4

Vehicular Communication Environments

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Communication to and between road vehicles (cars, truck, buses, trains, etc.) are of growing interest. This is partly due to the attractive services that cooperative intelligent transport systems (C-ITSs) provides, mainly in the areas of traffic safety and traffic efficiency. An enabler for C-ITS is wireless vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, collectively referred to as vehicle-to-X (V2X) communication. Another driver is the advent of *moving networks* in the context of 5th generation (5G) systems. Moving networks includes the use of vehicles as mobile or nomadic base station (BS), with the purpose of providing connectivity to both vehicle passengers and to users outside the vehicle.

In this chapter, we will discuss key issues in V2X communication: propagation, antennas, and physical (PHY) and medium access control (MAC) layer algorithms. Measurements, characterisation, and modelling of radio channel are reported for road, railway, and special environments in Sections 4.1.1, 4.1.2, and 4.1.3, respectively. Antennas are discussed in Section 4.2, while PHY and MAC layers are treated in Section 4.3.

4.1 Radio Channel Measurements, Characterisation, and Modelling

4.1.1 Road Environments

4.1.1.1 Measurement, characterisation and modelling

Vehicular connectivity will be rolled out via several radio access technologies; Third generation (3G)/Fourth generation (4G) long-term evolution (LTE), wireless local area network (WLAN), Bluetooth, 802.11p (ITS-G5/wireless access in vehicular environments (WAVE)), and possibly 5G in the future. Vehicular environments being highly dynamic pose new challenges for each

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of these technologies. Among all challenges faced, the radio channel is one of the most critical ones.

Understanding the properties of the radio channel is extremely important for robust and efficient system design. Typically, three main approaches are used to characterise the properties of the radio channel; deterministic, stochastic, and measurement-based approaches [Abb14]. Measurement-based characterisation and modelling for vehicular channels is of particular interest in this section.

A number of measurement campaigns have been performed and results have been reported to characterise the underlying propagation mechanisms, dynamics of the channel, and the antenna/environment interactions in scenarios such as line-of-sight (LoS), non-line-of-sight (NLoS) due to buildings at the street crossings and obstructed line-of-sight (OLoS) due to shadowing by other vehicles.

Double directional channel sounding is one of the techniques which are used to analyse the antenna/environment interaction. In Renaudin and Oestges and Martin Käske et al. [RO14, MKT14], double directional multiple-input multiple-output (MIMO) channel sounding campaigns were conducted on the campus of Aalto University, Finland and TU Ilmenau, Germany. The aim of the measurements was to separately investigate the impact of moving scatterers (e.g., other vehicles) from the inherent dynamic of the observed channel caused by the movement of transmitter (TX) and receiver (RX), which allows us to model both effects independently in the channel model. In Renaudin and Oestges [RO14] similar, but more extensive, measurements were performed in urban, sub-urban/campus, highway, and underground parking environments. Considered scenarios were, vehicles traveling in the same direction, vehicles traveling in the opposite direction, and vehicles approaching intersections from perpendicular directions with/without LoS obstruction by buildings.

Vehicles approaching intersections at an urban crossroad often experience NLoS conditions due to the buildings at the corners. Propagation loss in such a situation can be very high at 5.9 GHz, which can greatly impact the link reliability for V2V communications. In Schack et al. [SNG+11], this issue is discussed and 3D ray-optical path loss predictions are compared with narrowband measurements at 5 GHz. It is found that the maximum communication range is quite low in the urban areas under NLoS conditions as compared to the LoS conditions due to worse signal-to-noise-ratio (SNR) levels at the RX.

Similarly, Paschalidis et al. [PMK+11] address a measurement campaign focused on V2V communication at crossroads for two selected scenarios shown in Figure 4.1, e.g., vehicles traveling on perpendicular streets and non-traffic-light-regulated left turn.

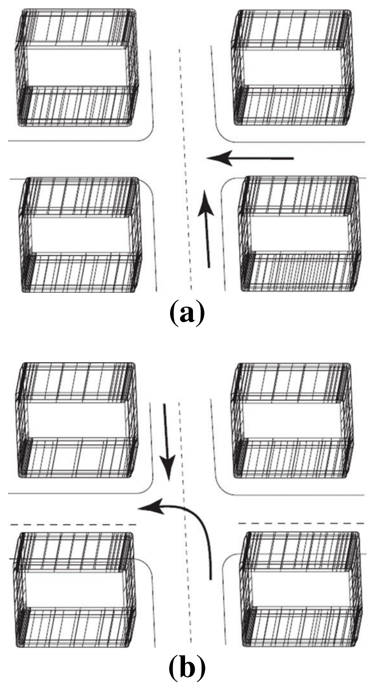


Figure 4.1 Illustration of measurement scenarios. (a) *Cross traffic* on a major-minor intersection, and (b) *Left turn* on a major-major intersection.

The measurements were performed in Berlin with the Heinrich Hertz Institute (HHI)-Channel-Sounder, a true 2×2 MIMO wideband radio channel sounder operating at a carrier frequency of 5.7 GHz. The antennas were positioned at the side doors, to achieve a high spatial separation. The focus of the investigation is set on the received power at each antenna.

It is found that the received power level fluctuates strongly and largely independently for each channel (Figure 4.2). This effect is more pronounced when the vehicles have larger distances from each other. The paper stresses that different effects such as shadowing or preferred angles of arrival/departure seem to be pronounced in different scenarios. As a consequence, the choice of an optimal MIMO technique for such a setup can not be universal.

In road environments, LoS between communicating vehicles can be blocked due to the presence of other vehicles. It is observed that the communication link in the crowded traffic scenarios experience severe fading, which is typically due to the obstruction by taller vehicles [BVF^{+}11a]. In Abbas et al. [ATK12] a measurement-based analysis is performed to analyse the impact of LoS obstruction. The measurements were performed in varying traffic

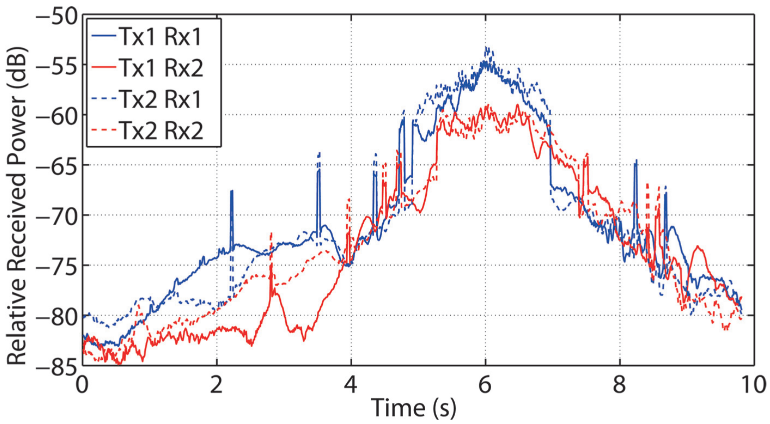


Figure 4.2 Relative received power for the four MIMO channels for the left turn scenario.

conditions from light to heavy traffic in the highway and urban scenarios. From the measurement results, it was observed that LoS obstruction by vehicles induce on average an additional loss of about 10 dB in the received power.

To validate the findings in Abbas et al. [ATK12], a measurement campaign was performed where a truck was used as an obstacle in a controlled way. Wideband 1 $\times$ 6 single-input multiple-output (SIMO) measurements were performed with the RUSK LUND channel sounder in rural, highway, and urban scenarios. In Vlastaras et al. [VAN$^+$14], the loss due to the shadowing of the truck (in dB) was observed to be Gaussian distributed with mean around 12 and 13 dB for the antenna with the best placement in rural and highway scenarios, respectively, confirming previous results (Figures 4.3 and 4.4). Parameters of path loss model, large-scale fading distribution, and auto-correlation were also provided. In Nilsson et al. [NVA$^+$15], multilink shadowing effects in measured V2V channels were investigated and it was found that the multihop techniques similar to the ones implemented in the

Figure 4.3 The two cars at TX/RX and the truck as obstacle used in the measurements. The total truck length was 980 cm with a container width of 260 cm and height of 400 cm from the ground.

