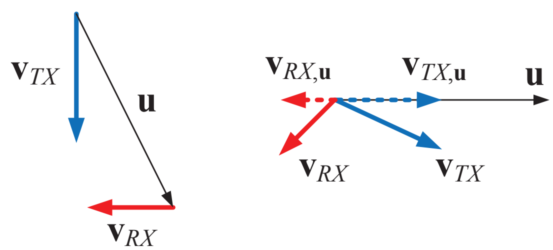


Figure 2.8: To the left, an intersection scenario, where two cars drive perpendicular to each other. To the right, the corresponding velocity vectors for the TX and the RX projected to the propagation unit vector.

Depending on the angles the MPCs arrive to the RX, the Doppler power spectrum looks differently, a uniform distribution of the MPCs around the RX results in a Doppler spectrum according the *Jakes* spectrum aka "bath-tub"curve [49]. The Doppler spectrum characterizes the frequency-dispersion, i.e., how the transmitted signal is smeared in frequency due to movements of the TX, the RX or scattering objects. In addition, the Doppler shift causes a beating effect, i.e., the envelope of the received signal approaches zero or attains low values in time periods equal $1/f_{Dmax}$. This time is approximately the same as the coherence time,

$$T_c \approx \frac{1}{f_{Dmax}}, \tag{2.18}$$

which describes for how long time the channel is time invariant.

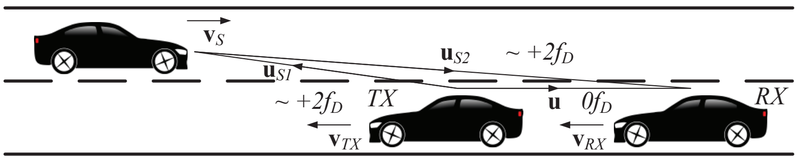


Figure 2.9: Doppler shift between two cars driving in the same lane and with the same speed. In the opposite lane is a car driving with the same speed as the other two, this car act as a mobile scatterer. The shown f_D are roughly the Doppler shift compared with a static scattering object. Note, that the total Doppler shift from the scattering vehicle can be 4 times higher than for a fixed scattering object and a fixed base station.

In a conventional V2N communication system the Doppler shift is usually quite low, e.g., in a GSM system (V2N) at 900 MHz the f_{Dmax} is 92 Hz when driving at 110 km/h. However, the Doppler shift can be rather high in a V2V communication system due to the communication between two vehicles can be scattered in other vehicles driving in the opposite direction, which leads to 4 times the Doppler shift, see Fig. 2.9. If all vehicles have the same speed as before but now the frequency is 5.9 GHz, the f_{Dmax} could be as high as 2404 Hz. The high Doppler shifts in V2V communication constituted one of the challenges when developing the 802.11p standard from the original 802.11a standard, which was designed for WLAN indoor communication.

2.3.7 Wide band characteristics

The small scale fading presented in 2.3.5 describes the influence of the superposition of the different MPCs, on a wave length scale, on a narrow band communication system. In a wide band system, which is common today since high data rates are desired, the channel transfer function is not flat over the used bandwidth, but it exhibits frequency selectivity. Another way to describe wide band systems, is that the received signal is significantly longer than the transmitted signal, this is called delay dispersion. The frequency-selectivity and delay-dispersion are equivalent, they are related by a Fourier transform between time (delay) domain and frequency domain. If the RX receives a data symbol and at the same time receives data symbols from other MPCs with information from the previous data symbol, these two symbols will interfere with each other. This effect is called inter-symbol interference and if no measures are taken it will cause bit errors.

It is rather complex to describe the wide band characteristics of a wireless channel stochastically. To simplify the process a common assumption is to use the wide-sense stationary (WSS) assumption and the uncorrelated scattering (US) assumption. WSS means that the statistical properties of the channel do not change with time [50], i.e., the temporal autocorrelation of the channel is only dependent on the time lag. It also means for a flat Rayleigh fading channel that the mean power and the Doppler spectrum do not change with time, while the instantaneous amplitude can change. WSS is typically fulfilled over an distance movement of 10λ but can in many cases be larger. The US assumption means that the MPCs are uncorrelated for different delays, i.e., each MPC fades independently. Applying both assumptions, i.e., the WSSUS assumption, then the channel can be modeled as a tapped delay line model, see (2.1) in 2.2.

Even after applying the WSSUS assumption the description is complex, therefore straightforward models or parameters are desired for describing the channel. An example is the 3D scattering function $P_S(f_D, \tau)$, which is a function describing the received power vs Doppler shift and delay. From the scattering function the power delay profile (PDP) can be extracted as [31]

$$P_\tau(\tau) = \int P_S(f_D, \tau) df_D, \tag{2.19}$$

and the Doppler spectral density (DSD) as [31]

$$P_D(f_D) = \int P_S(f_D, \tau) d\tau. \tag{2.20}$$

From the PDP the total received power is given by [31],

$$P_\tau = \int P_\tau(\tau) d\tau, \tag{2.21}$$

the mean delay is given by [31],

$$\tau_{avg} = \frac{\int P_\tau(\tau) \tau d\tau}{P_\tau}, \tag{2.22}$$

and the rms delay spread is defined as [31]

$$\tau_{rms} = \sqrt{\frac{\int P_\tau(\tau) \tau^2 d\tau}{P_\tau} - \tau_{avg}^2}. \tag{2.23}$$

Similar to (2.21-2.23), the same parameters of the DSD can be estimated. Applying the Fourier transform of the PDP, the coherence bandwidth (B_c) can be estimated as [31]

$$B_c \lesssim \frac{1}{2\pi\tau_{rms}}. \tag{2.24}$$

Applying the inverse Fourier transform to the DSD the coherence time (T_c) can be estimated as [31]

$$T_c \lesssim \frac{1}{2\pi f_{D,rms}}. \tag{2.25}$$

This expression is almost the same as (2.18). Both expressions give an approximation of the coherence time with different inputs. The difference depends on the shape of the DSD. The B_c describes how fast the channel varies in frequency (frequency selectivity) while T_c describes how fast the channel varies in time (time selectivity), beyond these two values the channel can seen as uncorrelated in both dimensions.

The V2V channel is a highly dynamic time-variant channel, since both the TX and the RX often are moving with high speeds. Due to this, the V2V channel essentially does not fulfill the WSSUS assumption [51] for longer time durations or larger bandwidths. One way to characterize non-WSSUS channels is to regard them as an extension of the WSSUS case. This can be done by assuming that the fading process of the channel is an ergodic process and dividing the measured data into smaller regions where the WSSUS assumption is valid over these small regions. Practically for V2V channels, this means performing averaging of the measured samples within a smaller time window, determined by the speed of the TX and the RX. An example of a V2V scattering function is shown in Fig. 2.10, were the WSSUS assumption is valid.

