Angle-dependent path loss measurements impacted by car body attenuation in 2.45 GHz ISM band

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***Abstract*—In the past few years more and more wireless applications (e.g. WLAN and Bluetooth) have migrated into the automotive domain. With the increasing number of devices, coexistence investigations in the 2.45 GHz ISM band are gaining importance to enable reliable communications with real time requirements like voice transmission and streaming applications.**

This paper presents initial results on angle dependent path loss measurements impacted by the influence of a car body on electro-magnetic wave propagation. To this effect, a measurement methodology was developed to gather the attenuation effects of the car according to different antenna positions and measurement angles. Various kinds of attenuation measurements were performed. Vehicle shell attenuation measurements were transformed into angular-dependent path loss metrics and related to vehicle-specific attenuation properties like window inserts, roof columns, trunk or engine hood. Focus of attention was drawn to free space attenuation and intra-vehicle attenuation measurements.

***Index Terms*—Vehicle-to-free space, Intra-vehicle, Path loss, 2.45 GHz ISM band, Coexistence, WLAN, Bluetooth, Kleer**

I. INTRODUCTION

With the tremendous increase of new wireless technologies, the desire for unlimited connectivity arises.

Communication applications enabling wireless connectivity between vehicles on the one hand and between vehicles and the infrastructure on the other hand (Car-to-X communications, [1]) are currently being researched and developed to increase traffic safety and efficiency in order to provide improved convenience to the driver. This also leads to the migration of wireless systems into the car. With an increasing number of devices, especially consumer electronic devices (CE-devices), the challenge to enable coexisting wireless device functionality with defined link quality metrics needs to be met. This challenge particularly arises at 2.45 GHz ISM frequencies for typical short range communication standards like WLAN, Bluetooth and Kleer [2] in consumer electronics. In order to enable high quality wireless applications between CE-devices and vehicular on-board systems, interference from devices and infrastructure systems outside the car needs to be reduced to an acceptable limit. Previous measurement results of car attenuation [3] and channel measurements for ultra wideband [4]-[6] have been published. In this paper the main focus is the 2.45 GHz ISM band, where communication systems like WLAN, Bluetooth and Kleer are resident.

The effective transmission range of wireless systems communicating inside a car produces an even larger zone of electromagnetic field exposure outside the vehicle. This causes interference with other wireless systems operating in the same frequency band, resulting in performance degradation or even complete interruption of the services. Contrary to the majority of communication applications, the range of in-vehicle communication systems shall be restricted to the interior of the user compartment. This study focuses on measuring the path loss for different scenarios in the 2.45 GHz ISM band to determine realistic values for the path loss between a transmitter inside the car and a receiver outside of the car. Based on these measurements we derive suitable proposals to reduce the effective range of on-board wireless systems, or ideally to restrict the operation only to the cabin of the car.

All measurements were carried out at the BMW drivetest center in Aschheim, near Munich. Biconical antennas with low gain variation over frequency [7] were used.

II. MEASUREMENT SETUP

The received power is measured in different setups:

i) The transmitter is placed inside the car and the receiver is placed at different distances and angles around the car. The measurements are performed on a plane asphalt surface (see background in Fig. 1)
ii) Additionally, one scenario is measured with both transmitter and receiver inside different cars, to study the effect of intra-vehicle interference from one car to another. A schematic overview of the different positions in this scenario can be seen in Fig. 5.

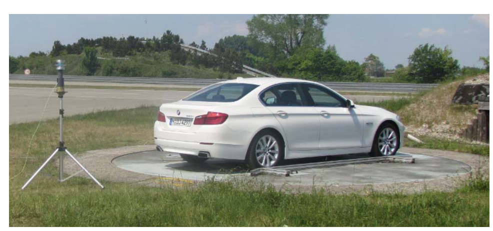

Fig. 1. Car-to-Free space scenario with antenna and BMW 5 Series

A. Measurement instruments setup

Both transmitter and receiver consist of wide-band biconical antennas with omnidirectional radiation patterns in azimuth. The transmitter TX consists of a signal generator connected to an antenna that is located at different positions inside the car. The receiving antenna RX is placed outside the car in setup i) and inside another car in setup ii). In each scenario the RX antenna is connected to a spectrum analyzer. With this setup, a frequency response measurement is performed to measure the received power at defined frequencies, distances and angles around the car. Several frequency bands can be measured this way. To maintain a maximum dynamic range of this setup, the transmitter signal generator is set to a maximum output power of 15 dBm.