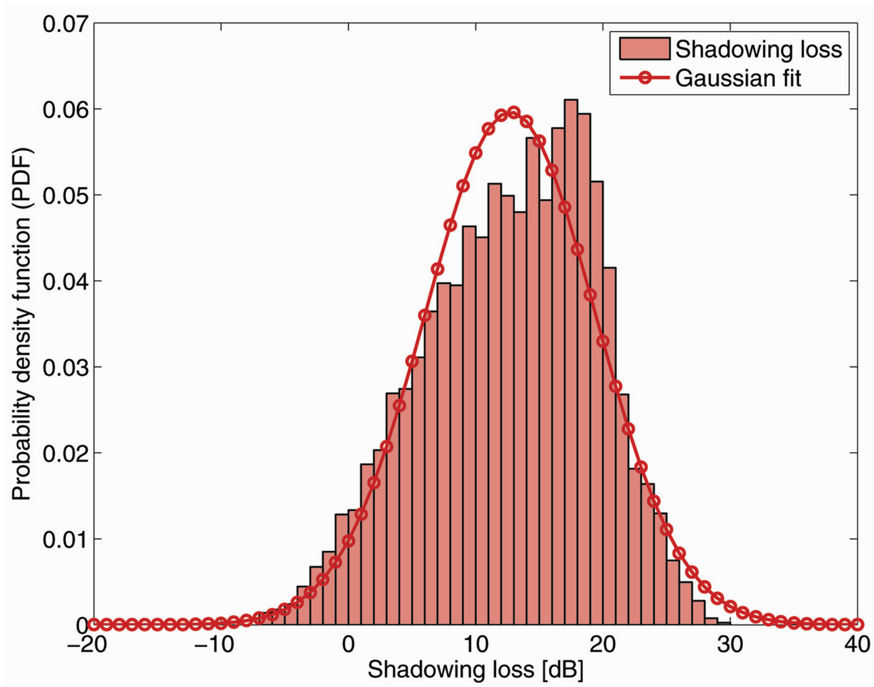


Figure 4.4 Shadowing loss due to the truck for antenna 1 in the highway scenario.

ETSI ITS-G5 standard can overcome the shadowing losses by relaying the information via another car.

Mobile terminals such as smartphones and tablet computers utilising direct high-data rate applications and services in cellular networks are often operated from inside vehicles such as cars and buses. The antenna systems in smartphones utilising multiple antennas for techniques such as spatial diversity, beamforming, and MIMO, also the directional properties of the channel, including the immediate environment, is of great importance for accurate performance evaluations. How this channel modelling could be done and what specific impact the car environment may have were investigated in Harrysson et al. [HMHT13] for frequencies around 2.6 GHz.

The investigation was based on channel measurements in two different static scenarios with an upper body phantom and a four-antenna handset mock-up located outside and inside a common type family car (station wagon), in the LTE band at 2.6 GHz for a synthetic 4×4 MIMO arrangement.

It was found from the measurements in the investigation that the penetration loss due of the test vehicle vary on average between 1.6 and 7.9 dB depending on the outer channel, i.e., the scenario and orientation of the car relative the BS, as shown in Figure 4.5.

From the measurements with a 128-port cylindrical array antenna both with the car absent and with the antenna placed inside the car, directional channel parameter estimation was performed to form the propagation channel model as a part of a composite channel model.

Combined with measured antenna patterns of the handset-plus-user it was found that this channel model produces channel properties such as path loss and channel statistics very similar to what was found by the direct measurements with the handset-plus-user in the same channel (Figure 4.6).

Similar analysis to find the vehicle penetration loss (VPL) was performed in Virk et al. [VHK[+]14] based on empirical as well as numerical evaluations.

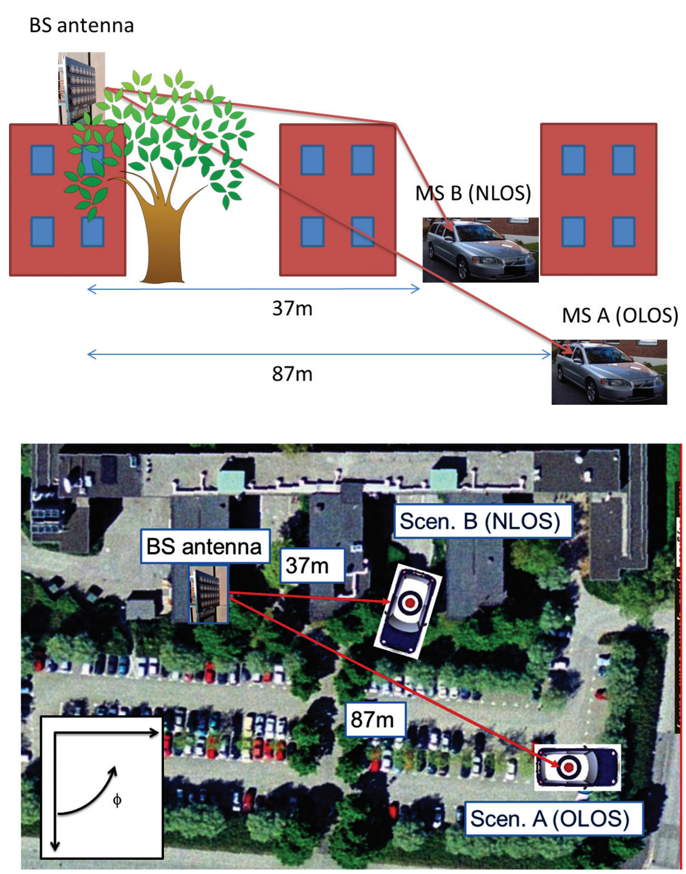


Figure 4.5 Illustration of the two measurements scenarios and the car orientations.

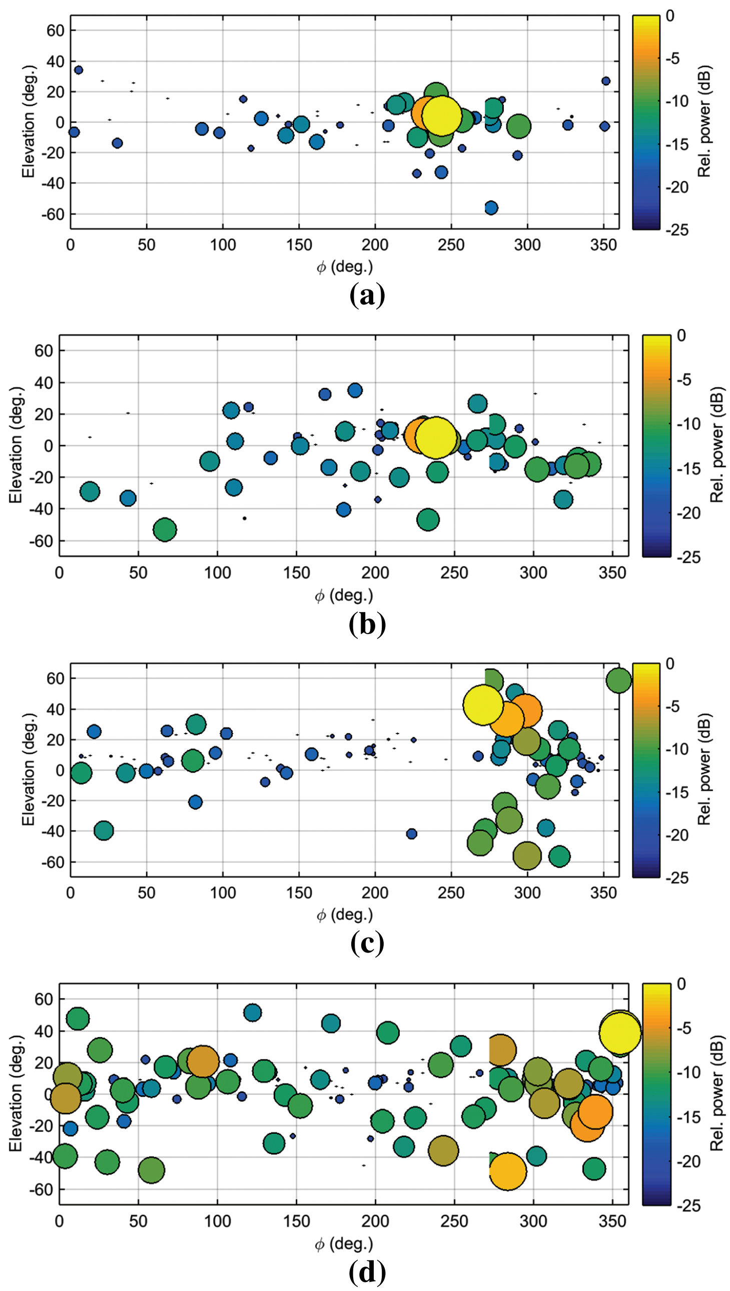


Figure 4.6 Estimated multi-path component (MPC) power versus elevation and azimuth at the MS (DoA) in the different scenarios: (a) A outside, (b) A in car, (c) B outside, and (d) B in car. The colour of the circles represent the relative total power of the MPCs.

