IEEE 802.11 Systems in the Automotive Domain: Challenges and Solutions

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Abstract: Customer demand for infotainment systems has garnered great attention from car manufacturers. System features have become a decisive factor when choosing among car models. As consumers become more dependent on their portable electronic devices (e.g., mobile phones, tablets), they expect to have seamless integration of their devices inside their cars. This allows them to use the same features supported by their phones in the cars. Car manufacturers aim to make their infotainment systems user-friendly. A key factor to achieve this goal is facilitating a wireless connection between mobile phones and car computers. IEEE 802.11 systems are the most popular candidate to provide high data rate connections utilizing the unlicensed industrial, scientific and medical (ISM) radio band. However, due to the limited available spectrum and the high density of devices inside the car, the achieved throughput could be strongly affected by interference and coexistence challenges. Furthermore, strong interference between the networks in different cars plays a crucial role in the automotive domain. This paper highlights the interference problem between IEEE 802.11 systems in cars. Two solutions in the 802.11n standard, namely transmission power control (TPC) and multiple input multiple output (MIMO) techniques, are discussed. Results show that both techniques could improve system performance. Transmission power control is essential to control radiation to surrounding environment.

1 INTRODUCTION

Car infotainments systems have improved dramatically in the past years. Changes have been driven by customer demand to stay connected and to enjoy various applications in their cars. Infotainments systems have attracted the interest of big technology companies like Google and Apple, and both companies have developed new platforms for cars–Android Auto and CarPlay, respectively. This innovation is expected to lead to growth of connected cars. This growth is not unlike the transition of cell phone use for calling and texting to their widespread use of innovative functions.

The number of accidents related to cell phone use while driving has increased dramatically in recent years. According to a study from the National Safety Council in the USA (National Safety Council, 2013), nearly 26 percent of all crashes involve drivers talking and texting on cell phones. One key advantage of new infotainment systems is that seamless integration of new functions utilizing wireless connections is expected to reduce the number of accidents resulting from cell phone use while driving.

A number of wireless systems have rapidly migrated into the automotive industry in recent years as a part of infotainment systems. WLAN[1], Bluetooth[2] and Kleer (Kleer, 2007) are among the most widely used in the 2.4 GHz ISM band. Bluetooth is used mainly for hands-free calling and music streaming, while Kleer is used for high quality music streaming. WLANs are used to provide Internet connectivity for vehicle passengers using a shared connection to cellular networks. The WLAN use in cars is not restricted to Hotspots, several applications rely on WLAN–like screen mirroring using Wi-Fi direct[3]. Notably, Android auto and CarPlay functions will use

[1]WLAN, Wi-Fi and 802.11 will be used interchangeably in this paper

[2]It was standardized by IEEE as 802.15.1, now it is managed by Bluetooth special interest group (SIG)

[3]Called also Wi-Fi P2P

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Wi-Fi direct to enable wireless connection between cell phones and car computers. This feature makes them more user-friendly by alleviating the need for wired connection (e.g., USB).

Currently, the number of cars equipped with WLAN is minimal and is restricted to premium-priced automobiles. This exclusivity will likely change relatively soon due to the attractiveness of WLAN for various applications and the availability of high supported data rate. According to a report from GSMA (Sbd, 2012), all new cars will have WLAN by 2025. Consequently, millions of new overlapped basic subscriber sets (OBSSs) will coexist with current networks, moreover they are mobile with different speeds, which makes any kind of network planning not possible. Unlike indoor scenarios (e.g. offices, homes), interference between vehicle WLANs is extremely high due to weak attenuation of car bodies. Simulations and measurements in (Blesinger et al., 2013; Blesinger et al., 2012) show that the attenuation of car bodies and windows is very low; mean path loss does not exceed 85 dB at 50 m distance around the car. This demonstrates the severity of coexistence problems in this domain. Several factors affect path loss (e.g., antenna position and window type), which should be taken into account by car manufacturers. Mutual interference between concurrent 802.11 systems in cars is studied in (Pfeiffer et al., 2014). Measurements validate the notion that the achieved throughput is strongly affected by the WLAN connection in a neighboring car. When both 2.4 GHz and 5 GHz ISM bands are considered, the results show that the interference in the 2.4 GHz band is higher due to the lower path loss. A study on the effectiveness of WLAN in vehicles is presented in (Heddebaut et al., 2004). The objective was to characterize radio frequency (0.7-6 GHz) propagation inside vehicles. Measurements show that mean attenuation ranges from a few decibel to more than 40 dB, depending on the antenna positions. As such, good link quality for WLAN inside the vehicle should not be difficult to achieve. In (Kukolev et al., 2015), channel measurements are conducted inside the vehicle in the frequency band 5.8 GHz. The primary focus is centered on IEEE 802.11p standard for both intra-vehicle and out-of-vehicle environments. The measured power delay profile (PDF) is described using a double exponential model; delay spread is small resulting in negligible effect on inter-symbol interference (ISI).