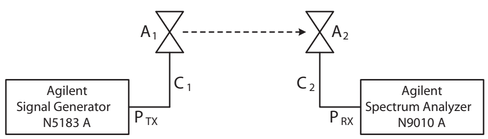

Fig. 2. Measurement equipment

Inside the frequency band of interest, the received power is measured in increments of 5 MHz. In order to eliminate small scale fading, 11 measurement points are taken within a bandwidth of 10 kHz with 1 kHz spacing (Fig. 3). Together with the internal averaging of the spectrum analyzer, which is set to 3, in total 33 single measurements contribute to one value of RX power at the desired frequency point. This is a trade-off between measurement accuracy and measurement duration.

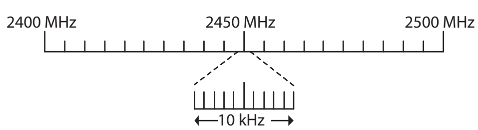

Fig. 3. Schematic view of measurement points

B. Measurement scenarios

To cover a wide range of applications, five scenarios with four different TX antenna positions (Fig. 4) inside the car are defined, which are representative for future use cases in vehicular connectivity. Position 1 (head-position) represents

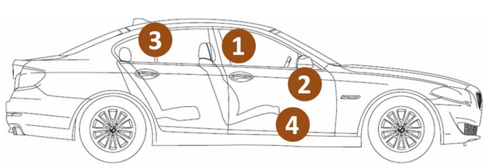

Fig. 4. Different antenna positions inside the car

the driver using a mobile phone or wireless headset for telephony. Position 2 (center console) represents a built-in antenna in the area of the center console. Typical use for Position 3 (antenna-module) is a wireless hotspot (e.g. IEEE 802.11b/g access point) for the rear passengers, and is located underneath the roof-top antenna which is placed at the center of the rear part of the vehicle roof. Position 4 (front passenger footwell) is selected to determine the influence of an antenna operating at such a location.

TABLE I
TRANSMIT ANTENNA POSITION OVERVIEW

Position	Description	Height over ground
1	Head-position	1.2 m
2	Center console position	0.8 m
3	Antenna-module position	1.4 m
4	Front passenger footwell position	0.6 m

To gather the effects of metalized windows (infrared absorbing glass) on the wave propagation, two different types of cars are used during the measurement as shown in Table II.

TABLE II
CAR SCENARIOS OVERVIEW

Car	Windows	Antenna positions
BMW 5 Series (F10)	standard	1, 2, 3, 4
BMW 7 Series (F01)	metalized	3

1) Scenario i): Vehicle-to-free space measurements: In the vehicle-to-free space scenarios the TX antenna is placed inside the car at different positions (see Table I), the RX antenna is always mounted at a fixed height of 1.6 m over the ground. The car is placed on a turntable which can be rotated by 360° so that the antenna is always positioned directly on the rotational axis of the turntable. The distance between the two antennas is constant for all measured angles. For the antenna positions on the symmetry plane of the car (Positions 1 to 3, Table I) the received power is measured on a half circle around the car in steps of 10 degree (0° front, 180° back). For the unsymmetrical Position 4, a full circle of 360° is measured. Six different measurement distances are chosen. The first one is the minimum distance which can be measured (between 3.3 and 3.6 meters). The other distances are set to 5, 10, 20, 35 and 50 meters.

2) Scenario ii): Intra-vehicle measurements: For the intra-vehicle measurement scenarios, both antennas are positioned inside a car and the transmission between two cars is measured. Two antenna positions are investigated. In the first scenario, both antennas are placed at the head-position (Position 1). In the second scenario both are placed in the footwell (Position 4). For the positions of the cars a 5x10 m grid is used (Fig. 5). The cars are placed on the grid at the stated numbers to represent driving direction and reverse driving direction. Path loss measurements are performed according to the methodology described in Sec. II-B1 for intra-vehicle measurements as well.