For the empirical analysis, ultra-wide band (UWB) measurements were carried out in an indoor industrial environment at an isolated storage facility in Helsinki for the frequency range of 0.6–6.0 GHz. A regular-sized hatchback car was used, where windows were coated either by aluminium metal foil or by commercially available automotive window films. Typically, measurements are time consuming and require a lot of effort. Numerical analysis can thus be an alternative to measurements, given that adequate computational resources are available. Therefore, VPL was also investigated using an finite-difference time-domain (FDTD) method carried out at the discrete frequencies 900 MHz and 1.2 GHz. From the measurements, the mean VPL evaluated for no-coating, window film, and aluminium metal foil case was 3, 6.6, and 20.7 dB, respectively, for the complete observed frequency range. Similarly, simulated VPL values at 900 MHz and 1.2 GHz were 14 and 16.5 dB by considering the aluminium metal foil coating on the car windows. The deviation in the observed results could be due to the inaccurate description of the material properties used in car simulation model. It is one of the known limitations in the numerical methods.

In Shemshaki and Mecklenbräuker [SM12] path loss models are evaluated for future site planning of RSUs using LTE technology at 800 MHz and 2.4 GHz. Two types of vehicular environments were considered, V2V where scenario assumptions are car-to-car (C2C), truck-to-truck and car-to-truck, and V2I where scenario assumptions are car-to-roadside unit (RSU) and truck-to-RSU. It is found that for satisfying coverage and capacity requirements using LTE technology, the empirical models for median path loss, i.e., original Hata model and the extended Hata model for future V2I links, and the extended Hata-SRD model for V2V links, are applicable to RSU site planning.

Measurements are, of course, always subject to noise and interference. Methods for mitigate the effects of noise and interference when estimating path loss and fading parameters were proposed in Abbas et al. [AGT14]. Two new path loss estimation techniques for censored data based on expectation maximisation (EM) and maximum likelihood (ML) approaches were developed. The accuracy of the proposed methods is tested against censored synthetic data, which has shown promising results by providing accurate estimates.

4.1.1.2 Stationary issues

The propagation characteristics of V2V channels are quite different from those of traditional cellular channels. In traditional channel modelling, the wide-sense stationary-uncorrelated scattering (WSS-US) assumption has been widely used to describe random linear time-varying cellular channels. In V2V channels, due to the dynamically changing environment, the statistics of channel changes over moderate time scales (non-WSS); due to the several taps interacting with one-and-the same object, such as buildings on the road side, the taps at different delays show correlated fading property (non-US). Therefore, the WSS-US assumption is not accurate for V2V radio communication channels for large time durations or wide bandwidths.

In Li et al. [LAC+13] a non-WSS-US channel model is proposed for V2V communication systems. The proposed channel model is based on the tapped-delay line (TDL) structure and considers the correlation between taps both in amplitude and phase.

In Laura Bernadó [LB11], a detailed analysis of the time-varying channel parameters, RMS delay and Doppler spreads, and stationarity time are presented. The analysis is based on the data collected in a vehicular radio channel measurement campaign, named DRIVEWAY09 [Abb14]. It is shown that these time-varying channel parameters are statistically distributed and can be modelled as a bimodal Gaussian mixture distribution.

The non-stationarity of V2V radio channels is analysed in He et al. [HRK+15] using three metrics: the correlation matrix distance (CMD), the wideband spectral divergence (SD), and the shadow fading correlation. The analysis is based on measurements carried out at 5.3 GHz using a 30×4 MIMO system in suburban, urban, and underground parking areas. It is found that the stationarity distance ranges from 3 to 80 m in different V2V scenarios, and is strongly affected by several factors such as the existence of a LoS, the speed of cars, and the antenna array size and configuration. Based on the comparison of the equivalent stationarity distances estimated by the three metrics, it is found that: (i) a large electrical array aperture improves the angular resolution and thus results in a smaller estimated stationarity distance; (ii) strong LoS and a small difference of speed between a vehicle of interest and surrounding vehicles lead to large stationarity distances; and (iii) environments with a large number of scatterers exhibit smaller stationarity distances (Figure 4.7).

To statistically model the time-variant V2V channels, the dynamic MPCs are characterised in He et al. [HRK+14] based on suburban measurements conducted at 5.3 GHz. The CMD is used to determine the size of local WSS region. Within each WSS time window, MPCs are extracted using wideband spatial spectrum of Bartlett beamformer. A MPC distance-based tracking algorithm is used to identify the birth and death of MPCs over different WSS regions, and the lifetime of MPC is modelled with a truncated Gaussian distribution. The MPC characterisation considers both angular and delay domain properties as well as the dynamic evolution of MPCs over

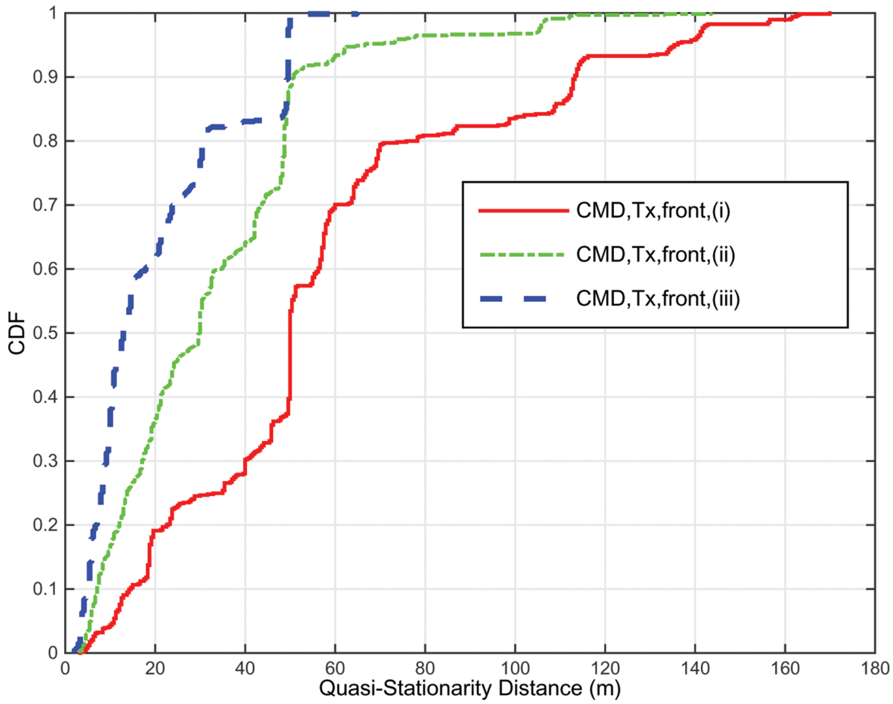


Figure 4.7 Results show that a large electrical array aperture leads to a smaller estimated stationarity distance.

different WSS regions. The results are useful for the scatterer modelling in geometry-based stochastic channel modelling.

Another approach to statistically evaluate the lifetime of multipath components for the V2V channel is presented in Paschalidis et al. [PMK$^+$12]. A new identification and tracking algorithm, which follows a geometrical approach, is introduced that can identify the strong MPCs. The algorithm identifies the MPCs in the delay domain and tracks them in the time domain. Moreover, discrete and diffuse scatterers can also be differentiated during the tracking process.

4.1.1.3 Modelling, and simulations

Realistic models of the propagation channel are always beneficial especially if they are capable to reproduce most of the channel conditions while keeping the amount of computational efforts as low as possible. Typically, measurement-based channel models give a very realistic view of the propagation environment, but a major drawback with the measurement-based models is that they are scenario-specific and require a lot of time and efforts.

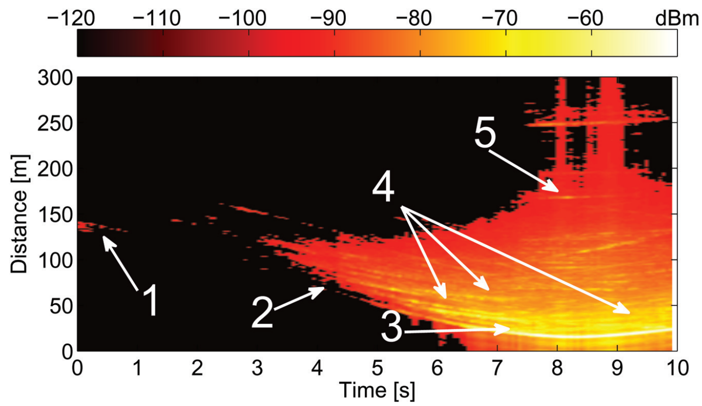
An alternative approach to that is the deterministic approach such as ray-tracing that aims to provide accurate or meaningful approximations of the channel for a specific propagation environment, given that an accurate description of the environment is available. Typically, the computational complexity of ray-tracing models is very high, but can be reduced at the cost of model precision.

For the ray-tracing models, there are a number of ways to develop a detailed and accurate topographic database including all objects on the surface depending upon the type of channel under investigation. One way is to use public-domain OpenStreetMap (OSM) database for the purpose of outdoors deterministic vehicular channel modelling. In Nuckelt et al. [NRJK13], a guideline to make use of OSM data is presented. It is also investigated that whether or not the available building data is capable to provide a satisfying accuracy required for an adequate channel modelling.

