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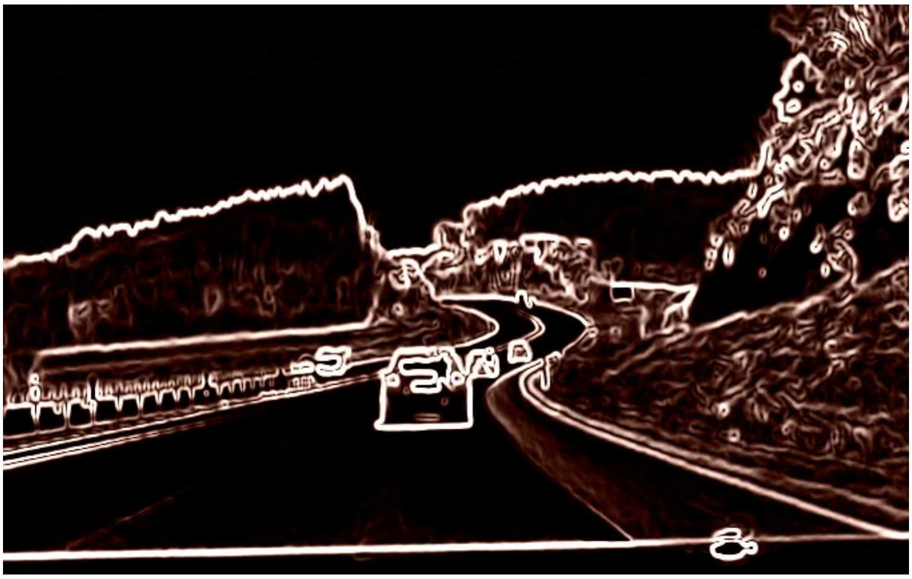

Joint multi link behavior for V2X communication

Master's Thesis in Signal and Systems

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Abstract

In this master thesis in Communication Engineering concerning V2X-communication, a method to measure the link quality of wireless protocol 802.11p is crafted and tested. This method is then applied to a field study to measure the effect of link quality in a multi link scenario. Several problems were identified, where solutions or possible ways to attack the problem are presented. Recommendations for further tests and analysis tools are also included.

Acknowledgements

We especially wish to thank Volvo Cars for giving us the oppurtunity to explore the fields of inter-vehicle communication at their premises, and to contribute to the further testing of this upcoming technology. Our supervisor Mikael Nilsson at Volvo Cars was very helpful and genuinly intrested in our work. We also wish to thank our academic supervisor Fredrik Tufvesson at LTH for all academic briefing and support. Other contributers to this work has been Taimoor Abbas at LTH with his work on the EM-algorithm. Per Olsson, a fellow student, was helpful in the fields of report writing, and also Henrik Broberg who gave a lot of technical support. We thank you all.

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Contents

Abbreviations

CAM Cooperative Awareness Message

DENM Decentralised Environmental Notification Message

LoS Line of Sight

LTH Lunds Tekniska Högskola

OFDM Orthogonal Frequency-Division Multiplexing

PER Packet Error Rate

RSSI Received Signal Strength Indicator

RSU Road Side Unit

SNR Signal-to-Noise Ratio

V2I Vehicle to Infrastructure

V2V Vehicle to Vehicle

V2X Vehicle to Vehicle and Vehicle to Infrastructure

1

Introduction

This thesis-work is focused on how communication links in a future of communicating cars will respond to a blocking car in respect to a scenario with multiple cars and thus multiple links in between those cars. As part in the research and development at Volvo Cars the conclusions here will be the basis for further field test.

1.1 Background

Much research in the automotive industry is focused on how vehicles in the future can communicate with each other (V2V-vehicle to vehicle) and with road side units (RSU) (V2I-vehicle to infrastructure). The main objective is to improve the vehicular environment to prevent accidents (traffic safety) and improve traffic flow (traffic efficiency) [1]. In Europe, the frequency spectrum allocated to the wireless protocol of IEEE 802.11p is thought to fulfill the needs of reliability and performance of this goal. The protocol has gained the necessary support from car-makers to become a standard. Volvo has several ongoing projects testing the technology and developing new functions involving 802.11p. One is DRIVE-C2X, which is a European cooperative project that has plentiful of resources and testing equipment. This is a project focused on functional testing of driver's reactions on new forms of input to the driving experience [2]. Another related project is called ETTE, which is developing communication hardware in the car [3]. To ensure reliable communication to the applications a good channel behavioral knowledge is needed. There are currently strong scientific value in doing field studies with several cars and links involved. Both Chalmers and Lund University have an extensive research and existing cooperation with Volvo Cars regarding vehicle to vehicle and infrastructure (V2X) communication. As master thesis students within the department of Signals and Systems at Chalmers, the examiner for the thesis will be from Chalmers. Working together with a supervisor from Lund University, expertise from both institutions are involved. By combining the resources of Volvo Car Corporation, Lund University and

Chalmers University this master thesis will look into the field of joint multi link behavior for V2X communication.

1.2 Purpose

This thesis will emphasise on understanding the joint behavior of multiple links in a realistic environment where the links are subjected to the effects of, e.g., shadowing and multipath. How the channel behaves is important to understand in order to estimate how reliable the links are. In particular, this project aims to deepen the knowledge of channel performance when two links are coexisting in a real-world scenario. If there is a correlation between the links behaviours this is important to know, especially when studying network reliability.

1.3 Limitations

The work will be done hardware-close, in the Physical layer in the protocol stack. Measurements of signal strength should be extracted from the packet data, in the RSSI-header (Received Signal Strength Indicator) [4]. The hardware is limited to what Volvo Car Corporation can provide, in terms of test cars, computers and other test hardware. This can have the effect that items can be used in regards that it was not intended for, thus limiting the results.

1.4 Objective

The main objective is to characterise the multi link channel behavior of a V2V communication system with respect to large scale fading, in an environment where several links are active. To determine channel characteristics the signal strength must be sampled at a suitable frequency during a given time interval. Suitable ways to measure signal quality could be either by measuring the signal strength or by analysing the packet error rate (PER). Important tasks that this thesis will handle are:

- Establish a test method.
- Find correlation between links.
- Find important aspects in the environment that affects the link quality in a multi-link environment.

1.5 Division of work

The tasks involved in making this thesis has been highly cooperative between the two co-writers of this report. However Linus Conradsson has had a higher responsibility in Matlab code-writing and creating test scenarios, while Daniel Horstmark has had higher responsibility in task managing the project and with acquiring the technical theoretical knowledge needed.

2

Technical Background

2.1 Fading and path loss

The environment where the communication system must function includes many obstacles to the link's performance. These range from landscape changes, weather effects and high relative speeds, all inducing problems like multipath, shadowing, fading and Doppler changes to the signal [5].

2.2 Communication standards

There are various approaches over the world to make V2X communication possible. The ultimate purpose of these technologies is to benefit safer driving conditions. By having inter-communicating vehicles the chance of avoiding a collision and perhaps get warnings of dangers ahead increases. In the longer perspective further developments are possible, including autonomous driving cars. 802.11p is designed to function decentralised, thus very different from current cellular communication approaches that use base stations [6]. In essence, every car will broadcast its location, speed, heading and alike in different types of messages. Surrounding cars can then make relevant actions in response.

The European implementation of 802.11p is called ITS-G5 and in the US it is called WAVE. These are a set of protocols functioning in the 5 GHz frequency band. Both supporting technologies are derived from the Wi-Fi protocol 802.11a, and this modification is named 802.11p [1]. It has been seen that Wi-Fi technology and its chip design can be reused in this purpose. A major benefit when designing a wireless protocol in a flexible traffic scenario is robustness and peer-to-peer ability, now possible in 802.11p [7].

2.2.1 System description 802.11p wireless protocol

Consequently to the natural effects named in section 2.1, the 802.11p protocol has been designed to cope with these properties, e.g., by reducing the channel width from 20 MHz in 802.11a to 10 MHz in 802.11p.

The dedicated frequency band ranges from 5.875-5.925 GHz in Europe. The transmission uses orthogonal frequency-division multiplexing (OFDM) utilising 64 subcarriers, where data transmission operates on the inner 52 of these [1]. On four of the carriers a known pattern is broadcasted. This is used by the receiver to mitigate some of the channel disturbances, like frequency and phase offsets [1]. Every carrier is using a modulation scheme, BPSK, QPSK, 16-QAM or 64-QAM, enabling data rates of 3 to 27 Mbit/s. Table 2.1 illustrates the specifications of the physical layer in the 802.11p standard [8].

Table 2.1: Table of IEEE 802.11p physical layer parameters

Parameter	Value
Bandwidth	10 MHz
Subcarrier spacing	156.25 kHz
FFT size	64
Used, data, pilot subcarriers	52, 48, 4
OFDM symbol duration	8 μs
Cyclic Prefix duration	1.6 μs
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding rate	1/2, 2/3, 3/4
Data rate	3, 4.5, 6, 9, 12, 18, 24, 27 Mbit/s

2.2.2 Message types

Essential to this thesis approach to monitor the link performance, is the system transmission of Cooperative Awareness Messages (CAMs). According to specifications these are broadcasted at a rate of 1-10 Hz [9], but remain at 10 Hz in the test equipment. (This is set and hard coded in a file). The CAMs contains information about the vehicle's location, speed and heading. Additionally when a message is received in the wireless card, a signal strength notification in dB-scale is recorded in the network card. This value can then be read from the card at any instant. A sampling frequency of 10 Hz is considered to be sufficient for observing changes in received signal power, even in a constantly changing traffic situation.

