Mutual Influence of Concurrent IEEE 802.11 Wireless Local Area Networks in an Automotive Environment

Florian Pfeiffer, perisens GmbH, Lichtenbergstraße 8, 85748 Garching bei München, pfeiffer@perisens.de
Ramy Mansour, Bernd Napholz, Daimler AG, D-71059 Sindelfingen, bernd.napholz@daimler.com
Erwin Biebl, Technische Universität München, Arcisstr. 21, 80333 München, biebl@tum.de

Summary / Abstract

More and more vehicles are equipped with in-car 802.11 Access Points to provide a high-speed Wireless Local Area Networks (WLANs). The WLAN in-car situation is especially challenging as often very high data rates need to be provided to several clients located in the vicinity (e.g. video streaming to several displays from a central media server) with many concurrent networks around (in urban or dense traffic situation). It is essential for the success of such wireless based time sensitive and data intensive applications that the function is reliable in moving and non-moving situations with multiple concurrent WLANs located in the surrounding. Particularly critical is that these applications like video streaming will preferentially be used in traffic jam situations and customers are very sensible to a quality degradation of a vehicle infotainment system.
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1 Introduction

Wireless Local Area Networks (WLANs) are broadly introduced in vehicle infotainment systems and are today mainly used to allow internet services for the vehicle passengers. In future, more and more data intensive applications as video streaming to several displays from a central media server will increase the transfer data rates. Since in-car WLAN based applications are still in an initial state, it is important to analyse the performance and the mutual influence of concurrent WLANs. The IEEE 802.11 standard allows only the transmission of a single radio on the same frequency channel and uses a Listen-Before-Talk (LBT) channel access which is a suitable mechanism for efficiently sharing common spectrum between multiple networks on the same channel. But the Carrier Sense Multiple Access (CSMA) method also means that an in-car wireless communication having a strong signal has to share the spectrum (and thus the data throughput) with other weak networks on the same channel which are located in the surrounding. In the CSMA method the station wishing to transmit listens to the channel (carrier sensing) and only transmits if the channel is idle. The Clear Channel Assessment (CCA) is the operation performed to determine if a channel is idle or busy.

This paper addresses the mutual impact of concurrent co-channel IEEE 802.11 connections for in-car 2.4Ghz and 5GHz WLANs. As an in-car WLAN is classified as an outdoor application, a limited number of channels are available in 5Ghz which makes it more likely to have other networks on the same channel. Moreover, it is not possible to do any channel planning as done for e.g. in a static office environment. Even the implementation of a dynamic channel selection to avoid co-channel interference is extremely difficult in a constantly changing environment.

The paper will present theoretical calculations; experimental analysis conducted as real world vehicle measurements. Data throughput measurements were performed to describe the mutual influence. Based on these measurements, we determine the distance between two cars in which mutual influence appears - in other words co-channel WLANs will have to share the available media access and thus the available throughput.

Most published WLAN investigations deal with the limit of achievable maximum net data rate [Yan02], [Eng11] and do not consider the mutual influence which will become more and more an issue with the increasing use of data intensive applications.

1.1 Frequency situation

The 2.4GHz band regulations have been relatively constant during the last years. The 2.4 GHz band starts with channel 1 at 2.412 GHz and is divided in 14 channels spaced 5 MHz apart (with the exception of channel 14 which is 12 MHz apart from channel 13). In US, the FCC allows channel 1 to 11 and in Europe the ETSI allows channel 1 to 13. In both regions, only three channels are non-overlapping in frequency space (1, 6 and 11).

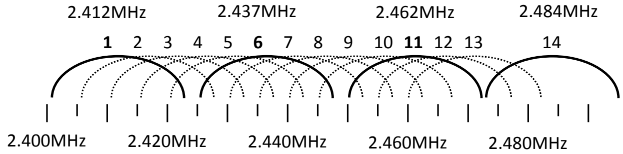

Figure 1: WLAN-channels in 2.4GHz band

The increasing density of radio frequency transceivers operating in the ISM 2.4GHz band (Industrial, Scientific and Medical radio band) encourages the utilization of the 5GHz band with up to 25 non-overlapping channels of 20MHz.