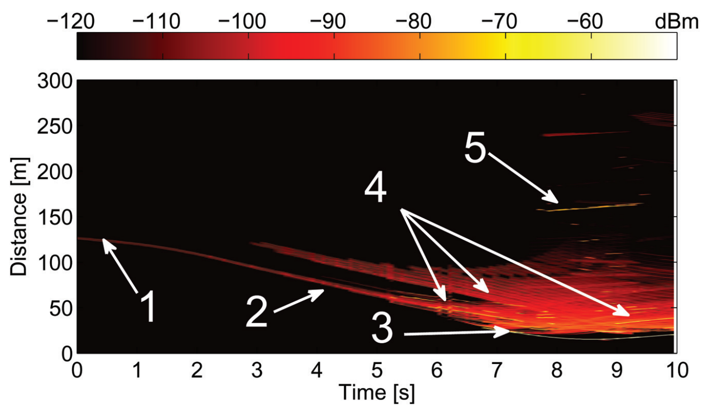
Furthermore, in Nuckelt et al. [NAT$^+$13], a ray-tracing approach is used for V2V channel characterisation in an urban intersection scenario. For the simulations, relevant building data has been obtained from the OSM database as described in Nuckelt et al. [NRJK13] and converted into ray-tracing format. Additional objects such as roadsigns, street lamps, parked cars, and pedestrians have been identified and added manually. For accuracy analysis, the channel simulation results obtained from the ray-tracing have been compared with measurement results. In Nuckelt et al. [NAT$^+$13] only two metrics, channel gain and power delay profile (PDP), were used for analysis and comparison. However, later on, in Abbas et al. [ANK$^+$14] a more detailed analysis of the same scenario is presented in terms of PDP, path loss, delay and Doppler spreads, eigenvalues, antenna correlations, and diversity gains.

It is concluded from the analysis that ray-tracing simulations seem to have a reasonable accuracy in the sense that they are able to capture most of the specular reflections in the channel, i.e., LoS or first order only as shown in Figure 4.8(a,b). However, it is unable to capture most of higher order reflections and diffuse scattering, as these were not implemented in the ray-tracer. This analysis has revealed some of the limitations associated to the ray tracing model, i.e., to achieve good accuracy, it is required that the higher order reflections and diffuse scattering is implemented in the ray-tracing models.

For the ray-tracing simulation in Abbas et al. [ANK$^+$14] 3D antenna patterns of the true antennas were used, measured in anechoic chambers after mounting on the car roof. Such realistic antennas patterns are very important



(a)



(b)

Figure 4.8 Power delay profile obtained from (a) the channel measurement data, and (b) the ray-tracing channel model. The physical interpretation of the multipath components (A)–(B) is detailed in [ANK$^+$14].

for realistic simulations. This is also stated in Eibert et al. [MSLM13], in which a new method is described to increase the accuracy of ray-tracing algorithms by using an approximation on vehicle antennas. It is shown that antenna systems mounted on conducting surfaces, such as car roofs, must not be evaluated as isolated but together with their surroundings. The used approximations in this method are only true if the far-field condition is kept. When the far-field condition is not fulfilled, the accuracy of this simulation method decreases strongly. With a maximum dimension size of approximately 4 m, the far-field condition at 5.9 GHz is held in for distances larger than approximately 620 m.

To achieve a high accuracy also for smaller distances, the vehicle is subdivided into antennas with smaller apertures, called sub-TXs.

To achieve realistic radio channel models we have so far considered either complex ray-tracing approaches or time consuming measurement-based approaches. Another simpler, yet realistic, channel modelling approach is the stochastic approach. With this approach, instead of site-specific realisations, the statistics of the channel is modelled. More realism can be achieved by combining a stochastic channel model and simple geometrical aspects, so-called GSCMs. In Große [Gro13], a hybrid model applicable to V2V and V2I systems has been developed based on wireless world initiative new radio (WINNER) channel model. The model relies on a flexible and scalable layered structure in which the modelling task is separated into quasi-static and dynamic parts. The novel hybrid model ensures a flexible geometry-based stochastic channel model (GSCM) approach in which user-defined randomness can be included.

Another stochastic modelling approach is presented in Shivaldova et al. [SWM14a] where a V2I performance model at 5.9 GHz band is developed based on extensive measurements data. For analysis, the entire communication range is divided into regions of high, intermediate, and unreliable link quality, based on quantised model parameters of the Gilbert model. SNR performance is then analysed separately for each of these regions. Based on the analysis, a V2I performance model is developed, which is used to generate V2I SNR traces and associated error patterns. The accuracy of performance model is evaluated by means of comparison of model generated and measurement-based parameters. See Section 4.3.1 for more details on this model.

4.1.2 Railway Environment

4.1.2.1 Propagation scenarios

Radio propagation depends on topographical and electromagnetic features of the environment. A propagation scene partitioning for railways was first proposed in Ai et al. [AHZ+12]. We further derive seven typical railway-specific scenarios: urban, suburban, rural, viaduct, cutting, station, and river. Detailed descriptions of above railway scenarios can be found in He et al. [HZAG15].

4.1.2.2 Measurement campaign

Both narrowband and wideband measurements were conducted

1. Narrowband measurements were carried out along the "Zhengzhou-Xian" high-speed railway (HSR) lines of China, using a operational GSM-R system at 930 MHz. Details of the measurement system can

be found in He et al. [HZA+13b, HZAD11a, HZA+13a, HZAD11b]. To record sufficient power data, more than 6000 HSR cells in the above seven environments where measured. The train had a speed of approximately 300 km/h.

2. The wideband measurements were carried along the railway line "LGV Atlantique" in a rural environment. The campaign combines 4×2 MIMO and carrier aggregation between the 2.6 GHz band (two carriers with 10 and 20 MHz bandwidth) and the 800 MHz band (one carrier with 5 MHz bandwidth). The train passed the area with a speed of approximately 300 km/h.

4.1.2.3 Characterisation and modelling

Path loss

A statistical path loss model at 930 MHz is proposed using the extensive measurement data. The model is based on Hata's formula, expressed as [HZAG15]:

$$\begin{aligned}\mathrm{PL(dB)} = {} & \Delta_1 + 74.52 + 26.16\log_{10}(f) \\ & - 13.82\log_{10}(h_\mathrm{b}) - 3.2[\log_{10}(11.75h_\mathrm{m})]^2 \\ & + [44.9 - 6.55\log_{10}(h_\mathrm{b}) + \Delta_2]\log_{10}(d)\end{aligned} \tag{4.1}$$

where f is the carrier frequency in MHz (i.e., f = 930), h_b and h_m are the BS effective antenna height and the vehicular station antenna height in metres, d is the TX–RX separation distance in kilometres, and Δ_1 and Δ_2 are correction factors. It is found that Δ_i can be modelled as a function of h_b (Table 4.1). The estimated correlation factors for each environment based on a regression fit are found in Table 4.1. The proposed model is validated by measurements [HZA+14].

A heuristic semi-deterministic path loss model is also proposed for the 930 MHz narrowband channel. The following main propagation mechanisms affecting path loss are considered: (i) Free-space propagation and reflection from the track. (ii) Diffraction: This mechanism mainly occurs in the case of cutting. Finally, the Deygout model is chosen. The proposed model is validated by the measurements. Details of the semi-deterministic path loss model can be found in Guan et al. [GZAK13b].

Then, a heuristic deterministic model in railway cutting scenario is proposed. The deterministic model approach consists of a 3D ray-optical channel model using a vector database and a multi-edge diffraction model based on a raster database. The ray-optical approach takes into account reflections

Table 4.1 Path loss model (in dB) and shadow fading models for HSR Environments, from He et al. [HZAG15, HZAO15]

Environment	Correction Factor	σ (dB)	d_{cor}(m)
Urban	Δ_1 = –20.47	3.19	57.1
	Δ_2 = –1.82		
Suburban	$\Delta_1 = 5.74\log_{10}(h_b) - 30.42$	3.33	112.5
	Δ_2 = –6.72		
Rural	$\Delta_1 = 6.43\log_{10}(h_b) - 30.44$	2.85	114.8
	Δ_2 = –6.71		
Viaduct	Δ_1 = –21.42	2.73	115.4
	Δ_2 = –9.62		
Cutting	Δ_1 = –18.78	3.63	88.8
	$\Delta_2 = 51.34\log_{10}(h_b) - 78.99$		
Station	$\Delta_1 = 34.29\log_{10}(h_b) - 70.75$	2.77	101.2
	Δ_2 = –8.86		
River	$\Delta_1 = 8.79\log_{10}(h_b) - 33.99$	3.09	114.6
	Δ_2 = –2.93		

and diffuse scattering based on the image method. All the railway structures are modelled in the simulator. By comparison with the measured data, the presented model has high accuracy. Details of the deterministic path loss model can be found in Guan et al. [GZAK13a].