In (Lin et al., 2013), a performance study of intra-vehicle wireless sensor networks (IVWSN) based on Bluetooth low energy and ZigBee under Wi-Fi and Bluetooth interference is presented; performance of both IVWSNs significantly degrades when Wi-Fi interference is introduced. Although the interference from the surrounding networks is not considered, it will definitely increase its influence. In previous work (Mourad et al., 2016), test drives were conducted to investigate WLAN performance in the vehicles. Highway and city center test drives in Germany demonstrate that achieved throughput inside the car under test is strongly affected by interference from surrounding networks. Currently, WLANs are primarily found in offices, homes, and public areas, as noted earlier, the number of cars equipped with WLAN is still limited.

In this work, the focus is on WLAN used for infotainment applications in vehicles, which is expected to be widely spread before the vehicular Ad-Hoc network (VANET). Having WLANs in vehicles will escalate the coexistence problem in the ISM bands. A consequence of millions of new mobile OBSSs, performance of the surrounding fixed Hotspots will be strongly affected. The high density of devices in vehicles and their mobility, in addition to low insertion loss between neighboring cars make this domain unique.

Wi-Fi has been studied in various indoor/outdoor scenarios and under many attenuation scenarios. However, studies of vehicular environment are limited. Consequently, this paper provides a first step into investigating Wi-Fi performance in realistic vehicle coexistence scenario. The main contribution of this paper is to study how the WLANs in two neighboring cars affect each other and to discuss solutions leveraging the most recent WLAN standard –802.11n– at 2.4 GHz. To accomplish this, two cars are parked near to each other and two WLANs are established in them. Throughput and power values are collected and analyzed. Both TPC and MIMO techniques are discussed.

The IEEE 802 community has recently recognized this issue in the sake of increased demand by car manufacturers. A new study group, namely wireless automotive coexistence, has been established under the working group 802.19. The groups effort focuses on wireless coexistence, optimizing the 802.11 and Bluetooth parameter settings for the automotive domain.

The remainder of this paper is organized as follows. Section 2 presents briefly the IEEE 802.11 standards family. Section 3 describes the measurements setup and the baseline, while section 4 shows the measurement results. In section 5, the results are discussed, and the paper is concluded in section 6.

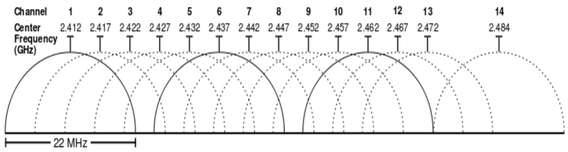

Figure 1: WLAN channels in the 2.4 GHz ISM band.

Table 1: IEEE 802.11 Standards.

Standard	*Description*	*Status*
IEEE 802.11	2.4 GHz, up to 2 Mbps	Finished 1997
IEEE 802.11b	2.4 GHz, DSSS, up to 11 Mbps	Finished 1999
IEEE 802.11a	5 GHz, OFDM, up to 54 Mbps	Finished 1999
IEEE 802.11g	2.4 GHz, OFDM, up to 54 Mbps	Finished 2003
IEEE 802.11n	2.4 GHz and 5 GHz, OFDM, up to 600 Mbps, MIMO	Finished 2009
IEEE 802.11ac	5 GHz, MU-MIMO in downlink, up to 1300 Mbps	Finished 2013
IEEE 802.11ax	2.4 GHz and 5 GHz, OFDMA, MU-MIMO for both downlink and uplink	Under development, expected 2019

2 IEEE 802.11 SYSTEMS

IEEE 802.11 systems provide wireless connectivity for various portable devices. The standards define both the MAC layer specification and the physical layer techniques. Table 1 shows IEEE 802.11 standards, as well as a short description about each and the year of release. Systems operate in both 2.4 and 5 GHz ISM unlicensed bands. Specifically in the 2.4 GHz band, 83.5 MHz are available, ranging from 2.4 to 2.483 GHz. Fourteen channels –22 MHz each– are defined in the standard, as shown in Fig. 1. Only three channels (1, 6 and 11) are not overlapped. Thus, these channels are used most frequently.

Coordination functions are used to control channel access. Two functions are defined in the standard: 1) distributed coordination function (DCF) and 2) point coordination function (PCF). The DCF, which is most commonly used, is based on the carrier sense multiple access/collision avoidance (CSMA/CA) channel access method. The device initiates transmission only in the event that it senses the medium idle for a time period (i.e., inter frame space [IFS]). After receiving the packet, the receiver then sends an acknowledgment to the transmitter. Given that the transmitter does not receive an acknowledgment after a certain period, the transmitter will repeat the transmission up to a certain maximum number before deferring the transmission, in such a case, the packet is lost.

The carrier sense is composed of two different functions: 1) clear channel assessment (CCA) and 2) network allocation vector (NAV). While the CCA indicates if the medium is busy for the current frame, the NAV reserves the medium for the transmission of frames following the most current transmission. Moreover, CCA is initiated based on two entities: 1) preamble detection (PD) and 2) energy detection (ED). Preamble detection is used to sense other Wi-Fi signals by detecting and decoding the preamble of these signals. If the station detects additional Wi-Fi signals, the medium should be marked busy throughout the time required for current frame transmission. Required time could be established from the Physical Layer Convergence Procedure header length field. According to the standard, PD threshold used in Wi-Fi is set to -82 dBm. ED is used to detect other system signals, like Bluetooth, that share the medium with Wi-Fi or with corrupted Wi-Fi transmissions that cannot be decoded. In contrast to PD, the necessary time for the current transmitted frame is unknown. As such, the device should check the medium for each time slot, verifying that energy is still present. The ED threshold used in Wi-Fi equals -62 dBm in a 20 MHz channel, allowing fairness in sharing the medium among various 802.11 systems and additional non-802.11 systems that share the same unlicensed frequency band.