While CAMs are continuously generated, another type of packet also exists called Decentralised Environmental Notification Messages (DENM) [1]. These are event-driven, and are, e.g., used when an emergency vehicle wants to notify surrounding vehicles of its presence. DENMs are not used further in this thesis-work.

2.2.3 Reliability Assessments

As a part of the ITS G5 standard a possibility of relaying some message types is included [10]. By allowing a message to do one or several jumps between nodes the range could be increased, e.g., in a scenario as in figure 2.1 where the direct line of sight is blocked. To determine the robustness of the network, the probability of a packet reaching its destination is calculated. It is important to know to what extent the different communication links are correlated for the calculations to be accurate. As in figure 2.1, if the blocking car B appears, this will probably affect both link 2 and 3 and cause them to decrease in signal strength. If then a reliability assessment simulation, perhaps containing several different scenarios, assumes that all links are uncorrelated, the output of the simulated links in the scenario in figure 2.1 will not correspond to reality.

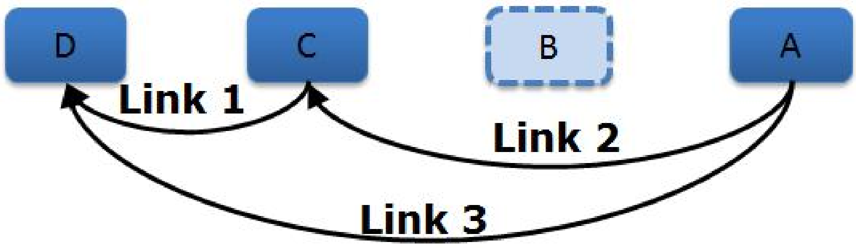


Figure 2.1: A scenario with three communication links and four cars labeled A to D. Direct LoS communication between A and C is obstructed by car B. To know the correlation between link 2 and 3 is vital to a reliability assessment.

2.2.4 Competing Technologies

802.11p is not the only technology competing to be the standard for V2X communication. Major telecom operators are pushing for the use of the cellular network and standards like 3G and 4G to be used instead, potentially with a smartphone used as a modem [11]. While having the advantage of already being deployed and having greater range these solutions suffers from higher point-to-point latency [12]. Therefore they might not be suitable for time critical safety applications. On the other hand they might very well be better suited for several other services such as traffic jam control and weather warnings. In the future a solution of both 802.11p and cellular technology is probable to be used [11].

3

Propagation Properties

3.1 Channel characteristics

As previously stated, the channel is constantly changing with the effects of reflection, scattering and diffraction, especially in the harsh channel environment surrounding a car. These fading effects are usually divided in what is large and small scale fadings, where large scale fading refers to multipath effects and shadowing, and small scale fading to fading occurrences typically on the level of a wavelength, like phase shifts due to the Doppler effect.

Other issues that can affect the signal are noise levels in the equipment in the participating unit as well as external noise levels (other cars in particular). Combined, the term Signal-to-Noise Ratio, SNR [dB], is used to define signal quality [1].

However, the main effect on signal strength is simply how far the distance between transmitter and receiver is, this signal strength degradation is called path loss and is a polynomial function of distance [13, p. 138].

3.1.1 Fading

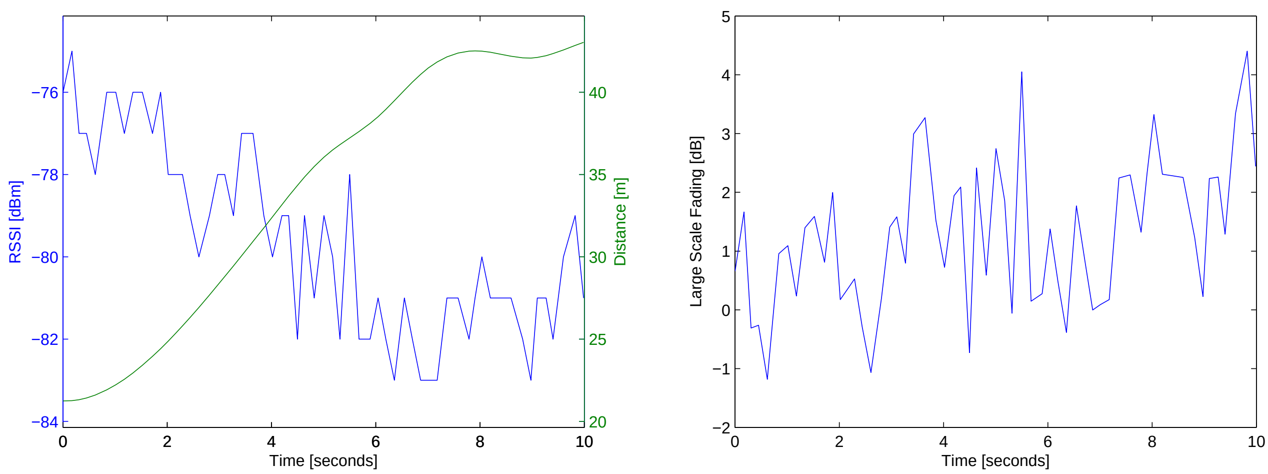
If the path loss degradation of the signal is subtracted from the RSSI value, the remaining signal strength residue is composed of the contributions of small and large scale fading. When disregarding the distance it is possible to make link comparisons on the residual. The path loss in dB-scale is often modeled to be proportional to the logarithm of the distance, and can be formulated as

$$P_r = P_0 (\frac{d}{d_0})^{-n} \tag{3.1}$$

or

$$P_r(dBm) = P_0(dBm) - 10n \log((\frac{d}{d_0})), \tag{3.2}$$

where P_r is the average received power at a distance d from a transmitting antenna, P_0 is the power received at a reference point at distance d_0 in the far field region of the transmitter and n is the path loss exponent, typically ranging from two to four in urban areas [13, p. 69]. Direct LoS path corresponds to n equals two [13, p. 139]. Values of n beneath two indicates some kind of amplification of the signal compared to free space. Examples of such phenomenon could be strong multipath signal paths, with objects in the surrounding acting as either waveguides or reflectors. If the distance between transmitter and receiver is known, and signal levels can be recorded at various distances, the path loss exponent can be estimated, in a certain signal environment. This is normally done by approximating a linear equation on a logarithmic scale, as equation (3.2) states. Having an estimate n for a channel means that the distance dependent path loss contribution can be subtracted from the signal strength. Thus the remaining part is the signal strength variations that depend on other circumstances than the path loss and is called large scale fading. If the resolution is high enough small scale fading is also visible. It is in the large scale fading that the effect of a blocking car entering in and obstructing the LoS of a communication link would be best visible. An example of raw data and the corresponding large scale fading can be seen in figure 3.1



(a) Raw data

(b) Large scale fading

Figure 3.1: An example of the removal of path loss. In (a) RSSI values and distance are displayed for the first 10 seconds of the main test scenario. In combination with the path loss exponent the corresponding large scale fading is calculated and displayed in (b).

4

Test Equipment

The network card, an Atheros AR5BHB116 is installed in a Nexcom VTC6100 computer. Modified and DRIVE C2X-specific applications have been developed, by a subcontractor to Volvo Cars, to enable use according to 802.11p standard. A block schematic is available in figure 4.1. Very little documentation of how this was implemented has been available. This had the effect that the actual performance of the system needed to be examined by tests.

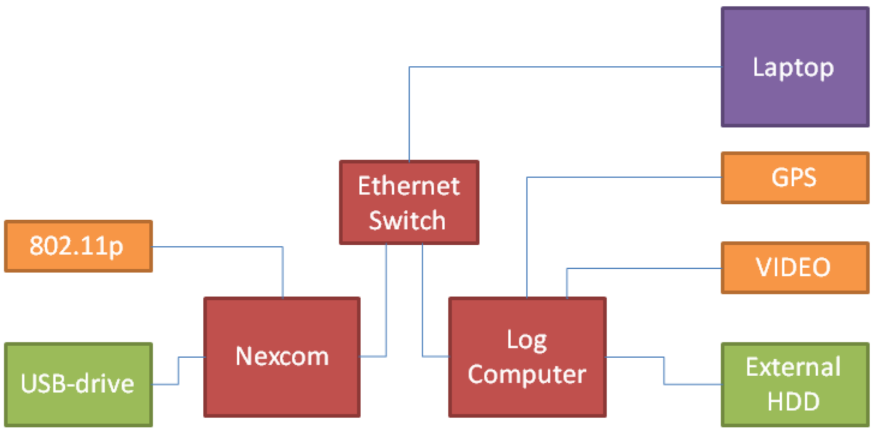


Figure 4.1: A block schematic of the test equipment used. The central part of the test equipment is the Nexcom computer with the 802.11p network card. GPS and video loggers were connected to a separate computer. The resulting logs were stored on an external hard drive and an USB drive.

4.1 Antenna

The antenna used on the cars is a dipole antenna mounted in a sharkfin as seen in figure 4.2, a standard part in new Volvo cars. It is normally located on the back-roof of the car.