The situation for the 5GHz band is not that clear than in 2.4GHz and is still evolving. In general the 5GHz band is divided into several sub-bands with different regulatory requirements around the world. One main requirement is the coexistence with existing systems (e.g. satellite communication, meteorology and military radars) which demands for certain sub-bands a limitation to indoor usage and/or an implementation of Dynamic Frequency Selection (DFS). Typically an in-car WLAN is classified as an outdoor application which will limit the number of available channels in 5GHz and therefore makes it more likely to have other WLANs on the same channel. Furthermore, a dynamic frequency selection is very difficult to implement in a dynamic car situation as the environment is constantly changing.

1.2 Collision Avoidance

In the CSMA method the station wishing to transmit listens to the channel (carrier sensing) and only transmits if the channel is idle. The Clear Channel Assessment (CCA) is the operation performed to determine if a channel is idle or busy. In the IEEE standard exact requirements for the CCA mechanism are specified. The standard differentiates between two cases for a 20MHz channel bandwidth [Per13], [IEEE12]:

- Signal detect CA threshold
  At or above -82dBm receiving power the WLAN-Hardware has to be able to detect the start of a valid OFDM packet with a probability of more than 90% within 4µs and hold the channel busy for the duration of the packet.
- Energy detect CA threshold
  If no valid OFDM signal is detected, the channel has to be hold busy for any signal at or above -62dBm within 4µs.

These two requirements where specified for the ODFM PHY (802.11a). With the 802.11n amendment and the support of 40MHz operation, additional specifications were needed. The primary channel has the same requirements as the OFDM PHY and the secondary channel is limited to the energy detect CA requirement. For the 802.11ac amendment, the signal detect CA threshold was adapted for a 40MHz VHT PPDU at or above -79dBm, for 80MHz VHT PPDU at or above -76dBm and for 160MHz at or above -73dBm. For more details concerning the CCA mechanism the reader is referred to the 802.11 standard.

The aforementioned CA thresholds for signal detect correspond to the minimum sensitivity level defined in the 802.11 standard and are not depending on the transmission power. This requirement is understandable and necessary to ensure a proper function of WLAN connections when AP and STA are located far away from each other. But in an in-car situation, AP and STA are located close to each other and usually having a strong receiving signal. But still the spectrum and thus the data throughput has to be shared with other weak networks on the same channel which are located in the surrounding. As the CA threshold defined in the IEEE standard is not depending on the Tx power, a power reduction of the vehicle's Tx power is not beneficial for the own performance – not before the surrounding networks are also reducing their Tx power.

2 Theoretical Model

In this section the maximum range of influence between two concurrent WLAN connections in two different cars is derived theoretically. A station that wishes to transmit first performs a clear channel assessment before it will begin a frame exchange sequence. If the station detects during this time a WLAN signal from another station at or above -82dBm (for 20MHz) it will classify the medium as busy and wait till the medium goes idle. In this case the available medium (and thus the maximum throughput) will be shared between both stations.

2.1 Radio Propagation Model

To calculate the maximum distance of influence, a simple propagation model based on geometric optics is used. Assuming a worst case scenario where both antennas are located close to the vehicle's window and are facing each other, the impact of the vehicle can be reduced to fading effect and window glass attenuation in a first approximation. The attenuation of glass was measured using two rod antennas facing each other in a distance of about 1m. The first antenna was located inside the vehicle on one side of the window and the second antenna outside the vehicle on the other side of the vehicle. Using a signal generator and a spectrum analyser the glass attenuation was measured by opening and closing the window. The measurement was performed at 2.4 and 5.2GHz and for normal glass and IR reflecting glass. The results are presented in the following table for normal car glass and IR reflecting car glass:

Table 1: Measured window glass attenuation

	Attenuation L_{win} in dB at 2.4GHz	at 5.2GHz
Non IR reflecting car glass	1dB	2dB
IR reflecting car glass	12dB	25dB

The IR reflection of car glass is provided with a thin metal coating which reflects the IR radiation and still being transparent for visual light. The measurements show that the metal coating has a strong impact on the radio wave propagation and even increases with frequency. Compared to 2.4GHz, the attenuation is double as high in logarithmic scale at 5.2GHz.

The propagation itself is approximated with a simple free space model. The model considers only the direct path (LoS - Line of Sight) from the transmitter to the receiver's antenna as shown in the following figure.