The new 802.11ax standard, which is still under development, aims at improving the throughput in the event of high density OBSSs as stated in the project authorization request (PAR): “This amendment defines standardized modifications to both the IEEE 802.11 physical layers (PHY) and the IEEE 802.11 medium access control layer (MAC) that enable at least one mode of operation capable of supporting at least four times improvement in the average throughput per station (measured at the MAC data service access point) in a dense deployment scenario, while maintaining or improving the power efficiency per station.” 802.11ax is the first 802.11 standard to support multi-user MIMO in both downlink and uplink. Moreover, the standard improves coexistence and spatial reuse by differentiating between inter-BSS and intra-BSS frames using a new field in the frame called BSS color (Stacey, 2015).

Table 2: Measurement Parameters.

Test cars	BMW X6 2016 and Toyota Camry 2003
WLAN boards	Mikrotik Router boards (RB953GS) with R11e-2HPnD radio cards
Power measurement hardware	PXIe-1075 chassis equipped with a PXIe-5663 vector network analyzer
AP position	Middle console or driver's footwell
Station position	middle back seat
Standard	802.11n
Channel width	20 MHz
Traffic type	UDP
Channel number	11
Channel center frequency	2.62 GHz
Scenario	Downlink
Link throughput	Maximum achievable
Antenna gain	4 dBi

Nonetheless, this new standard does not consider mobile Hotspots with speeds higher than 6 mph, due to the small market share of automotive at the time when the new group was formed. Regardless, it is expected that consumer electronic devices will not support this standard before year 2020, which is already notably late for the problem addressed in this paper.

3 MEASUREMENT SETUP AND BASELINE

Measurements are determined using Mikrotik Router boards (RB953GS) equipped with R11e-2HPnD radio cards. The Mikrotik boards are fully configurable, enabling power level and number of RF chains adjustments. WLAN connection is established between two boards, one acting as an access point (AP) and the other as a station. Their operating system facilitated bandwidth tests using both TCP and UDP traffic. The standard 802.11n with 20 MHz channel width was chosen for all measurements, as it is the most recent standard operating in the 2.4 GHz band. Measurement parameters are summarized in Table 2.

To define ground-truth throughput using the boards, measurements had to be conducted in anechoic chamber. Ground-truth throughput identifies board performance and acts as a reference for measurements in cars. Initially, two networks working on the same channel were established. Distance between

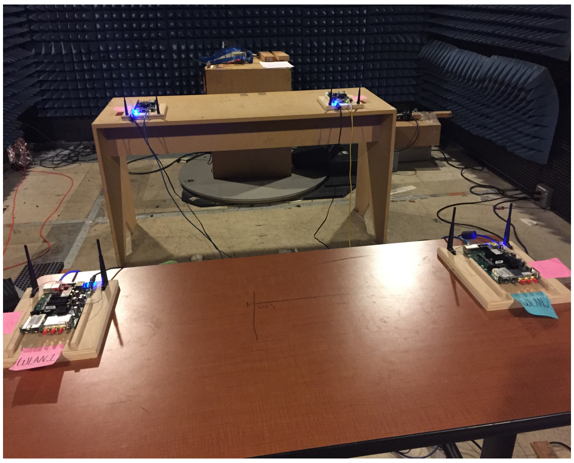

Figure 2: Test setup in the chamber.

the AP and the station is 1.5 m, and the distance between station 1 and station 2 is 1 m. These measures hold true for APs, as seen in the Fig. 2. Power was set to 16 dBm for both networks. A 60-second average was used, and throughput remained stable at near average. Results are shown in Table 3. The achieved throughput was 62.8 Mbps for the SISO case for both networks. For the MIMO case (2x2), 121 Mbps and 116.8 Mbps were the achieved values for networks 1 and 2, respectively. When two networks share the medium, network throughput for both is quite similar, and the sum of both throughputs is slightly lower than the maximum throughout for one pair. The drop in total throughput –compared to the case when either network functions independently– occurs when a second transmitter joins the channel, which increases the probability of corrupted transmission. This in turn leads to a decrease in the throughput. These findings substantiate work presented in (Rajab et al., 2015).

Throughout the experiment, two cars were parked parallel to one other, with 1.5 m separation distance between them, see Fig. 3. To simulate a real life scenario, two cars from different manufacturers –BMW X6 2016 and Toyota Camry 2003– were used. Additionally, two positions of AP –middle console and driver's footwell– were considered. The station was mounted on the middle console of the back seat, as shown in Figures 4 and 5. In this case, both LOS and NLOS for propagation inside the car were considered. A bandwidth test was performed for both SISO and MIMO (2x2) to establish a baseline for throughput without interference in the two cars for both positions of access point (footwell position is not shown in the figures). Transmission power was tuned from 0 dBm to 16 dBm with 2 dB step size. For middle console position, in both cars the maximum throughput was achieved for the SISO case, following the obser-

Figure 3: The test setup with the two cars.