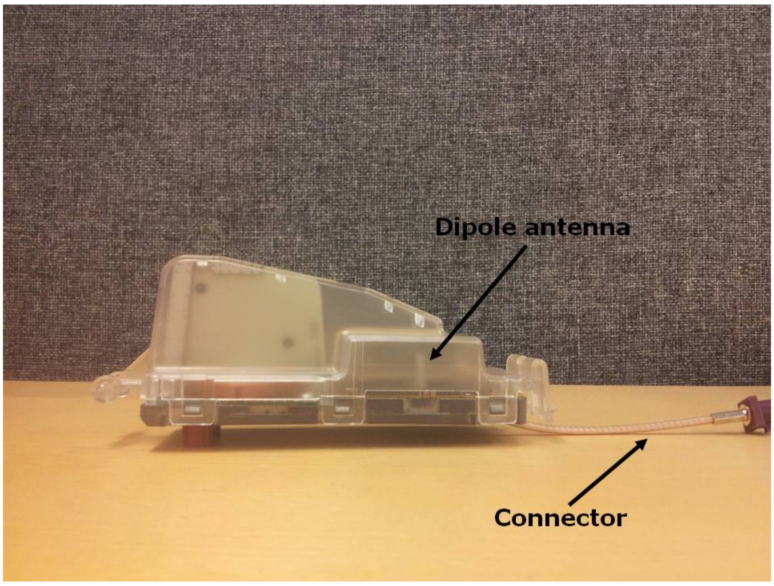


Figure 4.2: A transparent version of the antenna configuration, the dipole antenna is located in the lower end of the shark-fin.

4.2 The test cars

In the main test three different cars were used for transmission and reception, a model V70, V60 and XC70. The fourth car was a model XC90, without logging capabilities, to be used as a blockage of LoS. The full test-up fleet was photographed during the main test in Lysekil, seen in figure 4.3.

4.3 DRIVE-C2X interface

When starting a DRIVE-C2X car a whole range of sensors starts up, controlled by two computers located in the trunk. Here recordings of several video streams occur, GPS position and car status are logged. The interface of the car provides access by Ethernet-cable through a router to the computers. From here the trunk computers can be remotely controlled by a more accessible computer in the front seat, running the appropriate bash-scripts.

Figure 4.3: Test fleet during a warm day in May 2013. From left to right Volvo model XC90, XC70, V70, and V60

4.4 GPS-loggers

GPS data was initially intended to cover all cars, but only three GPS-loggers were functional during the main test. Thus, the blocking car ended up without GPS logs. The GPS-positions are logged every second. Their accuracy can be said to be around 5 to 10 meters, determined from the data set.

4.5 Integrated test system

Recordings to determine the link quality is achieved by running two terminal sessions through the remote computer, running a bash script each. One script logs the RSSI-value by the command *iw dev station dump*, and the other records timestamps when packets are received by the command *tcpdump*. To reduce the size of the recording, the later script is heavily filtered, storing only the necessary data.

4.6 Video recording

Mounting one HD-camera in the car furthest back provides an overview of the surroundings and car movement ahead. Additionally, low resolution front and rear cameras were already mounted in the V70 and XC70 from the DRIVE-C2X project.

5

Test Method

5.1 Verification and performance

The final test involved values of RSSI and PER. As the transmission frequency is known and received packets are recorded, if no packet is received when it should have been transmitted, this can consequently be regarded as a packet loss. Values in signal strength was extracted from the network card by using the bash scripts. Prior to any major test, it was essential to assure that the equipment was working at the correct frequency and that the RSSI indications of the network card was reliable. This was determined by tests.

5.1.1 Verification of RSSI–values

A known reliable attenuator, previously used in test at Volvo, was used to verify the RSSI-values. The two network cards were linked a by cable with the attenuator in between. The attenuator had a range of 1 to 121 dB attenuation. The test started with a maximum attenuation, it was then gradually lowered by 10 dB steps every 30th second, with the RSSI-value monitored on one computer. The following graph in figure 5.1 shows that the RSSI-value follows the attenuation applied. The sensitivity could be determined to be around -87 dBm, packets at signal levels below this have a high risk of failure to deliver and would result in a packet error. The steps of 10 dB attenuation corresponds to the reported signal strength. The resulting signal strength is not exactly 10 dB for each step, rather in a range from 9.4 dB to 11.7 dB during five steps. If this variance is due to the attenuator or the network card is hard to determine, but it is an error margin to consider.

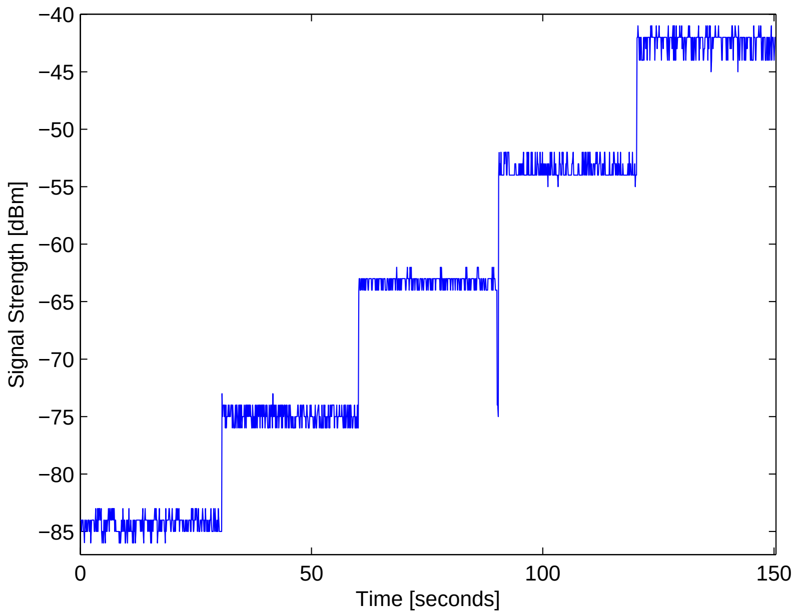


Figure 5.1: Signal strength received. Two network cards connected via a variable attenuator

5.1.2 Verification of output

Since little was known about how the network card had been modified, the output level needed to be checked and verified. The signal was checked in a Spectrum Analyser connected direct to the antenna output on the Nexcom computer used in one of the test cars. The result showed quite low signal levels, seen in figure 5.2. The bandwidth used is measured to be 8 MHz, fitting into the official 802.11p specification of channel widths of 10 MHz [8]. The transmission is determined to be at a frequency of 5.900 GHz.

5.2 Initial trials

Before the main test scenario, a pre-test was made. Here the bash scripts, signal levels compared to range was measured. Also how the signal is affected by having moving platforms. The procedure with bash scripts concluded to work well, GPS-position was not yet available in the test equipment, but points were located with the help of internet online map tools.

The signal levels were determined to be very low and packet errors started to appear significantly at already 75 m distance between transmitter and receiver.

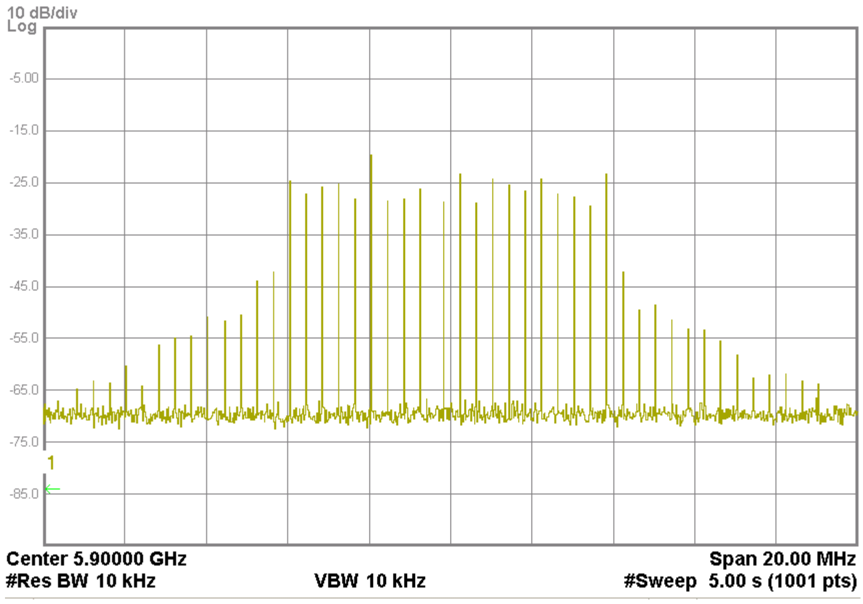


Figure 5.2: Spectra of the transmitted signal. Two network cards connected by cable with 8 dB attenuation.

5.3 Multi-link tests

After the initial trials, successful test were made to ensure that multiple links could be recorded simultaneously.

5.4 Main test scenario

The focus of the main test scenario was two main situations:

- one where four cars are driving in a car train as in figure 5.4. The leading car tries to communicate with the two last cars and another car is blocking the line of sight.
- one where communication is relayed from one car, through a second, arriving at a third.

The cars were named A to D, where car A was a model XC70 and was the leading car in the formation. Car B was a large model XC90 and served as a blocking of line of sight between car A and the trailing cars. Car C was an model V70 and served as both a blocking car, a relaying car and a receiving car. Car D was a model V60 and its main purpose was to be a trailing, receiving car. The direction of movement of the cars in the following scenario figures was to the right.

5.4.1 Scenario 1

The purpose of formation 1 in figure 5.3 was to investigate the effect of the blocking car B's distance from A and C had on the two communication links A to C and A to D. The distance was mainly assessed by measuring the time it took for a trailing car to reach the position of the one ahead. The distance between car D and C was approximately 50 meters when driving at 90 km/h, corresponding to 2 seconds. The distance between car C and A was approximately 150 meter, corresponding to 6 seconds and car B was varying its distance to A and C from 5 to 145 meters.