Finally, the semi-closed obstacles (SCOs), such as crossing bridges, train stations, etc., densely appear and compose challenging scenarios for propagation prediction are analysed and a hybrid model for propagation in such composite scenarios is presented. The validation shows that the proposed model accurately predicts the propagation loss. Details of the model can be found in Guan et al. [GZAK14].

Shadow fading

Shadow fading is analysed using the narrowband measurements at 930 MHz. The measurements suggest that a zero-mean Gaussian distribution fits the shadowing data (in dB). The mean value of the standard deviation σ of shadowing is presented in Table 4.1. The auto-correlation coefficient $\hat{p}_{\mathrm{auto}}$ of shadow fading components is found to follow an exponential decay function [Gud91]. The mean value of shadowing decorrelation distance d_{cor}, which is defined to be the distance at which the correlation drops to 1/*e* [HZAZ14], is summarised in Table 4.1. Moreover, the cross-correlation of shadow fading between two neighbouring BSs is found to depend upon the BS height and the tilt angle of the antenna [HZAO14], and a heuristic model is proposed. Details can be found in He et al. [HZAO15].

Delay-doppler spectrum

The delay-Doppler spectrum analysis is based on the wideband measurements. In a post-processing step power delay profiles and Doppler spectra and their evolution over time were derived. It is found that the near scatterers to the left and the right of the railway line are the poles of the gantries that support the railway electrification system. They are about 30 m apart and act as reflectors. The difference in the lengths of the LoS path and the first reflected path is smaller than the temporal resolution of the measurement and thus both rays appear to have the same delay. There are, however, also some reflections coming from gantries further away and thus show a longer delay in the Doppler-delay power spectrum. More details can be found in Kaltenberger et al. [KBA+15].

4.1.3 Special Environments

A few papers within COST IC1004 investigated propagation conditions in two kinds of special environments, namely maritime container terminal and in-vehicle environment. In this subsection, the main results of these investigations will be presented.

An extensive measurement campaign in the first of these environments (for frequency range from 500 MHz up to 4 GHz) have been carried out in the deepwater container terminal in Gdansk, Poland. The measurements as well as the investigated environment have been described in Ambroziak [AK14]. Since the Walfisch–Ikegami model [CK99] describes the environment quite similar to the container terminal, it was often used to predict basic transmission loss in this environment. In this model has been evaluated and then modified by tuning its coefficients. Evaluation revealed that the non-modified WI model cannot be used for path loss estimation in such environment, since the obtained mean error (ME), standard error of estimate (SEE), and coefficient of determination, R^2, 5.3 dB, 10.6 dB, and 0.01 dB, respectively. But its tuned version have achieved much better accuracy: SEE = 5.1 dB and $R^2 = 0.77$.

In Ambroziak and Katulski [AK13a] and [AK13b], an empirical propagation model for mobile radio links in a container terminal environment was proposed. This model, named mobile container terminal (MCT), takes into account the diversity of conditions occurring in different places of the container terminal. The terminal was divided into three sub-areas (LoS area, container area, and off-terminal area), where different propagation mechanisms have a crucial influence on the path loss. A full description of the MCT model with formulas for path loss estimation is presented in Ambroziak and

Katulski [AK13a]. The obtained SEE for the MCT is 4.7 dB. What is more, the obtained value of R^2 is 0.82. These results proves the accuracy and usefulness of the MCT model for path loss modelling in this special environment.

The second considered special environment is the in-vehicle environment. In Blumenstein et al. [BMM+14] wideband radio channel measurements carried out in the intra-vehicle environment were presented and discussed. Channels in the millimetre-wave frequency band (mmW) have been measured in 55–65 GHz (for different antenna placements and occupancy patterns) using open-ended rectangular waveguides. Blumenstein et al. [BMM+14] presented a channel modelling approach based on a decomposition of spatially specific channel impulse response (CIR) into large-scale and small-scale fading. The decomposition is done by the Hodrick–Prescott filter. The small-scale fading was parametrised utilising ML estimates for the parameters of a generalised extreme value distribution (GEV) and the large-scale fading was described by a two-dimensional (2D) polynomial curve. The comparison of simulated results with measurements has shown that for over 92.3% of cases *p*-value of the two-sample Kolmogorov–Smirnov test is higher than 0.1.

In Vychodil et al. [VBM+14] authors—based on an extensive measurement campaign—compared suitability of two frequency bands, namely UWB (3–11 GHz) and mmW (55–65 GHz) for ranging purposes in the intra-vehicle environment. It was shown that mmW band is more suitable for precise distance measurement, probably due to favourable material properties, therefore enhancing the distinctiveness of the first arrival multipath component. The average error and the standard deviation of error for UWB band equal 7.7 and 9.0 cm, respectively. For mmW band these errors are significantly lower and equal 1.6 cm (average) and 4.4 cm (standard deviation). Additionally, it was found out that the mmW band provides better distance measurement results for LoS as well as NLoS conditions, making it suitable for local positioning system deployment.

4.2 Antennas

The concept of C-ITS relies on high connectivity of the vehicles. In this context the vehicular on-board antennas, used to connect the vehicle to cellular or vehicular *ad hoc* network (VANET) become of particular importance. The main challenge in the development of such antennas is to satisfy both the performance and the esthetic constraints.

To evaluate the antenna performance in realistic conditions several approached have been proposed. In particular, the authors of Neira et al. [NCC+14] suggest a statistical method based on the radiation pattern of an antenna and a multipath simulation tool. By generating a number of incident waves with certain angle-of-arrival (AoA) distribution, the multipath simulation tool reproduces the realistic multipath propagation for highway, urban, and rural environments. The incident waves generate a voltage at the vehicle antenna ports, as shown in Figure 4.9(a). By analyzing the cumulative

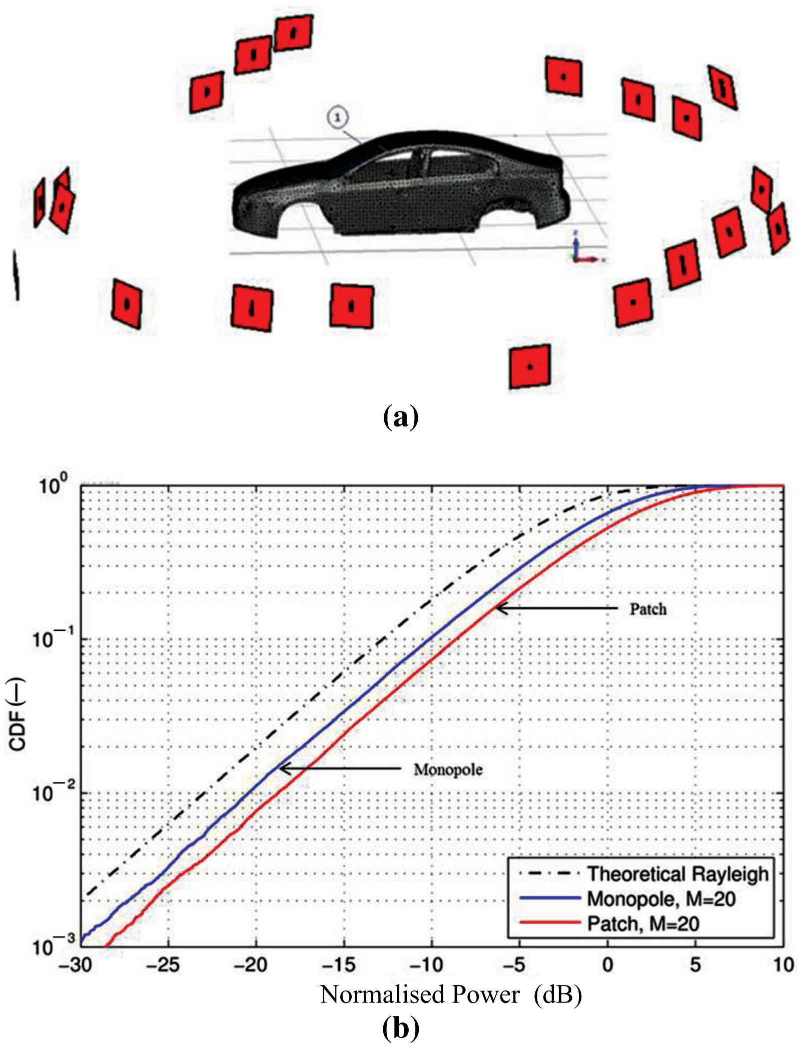


Figure 4.9 Comparison between a patch and a monopole antennas [NCC+14]. Both antennas are mounted near the vehicle windscreen. (a) Illustration of vehicle surrounded by sources of 20 incident waves, and (b) CDFs of the normalised power for 20 vertically polarised incident waves.

distribution function (CDF) of the received voltage the influence of the antenna types and positions on the system performance can be analysed. For example, Figure 4.9(b) shows the performance comparison between a patch antenna and a monopole.