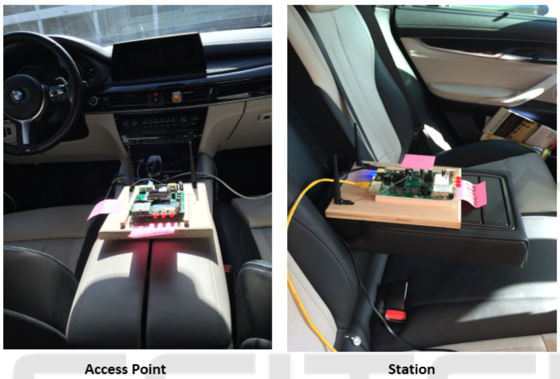

Figure 4: Board positions in the BMW, the AP is on middle console.

vations reported in Table 3. For the MIMO case, a slight reduction in throughput was achieved for low power levels. For the footwell position, a slight reduction (e.g., 5-10 Mbps) in throughput compared to middle console position is visible for all power levels, especially in MIMO case.

A National Instruments (NI) PXIe-1075 chassis equipped with a PXIe-5663 vector signal analyzer (VSA) was used to collect power levels. The device was mounted in several positions inside the cars. Data were collected using LabView software developed at the University of Oklahoma (Balid et al., 2016). The VSA was configured to sweep the entire band (i.e., 2.4-2.483 GHz) with a resolution bandwidth (e.g., the fast-Fourier transform (FFT) bin size) of 100 KHz. Spectrum sweep ran for ten seconds at each measurement point, and then data were post-processed in MATLAB to calculate probability distribution function (PDF) of the received power for different cases. PDFs were used to draw insights from the results.

Notably, results could vary given an alternative hardware implementation scheme and car model than the ones used in our setup. However, our results should be regarded as representative of available commercial devices and cars.

Table 3: Measurement results in anechoic chamber.

Network 1		Network 2		Description
Antenna Mode	Throughput	Antenna Mode	Throughput	
1x1	62.8	N/A	N/A	only network 1 is active
2x2	121	N/A	N/A	only network 1 is active
N/A	N/A	1x1	62.8	only network 2 is active
N/A	N/A	2x2	116.8	only network 2 is active
1x1	30.5	1x1	29.5	both networks are active
2x2	57.5	2x2	55.9	both networks are active
1x1	33.1	2x2	55.9	both networks are active
2x2	60.1	1x1	30.5	both networks are active

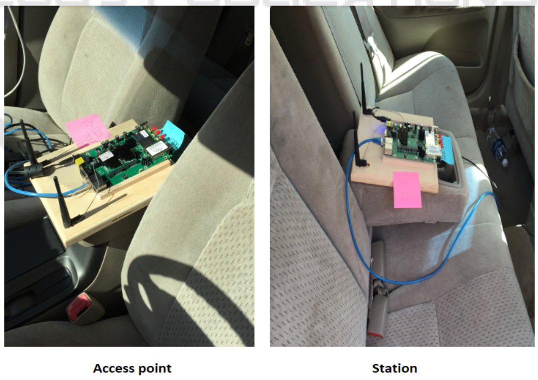

Figure 5: Boards position in the Toyota, the AP is on middle console.

4 MEASUREMENTS RESULTS

In this section, throughput measurements for various scenarios are presented; results are explained and analyzed using power measurements. In order get rid of small variations in throughput, sixty seconds average is used for each power level. Measurements

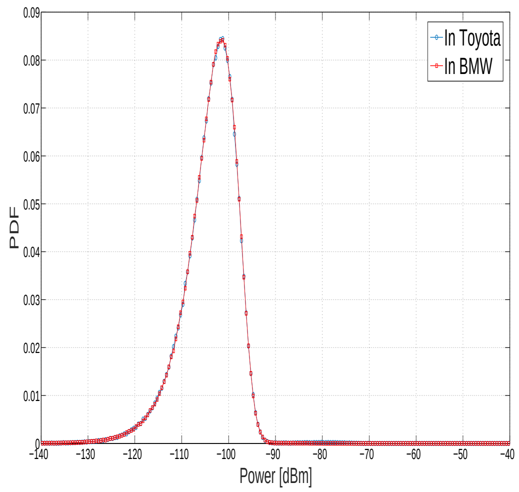

Figure 6: Background noise in both cars.