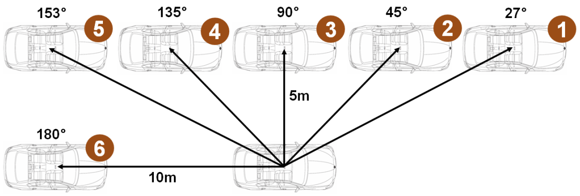

Fig. 5. Intra-vehicle scenario for driving direction

III. Measurement results

A. Path loss computation

Since the received power includes influences of the measurement setup (antenna gains and cable losses), the path loss has to be extracted. Therefore antenna gains and cable attenuations are taken into account.

According to the complete transmission path (Fig. 2), the path loss is then computed by the following equation:

$$PL[dB] = 10\log_{10}\left(\frac{P_{TX}}{P_{RX}}\cdot\frac{G_{A1}G_{A2}}{L_{C1}L_{C2}}\right) \tag{1}$$

with:

P_{TX}	: Transmit power	P_{RX}	: Received power
G_{A1}	: Gain antenna 1	G_{A2}	: Gain antenna 2
L_{C1}	: Attenuation cable 1	L_{C2}	: Attenuation cable 2

B. Vehicle-to-free space measurements

In this section first results in form of polar path loss plots are presented. As a representative frequency 2450 MHz is chosen, which is near the center of the 2.45 GHz ISM band. The Figures 6 to 10 show the top view of the car with the front of the car on the right (0°) and the rear on the left (180°). Different distances are indicated by greater distances from the plot's center. Values between the measured distances are linearly interpolated.

As an estimation for the detection range of wireless systems we choose a path loss of 80 dB. This corresponds to the energy detection threshold value of the IEEE 802.11 minimum receiver sensitivity [8] of about -80 dBm when transmitting with 0 dBm. In the figures the black outline encloses a corresponding area where the path loss does not exceed a value of 80 dB. If the 80 dB value exceeds the plot area, the threshold line is dashed.

In Fig. 6 the path loss with the transmit antenna in the head-position (Position 1) is shown. The influence of the car body columns can be seen very clearly. The starlike pattern results from diffraction at the columns and interference. It is obvious that the signal behind the columns is shadowed. In between, the signal propagates with a slight attenuation due to line-of-sight paths that are only obstructed by the windows. Because of this, the area enclosed by the contour lines is the largest among all five scenarios.

Fig. 7 shows the path loss polar plot of Position 2 (center console). Since the antenna is located below the window edge, a non line-of-sight propagation is predominant. In comparison

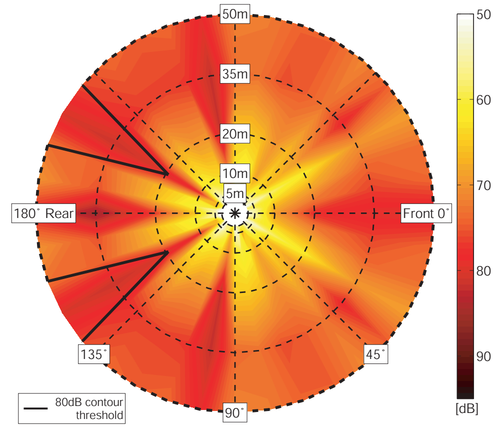

Fig. 6. Path loss for Scenario 1 (head-position)

to Fig. 6, the overall path loss is higher and the shadowing effect of the columns is less distinctive.

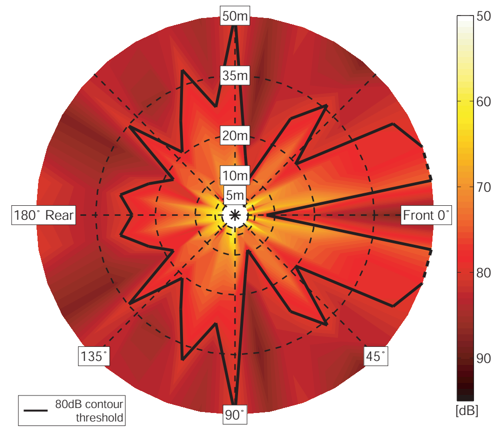

Fig. 7. Path loss for Scenario 2 (center console)

For Fig. 8 and 9 the transmit antenna is placed at Position 3 (antenna-module). Fig. 8 shows the pattern for the 5 series BMW with standard windows. The radiation pattern is similar to antenna Position 1 but the path loss is slightly higher. This issue can be observed because the antenna is mounted close to the roof, such that the line-of-sight path is less pronounced.