2.3.8 MIMO, Angular Spread, and Antenna Correlation

The MPCs received by an RX in a SISO system is causing degradation of the system performance due to fading of the received signal. In MIMO systems, more than one antenna is used at both the TX and the RX side, where the spatial domain is used to improve the performance. The improvement could be capacity, reliability, and signal-to-noise ratio (SNR), although not all of these benefits can always be achieved simultaneously. The MPCs originating from different obstacles due to reflection, diffraction, or scattering are received by all antenna elements differently at the receiver side, hence each combination of the TX and the RX antennas are represented by a unique faded signal. With M TX antennas and N RX antennas the MIMO channel can be described by

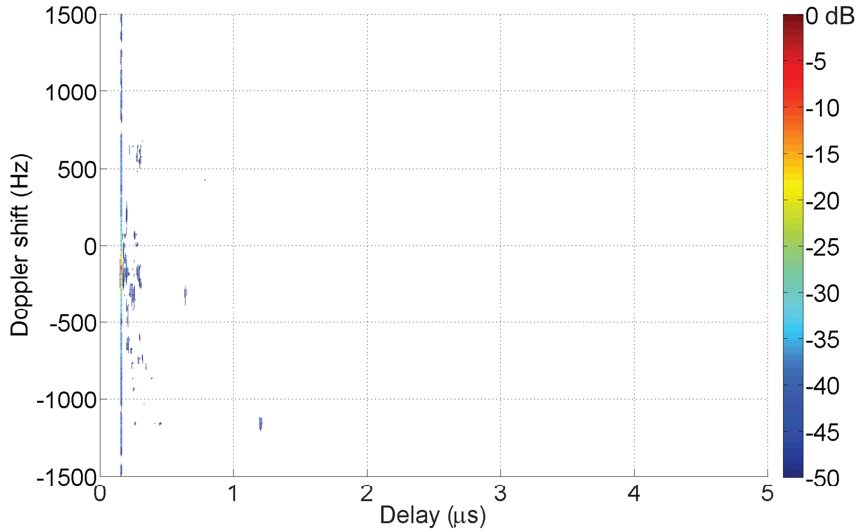


Figure 2.10: Scattering function of one measurement made on a highway in Lund, Sweden [52].

the following matrix [31],

$$H(t,\tau) = \begin{bmatrix} h_{11}(t,\tau) & h_{12}(t,\tau) & \dots & h_{1M}(t,\tau) \\ h_{21}(t,\tau) & h_{22}(t,\tau) & \dots & h_{2M}(t,\tau) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N1}(t,\tau) & h_{N2}(t,\tau) & \dots & h_{NM}(t,\tau) \end{bmatrix} \tag{2.26}$$

where,

$$h_{nm} = \int\int h_{nm}(t,\tau,\boldsymbol{\Omega_{TX}},\boldsymbol{\Omega_{RX}}) d\boldsymbol{\Omega_{TX}} d\boldsymbol{\Omega_{RX}}, \tag{2.27}$$

is the double-directional channel impulse response [53] with the angle of departure (AOD) $\boldsymbol{\Omega_{TX}}$ vector and angle of arrival (AOA) $\boldsymbol{\Omega_{RX}}$ vector in spherical coordinates. In the same way as with PDP and DSD for the SISO system, the angular power spectrum (APS) is also of interest for MIMO systems, e.g., the APS of the receiver side [54],

$$P_A(\boldsymbol{\Omega_{RX}}) = \mathrm{E}\left[|\int\int h_{nm}(t,\tau,\boldsymbol{\Omega_{TX}},\boldsymbol{\Omega_{RX}}) d\tau d\boldsymbol{\Omega_{TX}}|^2 \right]. \tag{2.28}$$

The vectors $\boldsymbol{\Omega_{TX}}$ and $\boldsymbol{\Omega_{RX}}$ can be divided into azimuth and elevation angles, $(\Theta_{TX}, \varphi_{TX})$ and $(\Theta_{RX}, \varphi_{RX})$. From the APS the total received power in the azimuth plane is derived as [54]

$$P_{A,\Theta_{RX}} = \int P_{A,\Theta_{RX}}(\Theta_{RX}) d\Theta_{RX}, \tag{2.29}$$

the average received azimuth angles is given by [54],

$$\Theta_{RX,avg} = \frac{\int P_{A,\Theta_{RX}}(\Theta_{RX})\Theta_{RX} d\Theta_{RX}}{P_{A,\Theta_{RX}}}, \tag{2.30}$$

and the rms angular spread is defined as [54]

$$\Theta_{RX,rms} = \sqrt{\frac{\int P_{A,\Theta_{RX}}(\Theta_{RX})\Theta_{RX}^2 d\Theta}{P_{A,\Theta_{RX}}} - \Theta_{RX,avg}^2}. \tag{2.31}$$

The angular information is of interest in V2V channels for different traffic scenarios. In a highway scenario most of the MPCs come from either the front or back direction. However, in an urban scenario, the scenario is different, here the MPCs are most likely coming from all directions, due to the large amount of scattering objects [55]. In addition, the angular information is of high interest when setting up verification methods presented in chapter 3.

A MIMO system achieves its full performance when the correlation between the signals at the different antennas is low, i.e., a situation when the angular spread is high. From the above described double-directional channel we can use a matrix notation for the MIMO system and calculate the spatial correlation matrix $\mathbf{R}$ [54] as

$$\mathbf{R} = \mathrm{E}\left[\mathrm{vec}(\mathbf{H}^H)\mathrm{vec}(\mathbf{H}^H)^H\right]. \tag{2.32}$$

The spatial correlation matrix $\mathbf{R}$, is a positive semi-definite Hermitian matrix with the size $MN \times MN$, which describes the correlation between all channel combinations in the MIMO system. From $\mathbf{R}$, we can derive the antenna correlations [54] as

$$\mathbf{R}_{TX} = \frac{1}{n}\mathrm{E}\left[\mathbf{H}^H\mathbf{H}\right], \tag{2.33}$$

$$\mathbf{R}_{RX} = \frac{1}{m}\mathrm{E}\left[(\mathbf{H}\mathbf{H}^H)^T\right]. \tag{2.34}$$

Note, the intuition of (2.34) is that the correlation matrix expresses nothing else than phase shifts between the signals received by the antennas, averaged over the incoming angular spectrum. The use of the antenna correlation is important when characterizing LTE MIMO systems, e.g., in the verification methods described in chapter 3. By applying different antenna correlations to the emulated channel, different user scenarios can be tested resulting in different system performance.

2.3.9 Multilink Shadowing Effects

The correlation between multiple links is a complex mechanism which can be modeled in one or several dimensions. Typical dimensions include time, distance, angles or Cartesian coordinates. In [56] cross-correlation of the large scale fading processes between two links are modeled according to the well-known Gudmundson model [45], where the distance is the Δd, i.e., the distance between two mobile users. Mawria [46] proposes a simple formula for the approximation of the link correlation versus angle θ in degree, seen from the mobile user to the two considered base stations, $\rho(\theta) = 0.9 - |\theta|/200$. A few others [23, 24, 57, 58] have also presented results on the cross-correlation of the shadowing process between two links in outdoor environment.

The area of multilink shadowing effects has not been the main focus when designing cellular or Wi-Fi networks, with the exception of the publications mentioned above and a few others. The communication with several users within range of the base station or the access point is handled by the medium access control (MAC) layer to avoid conflicts in the air. With the feature of dual connectivity within 4G and 5G, the correlation of the shadowing process between the two communication links towards the base stations is of interest. Another feature within 4G and 5G is the D2D communication capability, without communication to the base station the peer-to-peer network can transport a message from one device to another device. In the design phase of these peer-to-peer networks, reliable models of the simultaneously communication links are required. System simulators with proper cross-correlation models of the large scale fading between multiple links enable evaluation of different MAC schemes for peer-to-peer networks close to reality.

In ITS-G5 [59], there is a feature of relaying messages from one vehicle to another vehicle via a third one. This feature is useful in VANETs, especially since vehicles shadow each other frequently in heavy traffic. One of our main topic in our research activities has been to perform measurement based analysis of the multilink shadowing effects, with the aim to provide a model that can be used in system simulators, see the result in Paper II. Both in Paper II and III it has been shown that the cross-correlation between multiple communication links is low, both on highway and in urban intersections. However, this conclusion is only valid if the path loss is modeled properly, e.g., classifying the measured data into LOS, OLOS and NLOS cases and using different path loss model for each case. The effect of not doing this, which is the most common approach in the literature, is presented in Paper I. Furthermore, it has been shown that the cross-correlation between two links, where the TX antenna is the same for both links and the RXs antennas are located on the same vehicle, is low. This indicates that the antenna patterns have a large effect on the experienced large scale fading. The two links experience different large scale fading due to the weighting effect of the antenna pattern.