Another efficient way to characterise the performance of vehicular onboard antennas is OTA multi-probe testing. The very first attempt of placing a vehicle (Volvo C30) in an OTA multi-probe test system was performed by the authors of Nilsson et al. [NHA+14] and is shown in Figure 4.10. To understand the uncertainty of this particular testing approach, the authors have performed three experiments including: measurement setup analysis, channel sounder measurements, and coupling measurements. The performed measurements have three significant outcomes: (i) over-the-air (OTA) multi-probe testing setup is capable of simulating a realistic radio environments; (ii) the measurement uncertainty due to a large test object, such as a car, in the OTA multi-probe ring is $\leq$1 dB; the uncertainty due to the coupling of transmit antennas in the multi-probering is negligible, as the disturbance level was below –56 dB. All these results suggest that the OTA multi-probe testing setup is a way forward for an efficient way of characterising the performance of vehicular on-board antenna systems.

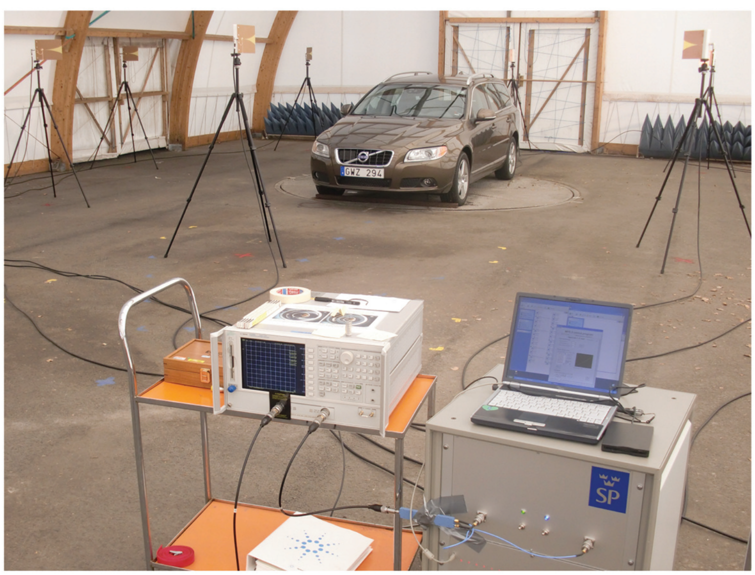


Figure 4.10 (OTA) multi-probe setup for a car at Volvo Cars test facilities [NHA+14].

For evaluation of the on-board antenna system performance, not only the testing methodology is of importance, but also the definition of the key performance indicators. To address the effects of antenna integration in a vehicle, the authors of Posselt et al. [PEK$^+$14] have suggested to use the condition number and channel capacity. The condition number represents the channel correlation properties, while the channel capacity gives an insight on the quality of service. By employing these system level parameters, it is possible to capture the impact of any particular antenna system on the overall system performance.

The above-mentioned system level evaluation parameters were used to assess the performance of a vehicular MIMO antenna for LTE based on a volumetric 3D design, introduced in Posselt et al. [PFE$^+$14]. The 3D antenna design was proposed to improve the utilisation of the available antenna housing space. In this context, the authors suggest to implement antenna functions directly on top of the vehicular antenna housing surface using MID technology. To assess the performance gain of a 3D antenna design relative a 2D antenna design, a reference antenna system has been developed, (Figure 4.11). Real-world LTE measurements have shown that a volumetric MIMO antenna design enables both efficient exploitation of the available integration space and improved system level performance.

For conventional 2D design antennas, integration of the 802.11p antennas along with the cellular antennas in the limited volume of the antenna radome is one of the main challenges. The cellular antennas are positioned in the rear and front regions of the antenna housing and the 802.11p antennas need to be placed in between of them such that the volume and interference constraints are met optimally. In [EPKM14] three possible 802.11p antenna positions are considered: (i) integrated in the cellular antennas, (ii) placed adjacent on one side of the housing, and (iii) placed on different sides of the housing. Evaluating the performance of different antenna prototypes on a ground plane and by performing measurement drives, the authors have concluded that 802.11p antennas placed on different sides of the housing, yield the best overall performance.

However, even under the optimal antenna placement, the antenna pattern will be influenced by the roof-top antenna housing material and its physical dimensions. Indeed, the authors of Ekiz et al. [EPKM13] came to the conclusion that the influence of the antenna housing on the pattern exhibits geometry and frequency dependent behaviour. Simulations and measurements in an anechoic chamber suggest that the performance loss due to dielectric antenna housing can be compensated by modifying the thickness of the radome.

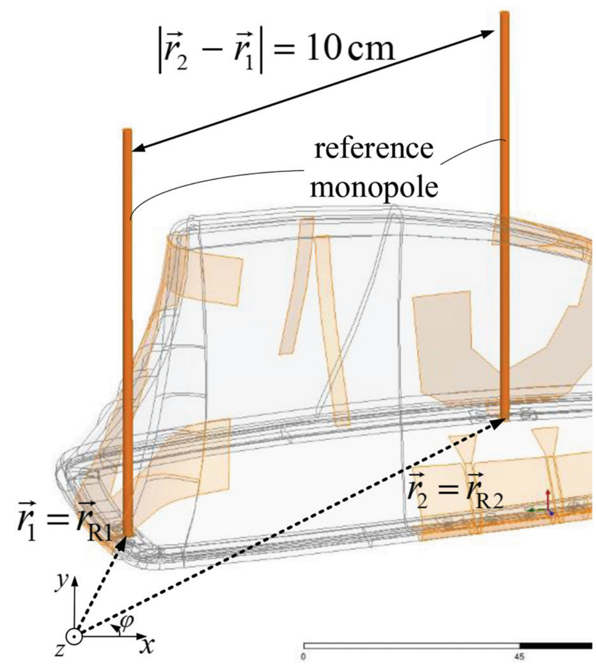


Figure 4.11 CAD model of the 2D reference monopole setup with 3D antenna shown for reference [PFE+14].

Along with the antenna radome, the ground plane materials has significant influence on the antenna pattern. In Artner et al. [ALM15] the performance of a simple monopole-antenna for 5.9 GHz on three different ground plane materials was compared. Following ground plane materials were compared: (i) an aluminium plate, (ii) a plastic plate with a metallised top layer featuring molded interconnect device (MID) design, and (iii) a carbon-fibre composite (CFC) plate consisting of unidirectional filaments with fiber snippets in random alignment on top. For both the MID and CFC plates, the relative efficiency and the maximum gain were reduced as compared to the aluminium ground plane.

Besides the antenna housing design and ground plane material, the antenna performance is significantly influenced by the environment. In this context, Reichardt et al. [RPJZ11] suggest an antenna design methodology for time-variant channels, that eventually leads to capacity maximisation. For antenna design, the authors have modelled five different scenarios in urban, rural and highway environments with a ray-tracer. Based on the radio channel parameters for these key environments, a 2×2 multimode MIMO antenna system including decoupling network has been designed and integrated into a car. The whole structure was measured in an anechoic chamber and the resulting performance increase has confirmed the advantages of the environment-aware antenna system optimisation.

4.3 Communication Systems

4.3.1 PHY Layer

The PHY performance of a wireless communication system mainly determines the robustness and reliability which can be achieved. For an efficient system design, a comprehensive understanding of the PHY data transmission is mandatory.

Basically, two different radio access technologies (RATs) are considered in the context of vehicular communications. On the one hand, *ad hoc* networks based on the IEEE 802.11 standards are indented to exchange data among vehicles or between vehicles and infrastructure (e.g., road-side units). For this purpose, the amendment p, also known as WAVE, of the 802.11 has been approved by the IEEE in the year 2009. On the other hand, 3G/4G cellular networks offer an attractive solution to enable wide-area connectivity of vehicles. In particular, LTE is a promising solution for relative low-latency and robust data transmission in vehicular environments. Both approaches have their specific advantages and disadvantages and a detailed evaluation of the underlying technologies is required.

The PHY of 802.11p suffers from the fact that is has not been designed from the scratch, rather it is a modified version of the 802.11a standard with only minor changes. According to the channel properties in typical vehicular environments the system bandwidth of 802.11p has been scaled to 10 MHz compared to the default 20 MHz option in 802.11a. In [Str13], the use of a larger channel spacing in 802.11p is investigated. The author motivates this option with a reduced channel congestion that affects or even simplifies the design of congestion control algorithms on the MAC layer. Due to the shortened orthogonal frequency division multiplexing (OFDM) symbol length, the main advantages are a reduced channel congestion and an increased robustness against the time variance of the channel.