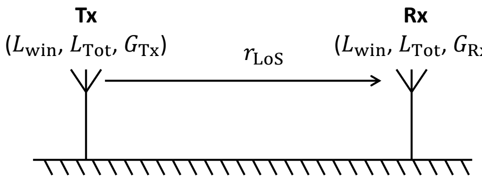

Figure 2: Line of Sight propagation model

The receiving power P_{Rx} can be calculated with

$$P_{\text{Rx}}[\text{dBm}] = P_{\text{Tx}}[\text{dBm}] + G_{\text{Rx}}[\text{dBi}] + G_{\text{Tx}}[\text{dBi}] - L_{\text{Tot}}[\text{dB}] - L_{\text{Free space}}[\text{dB}] \quad (2.1)$$

where P_{Tx} is the transmission power, G_{Rx} the antenna gain at the receiver's side, G_{Tx} the antenna gain at the transmitter's side and L_{Tot} the total loss. The free space loss $L_{\text{Free space}}[\text{dB}]$is

$$L_{\text{Free space}}[\text{dB}] = 10\log_{10}\left(\frac{4\pi \cdot r_{\text{LoS}}}{\lambda}\right)^2 \quad (2.2)$$

with λ as wavelength and r_{LoS} as LoS path length.
The total loss consists of the attenuation of the windows and the loss from the car environment (as we are considering propagation from car to car the window is passed two times and also the car loss occurs twice). To simplify the calculation, it is assumed that the loss factors of both vehicles are equal:

$$L_{\text{Tot}}[\text{dB}] = 2L_{\text{win}}[\text{dB}] + 2L_{\text{Car}}[\text{dB}] \quad (2.3)$$

In our simplified model, we use the following parameter for the estimation of the receiving power.

Table 2: Propagation model parameters

Transmit power P_{Tx}	+17dBm
Car loss (fading,…) L_{Car}	13dB
Antenna gain G_{Tx}, G_{Rx}	+3dBi

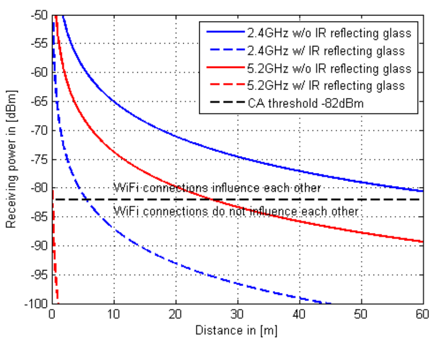

Figure 3: Receiving power from a WLAN transmitter to WLAN receiver both inside two different vehicles vs. distance (P_{Tx}=+17dBm, L_{Car}=13dB, G=3dBi)

It shall be mentioned that the car loss is a coarse estimation as the intention of the described calculation is not to give an accurate physical model but to give an indication for the influence of two in-car WLAN connections. Figure 3 shows the calculated receiving power in dBm against the distance between receiver and transmitter, both located in two different cars. The following cases are considered: with and without IR reflecting car glass at 2.4GHz and 5.2GHz, respectively. The bold black line indicates the CA threshold of -82dBm. If the receiving power is below this line, the two WLAN connections do not influence each other and do not have to share the media access. For the 2.4GHz case and normal car glass, the region of influence goes beyond 60m (solid blue line). By considering IR reflecting glass the distance reduces to 5.6m (dashed blue line). For the 5.2GHz frequency range, the influence range is strongly reduced due to the increased free space and glass attenuation. Without IR reflecting glass the range is about 25m (red solid line) and with IR reflecting glass, no influence at all is expected (red dashed line). It is worth mentioning again that we are considering a worth case scenario where the antennas are located at the car window.

2.2 Number of Cars within the Influence Range

In the last section the maximum range of influence was calculated analytically. In the next step, the number of cars inside this range shall be estimated as every car is a potential interferer. According to [Hof94] the average car length in Germany is 4.5m. In a traffic congestion situation, the average distance between two cars can be assumed to be 2m. This means that every 6.5m a car is located. Hence if the maximum influence range is 25m, about six cars (apart from the own car) are within this range on a single lane assuming a straight road. If we consider a road with several lanes, this number quickly increases as shown in the following plot. For the calculation a lane width of 3.75m was assumed which is equivalent to the lane width on the German Motorway (Autobahn).