Three conclusions regarding cross-correlation of the multilink shadowing effects in VANETs are: 1) low correlation between different V2V communication links are beneficial for the multihop techniques in ITS-G5. 2) low correlation between different antennas on the same vehicle is valuable to exploit diversity gain. 3) if the VANET simulators distinguish between LOS, OLOS, and NLOS, and proper path loss models are used for the respective cases, the remaining cross-correlation of the shadowing between the communication links is negligible, e.g., no further modeling of the cross-correlation is necessary.

Chapter 3

System verification

The need of new verification methods for wireless communication systems installed in cars have been identified by the automotive industry. The objective is to find methods that support measurements of the performance and robustness of the systems without field trails. In addition, increased usage of MIMO in several wireless communication technologies, requires new verification methods than those used for traditional SISO systems. This has been identified by the telecom industry since the beginning of 2000 and three main OTA verification methods have been presented, anechoic chamber methods, reverberation chamber methods, and indirect methods. Some of them have been standardized in 3GPP and CTIA for hand held devices, but none of them has been widely used or standardized when the DUT is a very large test object, such as a car. This chapter will introduce the verification methods used by the telecom industry and the consequences for the different methods when the DUT is a car.

3.1 Why over-the-air testing?

The two main reasons to perform OTA system verification, is to avoid opening or modifying the DUT and to include the self-interference effects caused by the device. Both reasons are important for cars. Opening the DUT means in a car installation that you first have to remove other parts to get access the DUT. Second, the car itself generates many signals from different ECUs, creating interference for the communication systems in the car, i.e., electromagnetic compatibility (EMC) is an important aspect. In the SISO systems, the transceiver performance of, e.g., a mobile phone is normally tested conducted using a special connector that is bypassing the antenna. This procedure always influences the test result to some degree, depending on how good the impedance matching of this special connector towards the transceiver and the antenna is made. The antenna is measured passively and together with the measured transceiver performance, the final performance of the device can be estimated. In none of these two measurements, the self-interference effects are considered. To avoid the issues with the conducted measurements on, e.g., mobile phones, the two standardization bodies 3GPP and CTIA have standardized two figure of merits (FOM) for SISO systems, total radiated power (TRP) [60] and total radiated sensitivity (TRS) [60, 61], or total isotropic sensitivity (TIS) as it is called within CTIA [61].

MIMO systems are highly dependent on the interaction between the propagation channel and the antennas of the user equipment (UE), circumstances that call for OTA testing. The above mentioned test methods for SISO systems, do not include the propagation channel and therefore new test methods are needed for MIMO systems. Significant research has been done [62–66] and are still on-going in this area. It is not a trivial task to emulate some of channel models mentioned in chapter 2, e.g., the tapped delay line model or the Saleh-Valenzuela model, especially emulation of the non-uniform field to enable measurement of the spatial multiplexing gain of the MIMO system. Several candidates of OTA methods have been proposed in the past by researchers, some of them have been standardized within 3GPP and CTIA, and some are under investigation [67]. The most important candidates are grouped into the three main methods as below.

- Anechoic chamber methods:
  - A1 Spatial fading emulator method [68]
  - A2 Multiprobe method (arbitrary number and position of antennas) [68]
  - A3 Ring of probes method (symmetrical) with prefaded signal synthesis technique [64, 69]
  - A4 Ring of probes method (symmetrical) with plane-wave synthesis technique [70]
  - A5 Two channel method [71].
- Reverberation chamber methods:
  - R1 Basic or cascaded reverberation chamber [72]
  - R2 Reverberation chamber with channel emulator [72].
- Indirect methods:
  - I1 Two stage [73]

I2 Radiated two stage - aka Wireless Cable [74]

I3 Decomposition [75, 76].

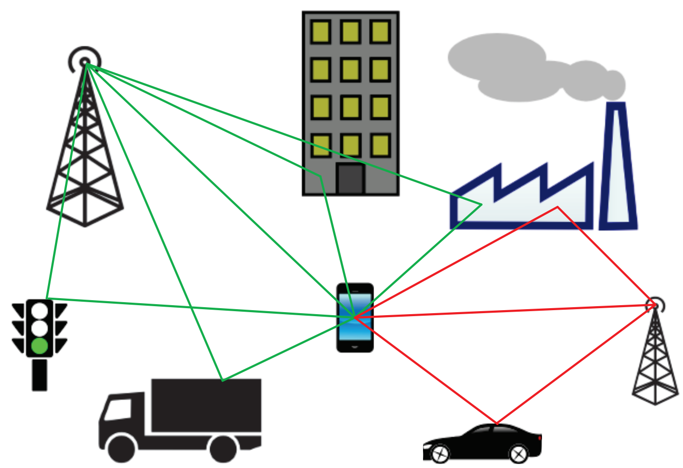
3.2 Anechoic chamber methods

The basic idea with the anechoic chamber methods using multiple probes, is to mimic the real life environment of the signals propagating from the TX to the RX, not only in time and frequency domain but also in the spatial domain, see Fig. 3.1. In an LTE system, the down-link signal is generated by a communication tester (base station simulator), which then is connected to a channel emulator and then to the multiple probes. The up-link signals from the DUT are received by an antenna placed inside the chamber and connected directly to the communication tester. There are several ways to emulate, e.g., a Rayleigh distribution of the varying amplitude in the test area, the simplest one (A1) is by using phase shifters and programmable attenuators to change the relative Doppler frequency and attenuation to the different probes configured in a symmetric ring. To also include the AOA and the angular spread, a configuration with arbitrary number of probes and positions (A2) can be used. A combination of A1 and A2 is what we have used in our research, and we call the setup a MPS, see Paper IV. The most common anechoic chamber method is to use a symmetrical ring of probes which generate the non-uniform electromagnetic field by either prefaded signal synthesis (A3) or plane-wave synthesis (A4). In both the synthesis methods a commercial fading emulator is normally used to emulate the real propagation channels using standardized channel models, e.g., an urban micro (UMi) cellular channel model defined by 3GPP [77]. This setup is more flexible since the clusters of the MPCs defined by the channel models are not limited to the physical number of probes and their position. Instead the channel emulator can generate a field from the probes so that a correct representation of the channel model exist in the test area. To find proper power weightings for each probe such that spatial characteristics of the propagation channel can be created in the test area has always been challenging. One method is called prefaded signal synthesis, and the details of it can be found in [64, 69]. The fourth method, called plane-wave synthesis [70] uses a different approach. First, power weights for each probe are estimated to generate a static plane wave in the test zone, i.e., the power is uniformly distributed and have a linear phase front. Doppler is added to the plane waves to achieve a Rayleigh fading channel and by adding angular spread and delay, a full representation of the channel model, e.g., the UMi channel model, is possible. The pros and cons of the two synthesis methods are in [64]. The last method, called the two channel method (A5) has gained little interest in the research community and is therefore not further treated.

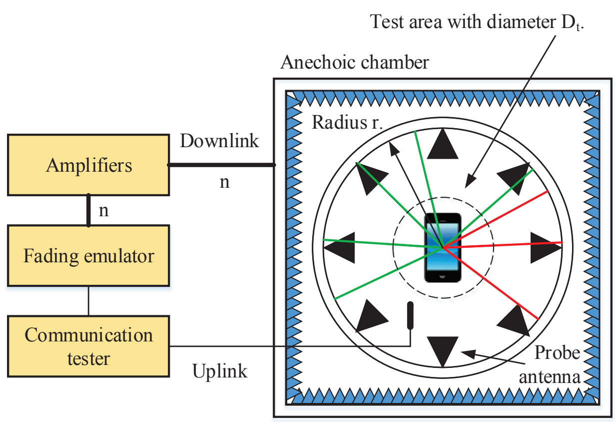
What is a suitable diameter of the test area, radius of the ring, and how many probes are needed for testing hand held devices? These questions have been deeply investigated [78–81]. One very important parameter for MIMO systems that define the size of the test area is the spatial correlation. For increased throughput in MIMO systems, uncorrelated signals in the spatial domain is the target. Therefore, the number of MIMO antennas on the DUT needs to be covered by the diameter D_t, of the test area, aka quite zone. The test area is determined by the number of probes, more probe antennas results in a larger test area. The spatial correlation should theoretically follow the Bessel function of the 1:st kind for a 2D uniform Rayleigh channel. The number of probes (K) needed to support the required D_t when performing plane-wave signal synthesis in 2D, is defined by the rule of thumb [78] as follows, $K = 2\lceil \pi D_t/\lambda \rceil + 1$, where $\lceil\cdot\rceil$ is the integer ceiling operator. The radius of the ring, is defined by that the DUT needs to be in the far field region. According to the phase uncertainty limit, defined by Fraunhofer distance $r_1 = 2D_A^2/\lambda$, where D_A is the largest dimension of the antenna radiator or as stated in [61] "would simply be the largest dimension of the DUT", i.e, D_t. Additionally, two other far field criteria is defined in [61], $r_2 > 3D_t$ the amplitude uncertainty limit, and $r_3 > 3\lambda$ the reactive near field limit. The largest ring radius r_i of these three criteria shall be chosen.