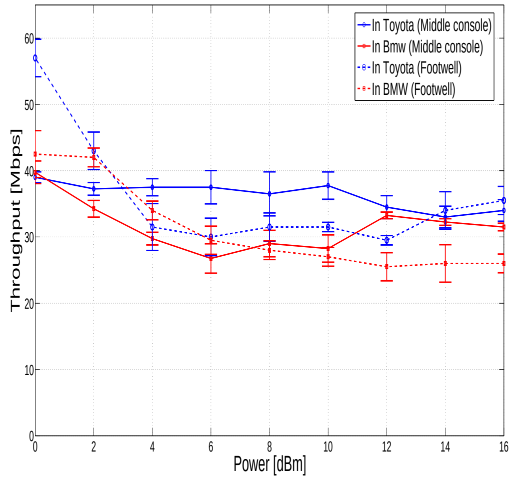

Figure 7: Throughput as a function of power for both AP positions, SISO in both cars.

were repeated four times, which was enough to get low standard deviation around the mean ($< 5Mbps$). Average values, in addition to the standard deviation around the means, are presented in the figures. Measurements were taken in a location where no active WLANs or other systems are performing in the same band. This is verified by spectrum sweep prior to the test. Fig. 6 shows the PDF of received power in both cars when all the networks are inactive, noise mean is approximately
-102 dBm and the VSA is positioned on the middle console. Fig. 7 and Fig. 8 show the achieved throughput for a transmission power ranging from 0 dBm to 16 dBm with 2 dB step size in both cars for SISO and MIMO cases, respectively. Continuous lines represent middle console position, while dashed lines represent footwell position.

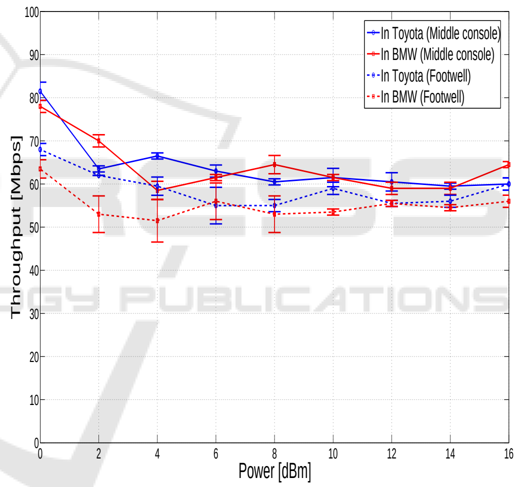

Figure 8: Throughput as a function of power for both AP positions, MIMO in both cars.

4.1 AP on Middle Console

In the SISO case and for power levels above 4 dBm, the sum of throughputs in both cars is slightly lower than the maximum achieved when only one network is active. These results are similar to when both networks operate in the chamber and demonstrate that when transmission power is relatively high, throughput is divided between the cars as a result of sharing the medium. This means that when multiple cars with WLANs operating on the same channel are located near each other (e.g., during a traffic jam) throughput will be divided between them, resulting in a dramatic reduction. Notably, a power level of 16 dBm is not the maximum-allowed transmission power, as limits depend on local regulations (e.g., in Germany 19 dBm is the maximum allowed by regulation offices). For power levels below 4 dBm, throughput in both cars rises, meaning that both networks can transmit more often at the same time. When decreasing power, probability of sensing an idle medium increases and leads to an increase in throughput. Notably, maximum throughput is not achieved even for a power level of 0 dBm. This result could be due to of low SINR values, which leads to erroneous transmissions when both networks transmit simultaneously.

Trends similar to those found in the SISO case are found in MIMO, see Fig. 8. Nevertheless, for low power levels, throughput in both cars tends to increase slightly, primarily due to low power. Probability of bad link quality for two streams increases; therefore, more errors are likely to occur.

Fig. 9 and Fig. 10 illustrate results when power is high in one car (i.e., set to 16 dBm) relative to different power levels in the second car. The same trend is visible in both figures. As power decreases throughput in the car with lower power decreases, as well. This can be explained by the fact that a car with the higher power has more chance to transmit by sensing the idle medium when compared to a car with lower power. For a power level of 0 dBm, throughput is reduced to approximately 20 Mbps in the car with lower power. This demonstrates unfairness in sharing the medium when various power levels are used by different car manufacturers. The same behavior is also observed in the MIMO case. (Figures are not included in an effort to avoid repeated information.)

Fig. 11 presents results when MIMO is used in one car (i.e., Toyota) and SISO in another car (i.e., BMW), which could be the case in different car models. The two networks share the medium evenly in a way similar to that described in previous cases. For example, at a power level of 16 dBm, the MIMO network achieves 63 Mbps (i.e., almost half the maximum achieved without interference); the SISO network achieves 30 Mbps (i.e., almost half the maximum without interference). Increases in throughput are similar for power levels below 4 dBm.

Fig. 12 shows the PDF of received power in the BMW vehicle when only the network in Toyota is active with different transmission power. VSA was positioned on the middle console (similar to AP position) as seen in Fig. 13. For a transmission power of 5 dBm, all packets were received with a power lower than -82 dBm. This phenomenon explains why throughput starts to rise in both cars at around (4-5 dBm). Given 0 dBm transmission power, networks should not sense each other and, therefore, throughput should rise to high value. However, low SINR could still lead to erroneous transmissions. As aforementioned, power PDFs are used only for comparison. Received power by the boards could be different due to various RF front-ends. In addition, PD threshold could vary depending on chip manufacturer, even when a threshold of -82 dBm is defined in the standard.