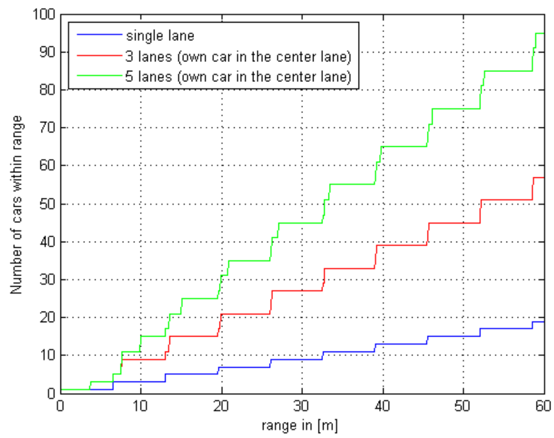

Figure 4: Number of cars within range for a traffic congestion

3 Car Measurements

As a real vehicle environment with complex car geometry and multiple reflections is much more complicated than the simplified propagation model introduced in the last section, real world measurements with real cars were carried out.

3.1 Measurement setup

In the cars a WLAN connection between AP and STA was established using identical hardware setup (see Table 3).

Table 3: Used WLAN hardware setup

WLAN AP	Cisco AP3700 with a single external rod antenna (the other three antenna ports were disabled and terminated to 50 Ohms) Tx power: 16dBm	
WLAN STA	Cisco AE6000 USB Stick with an internal antenna	

The AP was located between the driver and co-driver seat and the STA on the backseat as shown in Figure 5.

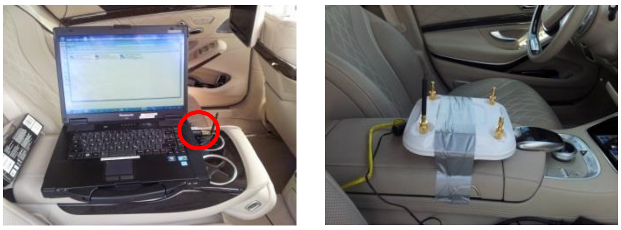

Figure 5: Position of AP in the front and STA in the back of the car

For the 2.4GHz measurement, a WLAN IEEE 802.11b/g/n connection was set up on channel 6. For 5GHz, channel 36 was used with IEEE 802.11a/n. The measurements were carried out on a free area (a parking place close to the Daimler plant in Sindelfingen) with no other WLAN connections in the vicinity. One car was parked and the other car was driven at walking pace in clockwise direction around the parked car (see Figure 6). The distance between both cars was increased with every turn to finally cover an area of about 20m x 80m with the parked car in the center. In both cars a simultaneous TCP throughput measurement using the free tool IPerf was performed during the test drive. The STA is configured as IPerf client and the AP as IPerf server which implies data transmission from STA to AP. To geo-reference the throughput data, GPS-coordinates are collected from a GPS receiver on the roof of the car. Additionally the path loss between both cars was recorded using CW signal generated with a signal generator and measured with a spectrum analyzer. In order to exclude interference from the CW signal, the frequency used lied far outside the WLAN bandwidth.

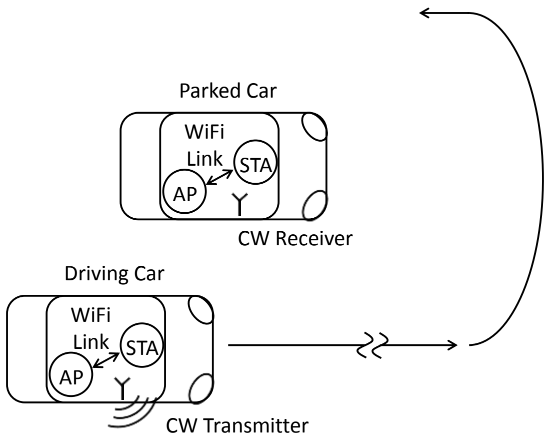

Figure 6: Measurement scenario with a car driving around a parked car

The next figure shows a picture of the two cars (here the Mercedes S-class cars with IR reflecting glass).

Figure 7: Photo of two Mercedes S-class cars with IR reflecting glass during the measurement

3.2 Path loss measurements result

Figure 8 shows the results of the path loss measurements for 2.4GHz and 5GHz without IR reflecting car glass. Every coloured heat-map point corresponds to an average of several measurement points.

