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Vehicle-to-Vehicle Communication

Measurement of Reliability and Range of Car2X Sensors and Development of a Car2X Sensor Model

MASTER'S THESIS

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AFFIDAVIT

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Signature

Acknowledgement

Mainly I would like to thank my family. During my telematics studies I got great support by my mother, my father and my sister. Therefore, I have to thank these three persons for being present, when help concerning the life outside of the University was needed.
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Abstract

Nowadays a considerable amount of devices are communicating and interacting to provide a smart environment for the users. These devices are not only smart phones or computer but also kitchenware and other everyday objects. Through this network of different devices with different jobs the life is becoming smarter and in most cases simpler. Car2X describes the communication between vehicle amongst themselves and information exchange with road infrastructure. The benefits of Car2X are not only a smarter or simpler usage with vehicles but rather smarter safety functions are possible, for instance, when infrastructure provides information about dangerous driving conditions via Car2X. Therefore, Car2X is becoming a significant part in the automotive industry and first prototypes are waiting to be realized in product line. Therefore, first steps to become familiar with the technology were required.

The first part of this thesis is set up on the results of the previous seminar project. The results were measured data of Car2X tests in different areas and scenarios. The measured scenarios cause a high amount of data and the supported analysis software by the measurement unit manufactures was not satisfying for Car2x analysis. Therefore, the raw measurement results of the seminar project were post-processed depending on the areas and blocking objects between the cars. Differences in range and reliability were illustrated in GoogleEarth and possible performance reasons were discussed. This classification splits the measurement results in area and environment classes and analysed tests were documented in tables. Intersection scenarios were analysed more specific because of the high dispersion depending on the intersection's geometry.

In a next step, effects of wireless propagation were studied and different existing wireless models were analysed. Depending on the results of the seminar project, a combination of geometric and stochastic models were chosen. Furthermore, this model was split into a specific model of intersections in urban and suburban areas and a general model to fit motorway, rural and suburban characteristics. After parametrisation of the models an evaluation was done.

Car2X performance is highly depending on the environment and the surrounding interacting objects. Objects can attenuate or support the wireless propagation of the Car2X. Therefore, the performance of the simple model is considerably depending on the manifold different areas and interacting objects. Furthermore, the developed model is deterministic and real time capable. This are key features for a model which should be able to used in vehicle dynamic simulators.

Kurzfassung

Eine Vielzahl von Geräten ist nicht nur auf die eigene Funktion beschränkt, sondern interagiert und kommunziert mit anderen Geräten. Diese Geräte sind nicht nur Smartphones und Computer, sondern auch zunehmend Haushaltsgeräte oder andere Alltagsgegenstände. Durch diese Vernetzunge verschiedenster Geräte wird in den meisten Fällen das Leben vereinfacht und eleganter gestaltet. Car2X beschreibt die Kommunikation von Fahrzeugen untereinander und den Informationsaustausch mit der Infrastruktur. Die resultierenden Vorteile für eine solche Kommunikation sind nicht nur eine Vereinfachung sondern auch ein Zugewinn für die Sicherheit. Ein Beispiel hierfür ist eine Infrastruktur die Information über gefährliche Straßenverhältnisse an die Fahrzeuge übermittelt. Darum ist Car2X eine wachsendes Teilgebiet der automotiven Branche. Auch mögliche Einsatzgebiete werden schon diskutiert und warten auf ihre Realisierung. Darum ist es wichtig sich schon während des Entwicklungsprozesses damit zu beschäftigen. Die Masterarbeit ist eine weiterführende Arbeit, die auf ein Seminarprojekt aufgesetzt ist. Die dynamischen und teilstatischen Messergebnisse unter verschiedenen Bedingungen wurden als Ausgangspunkt dieser Arbeit benutzt. Im ersten Teil dieser Arbeit wird über das Post-Processing der Messdaten und eine Analyse berichtet, die sich in weiteren Schritten immer weiter verfeinert hat. Die Unterschiede der erreichten Distanzen wurden via GoogleEarth illustriert und mögliche Ursachen diskutiert. Kreuzungszenarios waren sehr abhängig von der Kreuzungsgeometrie und daher wurden diese Messungen besonders behandelt.

Der zweite Teil dieser Arbeit beschäftigt sich mit Wellenausbreitungseffekte und mit der Auswertung und Analyse bestehender Modelle für Wireless Car2X Kommunikation. Aus diesen Modellen wurde eine Abwandlung für dieses Projekt gewählt. Das Modell selbst beinhaltet ein spezifisches Modell für Kreuzungen und ein allgemeines für verschiedene Umgebungen wie Autobahn, ländliches Gebiet und vorstädtische Siedlung. Danach wurden die Modelle entsprechend parametrisiert und evaluiert.

Car2X-Kommunikation ist sehr abhängig von der Umgebung und den vorhanden Objekten. Objekte in einem Testfeld können die Verbindung stärken oder auch schwächen. Das Modell beschreibt trotz der manigfaltigen Möglichkeiten an Geometrie und Objekten die Car2X-Kommunikation sehr beachtlich. Darüber hinaus ist das Modell deterministisch und echtzeitfähig. Das sind Eigenschaften, die für eine Einbindung in einen Fahrsimulator essentiell sind.

Contents

Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ADMA	Automotive Dynamic Motion Analyzer
CAM	Cooperative Awareness Message
CAN-BUS	Controller Area Network Bus
Car2X	Term for I2V, V2I and V2V Communication
CUA	Cost-Utility Analysis
C2C-CC	Car-to-Car Communication Consortium
DEB	Deterministic Behaviour
DENM	Decentralized Environmental Notification Message
ETSI	European Telecommunication Standards Institute
GPS	Global-Positioning-System
HiL	Hardware in the Loop
ITS	Intelligent Transport Systems
I2V	Infrastructure-To-Vehicle Communication
LOS	Line-Of-Sight
MD	Mathematical Description
MOVE	Mobility Model Generator for Vehicular Networks
MPC	Multipath Components
NLOS	Non-Line-Of-Sight
NS	Network Simulator
OSI-Model	Open Systems Interconnection Model
PDF	Probability Density Function
RTCA	Real-Time Capability
RX	Receive
SPL	Simplicity
SUMO	Simulation of Urban Mobility
VU	Vehicle Usage
TX	Transmit
V2I	Vehicle-To-Infrastructure Communication
V2V	Vehicle-To-Vehicle Communication

Symbols

Variables

λ	wave length of transmission frequency
AE	area exponent
d_b	breakpoint distance
d_r	distance receiver to middle of intersection
d_t	distance transmitter to middle of intersection
e	absolute error
e_{rel}	relative error
EE	environment exponent
E_L	loss exponent
E_S	street exponent
E_T	transmitter distance exponent
h_t	height of transmitter antenna
h_r	height of receiver antenna
i_S	boolean parameter for suburban loss
L_P	attenuation from transmitter to receiver antenna
L_S	loss from antenna to interpretation unit
L_{SU}	curve shift loss for suburban area
pdf_{Nak}	Nakagami probability density function
P_{RX}	receiving antenna sensitivity
P_{TX}	transmitting antenna power
w_r	width of receiver's street
x	distance between to Car2X systems
x_t	distance transmitter car to wall
x_{solid}	measured solid distance between to Car2X systems
x_{model}	calculated model distance between to Car2X systems

1 Introduction

1.1 General Information

Vehicle-To-Vehicle(V2V), Vehicle-To-Infrastructure(V2I) and Infrastructure-To- Vehicle(I2V) are becoming important topics and vehicle manufactures will deal with in the future. There are several different definitions of the three types of communication, but a well used term is Car2X and therefore it is preferred in this master thesis. There are still three main country-specific standards in progress. A consortium of experts, technology suppliers, and manufactures are still working to develop the three standardisation and realization for USA, Japan and Europe. For this master thesis standardization details are referred to the European standard. Figure 1.1 shows a Car2X propagation scheme. The figure is a schematic illustration of radio wave propagation and does not represent physical propagation.

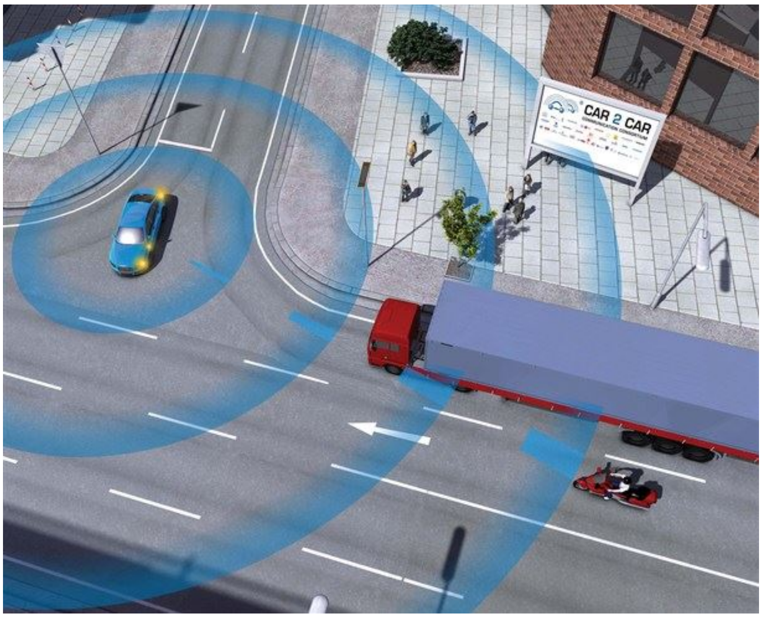

Figure 1.1: Car2x propagation scheme. Source: [9]

The European standardization is based on the IEEE 801.11p standard [18]. The IEEE 801.11p defines the physical and data link layer related to the OSI-Model (Open Systems Interconnection Model). On this fundamental description the European Telecommunication Standards Institute (ETSI) and the Car-to-Car Communication Consortium (C2C-CC) are building up the layers of the OSI-Model description and standardization [6].

C2C-CC is an association of vehicle manufactures (e.g. Volkswagen, BMW, Volvo, Renault), suppliers of vehicle manufactures (e.g. Swarco, Bosch, Continantal), research organisations and academic institutes [9]. Therefore, C2C-CC represents a considerable benchmark for the development progress.

The general European Car2X standard is called ETSI ITS-G5 (ITS ... Intelligent Transport Systems). The progress is now on the stage of the first simple realization and will increase to a standardization book including all Advanced Driver Assistance Systems (ADAS) handling standardization.

1.2 Car2X Standard Information related to Master Thesis

This master thesis deals with physical behaviours of Car2X. The operation frequency is 5.9 GHz and some channels with slightly higher or lower frequency. The bandwidth of all channels is 10 MHz. Figure 1.2 shows the bands of the ETSI ITS-G5 standard. The different bands are dedicated to different tasks. The transmitter power is set to 25 dB and and the receiver's sensitivity is -95 dB [13]. The network is a so called ad-hoc network. Ad-hoc networks are managed by the clients and no master or main device is included. Therefore, no infrastructure is needed to build up an ad-hoc network. The benefits of an ad-hoc are smallest possible latency time, network load is highly localized and local privacy. [18]. Furthermore a considerable advantage is the high flexibility [14].

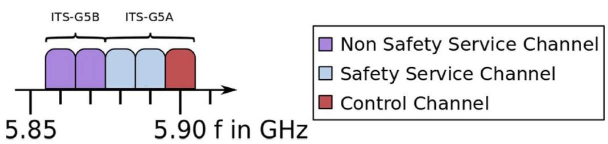

Figure 1.2: Channel assignment. Source: [18]

Several types of messages will be available. An important message type is Awareness Messages (CAM). Every client in the network sends this notification periodically to all in the area of the signal propagation. The message includes some basic information like Global-Positioning-System-Coordinates (GPS-Coordinates), type of client (Infrastructure, Truck, Car, ...) and so on. Figure 1.3 shows the whole format of CAM. The CAM message gives a considerable information of other Car2X featured road users. This message will be part of a first realization when the market gets penetrated by Car2X systems [6].

Length[byte]	Field		
1	messageId (0=CAM, 1=DENM)		
8	generationTime		
4	StationId		
1	StationCharacteristics	mobileITSStation	
1		privateITSStation	
1		physicalRelevantITSStation	
8+8+4	ReferencePositon	Longitude/Longitude/Elevation	
4		Heading	
32+4		Streetname/RoadSegment ID	
1		Position/Heading Confidence	
1	CamParameters	vehicleCommonParameters	vehicleType
2+2			Length/Width
4			Speed
2			Acceleration
1			AccelerationControl (break, throttle, ACC)...
1			exteriorLights
1			Occupancy
1+1			crashStatus/dangerousGoods

Figure 1.3: CAM format. Source: [18]

The CAM is highly relevant for safety. For instance, information about tail end of jam, rear end collision and intersection assistance will be application relying on CAM. Due to different tasks the CAM is split to different cases with different periodic frequency [18]. Table 1.1 shows the different use cases relying on CAM with the varying minimum frequency. Depending on the priority of a use case the periodic transmitting frequency of CAM is higher or lower. If the channel is nearly overloaded concerning a huge traffic jam the transmitting frequency of CAM is decreased by each client [20].

Use Case	min. Frequency Hz	min. Latency ms
Emergency Vehicle Warning	10	100
Slow Vehicle Indication	2	100
Intersection Collision Warning	10	100
Motorcycle Approaching Indication	2	100
Collision Risk Warning	10	100
Speed Limits Notification	1 to 10	100
Traffic Light Optimal Speed Advisory	2	100

Table 1.1: Overview use cases based on CAM. Source: [20]

First noticeable realizations of Car2X in vehicle will be a alert for the drivers. Perhaps the alert will be a red light or information on the infotainment screen [8].

Another important message type is Decentralized Environmental Notification Message (DENM). DENM are not sent periodically but event triggered messages. In case of this master thesis DENM was not used, but it is a necessary message type. An event for a DENM can be hard braking, accident, construction work, icy road and much more. The scope DENM is localized in certain environment [18]. Figure 1.4 shows the format of DENM. DENM is also transmitting position. But in comparison to CAM, the DENM includes the position of the depending situation.

Length[byte]	Field	
1	messageId (0=CAM, 1=DENM)	
6	generationTime	
4	Management	Originator ID
2		Sequence Number
1		Data Version
6		Expiry Time
1		Frequency
1		Reliability
		IsNegation
1	Situation	CauseCode
1		SubCauseCode
1		Severity
4	LocationContainer	Situation_Latitude
4		Situation_Longitude
2		Situation_Altitude
4		Accuracy
N-40		Relevance Area

Figure 1.4: DENM format. Source: [18]

1.3 Motivation

Car2X standardization is in progress by wireless standardization institutes and vehicle manufactures. The development of the standard is a consensus of different key features, e.g., safety and privacy. The benefits of Car2X are not only smarter and simpler handling of vehicles in traffic, but rather existing safety functions will becoming smarter. A Car2X featured vehicle is not only analysing the environment by the included sensors but also informations of infrastructure and interacting road users are available. Therefore, vehicles know the other vehicle's intention not only by the vehicle's sensors but also by the other vehicle itself. Another benefit is the range and reliability of Car2X. In comparison with radar sensors, Car2X featured vehicle can get information of other Car2X clients hidden by objects. Also the possible distances of Car2X wireless connection are larger than those of usually used radar sensors. Therefore a hybrid system, which is build up with Car2X and radar sensors, would cover a high amount of critical cases because the benefit of Car2X's range and radar sensor's precision are merged. Vehicle safety system would also be smarter if the infrastructure would send information about the road. Therefore, it is necessary to become familiar with Car2X. A way to approach this issue is done in this master thesis.

Furthermore the interconnection mobility will be 4 times bigger in 2020 than today and the automotive sector will be a considerable part of this increase. [22] As a result, the smart mobility and connection of all kind of devices is a coming part of life.

1.4 Content of Thesis

This master thesis is based on a seminar project [12]. The aim of the previous project was to become familiar with the new ordered hardware at the Automotive Engineering Institute (Part of Graz University of Technology). Afterwards, scenarios that would be interesting according to reliability and range were defined and tested in real areas. The gained measurement data were post-processed to illustrate them in GoogleEarth. Therefore a easy analysis without a need of license was done. Car2X is highly depending on the environment and interacting objects. Objects can support or attenuate the the wireless propagation. Therefore, GoogleEarth is preferred for the analysis because static interacting objects can be simply detected. The possible reason for the performance results in different areas are discussed and documented.