Fig. 14 compares the PDF of total power in both cars when the network in each is active independently and transmission power is set to 16 dBm. Clearly, the channel is quite symmetric. Received power in the BMW is slightly higher than that in Toyota, which could be the reason for higher throughput in Toyota, especially in the SISO case.

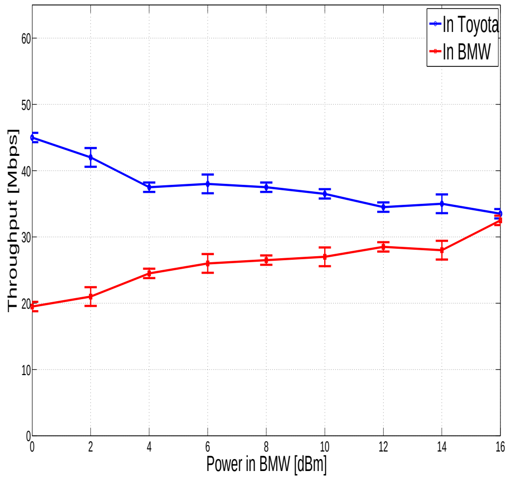

Figure 9: Throughput as a function of power in BMW, power in Toyota is fixed to 16 dBm, SISO in both cars.

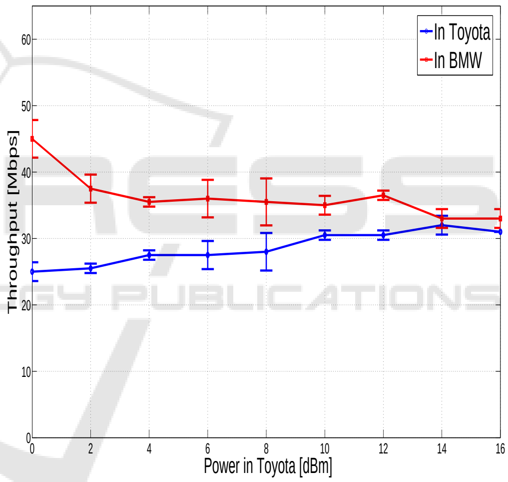

Figure 10: Throughput as a function of power in Toyota, power in BMW is fixed to 16 dBm, SISO in both cars.

4.2 AP in Footwell

In both cars, the access point was positioned in the driver's footwell, as shown in Fig. 15. No LOS between AP and the station led to a minor reduction of throughput without interference, especially for MIMO. Fig. 7 illustrates that the trend in throughput is similar to that of the middle console. However, it is clear that at the higher power level (e.g., approximately 6 dBm) throughput starts to rise for both networks when compared to middle console. This phenomenon can be interpreted by higher path loss between the two access points (and stations) in the two cars. In the first position, the majority of the signals

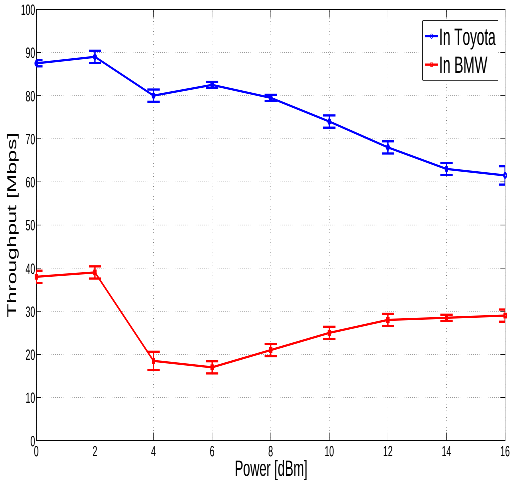

Figure 11: Throughput as a function of power, MIMO in Toyota, SISO in BMW.

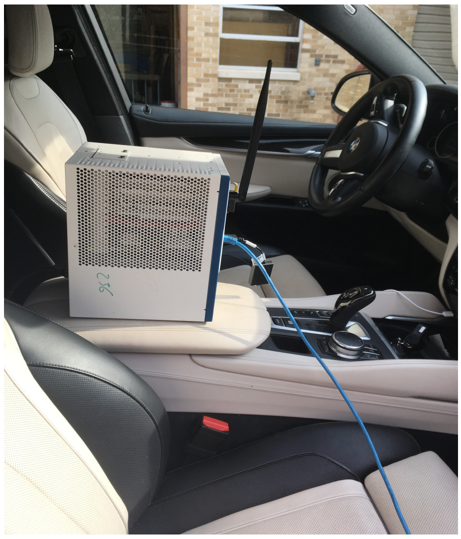

Figure 12: PDF of received power in BMW for four transmission power levels in Toyota, AP and VSA are on middle console.

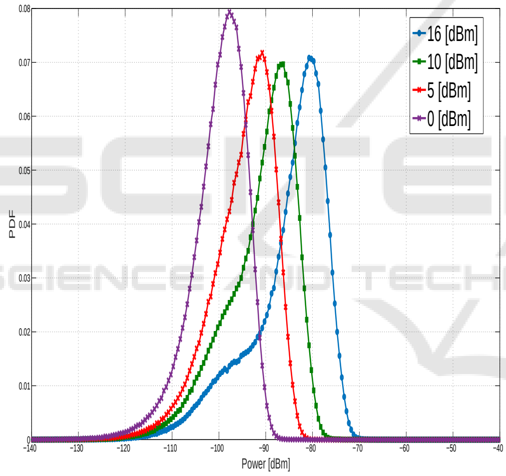

Figure 13: VSA position on middle console in BMW.