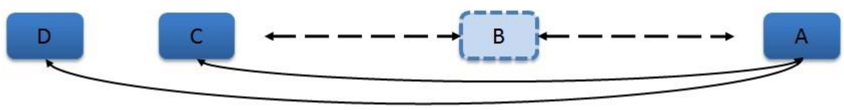


Figure 5.3: Formation 1 where Car B was varying its relative position in the train, from being very close to car A, to being far away from car A and very close to car B. Solid arrows indicate communication links and dashed arrows illustrates vehicle acceleration.

5.4.2 Scenario 2

Formation 2 to 5, in figure 5.4 to 5.8, tested the relaying scenario and investigated the correlation between links A to C and A to D. The purpose was to determine how the movements of the block B would affect the two communication links.

The formations were taken multiple times and measurement and data logging continued whilst changing. Distances between possible car positions were approximately 50 meters when driving at 90 km/h, corresponding to 2 seconds. Solid arrows indicate communication links and dashed arrows illustrate vehicle movement.

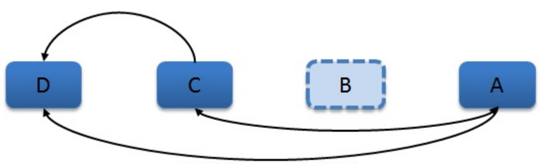


Figure 5.4: Formation 2 was the start position of the cars.

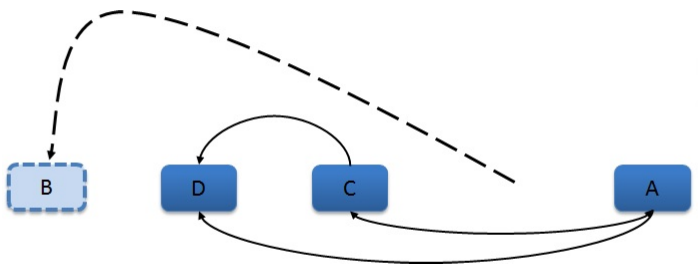


Figure 5.5: In formation 3 car B pulled out of blocking position and follows the car train. The change of signal strength in links A to C and A to D were of interest.

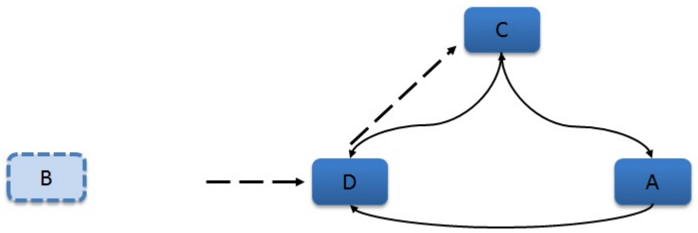


Figure 5.6: In formation 4 car C drove up to relaying position and car D advanced forward. The signal strength of links were to be compared with those in formation 5.

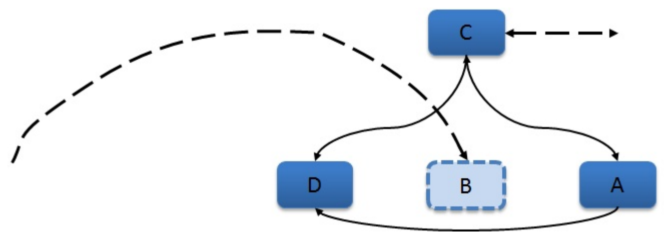


Figure 5.7: Formation 5 where car B entered blocking position. Car C had to allow car B to enter.

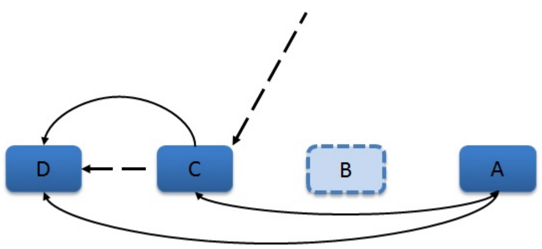


Figure 5.8: Formation 2 was take again. Car C and D fell back and the test scenario was repeated.

6

Data Processing

6.1 Improving data reliability

When the first results were analysed it was noted that there was an artifact in the receiver and RSSI sampling process. If a packet was lost and when a RSSI value was to be sampled, the RSSI value did not update. Thus the sampled value was that of the last received packet and not that of the lost one. In order to reduce the effect of this artifact, all RSSI values was classified either as received packets or packet losses. The packet losses were excluded from the data used for the linearisation.

6.2 Extracting large scale fading

Displaying the distance versus signal strength in logarithmic scale on the distance axis should produces a data set whose mean values can be linearly approximated. From the slope of this straight line the path loss exponent could be extracted.

A span of distances had to be used to get enough data points for a mean value calculation. For a better linearisation the spans were of logarithmic intervals.

With the path loss exponent determined the large scale fading could be extracted from the raw data and knowledge of distance when each package was received, thus removing the path loss for each RSSI value.

6.3 Compensating for truncated data

Verification tests indicated that the signal levels were low, and so the question arose if anything could be done to improve the linearisations. The signal strength approached the noise floor around -87 dBm. A probability close to 100 % for packet losses occurred a few dB below that, at around -95 dBm. Since signal strength values typically are normally distributed, packet error would start to occur at a mean signal level of about

−87 dBm, and affect the distribution of received packets. A principal graph of this is seen in figure 6.1. The cut-off makes the mean for each signal level higher than it actually should be without losses and this affects the path loss exponent calculations. The effect can be assumed to differ a bit between the test cars and their respective equipment.

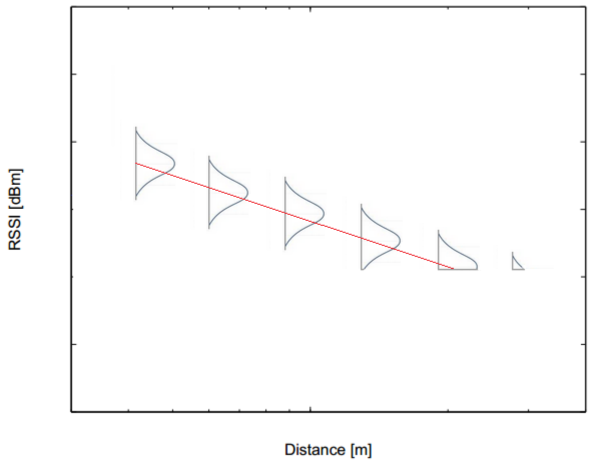


Figure 6.1: Principal graph to show that the probability of a received RSSI value at each distance is normally distributed. The red line represent the true mean value. If part of the values can not be received due to the noise floor the mean RSSI value will be higher than what is true. That is the case for the two bottom right distributions.

A way to compensate for the packet losses, and improve the linearisation model, is to try to figure out which distribution every signal level actually have, and recreate this distribution and make a mean on the basis of that. One possible way to achieve this is to use the EM-algorithm. With efforts made by Taimoor Abbas at LTH this algorithm was implemented in a Matlab script that could process the data and return actual distributions.

When applied on the data set a change in the mean value can be observed where the mean signal strength drops more rapidly as the distance grows, as can be seen in figure 6.2. The distance at which the significant drop occurs, depend on which link is observed. The resulting data set, after applying the EM-algorithm, was of a less linear character compared to without the algorithm. It was concluded that this was because of the distributions were not clearly cut off, but instead gradually degraded, resulting in an overcompensation from the algorithm. So, the EM-algorithm turned out to be a dead end for improving data in this case.

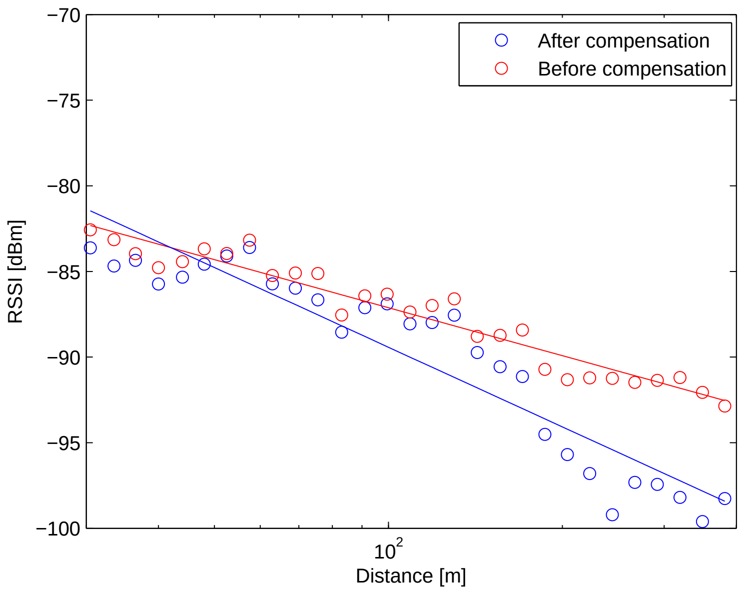


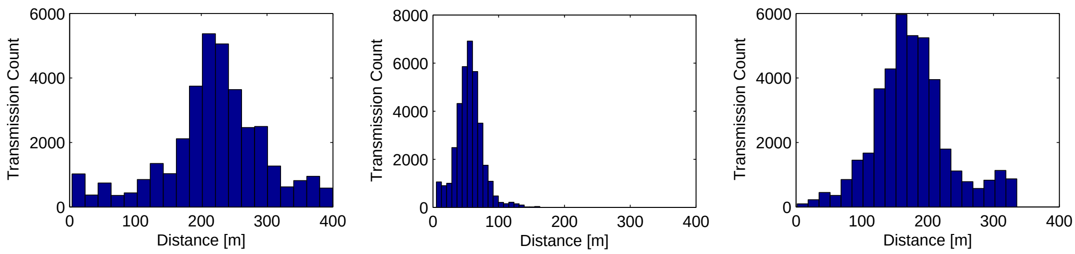
Figure 6.2: Linearisation of path loss on link D to A before and after compensation with the EM algorithm.