Second a model fitting the real Car2X system was required. Models for the propagation behaviour are necessary, because dangerous cases can be observed in a simulation. Furthermore one requirement of the model is the integration in a vehicle simulator. Therefore, the model has to be able to run in real time for a later Hardware in the Loop (HiL) implementation. A complex model with a high amount of parameters needs in most cases a high amount of data. Therefore, wireless propagation effects and realization of models are discussed. Furthermore, in this chapter the reasons for choosing the model and its realization are explained. It was realized in MATLAB®. Furthermore, two types of models were developed because of the special handling of intersections. Intersections need an additional model input because the measured scenarios were highly depending on intersection's geometry.

The third chapter discusses the different parts of the project. This project was a first contact with Car2X hardware. Therefore it is necessary to discuss critical development steps of the master thesis, because later Car2X projects should be able to benefit from this work. Additionally to the documented project items, future work is presented.

The last chapter of the master thesis sums up the project. Considerable steps are discussed in short sentences and gives a short and concise overview.

2 Measurement Dataset

2.1 Source of Measurement Datasets

A previous seminar project [12] delivered the measurement results of dynamic and static tests of two with Car2X featured cars in Austria. The measurement setup includes two cars featured with measurement hardware. The results were logged data of the measurement hardware. GPS-Coordinates, velocity, available amount of GPS-Satellites, accelerations and so on were provided by an Automotive Dynamic Motion Analyzer (ADMA). The Car2X-Hardware, which was provided by CohdaWireless$^{\mathrm{TM}}$, were configured to be conform with ETSI ITS-G5 standard. Furthermore, some source code modifications for the measurements were done [12]. On every periodic transmission (TX) and receiving (RX) message a notification via Controller Area Network Bus (CAN-BUS) was sent to the measurement unit. This setup was installed in both cars.

2.2 Scenarios

As described in the section above the measurement results were provided by a previous work. The work was the beginning part of two student projects at two different institutes. Hence, different measurement maneuvers categories were required. In case of this master thesis the main focus was to get good reliability and range performance results. The other institute was interested on more specific testing in intersections. Therefore, different scenarios were defined.

2.2.1 Dynamic Scenarios

The requirements of dynamic scenarios were defined as measurements of contraflow and convoy at different velocities. Hence the areas of these scenarios were on the motorway, rural and suburban environment.

2.2.2 Semi-Static Scenarios

In cases of semi-static measurements only one car was moving while the other stayed on the same GPS-Coordinates during the whole measurement time. This measurement was done at motorway areas.

2.2.3 Intersection Scenarios

This type of scenario is a specific case of the semi-static scenario. In this case one car stayed in a 90 degree intersection with different position to the middle of the intersection. The other car was coming along the intersecting road.

2.3 Post Processing of Datasets

The measurement hardware is made for high precision dynamic tests. Therefore, a high number of measurement values in time were logged. Also a software is available to simulate and analyse this kind of measurements. In case of the master thesis a more elaborate analysis was required. After several measurements, a high dispersion depending on the surrounding was detected. Therefore surrounding buildings, plants, bridges and so on should be analysed as well.
A good solution was the processing of the data to illustrate it in GoogleEarth. Due to this solution, surrounding buildings that could cause dispersions are simple to detect. Furthermore several trivial length measurements could be done in GoogleEarth and the required precision is good enough for Car2X performance tests in case of the master thesis.

2.3.1 GoogleEarth icons

Several icons, which are shown in Figure 2.1, were made to illustrate points of interests in the GoogleEarth map. The standard GoogleEarth data exchange of the measurement software provides only a line representing the driven route. So, no positions of lost, transmitted and received messages are illustrated with a standard export to GoogleEarth. Therefore several new icons were made to support later analysis. Also the cars are named EGO and TARGET in the the following chapters. Both cars are basically similar but EGO had an additional camera installed.

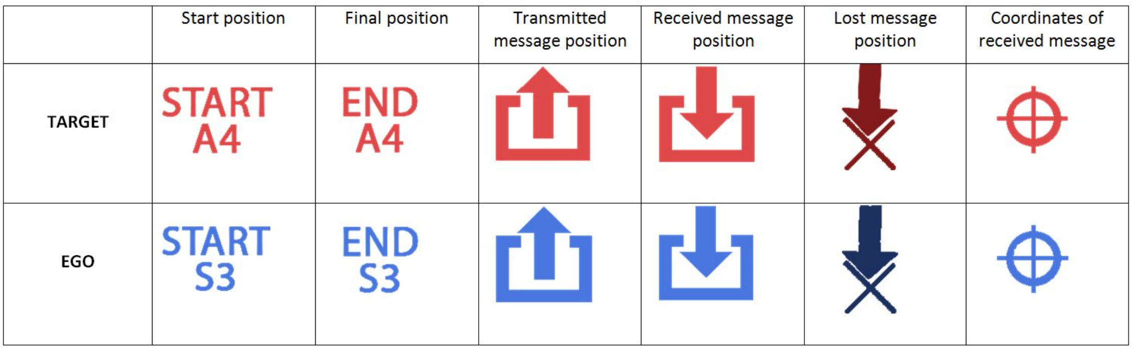

Figure 2.1: Created icons for points of interest illustrated in GoogleEarth.

2.3.2 GoogleEarth info boxes

Not only were icons made, but also info-boxes were created. The info-boxes can be opened by clicking on the icon.
Figure 2.2 shows the pop-up box of the start-icon. This info-box contains the identification number of the maneuver and a field for special occurrences and target velocity.

Figure 2.2: Pop-up box of start position icon.

The info-box of a transmitted message contains much more information than the start icon box. Figure 2.3 presents the transmitted and Figure 2.4 the received info box. These boxes are build up with the same features.

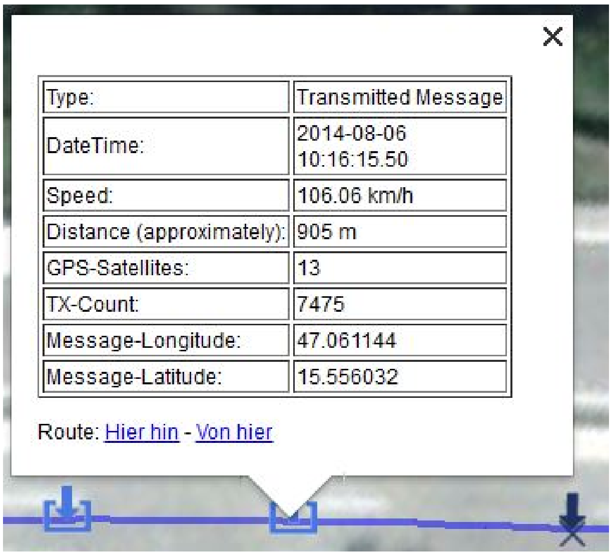

Figure 2.3: Pop-up box of transmitted message position icon.

The first field is the type, which can be 'Transmitted Message' or 'Received Message'.

The second field is the date and third the current velocity of the car. The distance was calculated with a spheric arc length approximation and is presented in the fourth field. The distances used in the model are measured via GoogleEarth and fluctuate due to the approximation. Furthermore the number of available satellites are shown in this box. The GPS-coordinates of the measurement unit are very accurate close to 2 cm precision. However, this precise system is highly depending on the number of satellites. The amount of satellites is decreasing when streets are getting smaller and boundary buildings are higher. The number of received and transmitted messages was counted in every car and is also displayed in the pop-up boxes. And last but not least the information about the location. GPS-coordinates are part of CAM and therefore these are also displayed.

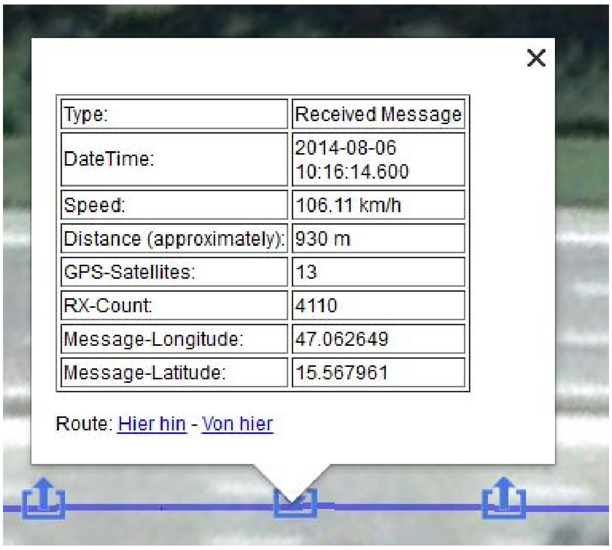

Figure 2.4: Pop-up box of received message position icon.

Due to the periodic transmission of messages, lost messages can be detected by computing the time between the received messages. Messages were sent every second and so the lost message position can be found. Further information was not available. This info-box is represented in Figure 2.5.

Figure 2.5: Pop-up box of lost message position icon.

The last icon supported by an info-box is the illustration of CAM coordinates. GPS-Coordinates are included in the CAM and as a result the position of the car is sent as well. The GPS-Coordinates are only stored values without any interpretation, therefore these coordinates of both cars were computed and illustrated in the GoogleEarth map too. Every car's Car2X hardware was counting the transmitted and received messages. This was implemented to guarantee that all messages were detected with the measurement hardware. The relationship between the received message and the computed position can be determined by the unique RX-Count, because it was declared as the same value in both boxes. Figure 2.6 shows this box. The corresponding icon shows the supposed location of the other Car2X system.

Figure 2.6: Pop-up box of received message coordinates icon.

2.4 Analysis

The analysis is performed for different cases, depending on the area and the maneuver. Therefore, not every combination of area and maneuver makes sense. Also, not every recorded measurement is presented in the following chapter, because otherwise the master thesis would explode in number of pages. The possible causes for striking long or short distance are discussed depending on the dataset. The interpretation of the CAM coordinates and transmitting icons are hidden to keep it clear for reliability and range performance determination.

2.4.1 Motorway

The motorway tests were also made in Austria. On Austrian motorways 130 km/h are allowed and in some cases it is decreased to 100 km/h or 80 km/h because of local emissions, high amount of vehicles, dangerous circumstances and tunnels. Therefore some tests, which were defined at a speed of 130 km/h, were tested with lower speed because of special speed limitation on the day of measurement.

2.4.1.1 Contraflow

Apart from different contraflow measurements on the motorway, one example is declared in this subsection. Both cars were set to a velocity of 100 km/h. In this example the motorway was limited to 100 km/h due to local emissions. The test cars were approaching themselves on the motorway at different direction. Figure 2.7 shows the GoogleEarth analysis at the first contact. The distance at this point is 1410 m and that is a surprisingly high value because there is non-line-of-sight (NLOS) between the cars.

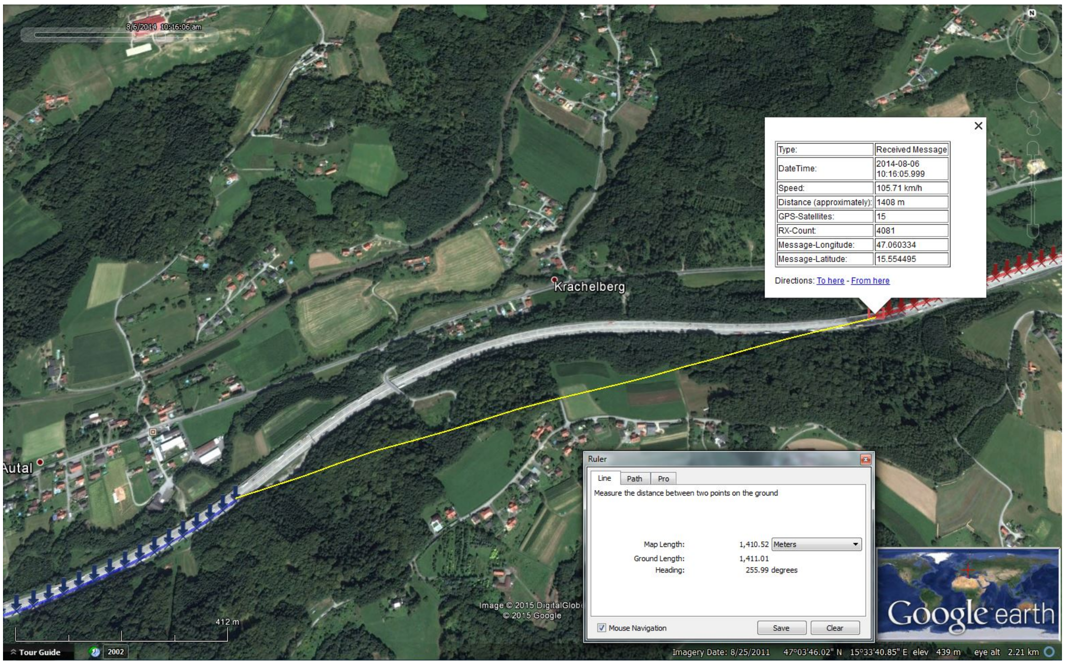

Figure 2.7: First contact at 1410 m contraflow on the Motorway.

A solid contact between the cars were established at a distance of 818 m, which is illustrated in Figure 2.8. This is also a good performance of the Car2X hardware. The same

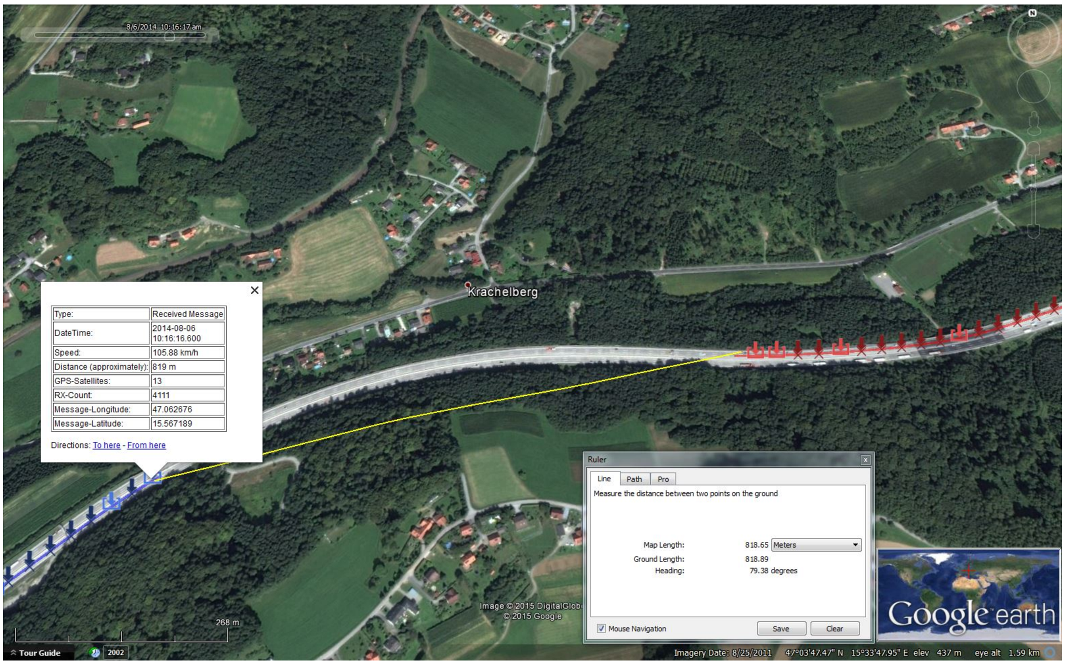

Figure 2.8: Solid contact at 818 m contraflow on the Motorway.

measurement was done by increasing the distance after meeting on the highway and the results are similar to the measurement of Figure 2.7 and Figure 2.8.

Figure 2.9: View out of EGO's front window.

This high performance of reliability occurred in most cases in the line-of-sight (LOS) cases. In cases of wood or other organic objects between, the field is influenced with a higher attenuation. The reason of the good performance in spite of the wood blocking LOS can be explained with the recorded video. Figure 2.9, that is a single frame of the EGO's video, shows the situation seconds before the cars were getting in wireless communication contact. On the right side, where the LOS-line is located is already wood. However, on the left side is a noise barrier installed. The surface of barrier is an additional supporting reflection and therefore ranges like LOS cases can be reached.

2.4.1.2 Convoy

In this scenario also both cars were moving on the highway. In contrast to the previous motorway measurement, the cars were driving in the same direction. During the measurement the following car's velocity was decreased until the connection was interrupted. Afterwards the following car was accelerated as long as the car was behind the front car. Consequently these tests delivered two performance results for one scenario.

Figure 2.10 shows the last solid connection during the distance between the cars was increasing. The solid contact ends at a distance of 645 m. Figure 2.11 represents the last transmitted message at a distance of 760 m.

Figure 2.10: Last solid contact at 645 m while increasing the distance.