Consider the case of a smartphone with D_t=0.1 m. The size of the samrt-phone is in the same range as a shark fin antenna on a car and is therefore a good reference. However, for a car, you could argue that it also could be the complete car that is the DUT, then D_t is 5 m. In the Table 3.1, a comparison is made between a smartphone (or the shark fin antenna itself) and a complete car regarding the diameter of the test area, the radius of the ring, and the number of probes needed.

As seen in Table 3.1 the required radius R_i and number of probe antennas are feasible for a smartphone but for a car and performing measurement on the 802.11p system the required radius is 983 m and the number of probes is 619. This is not practically possible and the cost would be enormous. With this in mind we started the research of the multipath propagation simulator setup for cars, see Paper IV, to see what could be achieved. In Paper V, we have demonstrated that even when we use only eight probe antennas at the frequency 5.9 GHz we have a Rayleigh fading channel at the DUT (shark fin when mounted on a car) for the tested SISO system. The measurement uncertainty is under control, the temporal behavior is according to expectations, the coupling between the probes is low, and the reflected/diffracted MPCs are reflected away from the test zone. Unfortunately the spatial correlation could not be analyzed since the data was not available. The conclusion we make



(a)



(b)

Figure 3.1: (a) The LOS component and MPCs between the TX and the RX (green lines), including an interfering base station (red lines). (b) Channel emulation using an anechoic chamber with a ring of probes, symmetrically distributed, inspired by [63].

Table 3.1: OTA physical requirements when the DUT uses MIMO technology.

	Frequency		
Parameters	700 MHz	2.4 GHz	5.9 GHz
D_t [m]	0.1	0.1	0.1
r_1 [m]	0.05	0.16	0.39
r_2 [m]	0.30	0.30	0.30
r_3 [m]	1.29	0.38	0.15
K	3	7	15
D_t [m]	5	5	5
r_1 [m]	117	400	983
r_2 [m]	15	15	15
r_3 [m]	1.29	0.38	0.15
K	75	253	619

is that for SISO system it is not necessary to fulfill the OTA physical requirements in Table 3.1, but for MIMO communication systems used by cars further investigations are needed.

3.3 Reverberation chamber methods

In contrast to anechoic chamber methods, the reverberation chamber (RC) is emulating a rich multipath environment [72]. Average of a longer period of time the power-angular spectrum is isotropic, but observed over the time period of a demodulated data symbol, it is known to be highly directional. This instantaneous directional multipath environment provides the DUT with diverse signals to the different antennas and enable measurement of spatial multiplexing capacity. The basic setup is a shielded box with installed mode-stirrers on the inside (R1), which are rotating to generate the rich multipath environment, see Fig. 3.2. The speed of the mode stirrer define the Doppler spectrum and by adding small absorbers inside the box at different locations it is possible to tune the exponentially decaying PDP. With the RC the polarization is not possible to change, i.e., the cross-polarization ratio (XPR) is 0 dB. Further control of the power delay profile and spatial aspects can be obtained by cascading two or more reverberation chambers.

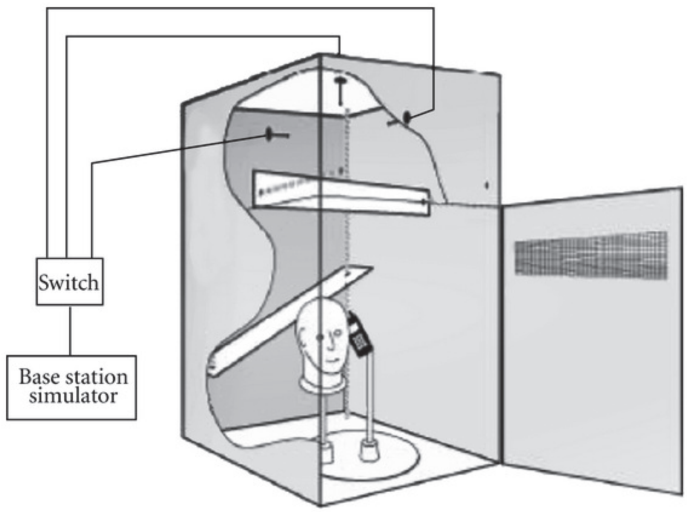


Figure 3.2: An example of a reverberation chamber setup where the DUT is a mobile phone together with an electromagnetic phantom head. From the 3GPP standard [68].

The use of a channel emulator together with a RC (R2) allows the temporal aspects of the desired channel model to be fully controlled. With a channel emulator capable of negative time delay (inverse injection), multiple cavity mode-stirred reverberation chambers, can accurately emulate the power delay profiles of 3GPP SCME channel models [62]. For a single box solution together with a channel emulator, the experienced field is often directional but can not be controlled as it can be in the anechoic chamber methods.

To my best knowledge there has not been any measurements performed in a RC when the DUT is a car, however in [82] the idea is mentioned. The issue with the RC and the DUT being a car is that even if the field inside the RC will be directional, the AOA is not possible to control. For a smartphone this might not be a big problem since as a customer, you basically rotate the smartphone in all three dimensions when using it. This is definitely not the case for a car, the AOA of the MPCs will most often be in the azimuth plane, with an elevation of around -5°to +15°. Due to that, the correct spatial multiplexing gain will not be measured for the wireless communication system built into the car.

3.4 Indirect methods

The indirect methods are fundamentally different from the anechoic and reverberation chamber methods in the sense that they involve two stages of measurements, see Fig 3.3 [62, 83]. First, the antennas of the MIMO device are measured in terms of gain and relative phase in all three dimensions in an anechoic chamber. In the second stage, the DUT is connected via cables to a channel emulator. This procedure violate the intention with OTA measurements by intrusion of connecting cables to the DUT, but it is a cost effective setup and several instruments can be reused from the SISO measurements. There are ways to perform the 3D antenna measurement without connecting any cables to the antennas of the DUT. In this case, the device needs a special test function that reports the received power per antenna and the relative phase between the antennas on an interface connected to a computer which runs the test software. In the second stage, still the special connector that by-passes the antenna is needed. In comparison with the AC methods with many probes, where each probe requires one channel of the channel emulator, the second stage in the two stage method (I1) only requires an equal amount of channels as the number of antennas on the DUT. In the second stage, the communication tester sends the signal to the channel emulator, which convolves the signal with the fading channel and with the 3D antenna pattern. The output of the channel emulator then represents the faded down link signal modified by the spatial properties of the DUT's antennas. Two large benefits of the second stage is that it does not require any anechoic chamber and rotation of the DUT is performed by synthesis in the channel emulator. One drawback is that the self-interference is not captured by this method.