In Fig. 9 the pattern for the 7 series BMW with metalized windows is shown. Note: In this car all windows except the rear window are metalized. A huge amount of radiation is being reflected by the metalization. As a result the radiated energy in the rear direction is higher than in Fig. 8. Due to the reflections the received power in the back of the car is even higher compared to a previously performed free-space calibration measurement.

Finally Fig. 10 shows the path loss pattern for the transmit antenna at Position 4 (front passenger footwell). In this scenario the antenna is placed at the lowest possible position within the cabin. The overall path loss is the highest for this scenario (except with metalized windows).

In order to compare the five scenarios, in Fig. 11 the mean path loss over all measured angles is plotted over the distance

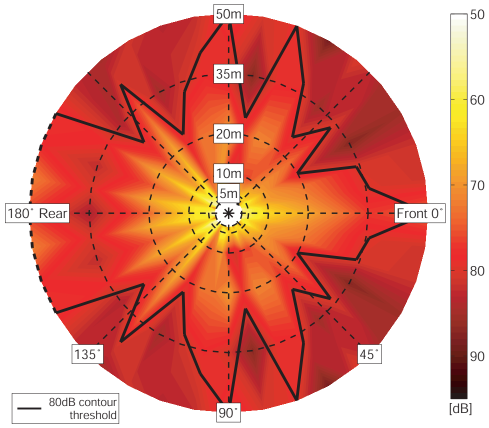

Fig. 8. Path loss for Scenario 3 (antenna-module)

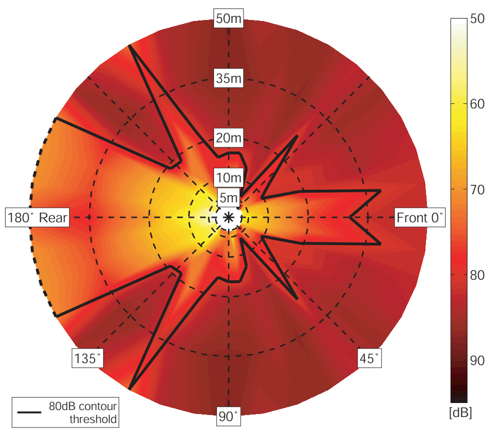

Fig. 9. Path loss for Scenario 4 (antenna-module, metalized windows)

for 2450 MHz. The maximum variation of the path loss for different antenna positions is about 7-10 dB. To show the effect of the variation over frequency, in Fig. 12 the mean path loss for one selected scenario is presented over the complete 2.45 GHz ISM band. The fluctuation of path loss over frequency decreases with increasing distance.

C. Intra-vehicle measurements

In the intra-vehicle measurement scenario, both transmitter and receiver are placed inside a car (Fig. 13). The results of the path loss measurements are shown in Table III.

TABLE III
RESULTS FOR THE INTRA-VEHICLE SCENARIO

Car position	**Driving direction head-position**	**Reverse direction head-position**	**Driving direction footwell position**	**Reverse direction footwell position**
1	68 dB	63 dB	86 dB	86 dB
2	77 dB	64 dB	84 dB	86 dB
3	54 dB	51 dB	83 dB	85 dB
4	66 dB	68 dB	84 dB	84 dB
5	65 dB	70 dB	85 dB	86 dB
6	72 dB		85 dB	

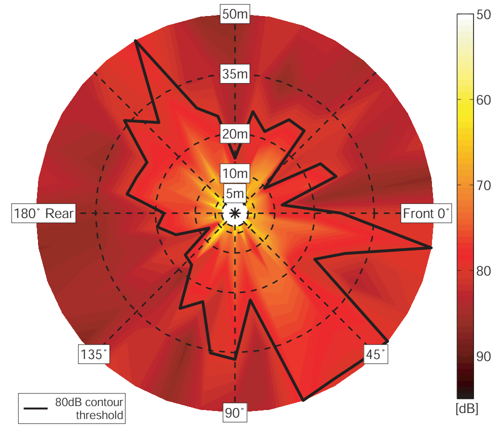

Fig. 10. Path loss for Scenario 5 (front passenger footwell)