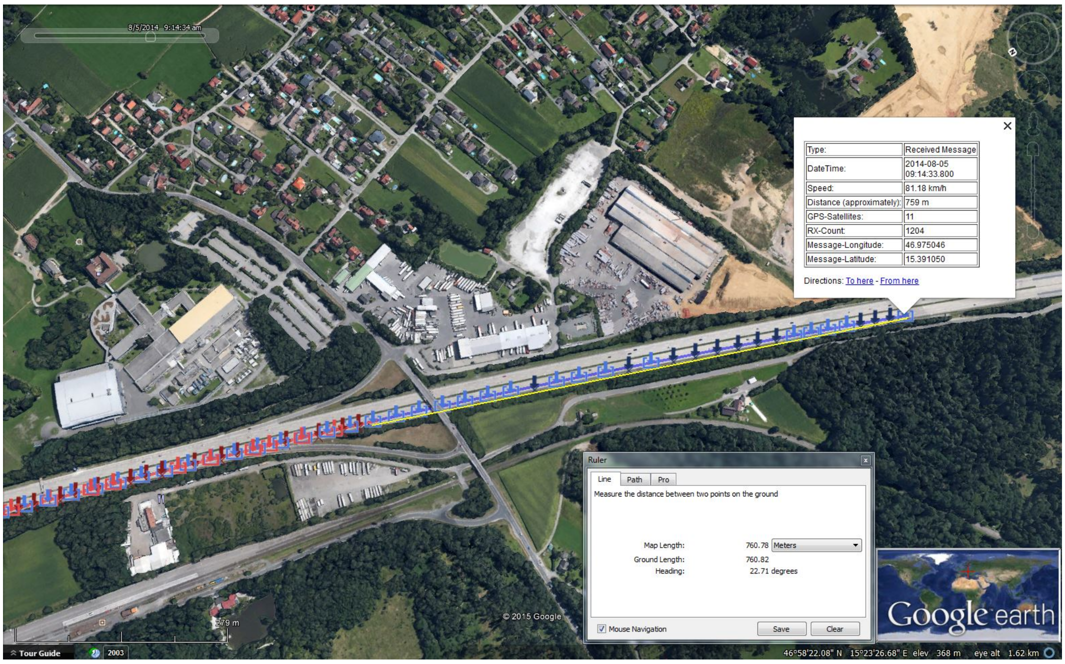

Figure 2.11: Last transmitted message while increasing the distance between the cars at 760 m.

Figure 2.12: View out of EGO's front window.

Figure 2.12 shows a screenshot of the recorded video by the measurement unit. Obviously, no attenuating objects are present. Therefore, this scenario example is classified to LOS. The performance results are nearly the same as in the above example. Analysing all three Figures 2.10, 2.11, 2.12 shows no visible reason for the slightly weaker result. Therefore invisible reason or simple fading are assumed.

2.4.1.3 Semi-Static

In this scenario one car parked during the whole time of measurement. In case of a motorway this may be problematic depending on the safety of the passengers and other road users. Therefore the non-moving car was parking in a motorway service area at the nearest point to the motorway. The motorway service area was not update to the GoogleEarth database at time of creating this master thesis and that is the reason the car seems to be parked in a field.

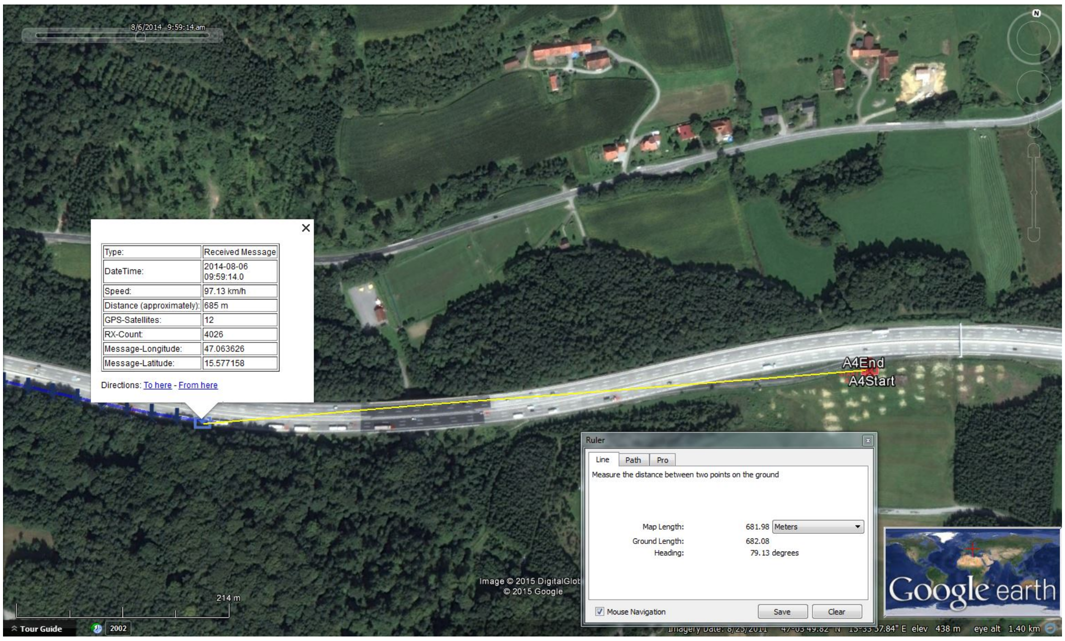

Figure 2.13: First wireless communication contact at a distance of 682 m.

Figure 2.13 and 2.14 illustrate the measurement and the reached distances. The longest distance of transmission was detected at a distance of 682 m and the solid contact was built up at 537 m. The results of the range measurement are again surprisingly high as in the previous scenarios. Despite of nearly LOS at the contact the distances are not as far. Also a reflecting noise barrier was on the supporting side to reflect some radio waves. The station's park area is placed higher and therefore the last section of the exit is a ramp and thus LOS is not guaranteed anymore. Figure 2.15 shows a single picture of the recorded video. On the right side of the picture the exit to the motorway service station can be seen. Hence some possible reasons were found, but a verification is not possible.

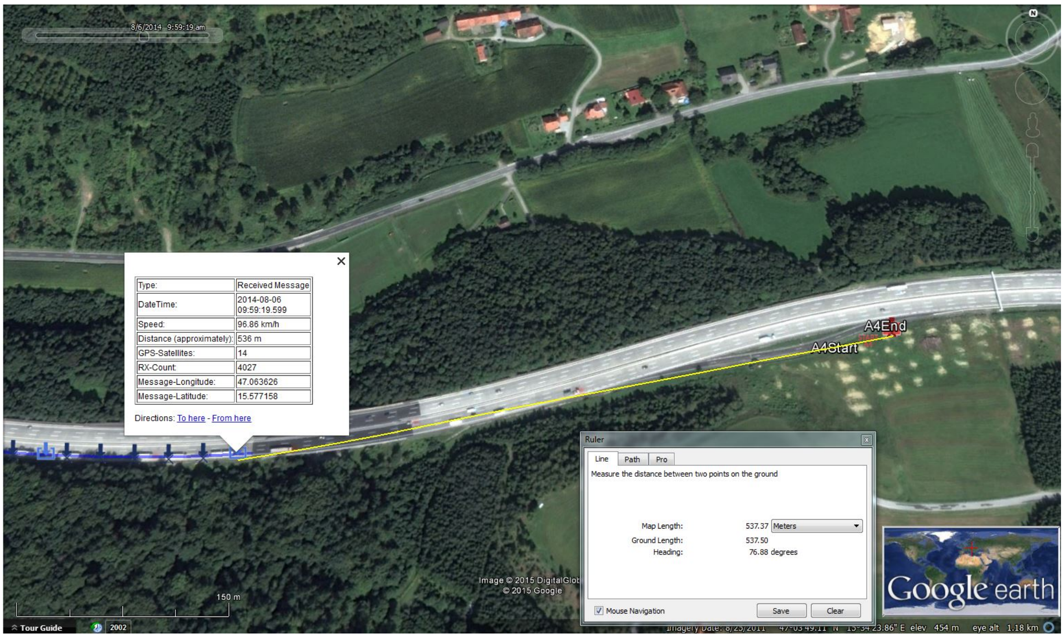

Figure 2.14: Solid contact at a distance of 537 m.

Figure 2.15: View out of EGO's front window.

2.4.1.4 Results

The communication dependencies on velocity (Doppler Effect) are low related to other effects. However, the influence of the slow periodic transmission (1 Hz broadcast messaging) leads to a maximum measurement error of 27.7 m at a speed of 130 km/h if only on car is moving. This maximum error is doubled by contraflow scenarios with two cars at a velocity of 130 km/h.
In addition to this measurement blurring by relative velocity, the environment around the interacting cars also are an important part of dispersion. One part of the environment dispersion can be described by the objects between a direct connection. Another part are supporting things, which are not placed directly between the cars, e.g, noise barriers on motorways.

Table 2.1 shows all measurement results including the three maneuvers previously analysed. The table contains the unique ID, the type of maneuver, the route, the date and more necessary the distances and the objects between a direct connection.

The last two examples and the first example are nearly the same when small measurement fluctuation is observed. Therefore, the contraflow and convoy can be handled as the same relating to this table. Regarding the scenarios, these two types have the highest relative velocity difference and the results are nearly the same. Therefore the semi-static based on lower relative velocity than contraflow and more than convoy, can also be treat as general.
For this reason, the scenarios of motorway measurement are not really necessary and have been ignored for further usage.

Furthermore, Table 2.1 shows no dangerous short distance, that would be to close to react on an event. Therefore, Car2X would improve the safety on motorway, e.g., traffic jam warning.

ID	maneuver	route	date	solid distance	objects between	maximal distance
				m		m
1	convoy	Graz to Lasnitz	04.08 2014	750	WOOD & WALL	920
2	convoy	Graz Lasnitz	04.08 2014	625	LOS	700
3	convoy	Sinabelkirchen to Ilz	04.08 2014	670	LOS	1200
4	convoy	Sinabelkirchen to Ilz	04.08 2014	710	LOS	880
5	convoy	Graz to Kaiserwald	05.08 2014	645	LOS	760
6	convoy	Kaiserwald to Mooskirchen	05.08 2014	710	LOS	1300
7	convoy	Kaiserwald to Mooskirchen	05.08 2014	650	LOS	1600
8	convoy	Mooskirchen to Steinberg	05.08 2014	460	HILL	520
9	convoy	Mooskirchen to Steinberg	05.08 2014	420	WOOD	580
10	convoy	Steinberg to Lannach	05.08 2014	620	LOS	690
11	convoy	Steinberg to Lannach	05.08 2014	890	LOS	910
12	semi - static	Graz to Lasnitz	06.08 2014	536	HILL	682
13	semi - static	Graz to Lasnitz	06.08 2014	500	HILL	570
14	semi - static	Graz to Lasnitz	06.08 2014	470	HILL	600
15	semi - static	Graz to Lasnitz	06.08 2014	380	HILL	510
16	contra-flow	Graz to Lasnitz	06.08 2014	818	WOOD & WALL	1410
17	contra-flow	Graz to Lasnitz	06.08 2014	800	WOOD & WALL	950

Table 2.1: All measurement results of motorway area.

2.4.2 Rural

The increasing and afterwards decreasing distance scenario was also done in rural areas many times, however intersection cases were not performed. Intersections were not measured because rural area is nearly similar to suburban regions. Therefore, intersections are analysed later in this thesis. Also semi-static scenarios were not measured, but the results would be similar to contraflow or convoy. This would be nearly the same because of the small relative velocity differences.

2.4.2.1 Contraflow

Similar to the previous measurement example of the motorway contraflow, both cars were moving. The velocity is of course lower than on the motorway. Figure 2.16 shows the first communication at an impressive distance of 620 m. Solid communication was detected at 460 m and is shown in Figure 2.17. The encouraging good performance might be due to the broad road and nearly LOS between the cars.

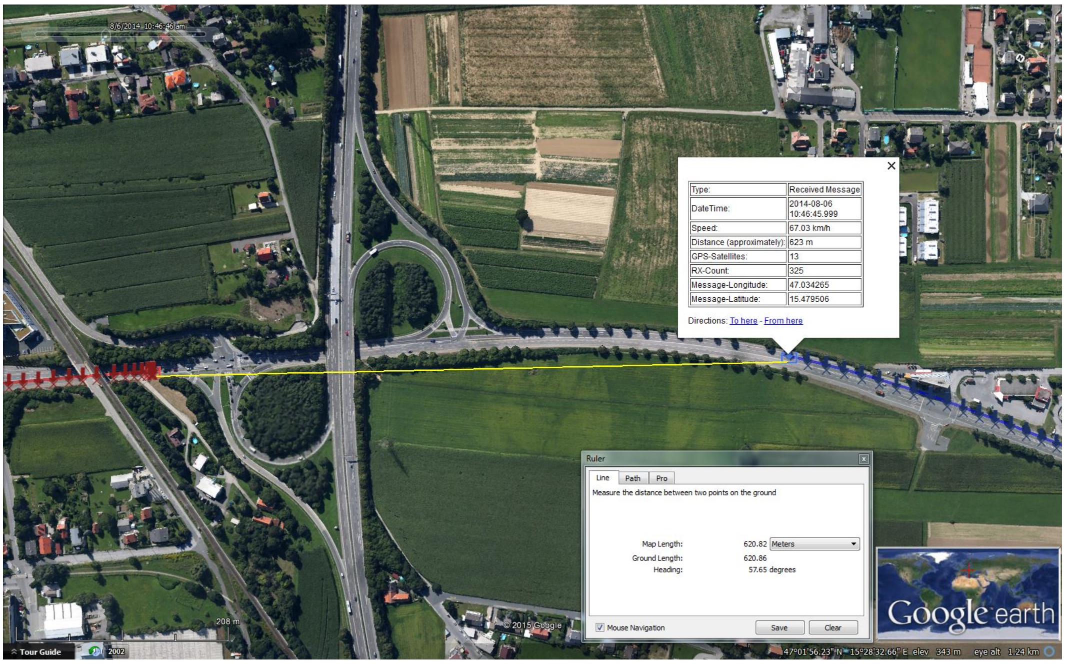

Figure 2.16: First wireless communication contact at a distance of 620 m.

Figure 2.18 represents the EGO's front view. Ego was crossing two bridges and the amount of traffic was also not negligible. Therefore, the performance of the Car2X communication can be ranked as remarkable good.

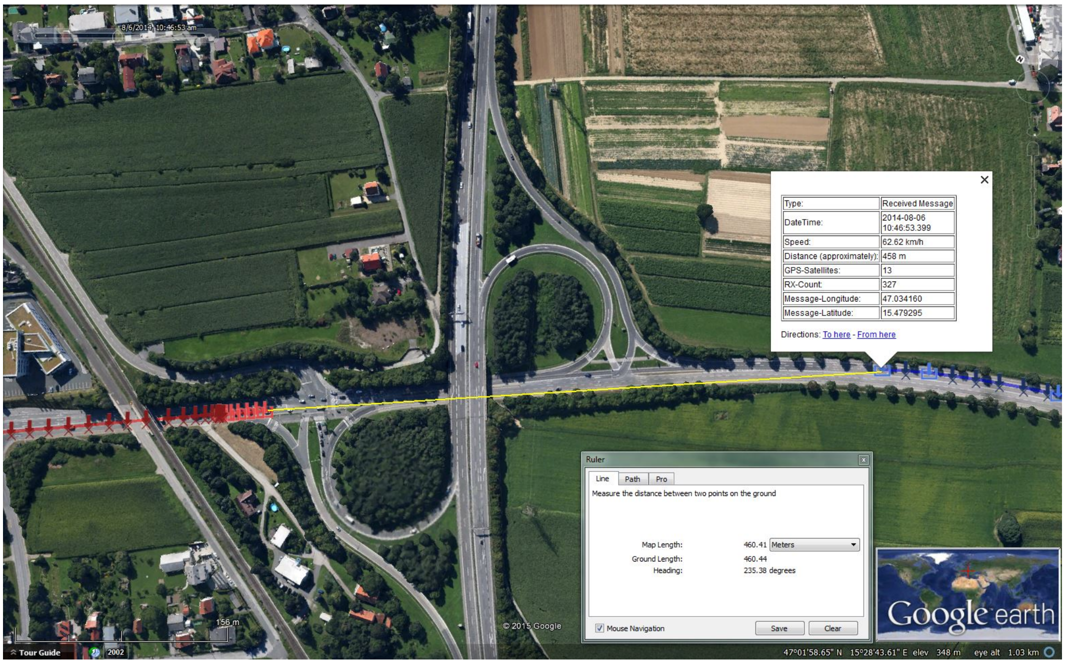

Figure 2.17: Solid contact at a distance of 460 m.