7

Results

7.1 Distance of operation

In figure 7.1 the distances between the two cars in a link is presented. By looking at the figure it can be seen that the average distance between cars D to C is the smallest whilst the distance between cars D to A is the largest.



(a) D to A. **(b)** D to C. **(c)** C to A.

Figure 7.1: Histograms over the distances the links were operating at.

7.2 Line of sight

The amount of packages received during LoS between the two cars in a communication link could be seen as an indication to what kind of channel each link experienced. In table 7.1 the percentage of the packets received that are experiencing LoS is presented. The results shows that the links D to A and C to A had a very low rate of LoS conditions whilst link D to C almost exclusively had LoS condition.

Table 7.1: Percent of packages received during LoS conditions per link.

Link	D to A	D to C	C to A
LoS	23.0 %	98.1 %	31.0 %

7.3 Packet error rate

The rate of the transmission had been set to a known frequency and the total time of the test session was know. By utilising these two facts and comparing the number of received packages at each receiver the PER found in table 7.2 was calculated. By comparing the PER with the LoS conditions in table 7.1, it can be seen that the high amount of LoS of link D to C results in a low PER. The PER is also dependent on the distance.

Table 7.2: Packet error rate per link.

Link	D to A	D to C	C to A
PER	44.0 %	3.6 %	26.7 %

7.4 Path-loss exponent

By placing all valid RSSI values recorded in a certain distance bin and calculating the mean value from these a linearisation using a least square method could be made. From the linearisation and the utilised equation (3.2) the path loss exponents were derived from the slope and the reference power was derived from the y-axis offset at the equivalent of 1 meter distance. In table 7.3 the parameters are presented.

Table 7.3: Path loss exponent and notional reference power.

Link	D to A	D to C	C to A	C to D	A to D	A to C
n	0.93	1.68	1.21	1.21	0.60	1.39
P_0	-68.49	-55.96	-59.65	-62.40	-76.17	-57.17

The resulting path loss exponent range from 0.60 to 1.68. Link A to D could possibly be disregarded due to potentially having synchronisation errors that were difficult to correct. Even the link D to A have a suspiciously low path loss exponent. A clue to why this behaviour appears could be seen when comparing the path loss exponents to the packet error rate in table 7.2. A high PER seems to result in a channel that seems to have better signal propagation properties and a lower path loss exponent. This is due to a majority of the packet errors occurring during poor signal strength conditions. Since RSSI values of lost packages are not possible to be recorded, a large number of low RSSI values are lost.

7.5 Large scale fading

By utilising the linearisations the resulting large scale fading was acquired for all links. Below, in figure 7.2, the link between car D to C is presented. It is clear that that this represent large scale fading with variations, both attenuative and amplificative effects, around zero.

7.6 Formation transitions

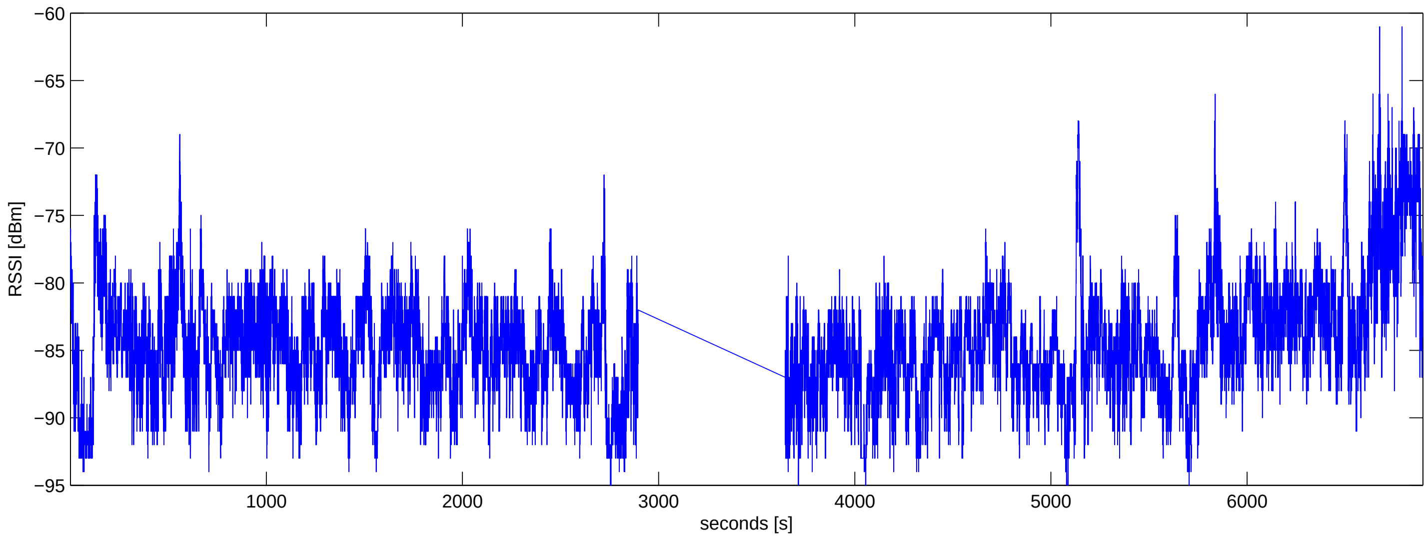
Since it is very difficult to draw any conclusions from the entire large scale fading curve of a whole link, the curve was split into smaller subsections. Each subsection corresponded to formation changes as of section 5.4. In figure 7.3 the cars starts by driving in a column. Then the block car pulls out of its position in the column and starts trailing the other three cars. Finally the car C also pulls out and allows car D to have LoS to car A. The scenario in figure 7.4 takes on from the last position in figure 7.3. The block car first drives in and blocks the LoS between car A and D, car C and A still have LoS. Then car D pulls in behind the block car and in front of car D, thus losing LoS with car A.

When comparing the behaviour in figures 7.3 and 7.4 with other repetitions from the same formation changes, similar behaviour can be seen. Though, many of the resulting figures were not as clean as these two, but rather disturbed by unintentional LoS, surrounding traffic and arching roads.

By looking at the transitions between a link having LoS between the cars and not a transition time can be determined. As seen in figure 7.3, when removing a blocking car it takes the RSSI values about 3 seconds to stabalize. This is consistent with other repetitions as well. On the other hand, when looking at the transition from having LoS and then losing it a different transition time is noted. In figure 7.4 the transition seems much faster, down to below 1 second. An explanation to the different behaviour when looking at the insertion of a block car is that the part of the transition time could be lost due to hitting the noise floor.

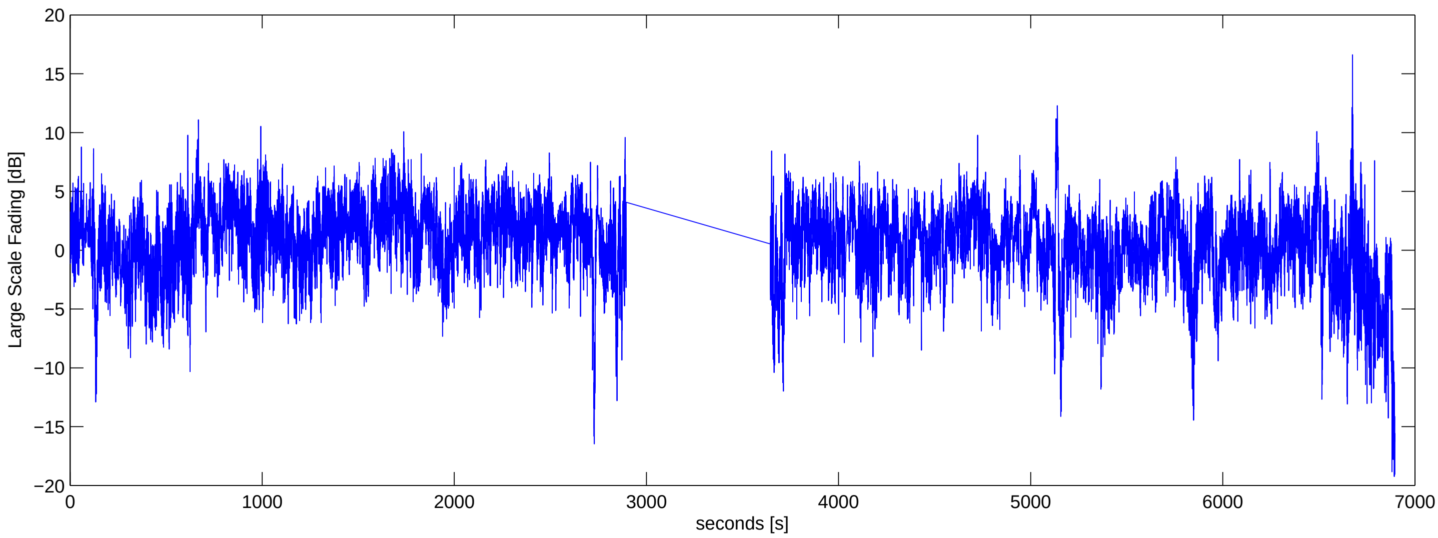
7.7 Link comparison

The links were analysed by plotting the large scale fading of two links against each other in a scatterplot. At each point of time the large scale fading in the link between car C



,

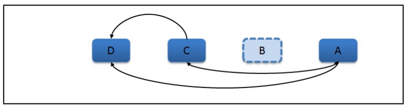
(a) Raw data.