To carry through robust and efficient design of V2V and V2I communication systems, a deep understanding of the underlying rapid channel propagation behaviour is required. In this context, real world link performance measurements, that are less expensive than channel-sounding experiments and more realistic than simulations, are in demand. A detailed overview of an extensive link performance measurement campaign carried out on the Austrian highways within the project ROADSAFE [ROA] is given in Shivaldova et al. [SPP+11]. During this measurement campaign, various combinations of the system parameters such as data rate and packet length were considered and the influence of system components, such as RSU antenna gain and placement, on the overall link performance were evaluated. For this purpose five RSU transmitters, each equipped with a set of two directional antennas were installed and V2I measurements with a sufficient number of repetitions were carried out.

Some outcomes of the ROADSAFE measurement campaign can be found in Shivaldova et al. [SWM13]. With respect to the system parameters, the authors were searching for a combination of data rate and packet length yielding the largest TP at a constant transmit power of 10 dBm. In this context, there are two possible approaches: (i) to increase the packet length or (ii) to increase the data rate. Increasing the packet length would decrease the total amount of non-payload overhead. However, the quality of the preamble-based channel estimates will be decreased due to the increased transmission time. While when using higher data rates, the time required to transmit a packet will be reduced, resulting in an improved quality of channel estimates. The measurements showed that, in contrast to theoretical considerations, using longer packets is more suitable approach for the TP increase in V2I communications, than increasing the data rate. Another set of measurements presented in Shivaldova et al. [SWM13] emphasises that not the change of the driving direction itself, but rather the mounting position of the RSU antennas with respect to the road geometry has significant impact on the performance. Based on the experimental results the authors suggest to mount RSU antennas in the middle of the highway, rather than on one side to avoid undesirable performance degradation.

Despite the high importance of the link performance measurements, they are rarely conducted due to their high costs and complexity. To make the results of such campaigns more accessible for the research community and to increase the reproducibility of the results, a computationally inexpensive link performance model was introduced in Shivaldova and Mecklenbräuker [SM14c]. This model is an extension of a simple two-state hidden Markov model introduced by Gilbert. As shown in Figure 4.12, Gilbert's model is fully described by only three parameters: the transition probability from the bad state to the good state, P_{BG}, the transition probability from the good state to the bad state, P_{GB}, and the probability of error P_{E} in the bad state.

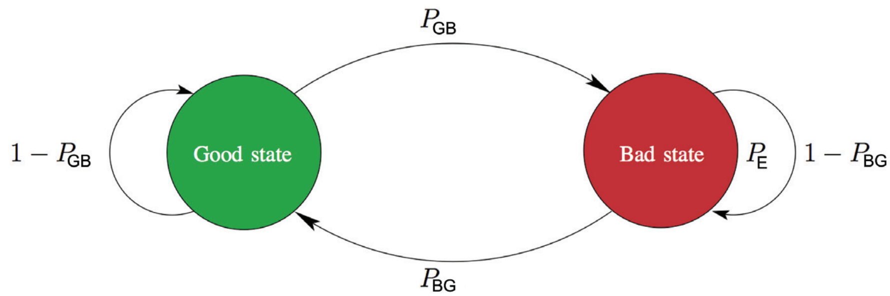


Figure 4.12 Schematic illustration of the Gilbert model [SM14c].

In this model, the good state is error-free. However, since the link performance is strongly distance dependent use of model with just two states would be insufficient and, therefore, the parameters of the proposed range-dependent modified Gilbert model should change depending on the TX–RX distance. To obtain the model parameters the whole coverage range is divided into equally large non-overlapping intervals and parameters are estimated for each of the intervals separately. Obviously, the size of these intervals constitutes a trade-off between the accuracy of the model and its complexity. The authors show that an acceptable level of accuracy can only be achieved by estimating the model parameters for intervals less than 10 m.

In Shivaldova et al. [SWM14b], a further extension of the range-dependent modified Gilbert model was proposed. With the proposed extension realistic SNR traces corresponding to the model generated error patterns can be produced. The SNR model is based on the superposition of three components: SNR trend, large-scale fading, and small-scale fading. The general SNR trend results from dissipation of the power radiated by the TX over the distance. It is constant in the bad state of the model and is exponentially decreasing in the good state. The amplitude and the power of the exponential function depend on the model quality levels. The large-scale fading caused by obstacles between the TX and RX that attenuate signal power through absorption, reflection, scattering, and diffraction is modelled as a correlated Gaussian random process. Finally, constructive and destructive superposition of multipath signal components resulting in a small-scale fading is modelled by a clipped Laplace distribution.

Channel estimation and equalisation significantly affect the PHY layer performance. The pilot pattern in an 802.11p frame is not optimised for channel conditions in high-dynamic scenarios (i.e., with small channel coherence times). Especially for long data packets, accurate channel estimation and equalisation is a challenging task. Nagalapur et al. [NBS14] propose a cross-layer approach, where special data bits are inserted in the higher layers before the packet is transmitted. A modified RX makes use of these a-priori known bits as training data for improved channel estimation. The RX is informed about the inserted training data using an unused bit in the SERVICE field. The algorithm has been evaluated against a channel estimator based on the standard pilot pattern. The novel cross-layer approach outperforms the conventional estimator and performs close to the ideal RX where perfect CSI is available.

A decision-directed channel estimator combined with a 1D Wiener filter operating in frequency direction is discussed in Nuckelt et al. [NSK11]. Different designs of the Wiener filter coefficients assuming either a rectangular-shaped or an exponentially decaying PDP of the channel are analysed with respect to the achieved performance gain. It is found that filter coefficients based on an exponentially decaying PDP provide robust and accurate channel estimates. The SNR loss of the proposed method compared to an ideal RX with perfect channel state information (CSI) is less than 1 dB.

A more general design of a novel estimator for V2V channels is presented in Beygi et al. [BMS15]. The authors propose algorithms to utilize the structure typically found in V2V channels, namely that specular and diffuse multipath components give rise to joint sparsity in the delay-Doppler domain. The fact that different regions in the delay-Doppler plane has different levels of specular and diffuse components is exploited by the channel estimator. In this work, the estimator performance has been evaluated by means of simulations and it is shown the mean squared error (MSE) of the proposed structured estimator is significantly below the MSE of unstructured estimators.

To improve the communication performance on the PHY, system configurations using multiple antennas are also considered and investigated in the context of vehicular communications based on IEEE 802.11p. In Shemshaki and Mecklenbräuker [SM14a, SM14b], an antenna selection algorithm for a 1×2 SIMO system is proposed. The decision which antenna link is chosen and used for the further decoding at the RX is drawn by means of a channel prediction method using either Lagrange interpolation or linear regression. The authors numerically evaluated the achieved benefit using computer-aided simulations and considered the bit error rate (BER) as figure of merit. A significant diversity gain of the SIMO system compared to the default single-input single-output (SISO) configuration was obtained. It is also found that the channel predictor based on linear regression slightly outperforms the Lagrange interpolation-based predictor.

Next generation cellular networks are attractive candidates to extend the possibly limited coverage of IEEE 802.11p and improve the connectivity of vehicles. Currently, several research activities are analyzing hybrid protocol stacks that allow a seamless connectivity using 802.11p and LTE, for instance. A key question is to find out in which kind of vehicular environments the PHY of 802.11p outperforms LTE and vice versa. The work presented in Möller [MNRK14] compares the PHY performance of the 802.11p and LTE in an urban intersection scenario. For this purpose, a virtual scenario with two vehicles and a BS on a roof-top has been created and a ray-optical propagation model has been applied to compute the channel properties of the radio links. Afterwards, an 802.11p and an LTE PHY simulator were utilised to evaluate the downlink packet error rate (PER) against the distance of the receiving vehicle to the centre of the intersection. It has been shown that the LTE PHY layer performance is predominantly limited by the impact of the local interference level. However, if the LoS path between two vehicles is obstructed, LTE outperforms 802.11p even under worst-case intercell interference conditions. Due to the elevated antennas of the LTE BS as well as large transmit antenna gains and a high transmit power, LTE networks typically achieve an almost seamless coverage over large areas while 802.11p links are usually very limited. The results further show the high potential of LTE networks even in time-variant scenarios that are typical for vehicular environments.

Due to the time-dispersive and time-variant nature of vehicular channels, also LTE RXs need to be equipped with channel estimators that efficiently and accurately allow the equalisation of the received signal. When designing an adequate channel estimator, the non-stationarity of V2V channels has to be taken into account. Hofer et al. [HZ14, HXZ15] have addressed this issues and proposed an iterative estimator of non-stationary channels for the LTE downlink. The algorithm utilises a modified subspace representation that was originally developed for contiguous training sequences. The subspace is adapted to delay spread and Doppler spread of the time-variant channel. For this purpose, a hypothesis test is performed that exploits the pilot pattern in the LTE OFDM time-frequency grid. The authors have found that the achievable performance increases if the observation region—in the time or the frequency domain—is increased.