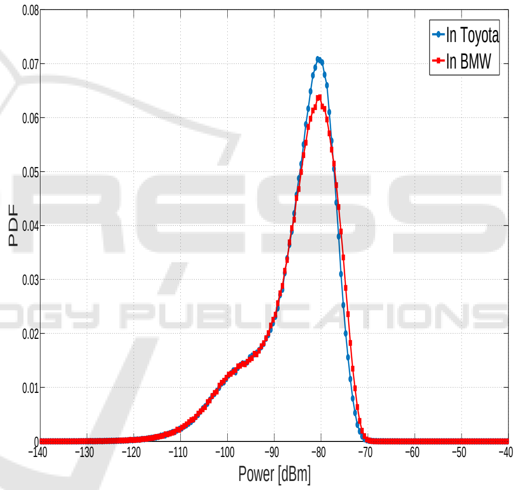

Figure 14: Received power in both cars for middle console position, the transmission power is set to 16 dBm.

are propagating through windows, which have low attenuation at this frequency.

In the second position, there are numerous reflections inside the car, so the signals reach the other car with lower power levels. At power level 0 dBm, throughput reached 43 Mbps in the BMW and around 57 Mbps in the Toyota. For MIMO (2x2), throughput in both networks was lower than the middle console position. This result is related to the absence of LOS and the multi-path propagation inside the car.

The VSA was positioned separately in the footwell of both cars to record power values, as seen in Fig. 16. Fig. 17 shows the PDF of total power for footwell position in both cars. In this position, the channel is asymmetric and the probability of receiving higher power level in the BMW is higher than that of the Toyota. Therein lies the explanation for higher throughput in the Toyota.

Finally, Fig. 18 demonstrates the PDFs of total power in the BMW for middle console and footwell positions. Transmission power for the network in Toyota in both cases is set to 16 dBm. It is clear from the figures that regarding the middle console case, received power from the network in Toyota is much higher than that of the footwell case. This explains why throughput rises at a lower power level for

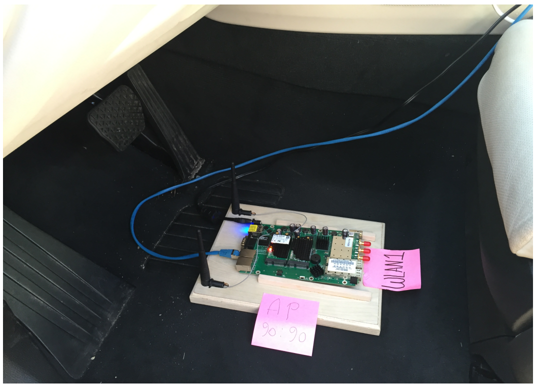

Figure 15: AP position in the driver's footwell.

Figure 16: VSA position in the driver's footwell in Toyota.

footwell. Most packets in the middle console case are received at power levels between -90 and -70 dBm; footwell position reception is at power levels between -78 and -100 dBm. It is clear that PDF is much wider for Footwell due to the richer multi-path environment, which makes packets arrive with wider power levels.

5 DISCUSSION

Consumer demand is cause for increased interest in Wi-Fi for both car manufacturers and big technology companies. In addition relying on Bluetooth for all intra-car applications is not possible due to low supported data rates. The main purpose of this work is to attract interest to this new Wi-Fi usage domain. Consumers have come to expect the same connectivity services in their cars as they enjoy in their homes and offices –especially due to the wide use of social media applications. Improvement in infotainment systems decreases the use of cellular phones while driving, hopefully reducing the number of accidents caused by

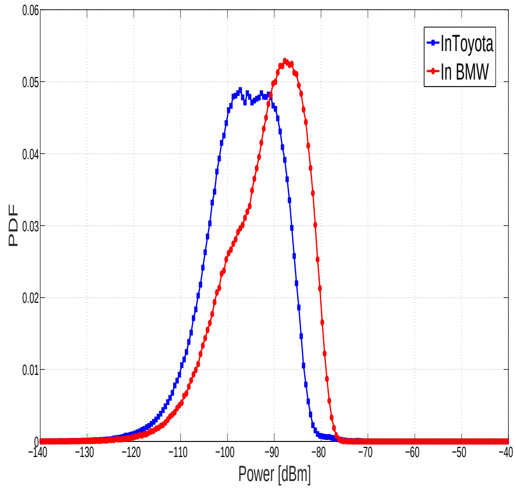

Figure 17: PDF of received power in both cars for footwell position, the transmission power is set to 16 dBm.