Corresponding to the theoretical calculations, the path loss is significantly higher at 5GHz. In difference to the theoretical calculation, the antennas were placed below the window line and therefore no direct line of sight path exists. Therefore the wave propagation between sender and receiver only occurs due to diffraction and reflection effects. As the diffraction decreases with increasing frequency, this effect further increases the difference between 2.4 and 5GHz.

To interpret the plots, it is necessary to determine the minimum path loss where no influence occurs. Taking into account the CA threshold of -82dBm, this can be easily calculated with the following equation:

$$L_{\text{no influence}}[\text{dB}] \geq P_{\text{Tx}}[\text{dBm}] + G_{\text{Tx}}[\text{dBi}] + 82\text{dBm} + G_{\text{Rx}}[\text{dBi}] \quad (3.1)$$

With a transmit power of about +17dBm for the USB WLAN sticks and an antenna gain of about 0dBi for the small integrated antenna, a minimum path loss of 99dB is necessary to have no mutual influence.

2.4GHz (without IR reflecting car glass) **5GHz (without IR reflecting car glass)**

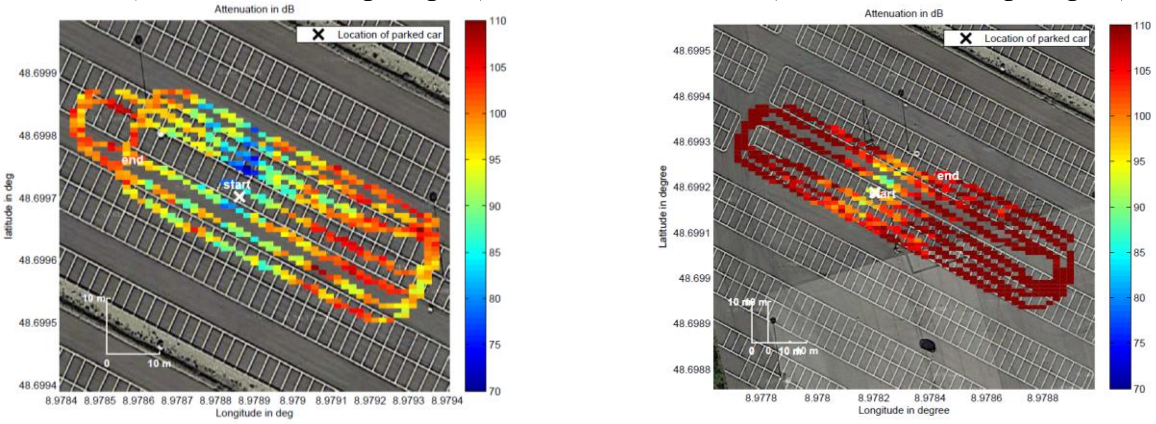

Figure 8: Measured path loss between parked and driving car (at the position of the driving car) Map data © GeoBasis-DE/BKG (©2009), Google

Therefore a path loss of minimum 99dB is necessary. According to the colour bar of the heat-map plot, 99dB refers to a dark orange colour.

As result of this, a mutual influence of the WLAN connections is expected for 2.4GHz throughout almost the entire test drive. For 5GHz only a limited mutual influence should occur around the parking car.

3.3 Throughput measurement results

At the beginning, a reference measurement with a single WLAN connection was performed. The normalized throughput is plotted as heat map in a satellite view of the parking area (see Figure 9). The throughput is always normalized to the maximum throughput measured. Dark red color indicates that the maximum throughput is achieved.

For both frequencies, the throughput remains almost constant over the whole measurement period. For 2.4GHz, only at two short sections the throughput reduces to about 60-70% of the maximum value and recovers quickly back to almost 100%. For 5GHz the throughput is slightly more unstable but still very constant.

Then, two simultaneous IPerf measurements in the driving and parked car were performed during similar test drives.