The second indirect method, radiated two stage (I2), does not violate the intention of OTA measurements. Here the second stage is also measured in an anechoic chamber to capture, e.g., self-interference, however not fully as the antenna measurement do not consider leakage between the antenna elements. In the radiated two stage method aka wireless cable, the same procedure is performed in the first stage, but the second stage is more complex, see Fig. 3.4. Here, the task is to establish “wireless cables”from one probe antenna to one antenna on the DUT. This can be preformed by adjusting the power and phases two each probe antenna so that maximum isolation between the different wireless cables is achieved. By measuring the transfer matrix $\boldsymbol{A}$ between the probe antennas and the antennas on the DUT, the calibration matrix $\boldsymbol{G}$ implemented in the communication tester shall satisfy the following expression, $\boldsymbol{AG} = \boldsymbol{I}_N \in \mathbb{R}^{N\times N}$. The calibration matrix $\boldsymbol{G}$ is together with the channel matrix $\boldsymbol{H}$ implemented in the communication tester to establish the wireless cables and emulate the desired channel model. The received faded signal at the DUT antennas can be expressed such as,

$$\boldsymbol{y}(f,t) = \boldsymbol{AGH}(f,t)\boldsymbol{x}(f,t) = \boldsymbol{H}(f,t)\boldsymbol{x}(f,t) \tag{3.1}$$

Is not a trivial task to achieve high isolation between the DUT antennas, several studies are presented regarding this [74, 84].

The last indirect method, the decomposition method (I3) [75], splits the performance tests into two parts: a static test for the antenna performance and a fading test for the algorithmic performance. The results from the separated measurements are then combined, the drawback is that only two radio paths with arbitrary polarization are possible [85].

We have performed LTE measurements on a car using the radiated two stage method but the data is not analyzed yet. C. Schirmer et al. have done similar measurements [86] and their conclusion shows that it is possible to emulate the desired propagation channel and that the test setup is stable over time.

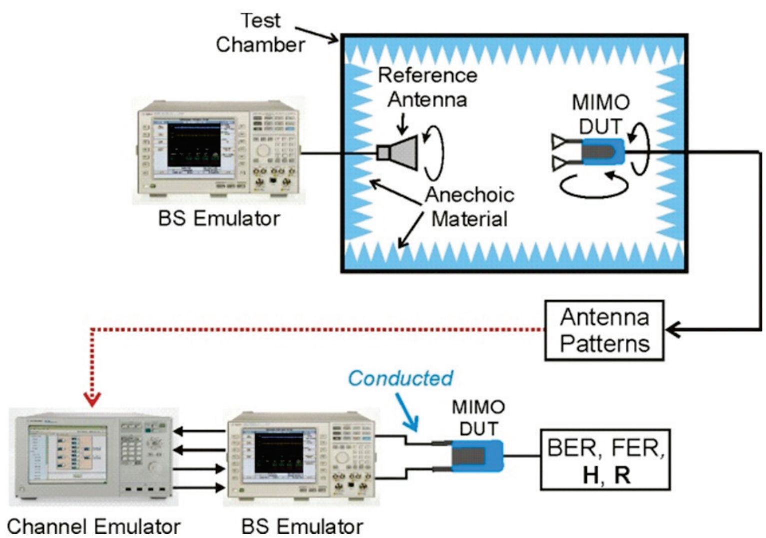


Figure 3.3: An example of the two-stage method, where the first stage is an antenna measurement (upper part of the figure) and the second stage is the performance measurement (lower part of the figure), e.g., a measurement of frame error rate vs. received power with the influence of both the antenna pattern and the channel characteristics. From the 3GPP standard [68].

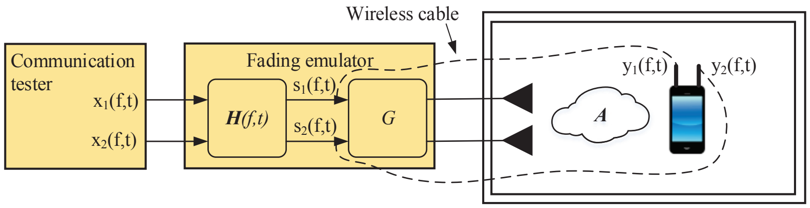


Figure 3.4: Schematic overview of the radiated two-stage method where the dotted lines are the established wireless cable connection between the fading emulator and the DUT. The figure is inspired by [84].

3.5 Comparison and Conclusions of the Over-the-Air Methods

A comprehensive analysis and comparison of OTA verification methods for hand held devices using MIMO are presented in [85], and the conclusions are presented in the Tables 3.2-3.3. There are pros and cons with all the three main method but considering the DUT to be a car, the following conclusions can be made for the three methods:

- Anechoic chamber: all studies show that building a test setup with multiple probes in a ring that has a test area large enough for a car is not feasible. Anyhow, the research we have performed, see Paper IV and Paper V, shows that a ring with eight probes and a radius of 5 m works well for measuring SISO systems and the desired repeatability is achieved. If it works for MIMO systems or not is left for future work.
- Reverberation chamber, is probably a good measurement system for wireless communication systems used inside the car, e.g., the Wi-Fi Hotspot, since the multipath environment inside the car is similar to the isotropic field generated inside a reverberation chamber. For communication systems between the car and an external transceiver the reverberation chamber is not a good solution since this communication more or less takes place in the azimuth plane.
- Indirect methods using the conducted setups is not a good idea since the self-interference will not be measured, this is big a part when verifying the complete vehicle performance. The radiated two stage is more promising in that sense, and since an anechoic chamber is not needed in the the

second stage, i.e., only a shielded chamber is required, which normally can be bought or rented to a lower cost. The drawback is the first stage, measuring the 3D antenna pattern for a car is not a trivial task [17].

- The channel models normally implemented in OTA verification methods when measuring on hand held devices are, e.g., the tapped delay line model or the more sophisticated Saleh-Valenzuela model. Both of these models are wide sense stationary. In V2X communication, and especially V2V communication, the system is highly time-variant and the wide sense stationarity assumption can not be applied [87]. Further research is needed in this area to also define a time-variant channel model that can easily be implemented in a channel emulator.

Table 3.2: Benefits and drawbacks of different MIMO OTA verification methods when the DUT is small in size, e.g., a smartphone. Most of the conclusions according to [88].

Method	**A1-A5**	**R1-R2**	**I1**	**I2**	**I3**
Hardware effort	High	Norm./Low	Medium	Medium	Medium
Measurement time	Fast	Fast	Medium	Medium	Medium
Equipment costs	High	Norm./Low	Medium	Medium	Medium
Calibration effort	High	Low	Low	High	Low
Spatial resolution	Medium	NA	High	High	High
Mechanical sens.	High	Low	Low	Low	Low

Table 3.3: Benefits and drawbacks of different MIMO OTA verification methods when the DUT is small in size, e.g., a smartphone. Most of the conclusions according to [88].

Method	**Highlights**
A1-A5	Fast and precise method.
R1-R2	Low costs and quick measurements.
I1	Simple anechoic chamber can be used.
I2	Self-interference is recognized.
I3	Very good compromise between effort and accuracy.
Method	**Downsides**
A1-A5	3D measurements difficult to perform.
R1-R2	No influence of AOA can be detected.
I1	Self-interference of the DUT not recognized.
I2	Complicated calibration process.
I3	Only two downlink streams possible.

Chapter 4

Vehicle-to-vehicle communication

Vehicle-to-vehicle (V2V) communication is facing the same bottleneck as the telephone system did when that was introduced in the 19:th century; to be able to speak to someone, the other person also needed to have a telephone. It is the same with V2V communication, for the VANETs to be successful on the roads, the penetration of V2V communication within the vehicle fleet needs to be high. The National highway traffic safety administration (NHTSA) in the U.S. is therefore in their notice of proposed rulemaking, regarding federal motor vehicle safety standards within V2V communication [89], presenting a forecast regarding the V2V communication in the U.S. market. The forecast is based on the assumption that dedicated short range communication (DSRC), i.e., 802.11p, transceivers are to be installed in 100 % of the new cars, two years after the mandate have been established. The forecast is also based on the assumption that seven years after the mandate is established, 100 % of the cars are equipped with the voluntary V2V applications. In Fig. 4.1 the forecast is presented as the car fleet penetration of equipped DSRC cars vs number of years and car fleet penetration of cars using V2V applications vs number of years.