The use of MIMO configuration has also been considered for cellular networks such as LTE or universal mobile telecommunications system (UMTS). In Ekiz et al. [EPL+13], the results of a measurement campaign at 800 MHz, which aims at a system-level evaluation multiple LTE antennas integrated into a vehicle, are presented. A monopole antenna was used as a reference antenna and compared against two integrated automotive qualified antennas. It was found that a similar performance could be achieved if the antenna spacing is about 7 cm. A further increased separation of the antennas, which would cause problems in terms of integrating the antennas into the vehicle, does not provide additional performance gains. In this paper, performance metrics such as capacity and condition numbers of the MIMO channel matrices are presented and discussed. The achieved results give important insights about the design and integration of multiple antennas into vehicles.

Further results of an investigation of the MIMO performance in LTE networks are shown in Ekiz et al. [EKM12]. The authors conducted a measurement campaign on a test track which was served by an LTE BS operating at 800 MHz. Two antennas—a front and back antenna—were integrated into a shark fin module, which was mounted onto the vehicle rooftop. The measurements were used to derive metrics such as received signal strength (RSS), SNR, and TP.

The concept of virtual MIMO is studied in Beach et al. [BGW11]. The basic idea is to use at least two conventional MIMO users and exploit the physically wide separation of their antennas. In this way, the complexity at the user terminals can be reduced whereas the overall system performance is increased. The authors have designed a virtual 4×4 MIMO scenario which is fed by channel data obtained from vehicular measurements conducted in urban environments. In this work, the Rician K factor and the achieved capacity are evaluated. It is found that the use of virtual MIMO improves the conditions for one of the cooperating users, but degrades the performance of the other at the same time. The benefit in terms of capacity was observed to be small, but the changes regarding the K factor were more significant. Further investigation of metrics such as spatial correlation and angular spread remain for future work.

Finally, the work presented in Reichardt et al. [RSSZ12] deals with the issue to what extend 802.11p can be used for both communication and radar sensing. The authors propose a system concept and present results of a measurement campaign to demonstrate the feasibility. Due to the small bandwidth of the signal the resolution is in the order of a couple of metres that is not sufficient for radar imaging. Furthermore, some OFDM subcarriers cause side lobes in the radar image. To improve the accuracy additional 60 MHz bandwidth from the adjacent industrial, scientific, and medical band (ISM) band is utilised. In this way, the resolution could be improved to 1.7 m.

4.3.2 Medium Access Control

To carry out practical and reliable design of communication systems, all system components need to be tested in realistic conditions. In Section 4.3.1, it has been shown that the performance of PHY layer is mainly influenced by the system parameters and components, by the environment, and the scenario. For MAC layer the performance is rather dependent on vehicular traffic density, network load, and particular type of message to be transmitted. In this context, careful definition of challenging vehicular scenarios becomes crucial. Alonso et al. [ASU$^+$11] have identified following demanding scenarios for testing the performance of MAC layer protocols:

- start-up phase of a VANET;
- two merging VANET clusters;
- emergency vehicle approaching traffic jam.

The two merging VANET clusters scenario was chosen in Alonso and Mecklenbräuker. [AM12] for performance comparison of two MAC layer protocols. The first protocol is the default carrier sensing medium access with collision avoidance (CSMA/CA), as defined by the IEEE802.11p standard, extended by a decentralised congestion control (DCC) mechanism. In this context, the DCC mechanism reduces the channel load by adjusting the transmit power, reducing the repetition rate of cyclic messages or even by dropping packets according to their priority. As an alternative MAC protocol the authors suggest self-organising time division multiple access (SoTDMA), an approach that divides the channel into time slots and allocates these slots to the nodes of a VANET. Analysing effects of the co-located transmissions on the performance of both MAC protocols, it has been shown that SoTDMA performs collision-free regardless of the channel load and the node position. Whereas the performance of CSMA/CA with DCC mechanism is highly dependent on the node location.

More details on how DCC mechanism is realised can be found in Alonso et al. [ASPM13], where the authors compare the performance of IEEE802.11p CSMA/CA MAC protocol with and without DCC. It turns out that parametrisation of the DCC state machine is essential for the overall performance. In particular, a well-balanced and realistic choice of the transmit power for different states, ensures substantial performance improvements. Moreover, it has been shown that the MAC performance is highly dependent on the traffic priority. For high- and medium-priority traffic, systems implementing CSMA/CA with DCC perform significantly better than systems without DCC. Whereas, for low-priority traffic the use of DCC mechanism leads to longer MAC-to-MAC delays and higher amount of omitted packets.

Above-mentioned collision avoidance MAC methods are intended to provide harmonised and fair access to the channel, and are obviously essential for smooth operation of the whole communication system. However, the description of the MAC layer protocol would not be complete without routing algorithms that facilitate seamless information transition through multiple hops. In particular, routing algorithms search for a suitable relay among the neighbouring nodes to forward packets to the desired destination. One of the most challenging characteristics of vehicular networks is high mobility of the nodes, resulting in strongly time-variant links that are difficult to maintain. With this constraints in mind Bazzi et al. [BMPZ13] propose two novel routing protocols: a position-based algorithm and a hop-count based algorithm. The proposed protocols exhibit good performance in terms of average network coverage and number of hops, as the other more complex routing solutions.

Although the overwhelming majority of existing studies on MAC layer focus on the protocol design, such important issue as clock synchronisation should also be taken into consideration. The existing synchronisation algorithms under linear clock model assumptions perform well for short periods, however, they will become problematic for applications with long-term requirements. In this context, a novel clock synchronisation algorithm adopting a statistical signal processing framework has been proposed in Sun et al. [SSBS12]. The authors consider a simple network comprised by two nodes that exchange time stamps over a channel with random delays. The data collected by one of the nodes is then used to estimate the clock values of the other node. The proposed scheme outperforms the existing synchronisation algorithms in many scenarios and is robust against different distributions of the random channel delays, incurred during the message exchange procedure.

4.3.3 System Simulations

For deep understanding and evaluation of all functions featured by complex vehicular systems, the performance evaluation of PHY and MAC layer alone will not be sufficient. It is necessary to evaluate the performance of the complete communication system under exceptional situations, such as safety attacks or severe failures. The basis for investigation of the system performance are the discrete event simulators. However, most of the existing simulators of this type are either lacking microscopic details of the unique car mobility dynamics or significantly abstract the radio propagation aspects.

To carefully reproduce the movement of individual drivers in presence of other cars, traffic lights, road junctions, speed limits, etc., Uppoor and Fiore [UF12] suggest to use the travel and activity patterns simulation (TAPAS) methodology. This technique generates the trips of each driver by exploiting information on home locations, socio-demographic characteristics, points of interests in urban area and habits of the local residents in organising their daily schedule. The TAPAS methodology was developed based on the real-world data, collected from more than 7000 households within the TAPAS-Cologne project. It is capable to precisely reproduce the daily movements of inhabitants of the urban area of the city of Cologne for a period of 24 h, for a total of 1.2 million individual trips. Comparison of the synthetic traffic with its real world counterpart underlines high accuracy of the proposed urban traffic modelling methodology.

The radio propagation aspects can be realistically incorporated into system level simulators by following the V2X simulation runtime infrastructure (VSimRTI) approach with integrate car2X channel model simulation (CCMSim) component, as proposed in Protzmann et al. [PMOR12]. In this simulation architecture, the higher layers of the communication stack are simulated with OMNeT++ and the lower layers with CCMSim. CCMSim includes an IEEE 802.11p PHY layer implementation and a stochastic vehicular channel model. The empirical channel model is based on the data acquired with the HHI channel sounder [PWK+08] during several extensive measurement campaigns.

For even more complete and detailed evaluation of the vehicular communication systems a virtual road simulation and test area (VISTA) has been built. The VISTA approach, details of which can be found in Hein et al. [HBK+15], aims at the holistic investigation of vehicle, road, driver, and radio environment, thus enabling realistic and real-time end-to-end system evaluations. The facility includes a semi-anechoic chamber with a build-in chassis dynamometer for emulation of realistic driving scenarios, facilities for electromagnetic compatibility measurements, a custom-designed multi-probe nearfield antenna measurement system and channel emulators. Integrating all these features in a single testing area allows for an end-to-end evaluation of the system performance.

4.4 Summary and Outlook

Vehicular communication is and will continue to be a hot research topic for years to come. One reason for this is the increased interest for mobile communication at higher frequencies, approximately 6–100 GHz. There is still a lack of knowledge in radio propagation at these frequencies, especially in NLoS. To achieve a reasonable link budget, high-gain steerable antennas might be required. Finally, PHY and MAC algorithms will need to be adjusted for higher frequencies.