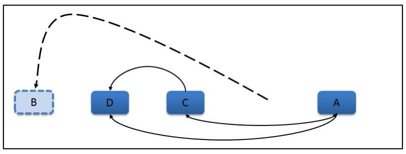
(b) Large scale fading.

Figure 7.2: Raw data (a) and large scale fading (b) of the entire link between car D to C. Note how the raw data fluctuates around -85 dBm and the large scale fading around 0 dBm. The big gap in the middle is due to a test break.

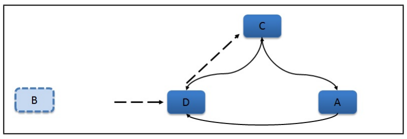
and car D were plotted against that of car D and car A. When the resulting figure is a cloud around 0 this indicates a weak or no correlation. In figure 7.5 the links are plotted like this. Any major conclusions are difficult to draw from the figure, but the main part



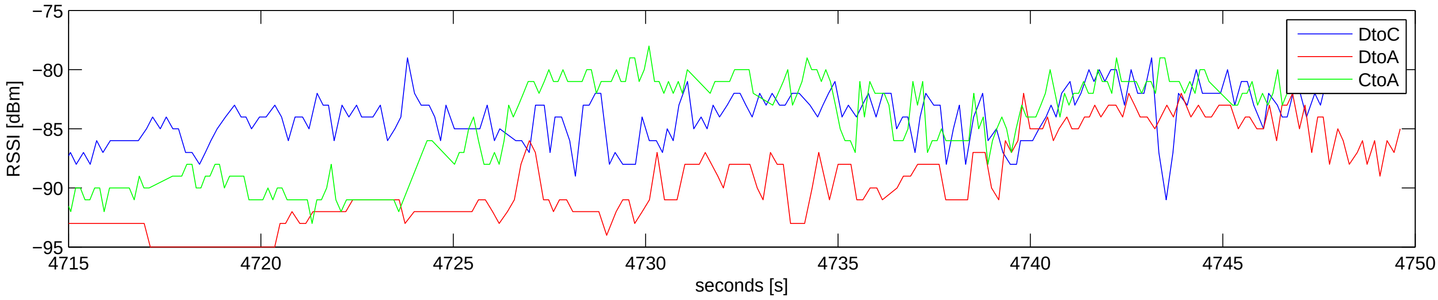
(a) Formation 2.



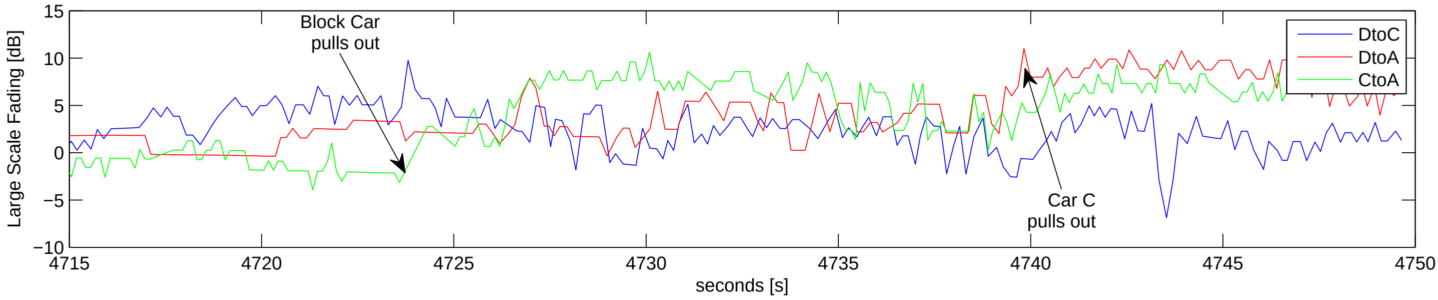
(b) Formation 3.



(c) Formation 4.



(d) Raw data.

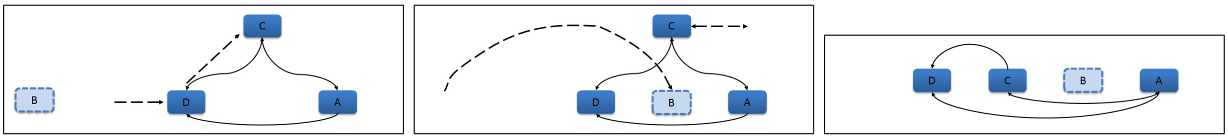


(e) Large scale fading.

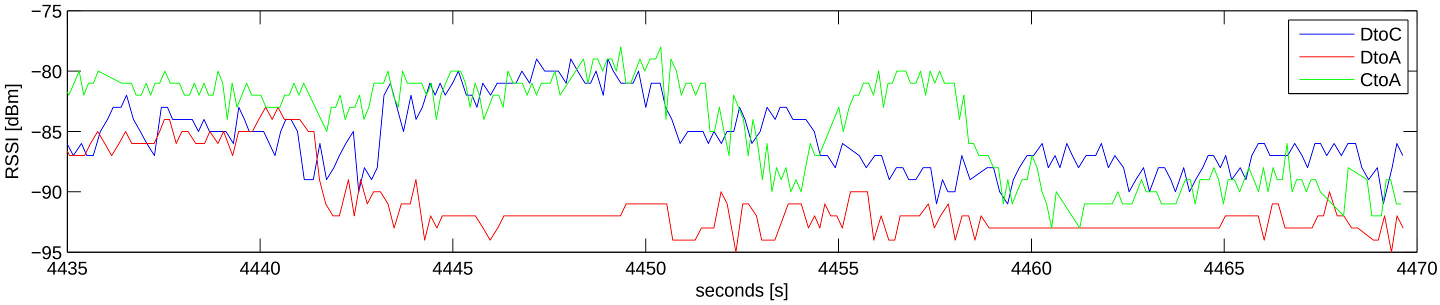
Figure 7.3: Raw data (d) and large scale fading (e) of the three links, starting in formation 2 (a). The effect of the block car is best studied by looking at large scale fading since the effect of distance attenuation is removed. When the block car pulls out the cars enter formation 3 (b) at time 4724, this is seen in the green curve which raises. The red curve remains unchanged due to that one car blocking LoS provides enough attenuation to make the link hit the noise floor. Lastly car C pulls out and car D advances at time 4739, thus ending in formation 4 (c). The effect is seen by looking at the red curve which raises.

of the data points are centered around zero. Though there are points present trailing out from the cloud that are clearly correlated.

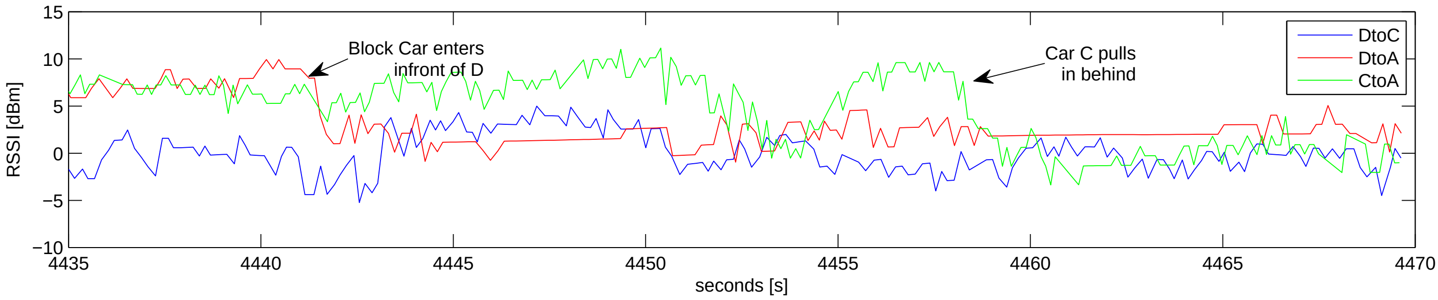
By looking at the separate scenarios and formations in more detail, it is somewhat easier to read the figures. In figure 7.6 it can be seen how car C and D first are blocked by the blocking car, this is the cloud in the bottom left corner. When the blocking car pulls out the link between C and A, signal strength increases and the cloud in the top right corner takes form. D to A does not experience any improvement since it is still in no LoS conditions due to car C. The top right corner cloud is the result of car C finally



(a) Formation 4. **(b)** Formation 5. **(c)** Formation 2.



(d) Raw data.



(e) Large scale fading.

Figure 7.4: Raw data (d) and large scale fading (e) of the three links, starting in formation 4 (a). The effect of the block car is best studied by looking at large scale fading since the effect of distance attenuation is removed. When the block car enters in front of car D at time 4442 the cars enter formation 5 (b) this is seen in the red curve which drops. Lastly car C pulls in behind car B at time 4458, thus ending in formation 2 (c). The effect is seen by looking at the green curve which drops. The red curve remains at the same level but ceases to update, thus the PER has increased to close to 100 % which can be seen by the flat red line.

pulling out and allowing the link between car D and A to have LoS.