You can ask yourself, when will it be more likely that you meet another car with an installed DSRC transceiver than not? Estimated from Fig. 4.1, it will be after around 14 years, that the probability is larger than 50 % ($P_{one} = \sqrt{P_{two}} = \sqrt{0.5} = 70.7\%$), that two vehicles within the fleet meets and both have a DSRC transceivers. Adding three years, i.e., after 17 years, it will be more likely that booth vehicles also are using V2V applications.

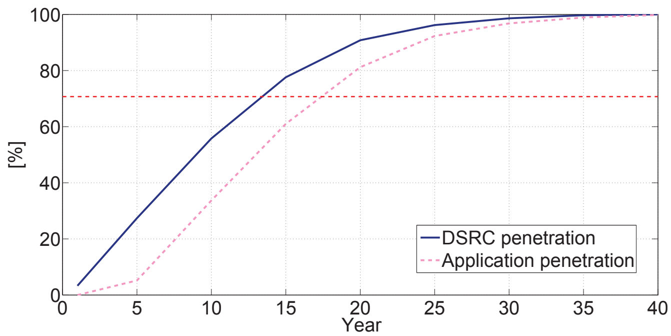


Figure 4.1: Vehicle fleet penetration of DSRC equipped vehicles vs number of years and vehicle fleet penetration of vehicles using V2V application vs number of years. The source of the data according to [89]. The red dotted line shows penetration level at 70.7 %.

The V2V communication can be used for several things, but mainly it will be used for road safety and traffic efficiency. In comparison with the on-board sensors (radar, laser, camera), the V2V communication seen as a sensor that can “see”around corners is quite different, since you need to trust the information received from external sources. The main aspects for the V2V communication to be included in the sensor fusion system in today’s vehicles and to contribute to road safety and traffic efficiency are the following;

- Penetration
  - Backward compatibility
- Socioeconomic aspects
  - Reduced number of injuries and fatalities
  - Automotive manufacturing costs, e.g., hardware and data plan
  - Consumer price
- Security & Privacy
- System requirements
  - Capacity
  - Range
  - Latency

One topic that is important regarding penetration, is that if the used V2V communication standard is updated with new features, so backward compatibility is a must. Otherwise, the vehicle fleet penetration once again will start from 0 % for the new version of the standard and the penetration of the old version will start to reduce, definitely not a desired situation.

NHTSA has also studied the socioeconomic benefits of a possible mandate on DSRC transceivers installed in cars in the U.S., together with two voluntary applications will be used, intersection movement assist (IMA) and left turn assist (LTA) [89]. NTSHA estimate a cost of $135-$300 per new vehicle, including equipment and investment of a security management system. Their assumption is also that the data traffic and the frequency spectrum is for free. The cost per vehicle correspond to an total annual cost of $2.2 billion-$5.0 billion. In year 30 after deployment, the prevented crashes will be 424,901-594,569 and lives saved 955-1,321 during that year [89]. Converting these property damage and reduction in injuries to reduced costs in monetary values is $53 billion to $71 billion. The “breakeven”analysis performed by NHTSA show that cumulative saved costs compared to cumulative cost for automotive manufacturers and buyers is between 8-11 years after introduction. In the U.S., they are proposing a mandate installation of DSRC transceivers, but no decision is taken. However, General motors launched DSRC in their Cadilac CTS model from 2017 [90] and recently Toyota announced that they will deploy DSRC from 2021 [91]. In Japan, Toyota's home market, there they already have 100,000 cars on the roads using the Japanese version of DSRC since 2015 [91]. In EU, the approach is different compared to the U.S., here the market is expected to see the benefits by implementing V2V communication in vehicles and road side units (traffic lights etc.) by themselves. However, until recently no automotive manufacturer have deployed V2V communication systems, due to the penetration issue. An exception in EU is Volkswagen, they have announced that they will deploy 802.11p transceivers as a standard device in many of their models within Volkswagen group from 2019 [92]. This is aligned with the memorandum of understanding within Car-to-car communication consortium (C2C-CC). One reason why it take so long time to introduce V2V communication system on voluntary basis, is that the willingness by the end customers to buy a safety feature that have marginal effect in the beginning of the deployment phase is low.

The common understanding for data security within V2V communication is to use asymmetric cryptography [93]. This requires to setup a public key infrastructure (PKI) for the management of the security credentials of the ITS-stations, e.g., a car or a traffic light. Within the ETSI the security concept, long-term certificates is used for identification and accountability of the ITS-stations and a short-term anonymized certificates for the V2V communication aka pseudonym certificates. By changing the pseudonym certificates frequently the privacy is protected. The developed security system within ETSI has a very high level of security. The major issue with the PKI management is that in the future it shall be able to serving hundred of millions ITS-stations, a topic that needs to be addressed in future specifications, as well in organizational, legal and policy recommendations [93].

The last aspect in the list of topics is the system requirements. Today there exist basically two competing communication standards, IEEE 802.11p [8] and 3GPP C-V2X [11]. The 802.11p is the basis for ITS-G5 [9] in EU, DSRC (WAVE) [10] in the U.S., and ITS [94] in Japan. The C-V2X standard from 3GPP is also called LTE-V or LTE-V2X in the LTE release 13, but C-V2X will also include new radio V2X (NR V2X) system, which is under development within 5G. The 802.11p standard is the incumbent V2V communication technology and was released 2010. The C-V2X is a new competing standard within V2V communication and was released 2016. The main difference between the two standards is presented in Table 4.1.

Table 4.1: The main features of the IEEE 802.11p and the C-V2X standards.

Feature	**IEEE 802.11p**	**3GPP C-V2X**
Main spec. released	2010	2016
Improvements	Initiated	Ongoing activity
Devices	Prod. samples	Test samples
Project phase	On the market	Tests planned
V2I support	RSU to deployed	eNB to be updated
Radio resources	CSMA/CA	SC-FDMA
Multiplexing	Time only	Time & Freq.
RX diversity	Not mandated	Yes
Time synch.	Not required	Required (GNSS)
Coding	Convolution	Turbo
HARQ	No	Yes

As mentioned before, 802.11p is already deployed on a small scale, but two automotive manufacturers have announced large scale deployment within a few years from now. For the C-V2X, only test samples exist of the transceivers, therefore only few tests have been performed. Regarding improvements of the standards, there are some discussions within the IEEE community to upgrade 802.11p and a working group called Next Generation V2X Study Group is initiated. In 3GPP, new releases of the standards are released within a time frame of 1-2 years, this will also be the case for C-V2X. However, 3GPP states that the basic features within C-V2X will always be backwards compatible with earlier releases. There radio resource management of 802.11p and C-V2X is totally different. The 802.11p standard is part of the 802.11-family, which all uses carrier sense multiple access collision avoidance technique (CSMA/CA) as the radio resource management. The C-V2X standard uses the same technique as the normal uplink in LTE, i.e., single-carrier frequency division multiple access (SC-FDMA), which uses both the time and frequency domain for transferring data. The 802.11p standard uses only the time domain for transferring data.

It is not easy to judge which of the two communication standards that is the best one. Both sides claim through white papers that their technology is the best. The issue with white papers is that they they can be highly biased and they are not peer reviewed. The capacity, the range, and the latency are the most critical system requirements for the V2V communication. Since none of the two standards have performed large scale tests in the sense that many vehicles are located closely together, no measurement of the capacity have been performed. However, several analytical evaluation and simulations have been performed and in Bazzi et al [95], comprehensive analytic evaluation is performed to show the capacity difference between the two standards. The conclusion in [89] show higher capacity for 802.11p at distances up to around 300 m, while C-V2X have higher capacity at larger ranges. The question is how long communication range that is needed? Ranges up to 300 m is good enough in urban environments, as well on highways during traffic jams. However, ranges up to 1000 m is desired in normal traffic on highways, but then the traffic density is much lower [96]. The latency is much shorter for 802.11p compared to C-V2X in general, since the direct V2V communication in LTE-V is scheduled through the base station in most cases, which introduce an extra delay [97]. Anyhow, for the V2V communication the latency is in the range of few milliseconds for both standards, which is good enough [96]. In congested situations, the delay is more unpredictable, especially for CSMA/CA, since in extreme congested situations the system will collapse.