The following test scenarios were measured:

- 2.4GHz (channel 6) both cars without IR reflecting glass (Mercedes CLS and GL A)
- 2.4GHz (channel 6) both cars with IR reflecting glass (Mercedes S-class)
- 5.2GHz (channel 36) both cars without IR reflecting glass (Mercedes CLS and GL A)
- 5.2GHz (channel 36) both cars with IR reflecting glass (Mercedes S-class)

The compilation of the measurement results is presented in Figure 8. The left column of plots represents the measured data throughput of the driving car; the right column the data throughput of the parked car at the position of the driving car. The rows represent the aforementioned test scenarios. It is obvious that the plots in the left and right column are almost mirrored. This shows the proper function of the IEEE802.11 channel access mechanism. If the receive power of another WLAN signal is greater than the CA threshold the common spectrum is shared between both connections.

2.4GHz (without IR reflecting car glass) **5GHz (without IR reflecting car glass)**

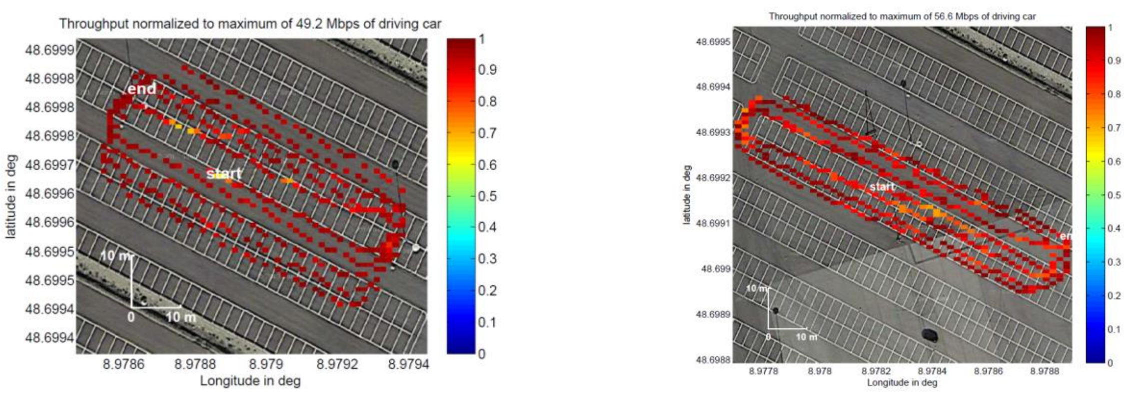

Figure 9: Normalized in-car WLAN throughput: Reference measurement without a 2nd WLAN connection in the surrounding
Map data © GeoBasis-DE/BKG (©2009), Google