Following, in figure 7.7 the right bottom cloud is the result of both car C and car D having LoS with car A. When the blocking car then pulls in front of car D the cloud in the top left is produced. Finally the link quality between car A and C is also diminishing when car C pulls in behind the blocking car.

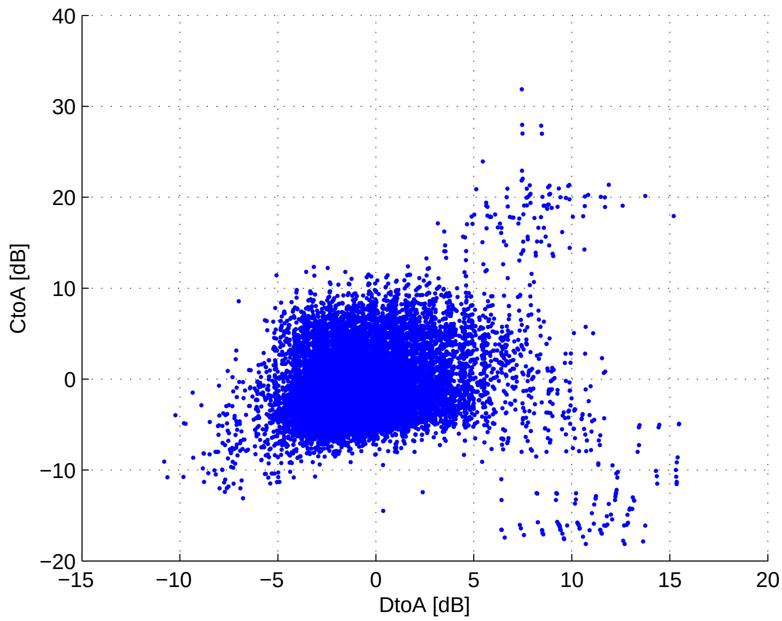


Figure 7.5: Correlation of the large scale fading of the links between cars C and A versus D and A. All available data from the main test is included. A large chunk of the data points seems to be centered around zero with a radius of 10 dBm in the x-direction and 7 dBm in the y-direction, these would correspond to the major part of the main test. Trailing out from the center a set of points are located in the top right corner of the figure. These points indicates that the links are from time to time affected by the same significantly beneficial channel characteristics. Examples of such could be when both car C and D have LoS with car A and driving through a tunnel. In the bottom right corner a similar cloud is observed where the link between D and A has beneficial channel characteristics whilst the link between C and A has not. Such an effect could have been created at one the occasions the formations were broken due to surrounding traffic and LoS between car C and A broken.

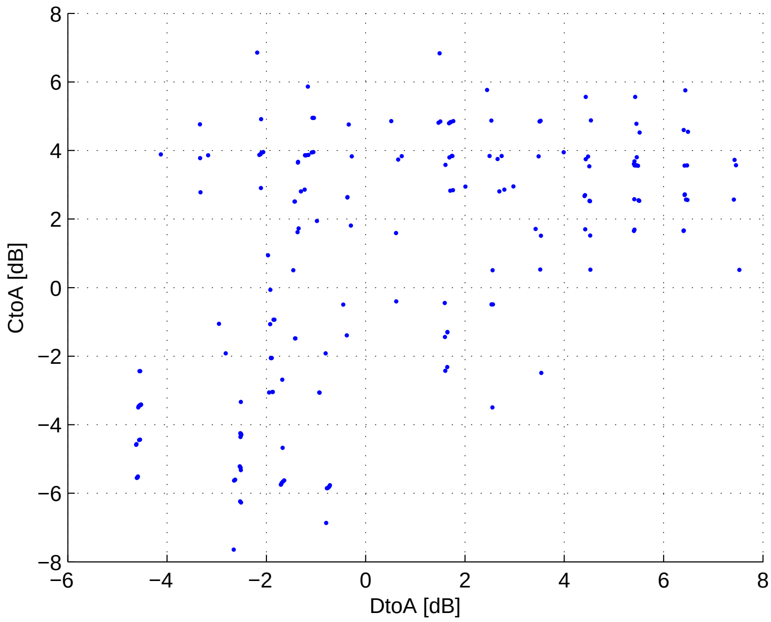


Figure 7.6: Going from formation 2 to 3 and changing into position 4. The cloud in the bottom left corner corresponds to when both car D and C are blocked by car B. When car B pulls out car C gets LoS with car A but car D still is blocked, now only by car C. This forms the top left cloud. Note how the D to A signal strength remains at the same level even though now only one car remains to block the LoS to A. The top right cloud is then formed when car C pulls out to the left lane and car D therefore gets LoS with car A.

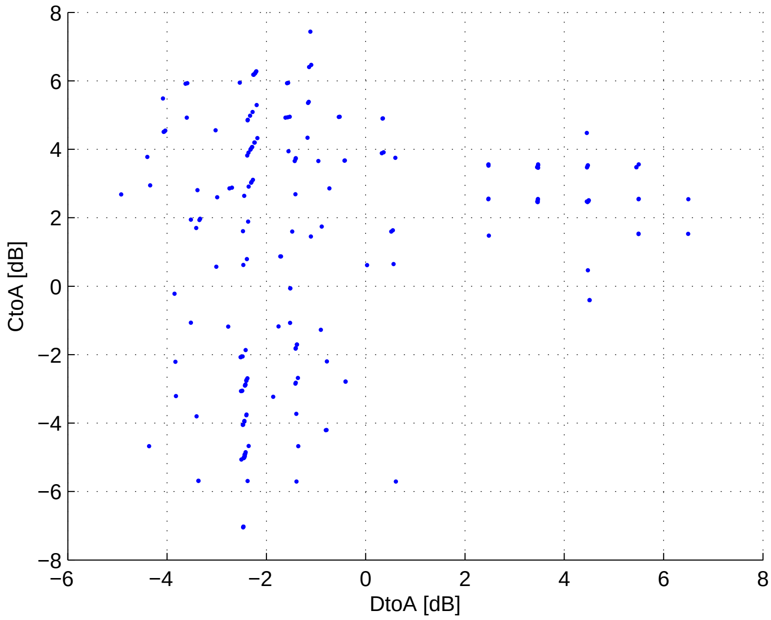


Figure 7.7: Going from formation 4 to 5 and changing into position 2. The top right cloud is formed when both car C and D have LoS with car A. When car C then falls in between car A and D and thus blocking the LoS for car D the top left cloud is created. The bottom left cloud is then formed when the block car B enters in front of car C and D. Once again note that the signal strength of link D to A is not noticeably changed when having only car C as a blocking car (top left cloud) compared to having both C and B as blocking cars (bottom left cloud).

8

Discussion

8.1 Evaluation of test method

The test method to use bash-scripts to monitor the network, and to record the RSSI-value was proven to be a good method. The 10 Hz CAMs are sufficient to observe any changes in the link quality. The dual recordings (RSSI, PER) on each car gives a lot of output and proper data handling is essential here for a good result. A more graphical interface would however be preferred, then the possibility of human errors would be lower because the test programs in its current state require a lot of modification in the scripts to work correctly. Additional details on the test method can be found in appendix A.

8.2 Test results

The results were not satisfactory due to low signal levels. Trying to compensate for this by the EM-algorithm proved unsuccessful. This is because the Normal distribution of the RSSI-values are not cut off sharply when the noise floor approaches, but show instead gradual decay. It was not possible to recreate distributions under these circumstances. This indicates that the receiver is not only limited by the received signal strength but also other parameters. One effect affecting the receivers performance could be Doppler shifts. In the analysis section the path loss exponent indicated channel propagation properties which were a bit too good to be trustworthy. Path loss exponents below 2 can occur in the case of beneficial propagation surroundings. In this field study it could be the rocky parts on the side of the road as well as other cars that acted like reflectors to the receiver. The railing in the middle of the road could act as a waveguide. But previous experience from Fredrik Tufvesson at LTH indicates that the path loss exponent should rather end up around 1.8.

8.3 Problems with signal levels

It is clear that the output signal levels should have been verified more thoroughly before moving to the main testing, now only one car was checked. The low signal level prevented the linearisations to reach a good quality. The EM-algorithm did not improve the linearisations and subsequently the large scale fadings were affected too. It could have been an improvement to install a signal amplifier to the car antennas. However, the cars were equipped with only one antenna to both send and receive, and since the amplifier works one way, the transceivers would lose either transmitting or receiving capabilities without larger modifications of the RF front end.

8.4 Correlation between links

In order to see a link's behavior in a multi-link scenario, the signal dynamics can not be as low as the one observed in the testing. This especially became a problem for the car furthest back in the car column. Since one car blocking LoS was sufficient to push the RSSI through the noise floor it was impossible to study the effect of insertion of a blocking car in front of two cars. What could be seen though, when moving cars from position 4 to 5 and from position 5 to 6, was that the blocking car had a similar effect on both car C and D. A similar effect was seen when moving from position 2 to 3 and 3 to 4 where the blocking car was removed from the LoS of both cars and then car D also regained LoS when car C was removed. Thus both link A to D and A to C showed a correlated behaviour when considering that two cars blocking the LoS caused the signal to hit the noise floor. Unfortunately only a few scenarios turned out well, thus providing very few position changes worth studying. However, a few interesting scenarios were found, where also the somewhat limited dataset pointed to interesting dual link behaviour, as the cases described in the previous chapter.