When it comes to frequency spectrum, the 5.9 GHz frequency band is allocated in China, EU, and in the U.S. to safety related applications, as un-licensed frequency spectrum. Both standards will be used for safety related applications, but in the U.S. the 802.11p standard is the only standard that is allowed to be used according the Federal communication commission (FCC) [98, 99]. In EU, the frequency regulation is technology neutral, but the ETSI EN standard [100] needs to be fulfilled since it is a regulatory document. The [100] defines that CSMA/CA shall be used as the radio resource management. So, how C-V2X will get access to the EU and the U.S. market is unclear at the moment. In

China the C-V2X technology is preferred.

Two questions that are seldom brought up are the radio resource management between different mobile network operators for C-V2X and the penetration of V2P communication. Even though 3GPP has standardized the scheduling mechanism on the physical layer, they have not yet solved how the scheduling shall be handled for the hand-over scenario, from one operator to another operator. An issue that needs to be solved before deployment of C-V2X [101]. The other question is regarding V2P communication, will that happen? 3GPP mention that this is a key benefit with the C-V2X technology. Independent of 802.11p or C-V2X, these chipsets have to be automotive qualified chipset, which are much more expensive compared to consumer chipset due to smaller volume and tougher requirements. The following question is, will there exist 802.11p or C-V2X consumer chipset in the future, either based on WLAN-chipset or 4G/5G-chipset? These chipsets will be more costly compared with the chipset without these technologies and the use case is not obvious. One use case though, is V2P communication to detect hidden pedestrians or bicyclist behind corners or other large objects. The drawback is that the power consumption will increase in the smartphone to enable this use case. So, will the consumers of smartphones pay more for their smartphone and at the same time get reduced stand by time?

To summarize, the history repeat itself. Around 20 years ago, there was a battle between 802.11a and HiperLAN(1/2) for WLAN and 802.11a won that battle. Now, we have a battle between 802.11p vs C-V2X and who will win is difficult to say. Anyhow, the only thing that matters, the longer time we wait until we start to deploy V2V communication, less number of lives will be saved!

Chapter 5

Summary and Contributions

This chapter summarizes the research contributions of the papers included in the thesis together with some overall conclusions both, academic and industrial, and topics for future work.

5.1 Research contributions

5.1.1 Paper I: On Multilink Shadowing Effects in Measured V2V Channels on Highway

Vehicles that use V2V communication will time to time shadow each other and a possible degradation of the communication can occur. To overcome this degradation, the V2V communication protocol in EU, ITS-G5, has the possibility to use mutlihop techniques to forward messages from one vehicle to another. For an efficient implementation of multihop techniques, knowledge of the multilink shadowing effects is important. However, these effects are not yet well understood and therefore in this paper we present a measurement based analysis of multilink shadowing effects in V2V communication systems with cars as blocking objects. Our focus has been to analyze and characterize the joint large scale fading when four cars were driving on the highway in different scenarios. All cars were equipped with transceivers using the 802.11p standard i.e., the lower layers of the ITS-G5 communication protocol stack (no multihop implemented), operating at the 5.9 GHz frequency band. From our analysis it is found that the coherence time of the large scale fading process for different communication links can vary from a few seconds to minutes. So even though that the transceivers transmit with a high repetition rate the receiving car can be shadowed in the range of minutes and will experience long periods with received power levels being much lower than predicted by the path loss model only. The results also show that it is essential to consider the cross-correlation of the large scale fading processes of different V2V communication links. The cross-correlation coefficients can have both large negative and large positive values. For the multihop technique in ITS-G5 it is therefore important to use links that receive signals with high concurrent received power levels to overcome the issue with shadowed cars. The measurements give a clear indication that this approach can be successful.

5.1.2 Paper II: A Measurement Based Multilink Shadowing Model for V2V Network Simulations of Highway Scenarios

Despite the fact that for multilink systems it is essential to model the correlation of the shadowing process for different links, as mentioned in Paper I, VANET simulations often neglect this cross-correlation, with only a few exceptions. In this paper, further analysis has been performed on the data from Paper I and the results show the importance of separating the measurement data into LOS and OLOS cases due to the distinct differences in received power as a function of distance between TX and RX. In addition, when estimating path loss model parameters each link should be estimated separately (not all links together, which is common). An improved two-ray path loss model for the LOS case to account for differences in antenna gains, car bodies, and antenna pattern is also presented. We have demonstrated that the applied path loss model has a large impact when estimating the correlation functions and our findings show that a two-ray model for LOS cases and a single slope model for OLOS cases are appropriate ones. These models yield estimates for the de-correlation distance that are smaller compared to a joint path loss model (LOS and OLOS data together). For the multilink shadowing effect we are presenting two simple linear regression models; one when using a joint path loss model for all links including LOS and OLOS cases, and another one when using a path loss model for each link, as well LOS and OLOS cases separately. The results show that joint model has a much longer de-correlation distances for both the auto-correlation and the cross-correlation. For the ross-correlation model, the de-correlation distance is only 24 m, resulting in limited probability of simultaneous large scale fading dips. By this, we conclude that it is important that VANET simulators use geometry based models, that distinguish between LOS and OLOS communication. Otherwise, the VANET simulators need to consider the cross-correlation between different communication links to achieve results close to reality.

5.1.3 Paper III: A Path Loss and Shadowing Model for Multilink Vehicle-to-Vehicle Channels in Urban Intersection

It is quite remarkable that so little attention has been paid so far to develop NLOS path loss models for V2V communication in urban intersections, since these are one of the most safety critical scenarios for V2V safety applications. An exception is the model by Mangel et al., but that path loss model has its limitations, the model is, e.g., not reciprocal and the blocking effects of other vehicles are not included. We propose a measurement based reciprocal V2V NLOS path loss model, for intersections, comprising single interactions from the intersection center area together with multiple interactions from the building walls. Our model is based on a measurement campaign with four cars and two trucks driving in two different groups at two different types of intersections in Gothenburg, Sweden. The received power in our measurements was generally higher compared to what is predicted with the Mangel model. The communication links will have longer ranges with our proposed model compared to the cases using the Mangel model, another aspect is that interference levels from other vehicles will increase. The analysis of PSR show that the probability to receive information from another vehicle around the corner approaching the same intersection is rather high before the moment when it is too late to take actions to avoid a collision. As mentioned in Paper I and Paper II, the different vehicles in an VANET will shadow each other sometimes. Using our proposed NLOS path loss model, the de-correlation distance of the shadowing process is around 2-4 m. By using the proposed path loss model, the analysis shows that the cross-correlation between different links is small, even for communication links with antennas located at the same vehicle. Overall, the same conclusions as in Paper II are highlighted also here namely, that geometry based models should be used for VANET simulations. By doing so, and using an appropriate path loss model, the de-correlation distance can be close to what is experienced in reality and cross-correlation can be neglected. The latter will make the implementation of realistic models in VANET simulators much easier.

5.1.4 Paper IV: Multipath Propagation Simulator for V2X Communication Tests on Cars

This paper shows first measurement results, world wide, of using a MPS on a car for a integrated wireless communication system. Verifying the wireless communication performance of, e.g., 3G or 4G systems today is done by field trails, which is time consuming and therefore costly. In addition, the tests are not repeatable since you can not control neither the traffic nor the radio environment. An OTA test method like MPS is used when testing performance of, e.g., smartphones. A method that is standardized both by 3GPP and CTIA, where both the test setup and channel models representing different real life scenarios is defined. To scale up the test method to suit a large car can result in specific issues and disturbances. In this paper we experimentally, by using design of experiments (DOE), study how different design parameters of the multipath propagation simulator affect the received signals. The value of the regression coefficients depends on the different DOE setups but the overall picture shows that the signal environment within the MPS is well under control and the concern about large size of the test objects could cause specific disturbance can be rejected.