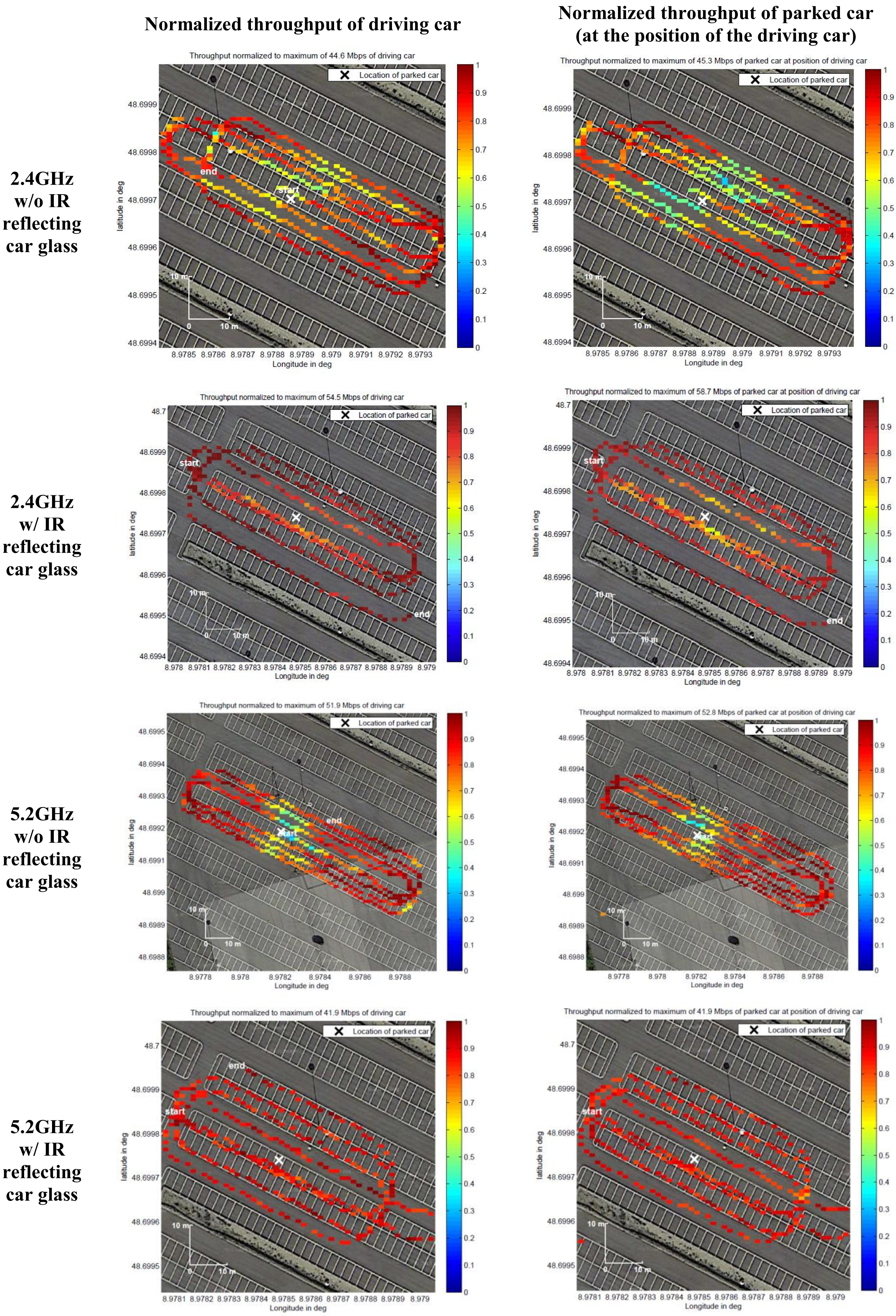

Figure 10: Normalized in-car WLAN throughput: measurement with two concurrent WLAN connections in two cars; one car surrounding the other parked car (at 2.4GHz and 5GHz; cars with and without IR reflecting glass) Map data © GeoBasis-DE/BKG (©2009), Google

For the 2.4GHz measurement, a strong mutual influence appears up to a distance of about 20m between both cars. Comparing the upper two plots in Figure 10 shows that the data rate does not always divide in equal parts. In some sections, the throughput of the parked car reduces to 30 to 40% (blue colours) when throughput of the driving car only decreases to 60 to 70%. This unfair media access is additional critical, as it makes it more difficult to guarantee a certain data rate. Comparing the figures with and without IR reflecting car glass for 2.4GHz (first and second row of plots in Figure 10) shows that the attenuation of the metallized car glass diminishes the mutual influence, but in the lanes next to the parked car the throughput is still reduced up to a distance of approximately 15 to 20m. Compared to the case without IR reflecting glass, the mutual influence significantly smaller and the measured throughput does not reduce below about 60% which indicates that the two WLAN connections do not influence each other constantly. This can be explained with fading effects where the signal power will again and again be above the CA threshold.

For 5.2GHz and non IR reflecting glass, the mutual influence appears up to a distance of up to 10m between both cars. Comparing the results to 2.4GHz it could be seen that as expected the influence range will be reduced. With IR reflecting glass, no influence at all occurs due to the high attenuation of the car glass.

4 Conclusion

This paper addresses the mutual impact of two concurrent in-car IEEE 802.11 WLAN connections operating on the same channel.

The influence depends on the frequency band (2.4GHz or 5GHz) and if a car is equipped with IR reflecting glass. The propagation loss increases with increasing frequency and thus the influence range is larger at 2.4GHz compared to 5GHz. The loss of car glass is approximately double as high at 5GHz compared to 2.4GHz. Especially the impact of metallized IR reflecting glass with a transmission loss of 12dB for 2.4GHz and 25dB for 5GHz has a strong impact on the influence range. When both cars are equipped with IR reflecting car glass, for 2.4GHz only a small mutual influence was measured and for 5GHz no mutual influence at all occurs. At 2.4GHz and without IR reflecting car glass the mutual influence occurs until a distance of about 20m and even beyond that. In a traffic congestion situation on a three-lane road, up to 20 cars would be in that region. At 5GHz the mutual influence occurs until a distance of 10m.