Figure 2.18: View out of EGO's front window.

2.4.2.2 Convoy

Besides contraflow, convoy driving scenarios were also performed in rural regions.

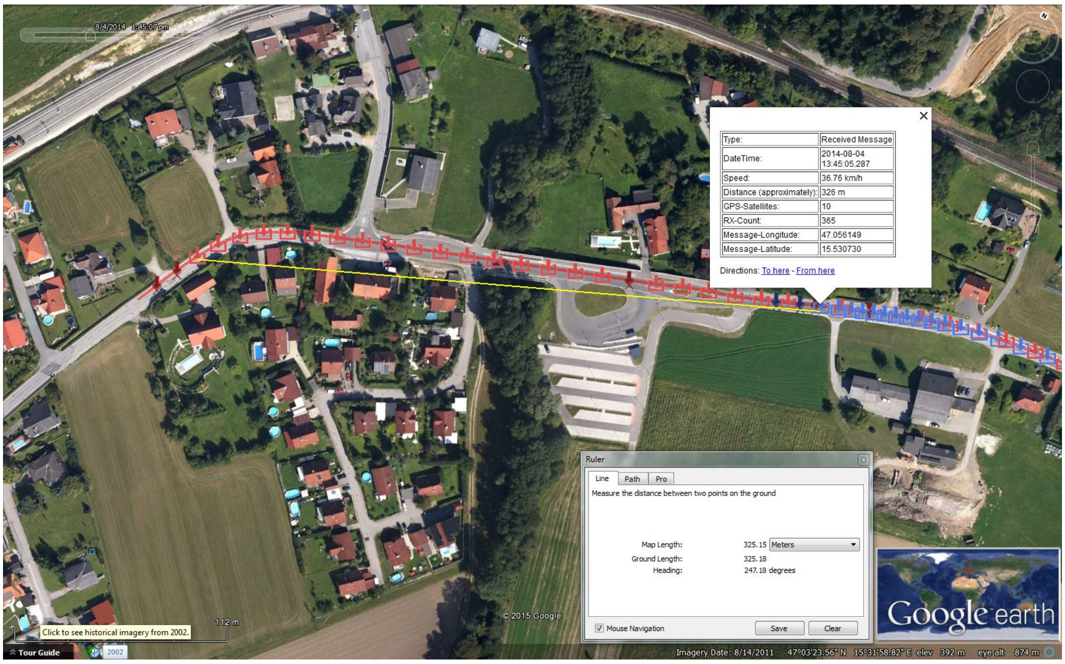

Figure 2.19: Solid contact and farest distance at 325 m.

Figure 2.20: View out of EGO's front window.

Figure 2.19 shows the last transmitted message while the distance between the cars was increasing. Related to this case the solid distance and the longest distance of connection are the same. Figure 2.20 presents the view outside the front window. This road is like a corridor through the wood. Wood and plants are not supporting the wave propagation, because most of the waves are absorbed by plants.

2.4.2.3 Results

Table 2.2 shows all results of rural measurement. This is a small dataset, however a high dependence on objects between the cars can be observed. However, considerable distances were detected. The shortest distance of solid contact was 250 m.

In comparison with motorway this distance is considerably smaller, but the conditions are different. The width of the street and curve radii are smaller than on motorway. Furthermore, more buildings, wood and plants are interacting with the wireless connection. Although the distances are enough to give the driver an alert resulting from dangerous a situation.

ID	maneuver	route	date	solid distance	objects between	maximal distance
				m		m
18	convoy	Lasnitz to Inffeldgasse	04.08 2014	325	BUILDINGS	325
19	convoy	Lasnitz to Inffeldgasse	04.08 2014	250	BUILDINGS &WOOD	250
20	contra-flow	Raaba	06.08 2014	410	BUILDINGS	410
21	contra-flow	Raaba	06.08 2014	280	BUILDINGS	450
22	contra-flow	Raaba	06.08 2014	460	LOS	682
23	contra-flow	Raaba	06.08 2014	450	LOS	450

Table 2.2: All measurement results of rural area.

2.4.3 Suburban

Suburban is also an interesting area for Car2X measurement. The velocities are significant smaller than in rural or motorway scenarios. However, the suburban areas can cause unclear situation, because of the high amount of interacting objects and the smaller street width.

2.4.3.1 General Scenarios

To sum up the scenarios of convoy, contraflow and semi-static, the measurement was done by driving around in suburban area. So, no special scenario was driven. Nevertheless free driving of both cars will show the performance. Additionally straight long roads are not often built in suburban areas.

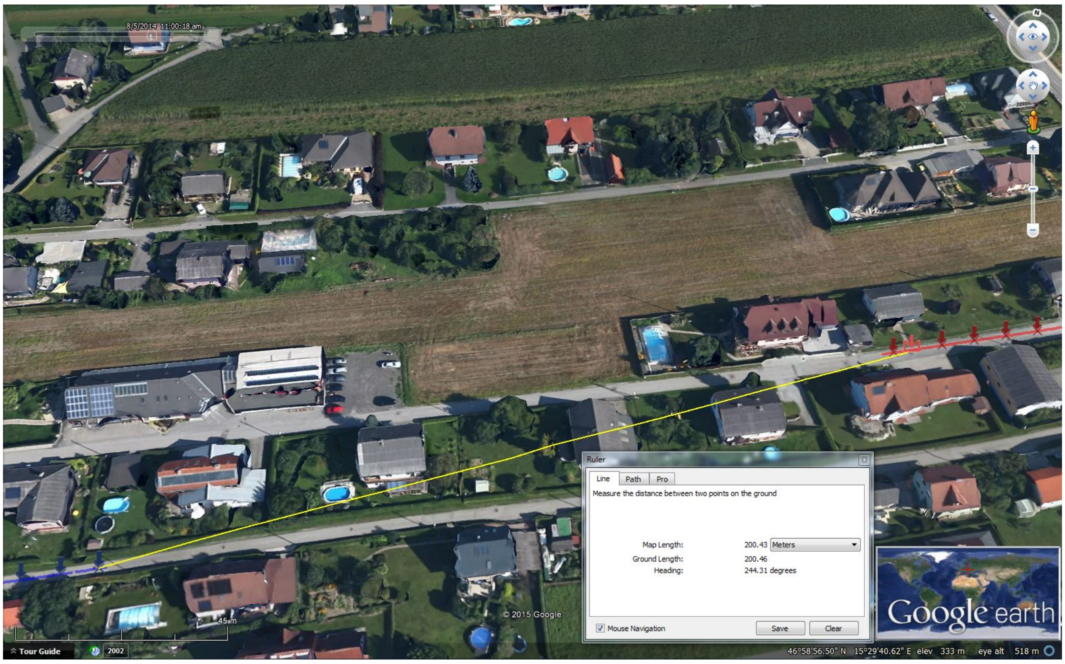

Figure 2.21: First wireless communication contact at a distance of 200 m.

Figure 2.21 and 2.22 shows the solid and furthest wireless communication. The furthest contact were detected at 200 m and the solid contact is observed at a distance of 130 m. Figure 2.23 represents the EGO's front view. The streets are even smaller than in the rural scenarios. Also more plants are growing. That can be the key reason for the weaker performance in comparison to previous measurement results.

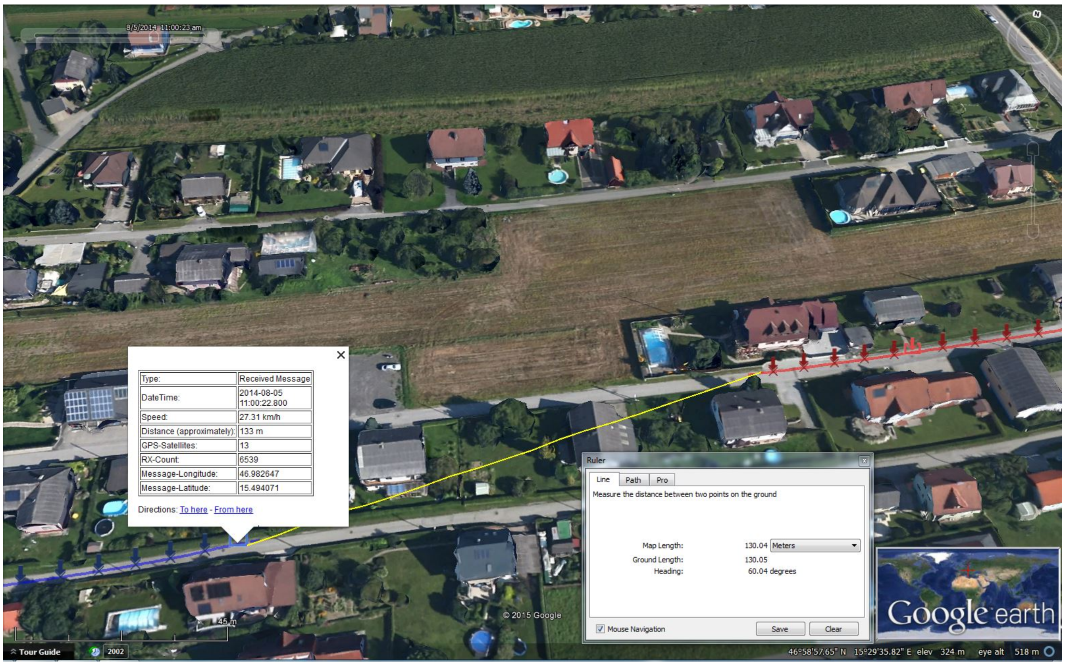

Figure 2.22: Solid contact at a distance of 130 m.

Figure 2.23: View out of EGO's front window.

2.4.3.2 Intersection

However lower velocity situations are more common in suburban and urban areas. It is not just lower velocity, also intersection scenarios are more frequent. Therefore, a new scenario is introduced in this section. During the measurement TARGET was parked in one street of the intersection with various distance to the middle of the intersection. EGO first came along the right or left side in view of the TARGET, then the car crossed the intersection (LOS) and afterwards the TARGET was increasing the distance until no messages were received anymore. The distance of EGO was measured to the middle of the crossing.

Figure 2.24 and 2.25 show the measurement distances. The distances are encouraging in contrast to the low velocity limit in suburban areas. Differently to previous tests, measured intersection distances corresponding to intersection's center.

Figure 2.24: First wireless communication contact at a distance of 153 m.

Figure 2.26 represents the view through the front window and also a lot of plants are on the right and left side of the car. Therefore a high attenuation by vegetation is assumed.

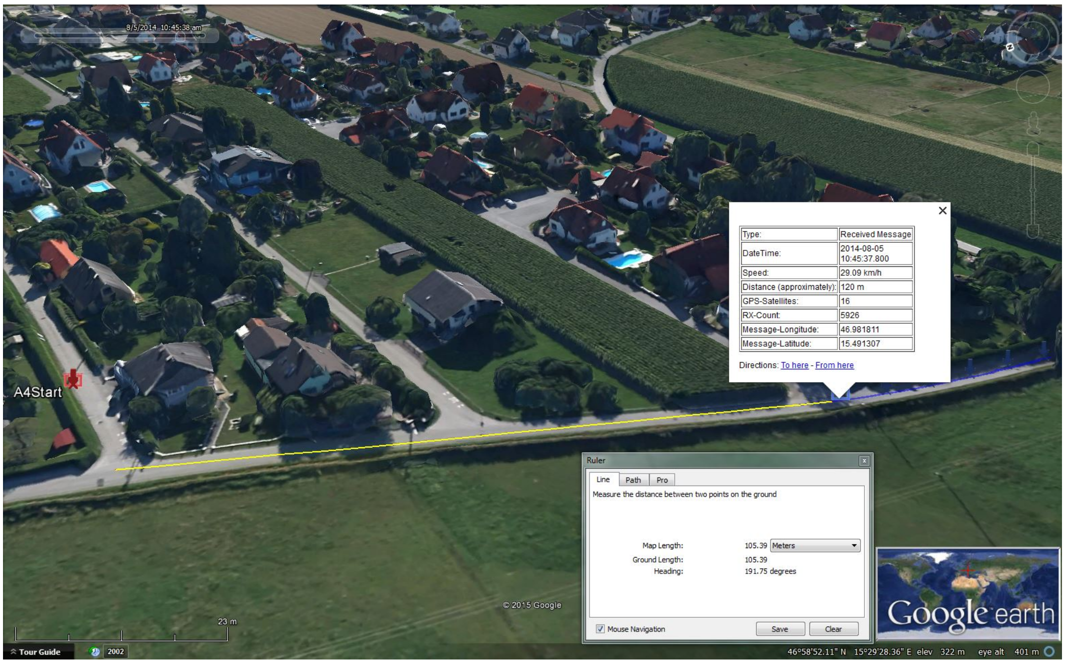

Figure 2.25: Solid contact at a distance fo 120 m.

Figure 2.26: View out of EGO's front window.

2.4.3.3 Results

The performance dependence on the relative velocity of both cars is negligible for suburban cases. As a consequence maneuvers like convoy, contraflow or semi-static would deliver nearly the same results if the environment would be the same. Table 2.3 shows all measured general scenarios.

ID	maneuver	route	date	solid distance	objects between	maximal distance
				m		m
24	general	Fernitz	05.08 2014	120	BUILDINGS & WOOD	220
25	general	Fernitz	05.08 2014	90	BUILDINGS & WOOD	160
26	general	Fernitz	05.08 2014	130	BUILDINGS & WOOD	200
27	general	Inffeld-gasse	06.08 2014	90	BUILDINGS	110

Table 2.3: All general measurement results of suburban area.

In case of intersections it is necessary to look at the results from a second point of view because of the high dependence on intersection's geometry. Table 2.4 shows data analysed in more detail. Furthermore this detailed analysis is necessary for the subsequent model building and parametrization. The variables of this table are defined in the following legend:

- wt: width of non-moving car's street
- xt: distance between non-moving car and wall in the direction of the moving car
- dt: distance of non-moving car to the middle of intersection
- wr: width of moving car's street
- dr: distance of moving car to the middle of intersection with solid communication
- dr_{max}: longest distance of moving car to the middle of intersection

ID	location	wt	xt	dt	wr	dr	dr_{max}
		m	m	m	m	m	m
28	Fernitz	15.5	7.2	25.2	6.0	115.0	115.0
29	Fernitz	15.5	7.2	25.2	6.0	115.0	152.0
30	Fernitz	15.5	7.2	25.2	6.0	55.0	72.0
31	Fernitz	15.5	7.2	25.2	6.0	105.0	153.0

Table 2.4: All intersction results of suburban area.

2.4.4 Urban

Also urban area scenarios are interesting content related to reliability and range. Furthermore, intersections are the often preferred scenarios, because Car2X would support dangerous situations such as recognition behind the corner without a direct view.

2.4.4.1 Intersection

Figure 2.27 shows the longest distance of 103 m of connection. Also the solid communication distance is the same. Again the Car2X system provides a considerable good performance, which would allow new function for ADAS.

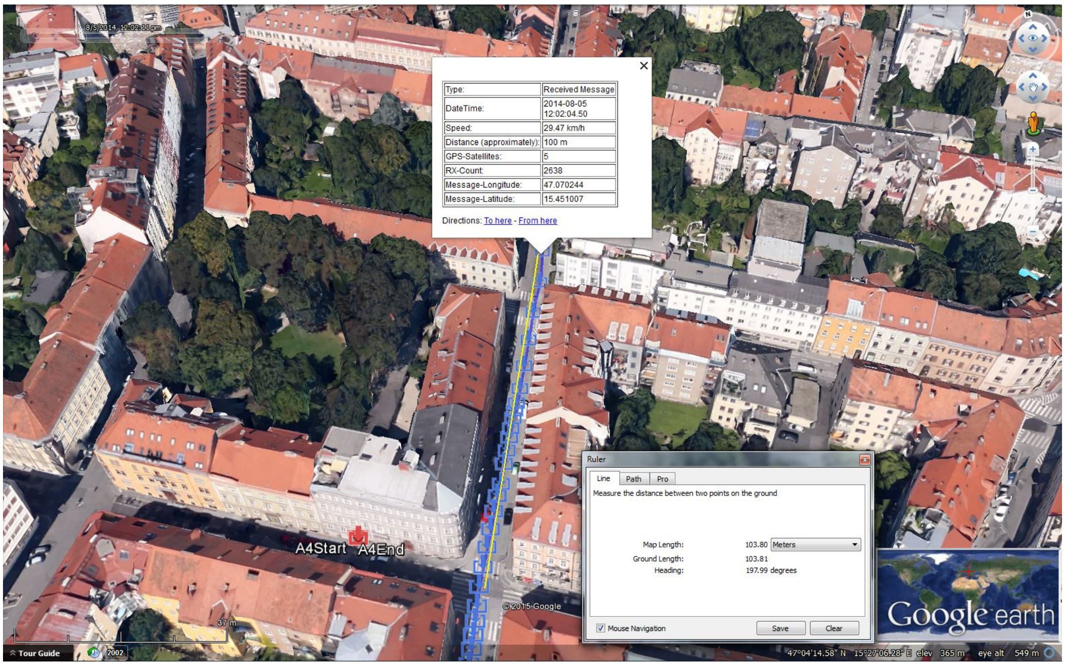

Figure 2.27: Solid contact and longest communication at a distance fo 103 m.