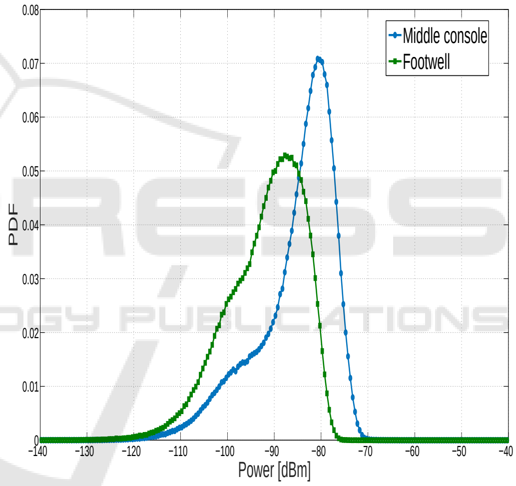

Figure 18: Power received in BMW in two different positions, the transmission power is 16 dBm in Toyota.

cell phone use.

The automobile Wi-Fi domain is different than other domains, thus previous research performed in building environments cannot be easily extended to the automobile domain. One major difference is the large number of devices assembled in a restricted space. For example, some car manufacturers will have more than three access points in a single car for different applications. Furthermore necessary coordination among the applications is not an easy task due to the complexity of automobile design. Also, the effect of mobility requires detailed investigation.

In the proposed test setup, two cars were parked parallel to one other with 1.5 m separation. In order to study more practical scenarios, similar measurements were performed with a 5.2 m distance between the cars. This separation emulates a free spot between them. Another investigated scenario was when the cars are parked in a line with 2.5 m distance. Similar results were achieved for all tests. Power distribution shows only a small decrease in power value (e.g., approximately 5-10 dB) when comparing tests.

The presented measurements show that given most vehicles are equipped with WLANs in the near future, millions of new mobile Hotspots will be traveling our roadways. Unlike networks in building environments, these Hotspots will radiate extremely high energy to surrounding cars. There is concern about the performance of surrounding Hotspots. One important example is hospitals, which were studied in (Al Kalaa et al., 2016). Hospitals utilize sensitive devices with BLE and ZigBee systems that operate in the 2.4 ISM band. In the event that hundreds of cars are parked in hospital parking, access points will most likely affect the wireless systems inside the hospitals.

Two solutions under the standard 802.11n umbrella are discussed in this paper, namely MIMO and power control. In (Herbert et al., 2014), a wireless channel inside the car was studied. Results demonstrated that the spatial correlation is well defined; thus deployment of MIMO antenna arrays should be effective in vehicles. The spatial multiplexing technique defined in the standard was used in the measurements. Although two data streams were transmitted simultaneously, a second antenna and RF front-end is needed, which increase the cost. To date, not all cellular phones support MIMO, due to limited space and increased cost. Limiting transmission power is essential for reducing interference to the surrounding networks. However, power should not be so low as to affect link quality inside the car, especially given that passenger devices can be located anywhere in the car. It is important to mention that this procedure should be standard in all cars. Not doing so leads to unfairness in sharing the medium, as measurements demonstrate above. National and international regulatory offices should take action to this end.

Two positions of AP are discussed, namely middle console and footwell. Given footwell position, attenuation between the cars is higher. Different AP positions were discussed in (Blesinger et al., 2012) and footwell position was proposed to reduce the interference to the surrounding cars. Directive antennas could be beneficial for this purpose as well. However, in this study, only the downlink is considered. User devices can be located anywhere in the car, thus not controlled by car manufacturers.

One possible solution for this problem is to offload sensitive application traffic, like video streaming to the 5 GHz ISM band. Regardless, the 5 GHz band has some challenges. The car environment is considered outdoors, and most available channels cannot be used without radar detection and dynamic frequency selection. Both of these are difficult to implement in a moving vehicle. In addition, coexistence with LTE in the unlicensed band (LTE-U) or license assisted access (LAA) could affect WLAN performance in the ISM band. Coexistence between WLAN and LTE-U/LAA remains an ongoing discussion among the IEEE 802 and 3GPP communities.

6 CONCLUSION AND FUTURE WORK

Future cars are projected to be equipped with advanced infotainments systems with options and capabilities similar to those currently available in homes and offices. Autonomous cars will allow passengers to efficiently use their in-car time for working or entertaining. Seamless integration of passengers' consumer electronic devices is a key. 802.11 systems are the most promising systems to achieve this integration, providing relatively high data rates in the unlicensed ISM frequency bands.

This work highlights the coexistence problem in the automotive domain, focusing on 802.11 systems used for infotainment applications. Performed measures show that interference between networks in cars will be very high compared to building environments. MIMO techniques could be used to boost the achieved data rates by spatial multiplexing; in addition MIMO could also be used to improve robustness by means of spatial diversity. On the other hand optimal tuning of transmission power is essential to guarantee good coverage inside the car and to reduce the interference with surrounding networks.

The effect of vehicle mobility is a work in progress, as it is quite important to understand the difference to other indoor/outdoor scenarios. Coexistence of Bluetooth and Wi-Fi in this domain is quite interesting and could lead to future work. It has yet to be determined whether or not hands-free calling using Bluetooth will work when several WLAN signals with relatively high power level are present. In addition, analyzing applications used in infotainment systems is necessary to determine necessary data rates for each application. Answers offer a better idea of the severity of throughput reduction due to interference.

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