5.1.5 Paper V: Measurement Uncertainty, Channel Simulation, and Disturbance Characterization of an Over-the-Air Multi-Probe Setup for Cars at 5.9 GHz

To get a deep knowledge and understanding of the uncertainty of the MPS and the disturbances within it, this paper follows up the initial results from Paper IV. To do so, three experiments were performed on an OTA multi-probe setup for cars at 5.9 GHz: measurement system analysis (MSA), channel sounder measurements, and probe coupling measurements. Four issues were in focus for the analysis; precision, realization of the wireless communication channel, coupling between the probes, and the influence of the test object size. The MSAs show that the precision of the chosen response metrics as defined by expanded uncertainty, u_e is below ± 0.86 dB, a level that would not violate best practice total uncertainty levels for comparable OTA methods. When the difference between performance on the RX antennas are larger than u_e the MSAs also show that the repeatability and reproducibility are under control, $G_{R\&R} < 9\,\%$. With the presented setup with eight TX antennas the analysis of the channel sounder measurements shows that generation of a desired wireless communication channel is possible. The coupling between the TX antennas in the multi-probe ring seems not to be a big problem since the disturbance level from other TX antennas than the transmitting TX antenna is -56.6 dB for horizontal polarization and -58.1 dB for vertical polarization. The size of the test object has an influence on the disturbance level, but only to a small degree. The conclusion we make from all above is that the OTA multi-probe setup is a way forward for an efficient way of characterizing today's wireless communication systems for cars.

5.2 General Conclusions and Future Work

Verification methods of wireless communication performance and robustness for automotive applications have been the desired outcome of my research. Have I achieved this goal? In this section I will present some general conclusions and future work of the subject, as well, hopefully answer the question.

Today's field trails are time consuming, costly, and not repeatable. Using field trails to verify the communication systems installed in cars is therefore not a way forward. Replacing field trails with verification methods performed in lab environments, requires deep knowledge of both the propagation channel characteristics of the V2X communication system together with the possibilities and limitations with different test setups.

The propagation channel for V2X communication is a complex process, especially for V2V communication, and is a highly dynamic channel. The channel has a significant effect on the received signal and the overall performance of the communication system. Therefore, it is important to characterize the channel properties by measurements or by, e.g., ray-tracing simulations. To describe the channel in a simplified way, different channel models have been presented in the literature, where the characterization parameters have served as a basis. Several measurement campaigns have been performed by researchers and engineers during the years to characterize the channel used for V2X communication. Different kinds of measurement setups have been used. One example is sophisticated instruments for channel sounding, where detailed information of the channel can be extracted from the recorded data. Another example is measurements with system specific transceivers designed for the V2X communication system. The bottleneck with channel sounding measurements is you normally only have one TX and one RX since the instruments are costly. Measuring with system specific transceivers on the other hand, the sampling rate and the bandwidth is often too low to be able to catch the small scale fading effects. In both cases, the measurements found in the literature, were typically done with test antennas and not production like antennas.

In our research we have performed measurement campaigns with system specific transceivers and production like antennas, and we have studied the effects of the production like antennas causes. We have estimated the effects that the antenna pattern and car body have on the path loss, and included antenna related parameters in the two-ray path loss model that we propose for LOS communication on highways. Regarding the spatial autocorrelation of the shadowing process, also here the impact of the antenna gain pattern has been analyzed. We have shown that the shadowing process is a non-zero mean Gaussian process if the influence of the antenna pattern is not removed when estimating the large scale fading, resulting in a very large de-correlation distance. However, removing the effect of the antenna pattern results in much lower de-correlation distance. An example of this we could observe when splitting the recoded data from measurements in an intersection into two sections, before and after the intersection. The reason for the reduced de-correlation distance, is that a omni-directional antenna at 5.9 GHz in free space is definitely not omni-directional when it is mounted on a car, due to curvature of the roof and possible rails on the roof. We could also see that the effect of the antenna pattern is so large, that the cross-correlation of the large scale fading process between two communication links, where the TX car is the same but the RXs antennas are mounted on the same car, is low.

We have also shown the importance to classifying the communication into LOS, OLOS, and NLOS cases. As mentioned above, an improved path loss model for LOS cases on highways is presented. We have validated the single slope path loss model for OLOS cases on highways, and we propose a new path loss model for urban intersections, which is reciprocal and consider other vehicles blocking the LOS to the intersection center.

From the V2V multilink communication measurements we have performed with system specific transceivers, we have been able to study the joint multilink shadowing effects, i.e., the cross-correlation of the large scale fading processes. We have presented two models of the cross-correlation as a function of the difference in distance between two RX cars driving on a highway. The two models use different path loss models as input. Using the path loss models we propose and distinguishing between the LOS cases and the OLOS cases, the cross-correlation can be neglected. By that, we stress the importance that VANET simulations should be based on the geometry and use different path loss models for the LOS and the OLOS cases. Doing so, it is not necessary to explicitly implement the cross-correlation model into the VANET simulator, which will make the situation much easier.

Future work as we see it within channel characterization, is that our proposed NLOS path loss model for urban intersections should be validated in other type of intersections and urban surroundings before one can claim that this model is generic. Another task, is to perform new multilink channel measurements with equipment that can also catch the small scale fading effects.

The verification methods developed in the telecom industry and academia have been the basis of our research to find a suitable verification method for automotive applications. In addition, the gained knowledge with channel models and its characteristics have also been used as input to the research we have performed in OTA verification methods.

The OTA verification methods can be classified into three main methods, anechoic chamber methods, reverberation chamber methods, and indirect methods. Our focus has been on anechoic chamber methods and some investigations on indirect methods. The reason why we not have been investigating the reverberation chamber method is that the isotropic field this method generates is not representative for V2X communication, where most of the received signals by the car is coming from the azimuth plane. Comprehensive research have been performed by others on different kinds of test setups within the anechoic chamber method and different ways of generating the desired propagation channel. A common understanding for OTA multiprobe setup within an anechoic chamber, is that the antennas mounted on the DUT must be within the test zone when testing MIMO systems. With a reasonable amount of probes, the test size normally is between 0.5 to 1 wavelengths, i.e., a test size large enough for measuring smartphones but definitely not a car. However, we wanted to challenge this common understanding and see if it anyhow is possible to use the OTA multiprobe setup as an verification method for cars.

We first tested if the OTA multiprobe setup could be used on a SISO system at 5.9 GHz, i.e., the frequency band 802.11p is using. We identified which parameters that influence the measurement results by performing several design of experiments. Further, we performed a measurement system analysis on the defined test setup. The results show that the repeatability and reproducibility is under control. In addition, both a channel with Rayleigh distribution and a channel corresponding to specific V2V communication scenarios on highways are possible to achieve. By this, we conclude that for SISO systems it is possible to use the OTA multiprobe setup with as few as eight probes. Unfortunately, we do not have data to analyze the spatial correlation, so we can not say that this test setup is possible to use for MIMO systems when the DUT is a car. This is left for future work.

Initial studies have also been performed on the indirect method - radiated two-stage aka wireless cable. These measurements were performed on a MIMO LTE system mounted on a car. We are still working on analyzing the data but other researches have also performed similar measurements on a car and the results looks promising. Further work will be performed.

Back to the question, have I achieved the goal, verification of wireless communication performance and robustness for automotive applications? The knowledge of the propagation channel for V2X communication has increased and two promising OTA verification methods have been identified. By these results, Volvo Cars will be able to reduce the field trails in the future and implement robust V2X systems that both can save lives and reduce CO_2 emissions.

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