Figure 2.28 shows EGO's front view. The street is narrow and bounded with high buildings. Also the velocity limit is set to 30 km/h and thus the performance of Car2X is remarkable.

Figure 2.28: View out of EGO's front window.

2.4.4.2 Results

A remarkable benefit of Car2X in urban area would be the prevention of dangerous intersection situations, because Car2X connection is possible without a direct view to the other Car2X featured vehicle.

Table 2.5 represents all measured urban intersection scenarios. Also considerable differences between different cases can be seen. Therefore, a more precise analysis is required. The measured distances of intersection are defined in the previous suburban section.

ID	location	wt	xt	dt	wr	dr	dr_{max}
		m	m	m	m	m	m
32	Gartengasse	13.0	3.0	14.5	10.5	110.0	264.0
33	Gartengasse	13.0	3.0	74.5	11.5	39.0	88.0
34	Gartengasse	13.0	3.0	14.5	10.5	103.0	103.0
35	Gartengasse	13.0	3.0	54.5	11.5	64.0	103.0
36	Gartengasse	55.5	3.0	54.5	13.0	66.0	90.0
37	Klosterwiesgasse	8.0	8.0	31.5	16.5	188.0	375.0
38	Klosterwiesgasse	6.5	5.0	15.5	16.5	195.0	395.0

Table 2.5: All intersction results of urban area.

2.4.5 Measurement Discussion

First, measurements of two Car2X clients were made at Graz University of Technology and documented in [16]. This measurements did not include the communication via CAM, however the payload was increased significantly. In case of this master thesis no variation of payload was done, but rather CAM was used and more scenarios were measured.

Due to a software bug of the Car2X hardware, the frequency for CAM could not be increased. So, the periodic CAM sending was default set to 1 Hz. If the frequency was higher, the uncertainty of maximal distance related to velocity of no communication would have been smaller.

The post processing of the measurement data to a GoogleEarth illustration was a important step in this thesis. The advantages are simple illustration on computers without a need for a license. Furthermore the measurement can be automatically viewed via GoogleEarth. Metadata is included by info boxes, which pop up when an icon is pressed. Also the recorded EGO's film is compressed to a small size, which can be played with any usual player.

Every measured area and scenario is illustrated with one example in the previous chapters. The examples are well chosen to represent the situation and environment. Furthermore, all post processed data is shown in the tables. These are used in the following model for parametrization and evaluation.

Distributed over all measured scenarios in some cases single messages got lost. This may have many reasons, but we think it highly depends on the surrounding. This effect is ignored in this thesis, because the occurrences were very rare.

To sum up, the analysis finished at this point. The high reliability and long ranges of Car2X are remarkably good. Depending on the high dispersion of some scenarios a good model is not simple to find.

3 Model

3.1 General

The attention related to Car2X is increasing and furthermore first ADAS usage is discussed. Therefore, models for simulations are required. Automotive manufactures are simulating a significant high number of scenarios. Additionally ADAS needs a lot of simulation to determine the system as safe in various maneuvers. The approaches to develop a good model are different.

3.2 Effects

First step of a model development should be to become familiar with wireless communication effects. In this chapter just the main effects are described in a compact way. The detailed description can be found in [14].

3.2.1 Multipath Components Fading

In most of the cases inactive objects are interacting with the propagation because of reflection on their surface. Reflection may cause a gain or attenuation to receiving signals. The transmitting frequency is about 5.9 GHz depending on the used channel. Therefore, the wave length is about 5 cm. Hence, a small position change of receiver, transmitter or interacting objects may cause a high change in the receiving power. Figure 3.1 illustrates this effect of multipath components (MPC). MPC is realized with random fading based on a probability distribution in the master thesis.

3.2.2 Shadowing

Due to movements of transmitter or receiver the LOS can be blocked. Therefore a high attenuation occurs depending on the size and material of the interacting object. Figure 3.2 shows the field attenuation by a shadowing interacting object. Furthermore, it shows a relative smooth margin of attenuation. This effect is considered in the intersection model, because of the high influence related buildings at intersection.

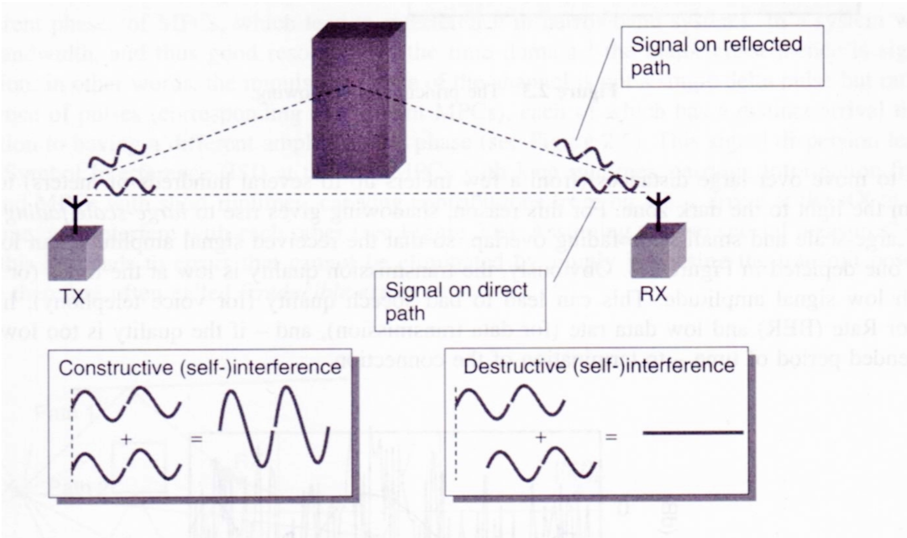

Figure 3.1: Multipath components fading. Source: [14]

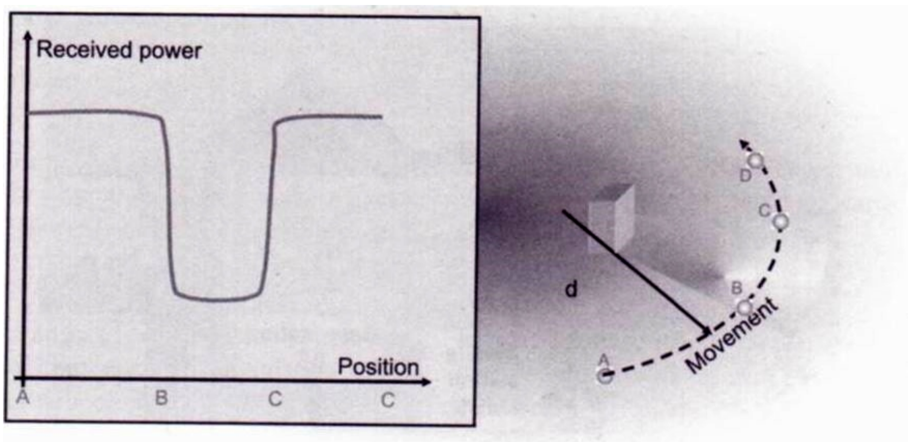

Figure 3.2: Shadowing. Source: [14]

3.2.3 Intersymbol Interference

As mentioned above, every multipath component is getting a phase shift, because of the different length of ways. Not only the phase shifts occurs but also amplitude modification. Therefore, interferences at the receiver occur and may cause irreducible errors. Figure 3.3 shows the impulse response in time of multipath components. In the right diagram are shown the different components with different amplitudes and arrival time. In general wireless propagation analysis not only one delta impulse but a binary sequence is sent. Intersymbol Interference is handled in same way as the MPC in this master thesis.

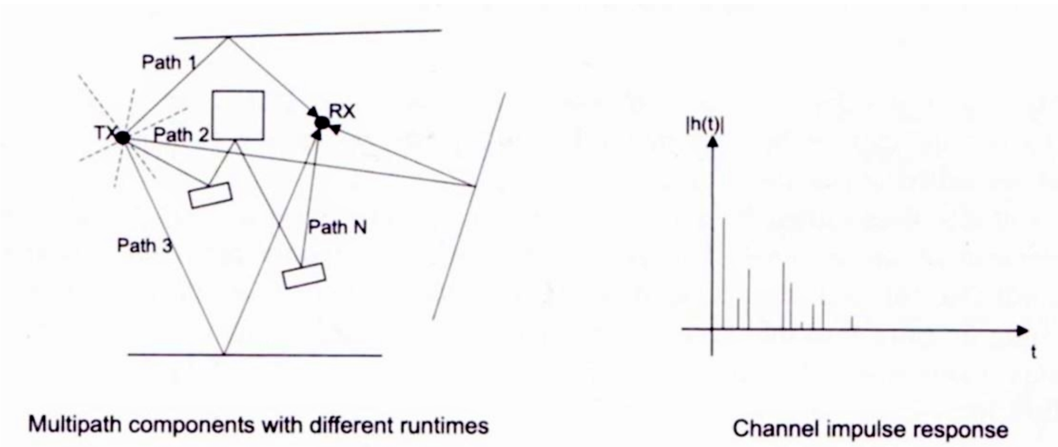

Figure 3.3: Intersymbol Interference. Source: [14]

3.2.4 Scattering

The reflection of an interacting object, which is not a transmitter or receiver, is in the most cases no simple progress, because in case of Car2X information of all surfaces, which can be reason for a reflection, has to be collected. Vehicles have a smooth surface, but buildings in most cases have a rough surface. Depending on the roughness of the surface the direct reflection is attenuated. Figure 3.4 depicts this effect. However, a simple solution for this effect are stochastic models based on probability distributions. These models do not fit every case in a perfect way, but in the most cases it is precise enough. Therefore this effect is illustrated by a probability distribution in this master thesis.

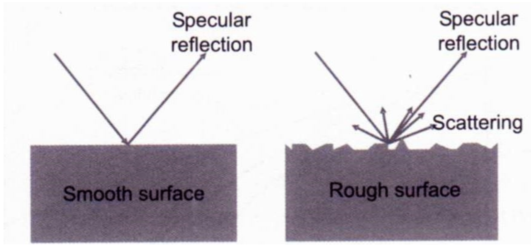

Figure 3.4: Scattering. Source: [14]

3.2.5 Breakpoint

A special effect of MPC is the breakpoint. Most wireless systems have a breakpoint of distance were the attenuation increases. The reason is the first wave reflection from the ground (180 degree phase shift) attenuating the receiver power. Therefore, height of transmitter, receiver and the wave length are parameters for the breakpoint length calculation.

Figure 3.5 represents the schematic explanation of a Two-Ray-Ground model. These model is a realization of different effects, but mainly of breakpoint. In case of this master thesis, the Two-Ray-Ground model is playing a main part of the model.

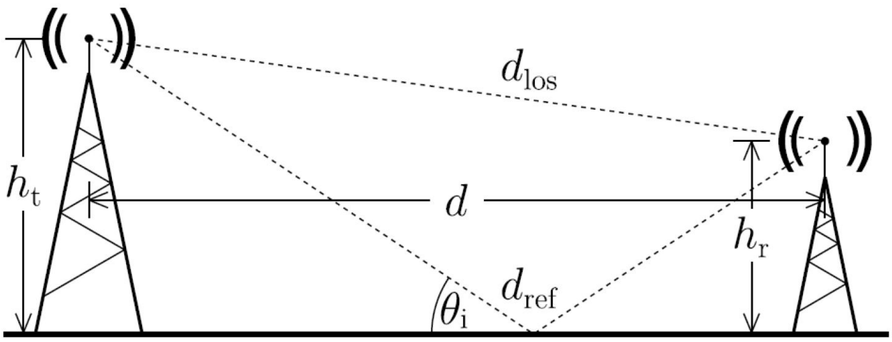

Figure 3.5: Breakpoint schematic illustration. Source: [18]

Figure 3.6 represents an attenuation depending on the distance. The attenuation increases by the power of two until the breakpoint is reached and afterwards to the power of four. In further models the exponents fluctuate around these values.

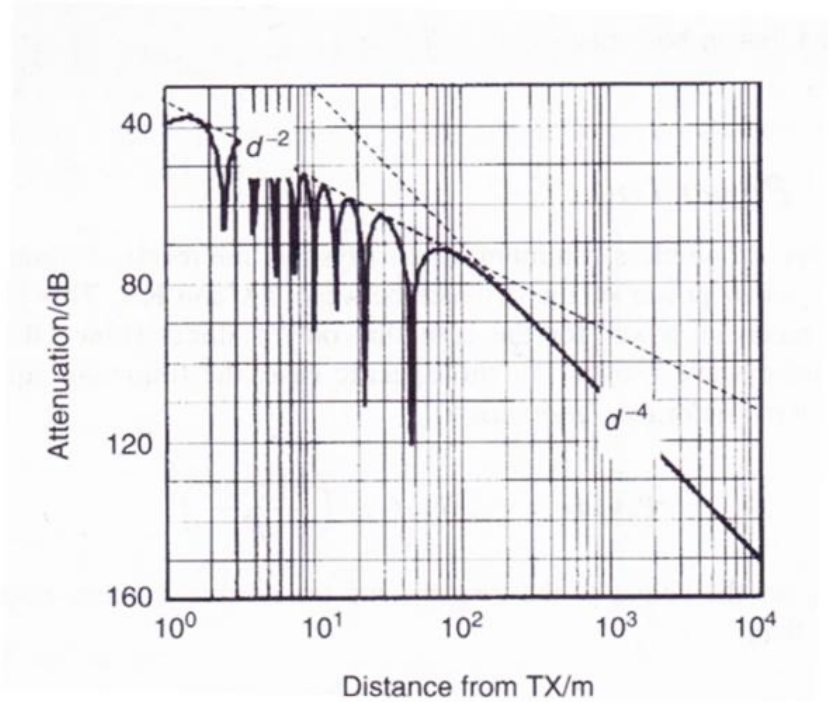

Figure 3.6: Breakpoint distance. Source: [14]

3.2.6 Reflection and Transmission

Apart from the influence of the surface roughness, some of the radio waves are penetrating the object. One of the most popular physical model, which represents this effect, is Snell's law. Figure 3.7 shows the effect including the distinguish between transversal magnetic and transversal electric case.

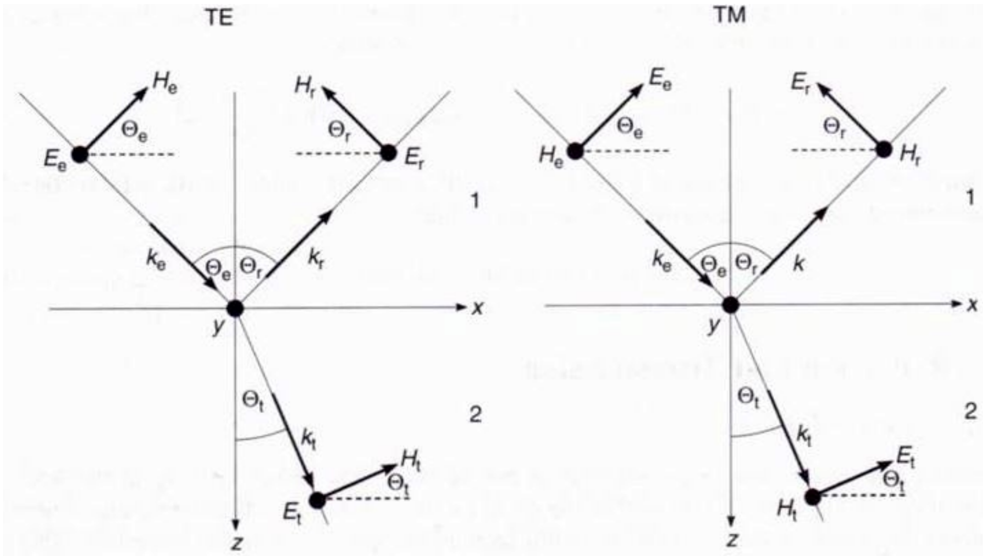

Figure 3.7: Reflection and Transmission. Source: [14]

In case of Car2X this effect is hard to describe physically because magnetic end electric behaviour is required. This effect is an interesting topic for indoor wireless models, because of the penetration through walls. However, Car2X performance negligible depends on transmission. In case of Car2X reflection are handled in same way as MPC.