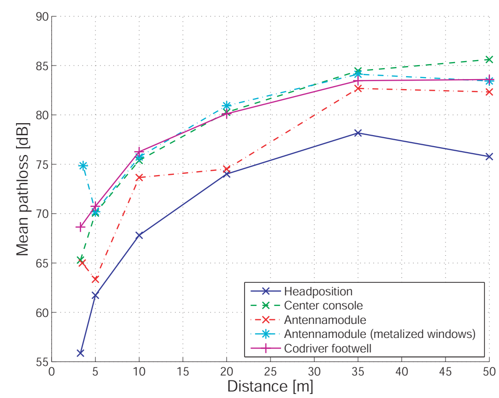

Fig. 11. Mean path loss over distance for 2450 MHz (Measurement)

According to the results in Fig. 11, for intra-vehicle scenarios antenna positions with the worst and best path loss values are selected. As the results in Tab. III show, the difference in these scenarios is in the order of 20 dB. The path loss is not monotonically increasing over the distance, because of the two way propagation. This can be explained by constructive and destructive interference at the receiver at certain distances.

IV. Conclusion

In this paper path loss measurement results for vehicle-to-free space and intra-vehicle measurement scenarios in the 2.45 GHz ISM band were presented. The objective was to select scenarios which represent future use cases and determine the difference among them in order to improve coexistence between CE-devices by reducing mutual interference through proper system positioning. Therefore varying antenna positions and the effect of metalized windows were evaluated. A measurement method and an instrumental setup was developed. Path loss values were computed from the measured power at the position of the receiver.

With regards to coexistence, the area of operation of the in-car devices should be minimized to keep the interference from and to other communication systems low. A huge path loss between in-car wireless systems and the environment is preferred.

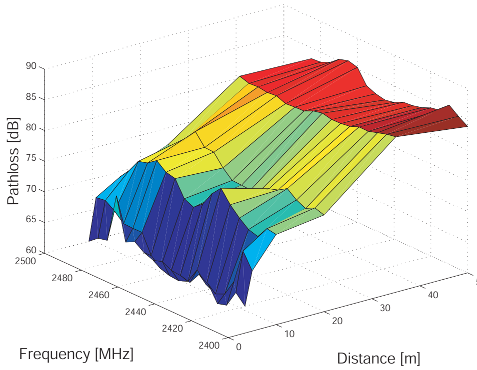

Fig. 12. Frequency variation for Scenario 3

Fig. 13. Intra-vehicle scenario with two BMW 5 Series

As the results show, the antenna position and also the characteristics of the windows have a huge effect on the path loss. For example, at the Position 1 (head-position) combined with standard windows a large effective range can be observed. Even at a distance of 50 meters, a considerable interference level can be identified. Additionally, a huge angular dependency of the path loss in the range of 0-20 dB can be noticed, especially when the antenna is positioned at head-position. This criterion can be explained due to diffraction effects. The signal is bent around the car columns and interferes at the observation spot [9]. The attenuation of the standard windows is quite low. In order to minimize the interference in the surrounding of the car, an antenna position with no line-of-sight path should be chosen. Metalized windows help to reduce the interference in the surrounding area. The best results were observed when placing the transmit antenna in the front passenger footwell (Position 4).

The key design parameters to increase quality of service of on-board wireless systems in a multi-car scenario are summarized as follows:

- The in-car antenna should be mounted in the bottom area of the car in order to prevent a direct line-of-sight path to other systems. In the presented scenarios, the average path loss variation is about 7-10 dB (Fig. 11).
- Heat absorbing glass (metalized windows) helps to increase the attenuation of any unwanted signal. In the corresponding figure (Fig. 9), energy reflected from the metalization is directed to the non metalized rear window where radiation can escape. Therefore metalization of all windows is favorable.
- Performance can also be increased by carefully selecting the type of antenna with an adapted radiation pattern to the in-cabin room of the car.
- Each system should control the transmit power to reduce excessive radiation and interference from and to other systems.
- In the intra-vehicle scenario, the difference between the two measured antenna positions is about 20 dB, which is approximately twice as high as compared to the vehicle-to-free space scenarios.

V. Acknowledgement

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