With increasing use of in-car WLAN and upcoming time sensitive high data application (as video streaming), the mutual influence will become more and more an issue. In an automotive environment, it is particularly critical that the data intensive applications like video streaming will preferentially be used in traffic jam situations. Additionally a car manufacturer cannot tolerate a quality degradation of a vehicle infotainment system. Here a shift to the 5GHz band is helpful as it reduces the range of mutual influence due to higher losses and allows more non-overlapping channels. But a shift to 5GHz will not completely solve the problem. The presented measurements where performed with standard WLAN hardware with a transmit power of about 17dBm (50mW) and still without IR reflecting glass an influence range of about 10m was measured. In US the FCC already allows a transmit power of 30dBm (1000mW) in UNII band 3 and also in Europe there are efforts to increase the allowed power. It should be always kept in mind that a higher transmit power does not only increase the communication range, but also will enhance the range of mutual influence. This trade-off can be improved with a well-functioning power transmit control (TCP).

To achieve the best coexistence performance in a dense WLAN scenario, always the maximum throughput with minimum power principle should be applied: The power should always be that high that the signal to noise ratio (SNR) is high enough to achieve the maximum data but not (or not much) higher. Especially in an in-car situation with a maximum distance between STA and AP of only one to two meters, it is not necessary to transmit with high power. But in praxis, it is often transmitted with maximum power. Additionally, the WLAN IEEE 802.11 standard does not directly reward a power reduction. The collision avoidance (CA) threshold which defines at which level of an external WLAN signal the media has to be set as busy does not depend on the own transmission power. This means that a power reduction is not directly beneficial for the own performance as the media has still to be shared with other networks. Even if these networks do not have to share the media themselves. But still a power reduction would be useful, if all surrounding networks are reducing their transmission power. One solution could be to have separate bands for short range applications (e.g. in-car applications) with a very limited transmission power and other for far range applications with high transmission power allowed.

5 Literature

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About the authors

Florian Pfeiffer was born in Starnberg, Germany, in 1976. He received the Dipl.- Wirtsch.-Ing. (FH) degree in industrial engineering from the Fach-hochschule München, Munich, Germany, in 2001, the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from the Technische Universität München, Munich, Germany, in 2005 and 2010, respectively. In 2009, together with Prof. Dr. Erwin M. Biebl, he founded an engineering company for high frequency electronics (perisens GmbH), where he is chief executive. Since 2013, he has been teaching a course about automotive radar technology as associated lecturer at the University of Applied Sciences, Ingolstadt, Germany (THI). Dr. Pfeiffer is a member of the Informationstechnische Gesellschaft (ITG) in the Verband Deutscher Elektrotechniker (VDE).

Ramy Mansour was born in Florida, USA in 1988. After graduating from high school in Cairo, Egypt he moved to Munich, Germany to study at the Technische Universität München. Mr. Mansour completed his B.Sc. in 2013 and is currently working on his master's thesis at Daimler AG in Sindelfingen.

Bernd Napholz was born in Öschelbronn, Germany, in 1964. He received the Dipl.-Ing. degree in electrical engineering from the Technische Universität Stuttgart, Germany, in 1992. At Daimler AG he is since 2009 responsible for wireless coexistence investigations and successful integration of wireless systems for all vehicles lines.

Erwin M. Biebl was born in Munich, Germany, in 1959. He received the Dipl.-Ing., Dr.-Ing., and Habilitation degrees from the Technische Universität München, Munich, Germany, in 1986, 1990, and 1993, respectively. In 1986, he joined Rohde & Schwarz, Munich, Germany, where he was involved in the development of mobile radio communication test sets. In 1988, he was with the Lehrstuhl für Hochfrequenztechnik, Technische Universität München. In 1998, he became a Professor and Head of the Optical and Quasi-Optical Systems Group. Since 1999, he has been Head of the Fachgebiet Höchstfrequenztechnik, Technische Universität München. He has been engaged in research on optical communications, integrated optics, and computational electromagnetics. His current interests include quasi-optical measurement techniques, design and characterization of microwave and millimeter-wave devices and components, sensor and communication systems, and cooperative approaches to sensor and communication systems and networks. Dr. Biebl is a member of the Informationstechnische Gesellschaft (ITG) in the Verband Deutscher Elektrotechniker (VDE), Germany, a senior member of the IEEE and an appointed member of the commission B of URSI,Germany.