3.2.7 Diffraction

Also diffraction is an effect of wireless communication. Waves can diffract around the corner of a homogeneous plane, illustrated in Figure 3.8. This effect is getting smaller with decreasing wave length. Therefore, it is negligible for Car2X systems in contrast to the other effects.

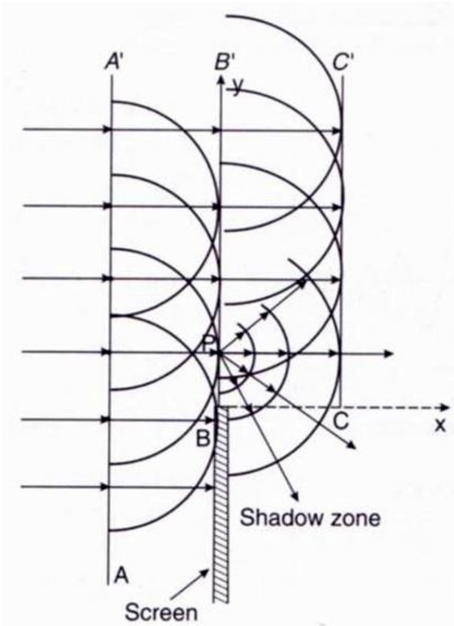

Figure 3.8: Diffraction. Source: [14]

3.2.8 Discussion

Based on these effects, models were developed to fit one or more effects. Not every effect is playing a considerable role in a Car2X environment, but it is a background knowledge, which is needed for analysing existing propagation models.

Many of these effects are commonly realized with a stochastic model. Stochastic models are not high precise approaches, but they are simple to develop, faster in calculation. Therefore this is a widespread realization. Furthermore to determine approximative distance, the Two-Ray-Ground model is commonly used.

3.3 Relevant Models

Three main approaches exists for channel modelling. Most of the models are hybrids of this three approaches and fit more or less the explained effects. In common cases the models are divided to LOS and NLOS models. This is due to weaker NLOS range and the higher NLOS fading.

First, deterministic models are described. The background of a deterministic wireless propagation model are Maxwell's equations. So knowledge about shape, material, magnetic and electric behaviour is required. This high amount of data has to be collected and afterwards a high computation (finite-elements-calculation) effort is required.[10]

Second, geometric-based models are also called ray tracing models. The direct rays and all possible reflections are calculated to determine a possible connection. This approach is a non-deterministic polynomial time problem and requires again a high computation.[10]

Third, stochastic propagation models are ignoring geometric or physical equations. These models describe the explained effects with general stochastic equations and therefore the results may not be precise as other models. They are very popular to model small scale fading, like MPC and scattering.[10]

As mentioned above in reality most models are hybrids of the three approaches. Furthermore, the commonly used models are not exactly realized like these approaches, but a simpler hybrid version of all is made. The following models are a small collection of possible realization, which appear more frequently in research.

MIMO Model (M_A)
'A geometry-based stochastic MIMO model for vehicle-to-vehicle communications' [10] is a hybrid of geometric-based and stochastic model. A geometrical feature is for example the width of the road. Effects like scattering are developed by stochastic models. The model may fit a lot of scenarios and situations very precisely, but it is very complex.

SUMO MOVE Model (M_B)
'Realistic mobility models for Vehicular Ad hoc Network (VANET) simulations' [4] is an association under construction of MOVE (MObility model generator for VEhicular networks) and SUMO (Simulation of Urban MObility). In other words this is a combination of a driving and a wireless network simulator. However, the master thesis should deliver a mathematical model which has the possibility to fit any vehicular simulation tool. So this model is not a suitable solution.

NS based Models (M_C, M_D, M_E)
'Simulation of IEEE 802.11p Vehicular Networking with Real-Life Traffic Scenario' [19] is also a symbiosis of two simulators. The connected simulators are SUMO and NS (Network Simulator). NS is a widely used tool because the operational area is widespread. NS requires a full setup of network layers. Also 'What details are needed for wireless

simulations? - A study of a site-specific indoor wireless model' [2] is a symbiosis of NS and a geometrical model. An absolute NS model is 'Vehicular Network simulation propagation loss model parameter standardization in ns-3 and beyond' explained in [3].

Trace-based Model (M_F)
'Trace-based simulation of C2X-communication using cellular networks' [7] repesents a trace-based simulation, however this master thesis should generate a deterministic simple model. Therefore it would not be a suitable compromise.

Payload Model (M_F)
'Broadcast Reception Rates and Effects of Priority Access in 802.11-based Vehicular Ad-hoc Networks' [21] is a simple model. Based on the Two-Ray-Ground propagation, which was earlier called breakpoint. Fading was simulated with a random Nakagami probability distribution. Furthermore, the payload was varied, however the scenarios were made static. Therefore, this model is not fully satisfying.

Geometry stochastic Models (M_G, M_H)
These models based on the same approach. The idea in this is to combine geometrical features with stochastic fading description. The Model and parametrization is described in the 'Validation of a non-line-of-sight path-loss model for V2V communications at street intersections' [1] and '5.9 GHz inter-vehicle communication at intersections: a validated non-line-of-sight path-loss and fading model' [11].

The discussed models are often featured in the research, therefore these wireless propagation models are suitable for different requirements. A high amount of different wireless propagation models and realization have been developed and documented and the analysis of every model would exceed the working time of the master thesis.

3.4 Model Evaluation

The model requirements are in many cases different and therefore various models are developed. In case of this master thesis followed model features are required.

- **Real-time capability (RTCA)** defines equal calculation time for every possible state of the model. Furthermore, the calculation time has to be low enough such that the time constraints are fulfilled. The model's real-time capability was assessed into three steps. Number 0 was given for non-real-time capability, 1 for unclear operations in the model (e.g. simulators) and 2 for models satisfying the timing requirements.
- **Mathematical description (MD)** qualifies the accuracy of mathematical documentation. This requirement was also ranked into three possible states. Number 2

was given for a full mathematical documentation, 1 for a rough documented model calculation and 0 for no mathematical description.

- **Deterministic behaviour (DEB)** describes the bounded results related to the input parameters. In other words, simulations with the same input parameters must deliver the same results. Determinism was ranked into three possible states. Number 2 was given for a clear deterministic behaviour, 1 for quasi-deterministic and 0 for non-deterministic behaviour. Quasi-deterministic models those whose output does not strongly vary, e.g, stochastic realized fading.
- **Simplicity (SPL)** defines a subjective opinion related to realization effort. This is also ranked into three steps. Number 2 is given for simple realizable models, 1 for usual effort and 0 for a very costly realization.
- **Vehicular usage (VU)** defines the described operation field. The model was ranked with 2 for a automotive operation field and 0 for a different field of application.

A common way to determine decisions is a Cost-Utility Analysis (CUA). CUA supports the decision related to every criterion's importance and therefore it is generally used for a high amount of criteria. First the criteria has to be ranked and a common method is the cross table 3.1. Every criterion is compared with each other. Number 0 is written in a field when the vertical criterion's importance is higher than those of the horizontal criterion. Number 1 is entered when both criteria have the same importance and a 2 is written if the horizontal criterion's importance is higher.

	RTCA	MD	DEB	SPL	VU	Criterion Importance
RTCA	x	1	2	2	2	7
MD	1	x	2	2	2	7
DEB	0	0	x	0	1	1
SPL	0	0	2	x	1	3
VU	0	0	1	1	x	2

Table 3.1: Criteria cross table

Table 3.1 shows the cross table of the criteria. The last column represents the importance of every criterion, which is result of row summation. Real-time capability and mathematical description are the best ranked requirements. The next ranked criterion is simplicity. The last two criteria SPL and VU are low ranked and therefore these requirements would be nice but not necessary.

The CUA is also used to determine good decisions related to the criteria. In case of the master thesis, CUA should support finding the best model approach regarding to the ranked requirements.

The reached importance value of each criterion is for further calculation used as criteria weight W. Every model was analysed related to the defined requirements. Furthermore, the assessment of requirement is split into steps. In case of an unclear match of model behaviour and requirement the rating was set to 0. After the rating, every assessment is multiplied by the weight and summed up with the other requirements. The summation's result is defined as R and furthermore a relative result R_{rel} is introduced. The relative result is the normalized absolute result by the maximum reachable result. Table 3.2 represents the model evaluation related related to ranked criteria.

MODEL	RTCA	W	MD	W	DEB	W	SPL	W	VU	W	R	R_{rel}
M_A	2	7	2	7	1	1	0	3	2	2	33	81.5%
M_B	1	7	0	7	0	1	1	3	2	2	14	35.0%
M_C	1	7	0	7	0	1	1	3	2	2	14	35.0%
M_D	1	7	0	7	0	1	1	3	2	2	14	35.0%
M_E	1	7	0	7	0	1	1	3	2	2	14	35.0%
M_F	0	7	2	7	0	1	0	3	2	2	18	45.0%
M_G	0	7	0	7	0	1	2	3	2	2	10	25.0%
M_H	2	7	2	7	1	1	2	3	2	2	39	97.5%

Table 3.2: Model evaluation.

The best evaluated model M_H is reached a requirement matching of 97.5 %. This model conforms to every requirement that can be assumed as fortunate coincidence. The second best model M_A has compared to M_H a higher complexity, which was not the intention of the thesis. All other models are ranked low compared with M_H and M_A. Therefore, Model M_H will be the approach for the model realization, but it is made for modelling wireless propagation in intersection. Therefore this approach is adapted for general cases in the master thesis.

3.5 Model Realization

In most cases the dispersion of ranges was very low. Apart from these cases, intersection are highly depending on geometry. Therefore the dataset was extended by geometric information of the intersection. Due to these different cases, two model types were developed. One model fits the general cases including contraflow, convoy and quasi-static and the other model fits only intersections in urban and suburban areas.

3.5.1 General

General models should fit general situations of Car2X. Additionally the model should fit different areas, like motorway, rural and suburban. Consequently different areas and different places of measurement yield to different objects blocking the LOS. Therefore areas are defined as follows:

- suburban
- rural
- motorway

These different areas lead to different attenuation and furthermore the fading is highly depending on the number, size and shape of interacting objects. The different fading was realized with Nakagami distribution, because Nakagami is fitting LOS as well as NLOS scenarios by variation of only one parameter. Nakagami is based on the Euler-Gamma distribution and with correct configuration it is comparable with a Rice and Rayleigh distribution. Equation (3.1) shows the Probability Density Function (PDF) of Nakagami. The function $\Gamma(m)$ represents a Euler's Gamma function [14]. The characterising parameter of Nakagami PDF is the m-factor, which is able to modify the Equation to Rayleigh or Rice. Parametrization values are later declared.

$$pdf_{Nak} = 2\left(\frac{m}{\Omega}\right)^m \frac{1}{\Gamma(m)} x^{2m-1} e^{-\frac{m}{\Omega}x^2} \tag{3.1}$$

Also a split due to the interacting objects blocking the LOS was required. Therefore following special propagation behaviour classes were defined.

- LOS
- Wood & Wall
- Buildings
- Wood
- Buildings & Wood
- Hill

The mathematical Equation (3.2) describes the general model for all cases in the master thesis. The Car2X's receiver sensitivity is declared with P_{RX}, the transmission power with P_{TX}. The Equation contains two types of loss. The first type is the system loss L_S, which is constant for every case. The second type is the path loss L_P.

$$P_{RX} = P_{TX} - L_S - L_P \tag{3.2}$$

Furthermore Equation (3.2) is a simple link budget calculation. Link budget calculation describes the start point (P_{TX}), the end point (P_{RX}) and all losses between. The necessary hardware specification are defined in the hardware specification paper [13]. The maximum transmit power P_{TX} is 25 dB and the receive sensitivity P_{RX} is -98 dB. The system loss L_S is about 3 dB. So, all necessary parameters are defined by the specification except of the path loss. The path loss model is defined in following Equations (3.3), (3.4) and (3.5). This path loss model is a possible interpretation of a Two-Ray-Ground model.

$$L_P = 10 \log \left(x \frac{4\pi}{\lambda} \right)^{AE+EE} \qquad \text{for x} \leq d_b \tag{3.3}$$

$$L_P = 10 \log \left(x^2 \frac{4\pi}{\lambda d_b} \right)^{AE+EE} \qquad \text{for x} > d_b \tag{3.4}$$

$$d_b = \frac{4 h_t h_r}{\lambda} \tag{3.5}$$

Parameter definitions:

- x: direct distance between the clients
- λ: wave length of the transmitting frequency
- AE: exponent of the different areas
- EE: exponent of environment between the clients
- d_b: distance of breakpoint (two-ray-ground model)
- h_t: height of transmitting car's antenna
- h_r: height of receiving car's antenna

The next step is to parametrize the value of the simple model. The parametrization was a result of minimizing the mean squared error in MATLAB® and adjustment of the parameters. The minimization of the mean squared error was automatically done by varying the parameter until the error reached a minimum. The adjustment was done to minimize the influence of outlying examples of the small dataset. Therefore the parametrisation is the main result of adjustment with consideration to the minimization of the mean squared error.

The error of the simulation was calculated into two different ways. First an absolute error was calculated, which is shown in (3.6). Furthermore, an relative error (3.7) was calculated.

$$e = x_{solid} - x_{model} \tag{3.6}$$

$$e_{rel} = \frac{|e|}{x_{solid}} 100\% \tag{3.7}$$

The resulting parametrization is shown in Table 3.1 and 3.2. The m-factor of the Nakagami distribution is the distinctive value, which describes the fading. The fading values that characterize different areas are provided from [21]. In case of the motorway Nakagami is still almost the same as a Rayleigh distribution. If the factor is increased the Nakagami is similar to the Rice distribution. Rayleigh distribution is preferred for LOS scenarios and Rice distribution describes NLOS fading.

	URBAN	SUB-URBAN	RURAL	MOTOR-WAY
AE	0.80	0.87	0.57	0.45
Nakagami m-factor	3.00	2.35	1.75	1.00

Table 3.3: Area Exponent.

	LOS	WOOD & WALL	BUILDINGS	WOOD	BUILDINGS & WOOD	HILL
EE	1.580	1.550	1.740	1.750	1.795	1.750

Table 3.4: Enviroment Exponent.

3.5.1.1 Simulation

Figure 3.9, 3.10 and 3.11 are simulation outputs of the MATLAB® script. The blue line is the simulation propagation loss over the distance. The red line is the receiver sensitivity. The green and magenta lines are values resulting from the measurement. The green line is the longest distance with solid transmission and the magenta line is the longest measured distance of communication. If there is only the magenta line then the solid distance is the same as the longest distance.

The simulation of every real measured scenario is remarkable good if the model (blue line) hits the cross made by the green line (real solid distance) and the red line (receiver sensitivity). As it can be observed in Figure 3.9, 3.10 and 3.11, the cross (green and red line) hits the model (blue line) many times very precise and this is a considerable good benchmark for the model.

The simulations of the measured suburban results are similar because of almost equal environments. E.g, the rural simulation curves have different gradients, which is a consequence of the environment exponent. Therefore the model is operating regarding to the different objects blocking LOS and areas. This behaviour example can be seen best in Figure 3.11.

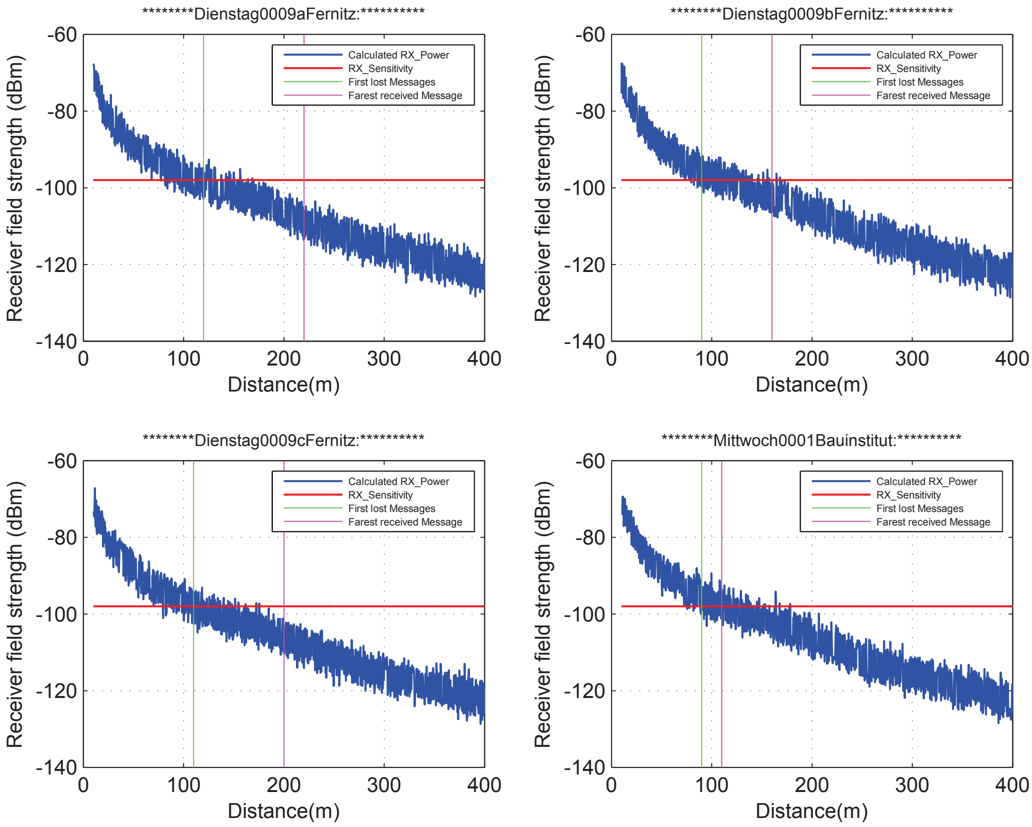

Figure 3.9: Simulation of suburban area.