9

Conclusion

In this report a test method was established and applied on a real scenario involving several cars and links. Recorded variables were time, position, RSSI, Packet Error indication, and LoS/Non-LoS indication of each packet derived from video. It was clear that an ordinary cam-recorder is preferred over any in-built cameras, because of image quality and the possibility to comment in-drive during tests.

Due to problems with low signal levels generally, an EM-algorithm was used on the data set to estimate the distribution of RSSI-values correctly, even at signal levels below the noise floor. However, the problems with low signal levels and strange receiver behaviour were too steep to overcome.

To summarise, the scope was too comprehensive to pass with current equipment status. Learnings from synchronisation, data handling and equipment have resulted in the establishment of a good method to handle future tests. Correlated behaviour between links D to A and C to A could under some circumstances be seen. Important aspects in the environment that affects the link quality in a multilink environment proved difficult to achieve due to the other objectives being too time consuming.

Also many points of improvement will be beneficial to further testing.

9.1 Further work

Apart from the obvious requirement for the coming test; to improve signal levels, the synchronisation must also be improved since all variables are interconnected. A good way to do this would be to attenuate the signal levels on all cars simultaneously. This would make a clear dip in signal levels regardless of timing errors and at that time also start filming with a cam-recorder. Further methods to improve timing issues can be seen in Appendix A.3.

Much trouble in this project has been due to the low signal levels. This problem needs to be addressed in future tests. If new equipment is acquired, it will need throughout testing to evaluate its performance and to see if it will pass the testing requirements.

Additional improvements to increase the accuracy of the test result could be made by complementing the test involving obstruction of LoS with a signal propagation model estimation procedure. Possibly by driving the test route beforehand, importantly close in time and with the same weather conditions, and during this test vary the distance between transmitting cars. The important aspect being that the amount of RSSI values collected at each distance is large enough to provide a true mean value at all distances involved in the final tests.

The resulting outcome of any future tests is all about removing or making the error contributions as small as possible, because it will be subtle changes in signal strength when observing multi-link scenarios like the ones tested in this thesis.

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A

Appendices

A.1 Data logging

This appendix contains a description on how to start the data loggers and set them up. A USB-flash drive is the easiest way to transfer scripts to the Nexcom computers. Hint - use the commands */mount* and */umount*.

Please note that each logging of RSSI and packages involves multiple read and writes to the drive. In combination with large data logs, this causes much wear on the compact flash cards of the Nexcom computers, and could potentially ruin the cards in the long run.

A.1.1 Check network status

In order to verify that all cars and their Nexcom computers are up and running the commands *tcpdump* or *iw dev wlan0 station dump* could be used. The *tcpdump* command will show a running log of all the packages received and each individual car is recognised with a MAC-id. The command *station dump wlan0* might need to be changed to match the current network device. This command will show a list of all devices the car has communicated with since last boot.

A.1.2 RSSI

Prepare the script for RSSI logging by modifying it for each car. This is done by editing the MAC-filter to correspond to the network ID of the other car in the communication link that is wished to be recorded. The program will also ask the user to specify each *.tmp* and *.log* file with a link specific file name. Make sure that the path names are pointing to the correct directory! If several communication links are to be recorded multiple scripts must be created!

The scripts are loaded onto the log computers of the respective cars and are launched from top root level.

To abort the scripts issue the command *Ctrl + C* in the current terminal. If the script is aborted in any other way, e.g., by turning off the computer, the script will still produce the output file.

A.1.3 Packets

The packet logging script must contain one MAC-filter per car to be logged. Each MAC-filter needs to be modified to correspond to the network card of the other car and be provided a link specific file name for the output file. Make sure that the path names are pointing to the correct directory!

In order to get the transmission of packets to work it is important to note that the CAMs require a valid GPS-position in order to be transmitted.

The scripts are loaded onto the log computers of the respective cars and are launched from top root level.

The packet logging script is aborted by pressing *Ctrl + C* in the current terminal window. If the script is aborted in any other way, e.g., turning off the computer, the resulting *.tmp* file must be post-processed to filter on MAC-address. This can be done by a separate script run in a Linux distribution, e.g., the Nexcom computers. The MAC-addresses and file names need to be appropriately modified in the script.

A.1.4 Video

The Video logger is launched automatically with the startup of the Nexcom computers in the DRIVE-C2X vehicles. In another car a manually held camera should be used, and preferably placed in the front windscreen.

A.1.5 GPS

The GPS logger is launched automatically with the startup of the Nexcom computer when reception of a satellite signal is available. It can take a few minutes to stabilise its position.

A.2 Data extraction

This appendix contains a description on how to gather the data from the resulting logs. A USB-flash drive is the easiest way to transfer the log files to a computer for analysation. Hint - use the commands */mount, /umount* and */cp* for this.

Before the data is assembled into the one data matrix described in appendix A.4, make sure that it is synchronised according to appendix A.3.

A.2.1 RSSI

Once the files with the extension *.rssi* are located on the analysis computer the easiest way to extract the data to a file type compatible with Matlab is to open the files in Excel. There, split the column into three with delimitations as spaces. Save the files as **.xls* and transfer it with the import data tool in Matlab. Convert the resulting cells to arrays using the Matlab function *cellkiller*.

A.2.2 Packets

The files with the extension **.pack* are extracted in a similar fashion. Open the files in Excel and split the column into three with delimitations as spaces. Save the files as **.xls* and transfer it with the import data tool in Matlab. Use a separate script to applicate it to the collected data matrix.

A.2.3 Video

The video log in the DRIVE-C2X cars is automatically transferred to the external hard drive connected to the Nexcom computer. This is done when the Nexcom computer boots for the first time after being turned off. In order to view the files they need to be decrypted using a Matlab software with a decryption key. After decryption the videos can be viewed with a normal video viewing software, e.g., with *VLC Media Player*. If a manual video recorder is used, just move the video file to a computer and start synchronise.

A.2.4 GPS

In the same fashion as the video log, the GPS log in the DRIVE-C2X cars are transferred to the external hard drive on the next boot up. The GPS coordinates are stored in a matlab data struct together with time stamps and miscellaneous drive data. When the position is synchronised run the distance calculator.

A.3 Synchronisation instructions

In order to achieve good data quality, it is of utter importance that the different data sources are able to be synchronised. Since the timestamps provided by the test equipment can be erroneous, the synchronisation is preferred to be done by looking at the raw data. Start the test with the following:

A.3.1 Preparations

- Have one person per car and one test coordinator.
- Start all cars and their log computers.
- After a few seconds up to a minute, video and GPS logging will be initiated.
- Park all cars such so that their cameras have a clear field of view of the coordinator.
- Launch the RSSI and packet loggers on the Nexcom computers.

Now all cars are logging video, GPS, RSSI and packets, although they are not yet synchronised.

A.3.2 Synchronise the video with the RSSI and packet logs

Procedure

- At a clear visual signal by the coordinator - apply a screening material around the antennas.
- Wait one minute.
- At a clear visual signal by the coordinator - remove the screens.

Post processing

Now we are able to synchronise the Video with the point at which the RSSI and packet logs loses all packets and signal strength plummets! Cut and discard previous data at this point.

A.3.3 Synchronise the video with GPS - Method 1

Procedure

- Find a distinct geographical location and record the coordinates by either a GPS or map tool.
- Drive over the recorded coordinates and note with as great precision as possible the time difference between the cars.

Post processing

Through examination of the video, the time at which the cars passes the known location can be determined. The point of time when the last car passes the location is considered the starting point of all the logs. Add the recorded time difference between the cars passing the location, thus making the second to last cars log start some second after it has passed the location and, following, the first cars starts the furthest away. Now cut the GPS and video data to these times. Further cut the RSSI and packet logs to correspond to this new starting point by using the time from the video timestamp or a stopwatch (counted from the application of the screens to the last car passing the known location).

A.3.4 Synchronise the video with GPS - Method 2

Procedure

- All cars are parked for at least a minute with the coordinator visual in the video.
- At a given signal by the coordinator, the cars all start to accelerate rapidly.
- Continue driving for at least 10 seconds.

Post processing

This is a slightly simpler method to postprocess. The acceleration will be visible in the GPS log and video. Cut and discard both GPS and video at the start of the acceleration. This will be the new starting point of all logs! Further cut the RSSI and packet logs to correspond to this new starting point by using the time from the video timestamp or a stopwatch (counted from the application of the screens to the last car passing the known location).

A.4 Data processing

The data needs to be assembled into one matrix for the analysing Matlab programs to function. Each link must have the data structure illustrated in table A.1.

Table A.1: Example Matlab Data matrix

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Time elapsed	System clock	Signal Strength	Packet Error indication	LoS indication	Distance
0	28059,012	-79	0	0	77,876
0,143	28059,156	-93	0	0	79,967
0,304	28059,317	-85	0	0	82,113
. . .	. . .	. . .	. . .	. . .	. . .

A.4.1 Video recordings

If the test scenario involves several moments or scenarios, this will be documented in the video. The time stamps for the start and stop for each scenario is available in the video. Look through the video and note the start of each new phase in the test. Now you can observe the results in the analysing programs without constantly having to check back at the video, since you know the time stamps.

A.4.2 Analysis programs

When analysing, the RSSI-value is fundamental, the following programs can be used to monitor it in respect to the other values, like packet error occurrences or distance between cars. The scenario can also be replayed using GPS positions and displayed in a map provided by Google.

- *rssipe* displays RSSI-value and Packet error in one graph.
- *rssidist* displays RSSI-value and distance in one graph.