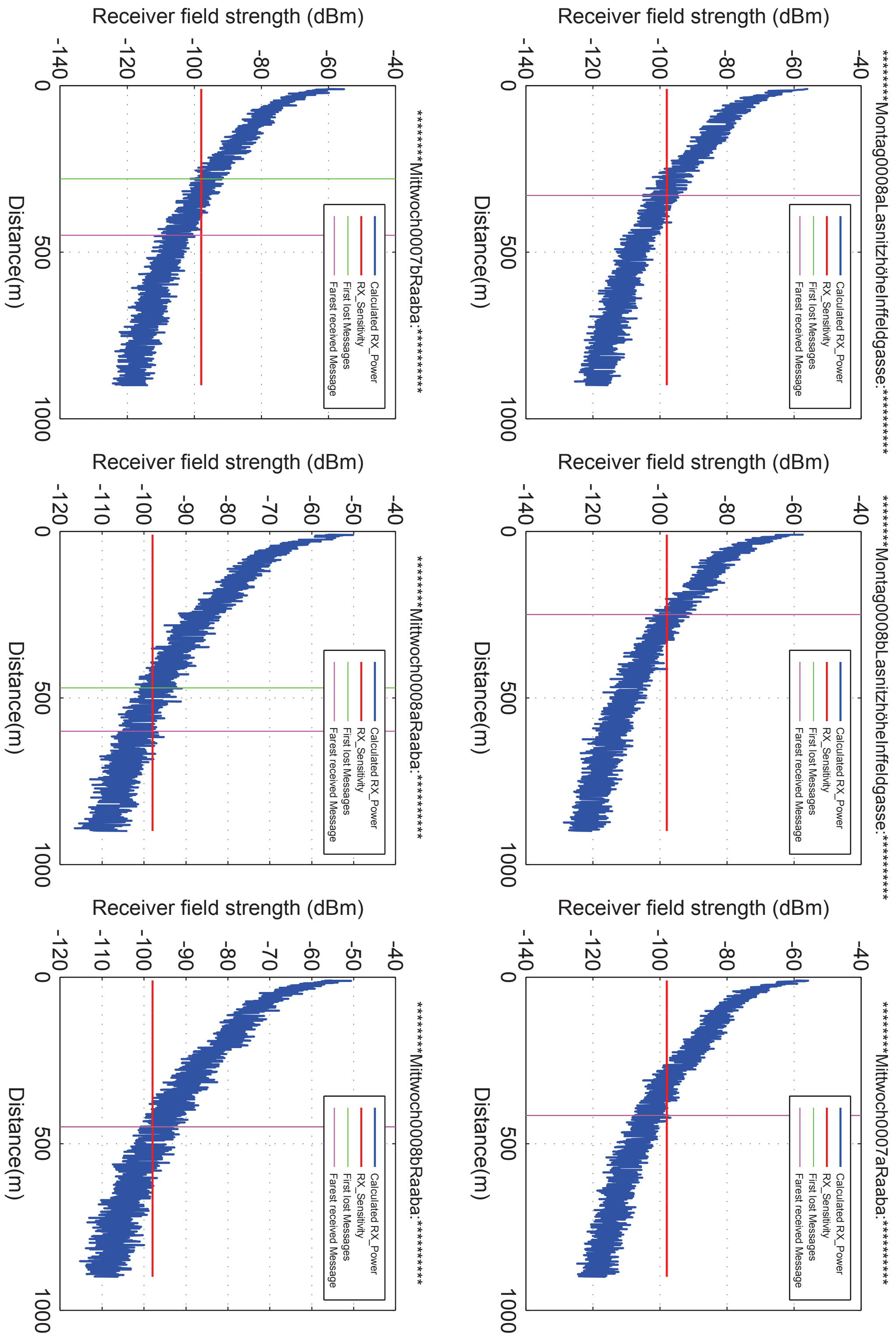

Figure 3.10: Simulation of rural area.

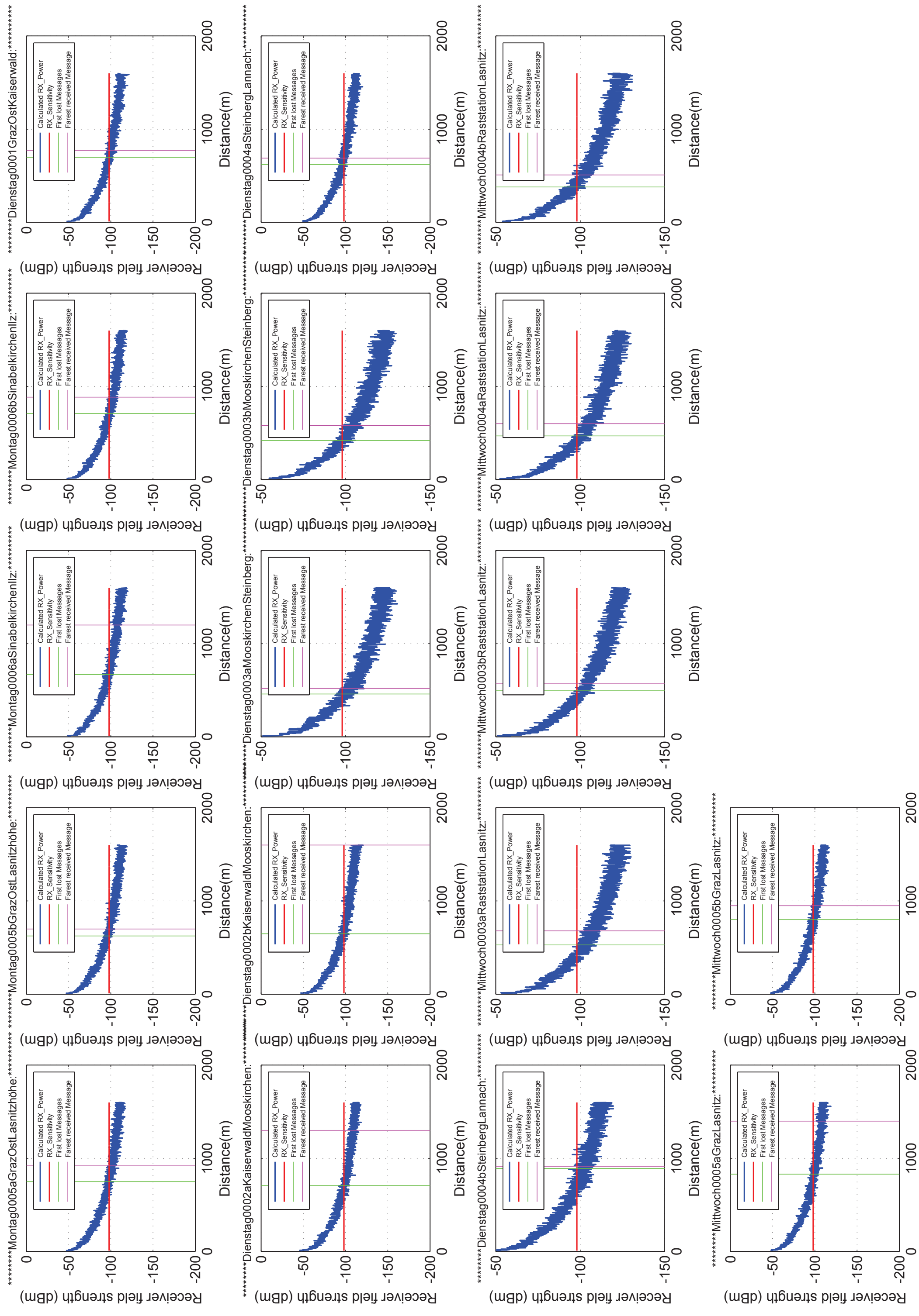

Figure 3.11: Simulation of motorway area.

3.5.1.2 Results

Table 3.5 shows the errors of all simulated scenarios based on real measurement. The corresponding real scenarios are obviously indicated by the ID. The error was calculated without fading and therefore the error values are reproduceable. The reason for the reproducibility is the deterministic model. If fading is included to the simulation, the error varies because of random Nakagami distribution.

Due to the 1 Hz periodic broadcast messaging a measurement error was made at every measurement. If the relative velocity between the cars is raising also the possible maximal measurement error is increasing.

The evaluation of the model is done with the relative error e_{rel}. The relative error has a benefit in contrast to the absolute error because it depends on the solid distance. In addition to this, relative error e_{rel} provides the comparability between the different areas. Furthermore the model was adjusted to be on the pessimistic side. Therefore high absolute errors are in most cases negative, as shown in Table 3.5. If a negative absolute error e is calculated then the real measurement reached a further distance than the model. Furthermore to classify the model, a mean relative error, a relative variance and a relative standard deviation of each area was determined. On motorway the model has a mean relative error of 9.14% and a relative standard deviation of 6.8%. In rural area the model has a mean relative error of 11.15% and a relative standard deviation of 6.3%. Suburban simulation has a relative mean error of 16.8% and a relative standard deviation of 4.3%. The errors seems to be high, but the model performance has to be set in contrast with real measurement. Nearly every measured scenario is independent to other examples. Not only velocity and area is different, but also the environment of the surrounding. The model's input are only area and LOS blocking objects and therefore the model is remarkable good fitting the real world. Special cases are suburban, because the environment is very fluctuating. Suburban can be villages with a high or low amount of plants. In case of abundant vegetation, the environment attenuates highly the wireless propagation, which is remarkably higher than at suburban area with low vegetation. This considerable environment fluctuation, is mostly observed in suburban area. Therefore to increase the the weaker performance of suburban simulation, more input parameters and a specified suburban model is required.

A higher precision can be reached by a more complex model. A more complex model requires in most cases more input parameters and therefore the models are often harder to parametrize. More inputs are, e.g, geometry of surrounding, electric and magnetic behaviour of objects and so on. Therefore, the simulation model was well chosen and well parametrized related to the small dataset. Furthermore simulation with fading, that is illustrated in Figure 3.9, 3.10 and 3.11, has a better visual fitting because boundaries are more flexible. Fading is also detected in real wireless propagation [14] and therefore it is necessary to include this effect to a model.
The implemented general model is a similar approach as the intersection model. The

general model is a mathematical description of all other scenarios than intersection.

Due to the defined requirements, the model choice was a considerable good compromise. Real-time capability and deterministic behaviour (if fading is no included) is provided by the models. Furthermore, the models are simpler in contrast to other models.

ID	area	e	solid distance	e_{rel}
		m	m	%
1	motorway	4.8649	750	0.6
2	motorway	56.6517	625	9.1
3	motorway	11.6517	670	1.7
4	motorway	-28.3483	710	4.0
5	motorway	36.6517	645	5.7
6	motorway	-28.3483	710	4.0
7	motorway	31.6517	650	4.9
8	motorway	-53.6937	460	11.7
9	motorway	-13.6937	420	3.3
10	motorway	61.6517	620	9.9
11	motorway	-208.3483	890	23.4
12	motorway	-123.6937	536	23.1
13	motorway	-93.6937	500	18.7
14	motorway	-63.6937	470	13.6
15	motorway	26.3063	380	6.9
16	motorway	-75.1351	818	9.2
17	motorway	-45.1351	800	5.6
18	rural	-13.8789	325	4.3
19	rural	21.0310	250	8.4
20	rural	-98.8789	410	24.1
21	rural	31.1211	280	11.1
22	rural	-53.0460	460	11.5
23	rural	33.9540	450	7.5
24	suburban	-11.6216	120	9.7
25	suburban	18.3784	90	20.4
26	suburban	-21.6216	130	16.6
27	suburban	18.3784	90	20.4

Table 3.5: General model error at different areas.

3.5.2 Intersection

Intersections are handled in a more precise description. Due to the high fluctuation, a more geometric model was required and found in [1] and [11]. Therefore, the following model descriptions are extracts of [1] and [11]. Similar to the general model, Equation (3.8) is the approach to determine all losses between the Car2X clients. The new term of the link budget equation is $i_S L_{SU}$. The parameter i_S is a boolean factor set to 1 for suburban modelling and for urban the factor is set to 0. In addition to this boolean value, a constant loss L_{SU} is subtract from the link budget for suburban scenarios. This is a consequence to the higher amount of wood and plant in suburban area [1]. The technical specifications, like transmission power P_{TX}, receive sensitivity P_{RX} and system loss L_S are equal to the general model. The path loss Equations (3.9) and (3.10) are similar to the general model with additional geometry inputs and exponents. The breakpoint d_b is calculated equally to the general model, shown in Equation (3.5).

$$P_{RX} = P_{TX} - L_S - i_S L_{SU} - L_P \tag{3.8}$$

$$L_P = 10 \log \left(\left(d_t^{E_T} \left(\frac{1}{x_t w_r} \right)^{E_S} \frac{4\pi d_r}{\lambda} \right)^{E_L} \right) \quad \text{for } d_r \leq d_b \tag{3.9}$$

$$L_P = 10 \log \left(\left(d_t^{E_T} \left(\frac{1}{x_t w_r} \right)^{E_S} \frac{4\pi d_r^2}{\lambda d_b} \right)^{E_L} \right) \quad \text{for } d_r > d_b \tag{3.10}$$

Parameter definitions:

- d_t: distance transmitter to middle of intersection
- d_r: distance receiver to middle of intersection
- w_r: width of receiver's street
- x_t: distance transmitter to the wall in direction of receiver
- d_b: distance of breakpoint
- λ: wave length of the transmitting frequency
- E_T: transmitter distance exponent
- E_S: street exponent
- E_L: loss exponents

Figure 3.12 is a visualisation of the geometrical dependencies. The corresponding distances that are used for the model rely on the middle of the intersection. The middle of intersection is in [11] called VirualSource, because a fictional wireless source is created for the wireless communication instead of the transmitter. The power of the virtual source is determined by the transmitter's position relating to the middle of the intersection. Further simulation and explanations are done with a non-moving transmitter and a receiver at various distance to the VirtualSource.

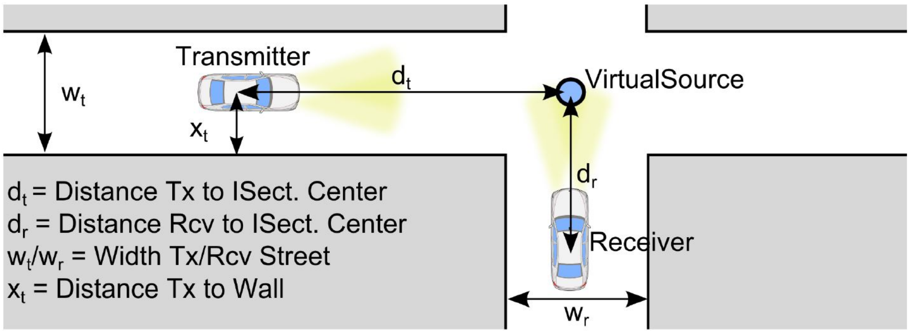

Figure 3.12: Geometric model of the Model. Source: [11]

Table 3.6 shows the final parametrization. The parametrization was taken from [11]. In the paper the parametrization is based on measurements in Munich. Furthermore this paper is an article of ITS [1], which can be assumed as encouraging. Urban and suburban environment of Austria are assumed to be as in Munich. So, no new parametrization was done and the model was implemented with all values of the paper. The calculation requires a breakpoint of distance equation. Fading is simulated by a normal distribution, which is also explained in [11].

L_{SU}	E_T	E_S	E_L
dB			
2.94	0.957	0.81	2.69

Table 3.6: Parametrization of exponents and suburban loss. Source: [11]

3.5.2.1 Simulation

Figure 3.13 and 3.14 shows the illustrated results of the simulation. Again the blue line is the simulated field strength at different distances. Receiver sensitivity is represented via a red horizontal line. The green line is the longest distance of solid transmission. The magenta line is the longest distance of any received message. If this two measured distances are the same, only a magenta line is printed. A remarkable good performance is achieved when the cross, which is made by the green and red line, hits precisely the model illustrated with the blue line. For this case the model fits considerably good the real measurements.

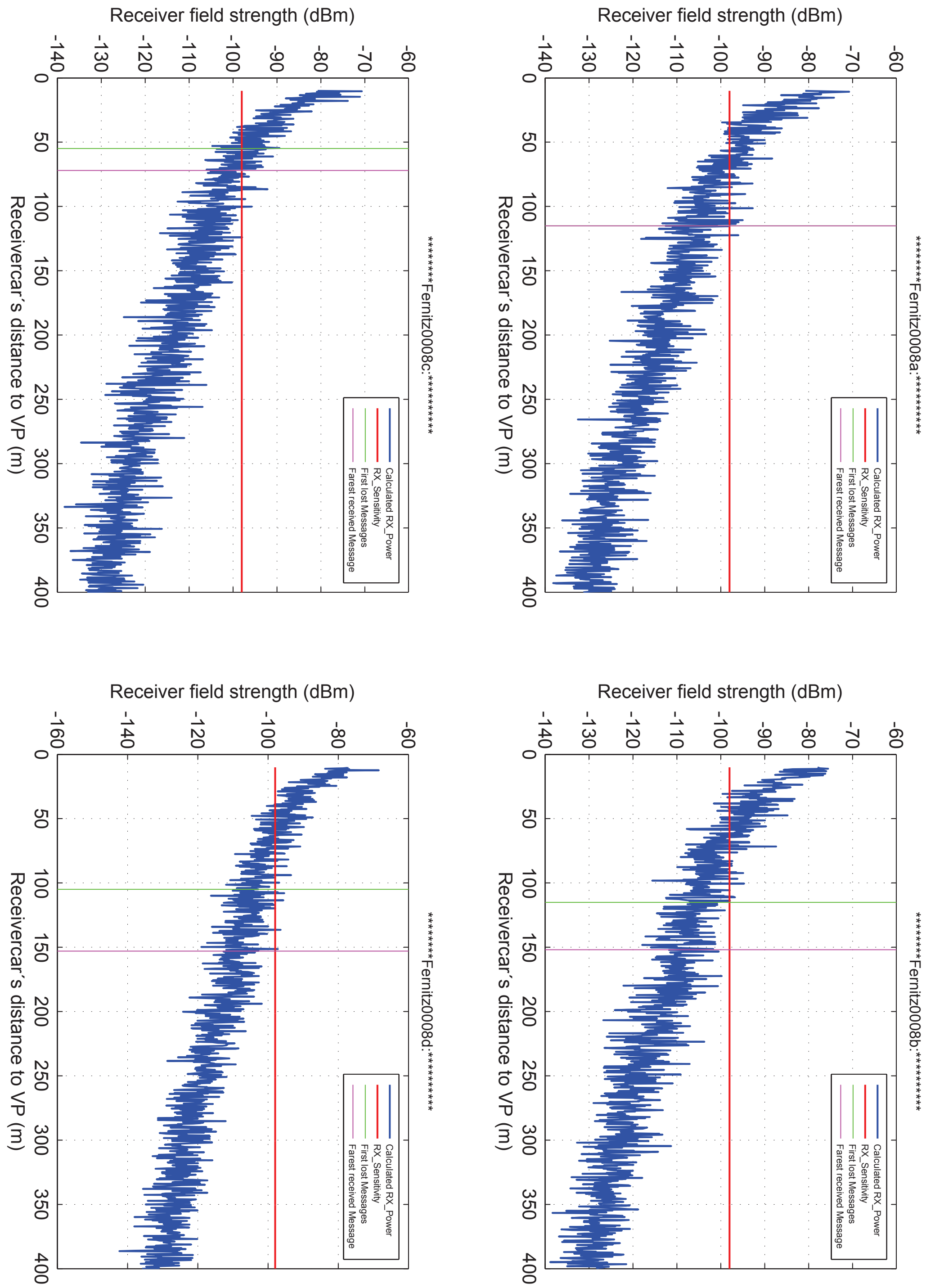

Figure 3.13: Intersection simulation of suburban area.

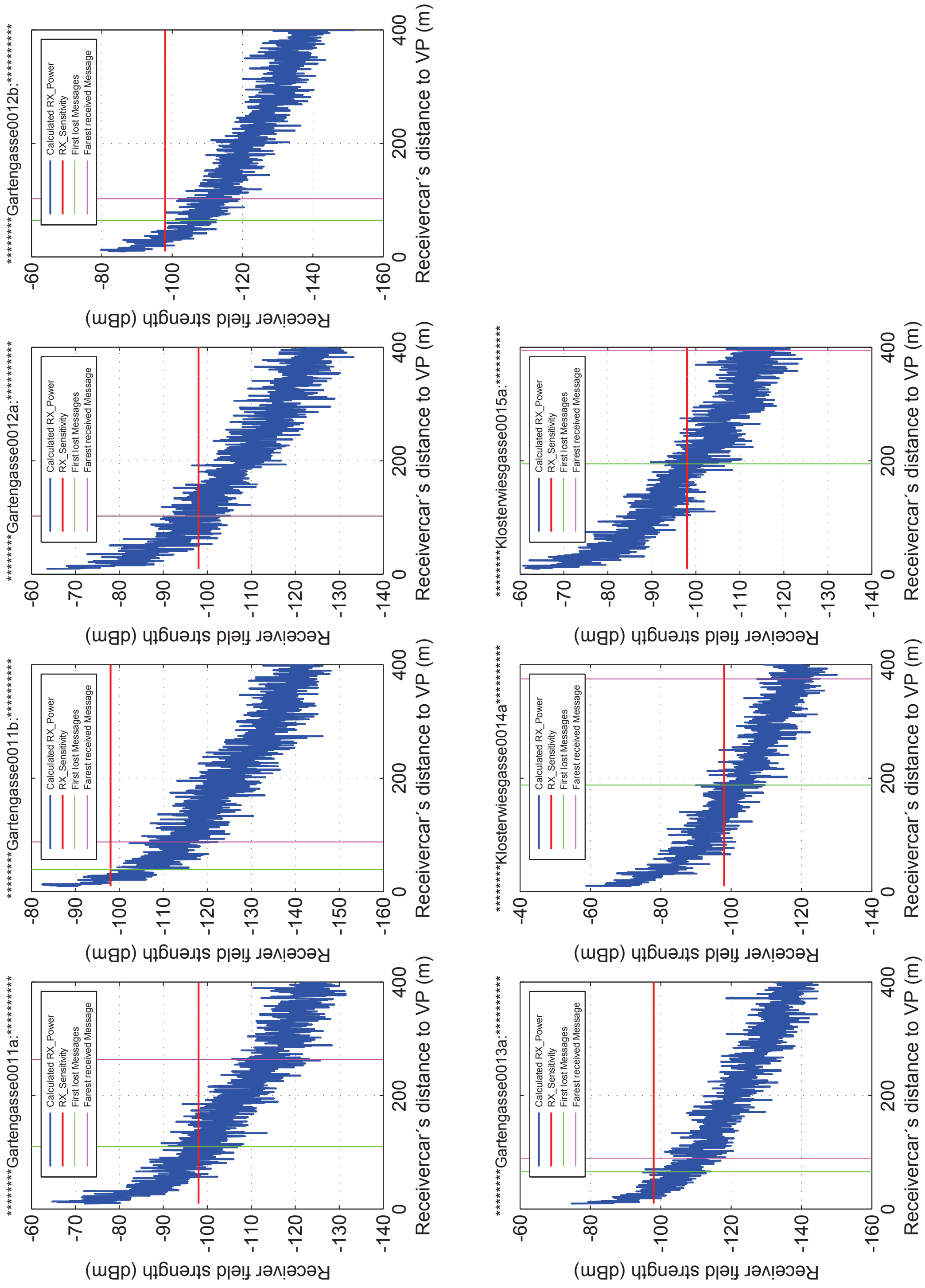

Figure 3.14: Intersection simulation of urban area.

3.5.2.2 Results

The error is calculated in the same way as in the section general model. Table 3.7 shows the absolute error e and the relative error e_{rel} of the intersection model.

The model has on suburban scenarios a relative mean error of 30.1% and a relative standard deviation of 14.8%. The model has on urban scenarios a relative mean error of 13.9% and a relative standard deviation of 10.1%. The more worse performance of the intersection model in suburban are because of the intersection's environment. All of the four documented real scenarios were measured at the same intersection. This intersection has no buildings, that are in front of the transmitter car, supporting the wireless propagation into the receiver's street. Therefore, the model evaluation of suburban is not recommended if no usual intersection should be modelled. However, the model's performance in urban are encouraging because of the high amount of interacting objects. The model is considering the geometry of the intersection, but parked and moving vehicles are neglected. Therefore, the model is a well fitting tool to simulate Car2X systems at intersections.

The model was parametrized for intersections in Munich [1]. Since the Graz and Munich are similar cities regarding the road structure, we used the same parameters.

ID	area	e	$d_r + d_t$	e_{rel}
		m	m	%
28	suburban	-56.20	140.2	40.0
29	suburban	-56.20	140.2	40.0
30	suburban	3.80	80.2	4.7
31	suburban	-46.20	130.2	35.5
32	urban	-9.43	124.5	7.6
33	urban	-16.51	113.5	14.5
34	urban	-2.43	117.5	2.1
35	urban	-33.31	118.5	28.1
36	urban	-32.97	120.5	27.4
37	urban	-35.12	219.5	16.0
38	urban	-3.86	210.5	1.8

Table 3.7: Intersection model error at different areas.

4 Discussion

The presented master thesis is the second part of a project. The first part of the project is covered by a seminar project [12], which was done in association of two institutes. The further discussion is divided into sub chapters.

4.1 Measurement

The measurement setup was built up by the Automotive Engineering Institute. The testing was supported by people of both institutes. During the measurements some scenarios became negligible. A good example of scenario, which did not break the communication, was shielding by a truck. So, after the first day, the maneuvers were updated and scenarios without a prominent effect were scrubbed.

During the following days of testing, the results related to range and reliability were surprisingly high. First estimates, which were made before the first test, were more pessimistic regarding range and reliability. Also an influence of buildings, wood and vegetation was detected.

The measurement of reliability and range delivered contact or no-contact results. Another measurement would be a transmitter included in one vehicle and the other vehicle is featured with a field strength sensor. Consequently, a considerable more Car2X benchmark points would be detected, because on every driven position a field quality is detected. Furthermore, more complex models are simpler to adjust on the environment of Graz, because of the huger dataset.

4.2 Model

A high number of wireless propagation models for vehicular usage are available. One of the available model is described in detail in this master thesis. Some models reach good performance because of its approach, but often these models do not offer a detailed description. Additionally, most models are based on vehicle and or wireless communication simulators. The aim of the master thesis was to implement a mathematical model that can be integrated in different simulation software. Therefore, a high amount of models were not adaptable. Another required feature of the model is real time capability.

Depending on the available dataset, a limitation to the possible models was done. Many models are build up with a free attenuation basis. So, in case of the master thesis a simple free attenuation, which was modified with area end environment exponents, was built up. Geometry features were additionally included for the intersection model. Small scale fading was simulated via a normal probability distribution for intersections and Nakagami probability distribution for general cases. Both distributions are widespread in channel modelling.

4.3 Simulation

The simulation of the measured results verifies the performance of the model. In most cases the model fits the reality very encouraging. However, in some cases longer distances in reality can be reached. So, the model is set to the pessimistic side and therefore in most cases the model will deliver shorter ranges as in reality. However, another set of parameter can be developed for a less pessimistic approach, which is not present in the thesis.

In both models the simulation of suburban scenarios are remarkably weaker than scenarios of other areas. This is described with the higher vegetation fluctuation. Suburban areas can be villages with a high amount of plants and trees between the building, but also small towns with low vegetation are possible. In case of abundant vegetation, the environment is highly more attenuating the wireless propagation than in higher populated villages. Therefore, suburban requires a more specific model with perhaps more input parameters, but this was not realized in this thesis.

Despite of the simplicity of the model, a considerable well performance was achieved to simulate Car2X wireless propagation except for suburban cases. Additionally the models are real time capable and simple to integrate in a vehicle simulator.

Furthermore the evaluation of the model is related to the different areas and interacting objects. For this reason a general evaluation can not be delivered in this master thesis. However, a considerable model approach for different scenarios is assumed, because of the diversity of examples.

5 Summary

Car2X is becoming a considerable role of ADAS in the future. Car2X provides information, that is not result of vehicles own sensor, but information of other Car2X featured vehicles or infrastructure. Apart from the security, which is not part of this thesis, smarter ADAS can be developed with additional Car2X information. The standardization of Car2X is still in progress, however first steps to become familiar with Car2X are necessary for automotive manufactures and research institutes.

The aim of the first project part was to become familiar with the ordered Car2X hardware and software. Afterwards a measurement setup was included in two vehicles to analyse the range and reliability of the Car2X system. Two institutes at Graz University of Technology were the main project controlling parts of the measurement. Additionally the different scenarios were defined by this two institutes. The results of the measurement were documented in a seminar project and this was the basis of the master thesis.

The high amount of measured data was post-processed to illustrate them more efficient. The data was illustrated in GoogleEarth. An export of the measured data was supported by the measurement's software. Due to just a simple line drawing in GoogleEarth resulting from this software, the measured data was further post-processed. The data was also illustrated in GoogleEarth, but more metadata was provided, e.g, pop-up info boxes were created.

During testing of Car2X in real scenarios, a high performance dependence on environment and objects was assumed. An analysis of only the range values would not be satisfying, therefore the environment and surrounding objects were also discussed. As a consequence, the illustration of the measured data in GoogleEarth was a remarkable good benefit. Furthermore in urban areas, GoogleEarth provides 3D-View of the surrounding buildings and analysis was becoming simpler. In case of motorway, which was not provided with 3D-View, an additional analysis by the recorded video was done. Furthermore related to motorway scenarios, no certifiable influence of velocity was detect and so issues related to velocity were negligible.

Another part of the master thesis was the development of a model. Therefore, different existing models were discussed. The requirements of a model are deterministic behaviour, real time ability and a mathematical description. Therefore, certain models are not possible or not preferable for the requirements and the small dataset. Most of the complex models, which could describe a remarkable performance, need a high amount of data to parametrize and adjust them. Other models were implementations based on existing simulators and these models are also not acceptable for the project.

Two different models were implemented and described in this master thesis. The first model is made for fitting general cases, e.g., contraflow, convoy or semi-static scenarios. The model is a simple link budget calculation with special focus on the path loss. The path loss calculation was a kind of Two-Ray-Ground model. The inputs of the model are the kind of area (motorway, rural, suburban) and blocking objects (LOS, Buildings, Buildings & Wood, Wood & Wall, Hill, Wood).

The intersection model requires further information depending on the geometrical environment. This model was adapted from article of ITS. The model performed very well in Munich and therefore the model was reproduced. The model performance was remarkably good. The geometrical inputs highly influence the calculation.

A remarkable weaker performance of suburban simulation was observed in both models, because the environment is very fluctuating. Suburban can be villages with a high or low amount of plants and trees. In case of abundant vegetation, the environment attenuates highly the wireless propagation, which is remarkably higher than at suburban area with low vegetation. This high environment fluctuation, is mostly observed in suburban area. Therefore to increase the the weaker performance of suburban simulation, more input parameters and a specified suburban model is required, which was not covered by this thesis.

These two models are pure mathematical solutions of wireless propagation modelling. More detailed models are discussed, however, in terms of simplicity the proposed model is encouraging googd. Furthermore a full documented approach is included in the master thesis. A general verification of the models can not be done, because the results are based on measurements in Graz. However, a remarkable good general behaviour is assumed, because of the different scenarios and areas, which were basis of parametrization.

Future work will be the integration of the model in a vehicle dynamic simulation software. The pessimistic interpretation of the models are good approaches to determine dangerous situation in traffic. Furthermore, vehicle manufactures are simulating a high amount of different scenarios to determine safety of a system. In case of the master thesis a scenario, which should show the limit of a current ADAS, will be simulated. This situation should be safer with Car2X and should illustrate the benefit of Car2X.

List of Figures

List of Tables

Bibliography

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