

Performance Evaluation of Concurrent IEEE 802.11 Systems in the Automotive Domain

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Abstract—Wireless systems have migrated into the automotive domain very fast in the recent years. Car passengers expect to have seamless integration of their consumer electronic devices in their cars. IEEE 802.11 systems are popular for entertainment services inside the car, however due to the fact that IEEE 802.11 use the unlicensed industrial, scientific and medical (ISM) radio bands, the wireless coexistence problem will lead to dramatic decrease of throughput. This can affect the performance of different applications in cars.

This paper presents both test drives and measurements in the lab. The target is to have an impression on the influence of the surrounding systems on 802.11 systems inside the cars. The results show that the WLAN signals from the surrounding strongly affect the throughput of the systems inside the cars. A throughput drop by 80% compared to maximum was observed in one test drive in the city center.

Index Terms—WLAN, Wireless coexistence, Automotive domain, 2.4 GHz ISM band, Intra-vehicle interference, IEEE 802.11

I. INTRODUCTION

The number of car accidents due to mobile phone usage while driving has recently dramatically increased; social media is one of the main reasons behind it. Seamless integration of the mobile phones into the car entertainment unit could reduce the need of catching the mobile phone while driving.

An increased number of cars are equipped with different wireless systems like Bluetooth (IEEE 802.15.1) and WLAN¹ (IEEE 802.11). These systems are used to provide connectivity services for the passengers inside the car and connect them to the Internet. Both systems (WLAN and Bluetooth) share the same unlicensed ISM frequency band at 2.4 GHz.

The 2.4 GHz ISM band became very crowded and the spectrum utilization is very high especially in homes and offices. Some examples of other wireless systems which use the same band are ZigBee, Microwave oven and Kleer [1]. This makes the coexistence of these systems a difficult task, especially when the distances between the devices is very small. The coexistence between WLAN and Bluetooth has been extensively studied. The coexistence of these systems is not avoidable as they are compatible to each other. The task group IEEE 802.15.2 has published recommendation practices on the coexistence between Bluetooth and 802.11b in 2003 [2]. 802.11 systems (also known as WiFi) have become very

popular in all domains in order to provide high speed wireless local area networking. In the cars, the mobile network is used to get access to the Internet. WLAN provides Internet connectivity for the passengers in the car as an access point (AP); in this case only one SIM card is needed and all the passengers devices could connect to the Internet using the WLAN.

Additionally, WiFi direct (or WiFi P2P) is used in order to provide peer to peer connection of the devices which is used for screen mirroring in the car [3].

Currently the number of cars with WLAN connectivity is not high and it is restricted to the premium sector. Nonetheless it is expected that the number of cars with WLAN will be increased very fast due to the users demands and attractiveness of WiFi for new applications like CarPlay [4] and Android auto [5].

In contrast to the building environment, the concurrent WLAN stations, which are called overlapped basic subscriber set (OBSS), are more critical in the automotive domain. The radiation from the car to the outside environment is very high due to the weak attenuation of the car windows. The measurements and EMV simulations in [6] and [7], respectively, have shown that the antenna position in the car is very important in order to limit the interference to the surrounding. However, even in the best proposed position [6] the mean path loss is smaller than 85 dB at 50 m distance from the car. This is quite low (assuming transmission power above 3 dBm) as the carrier sense threshold for most WLAN devices is -82 dBm. According to [8], the number of cars in a five lanes highway in case of traffic congestion is about 75 cars at 50 m range, which shows the severity of the problem. In [8], the mutual influence of concurrent 802.11 networks in two cars near to each other has been studied. The measurements show that the influence depends on the frequency band and the type of the windows; in the 5 GHz ISM frequency band, the influence is lower than in the 2.4 GHz ISM band, however it is still high.

II. MOTIVATION AND CONTRIBUTION

The main purpose of this paper is to highlight the issue of wireless coexistence in the automotive domain due to the limited available spectrum. The problem will be more noticed in the near future when most of the cars have connectivity services in the unlicensed ISM bands. The new IEEE 802.11ax standard [9] which is still under development (the project has

¹WLAN, WiFi and 802.11 will be used interchangeably in this paper

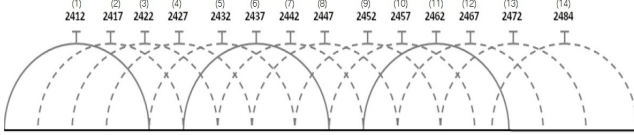


Fig. 1: WLAN channels in the 2.4 GHz ISM band

started in 2014) focuses on high density scenarios 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." However, the WLAN in the automotive domain is still not an important use case for the IEEE 802 community due to the limited number of devices in this domain currently compared to other domains. This trend is expected to change very soon as this market is massively evolving. In the automotive domain the Doppler effect plays a big role due to the fast relative movement of the cars. The IEEE 802.11 standards family consider a maximum speed of 6 mph corresponding to the pedestrian movement, higher speeds are not considered.

A new study group under 802.19 [10], called wireless coexistence working group, has recently (March, 2016) been formed to study the wireless coexistence between different systems in both 2.4 GHz and 5 GHz bands in the automotive domain. WLAN and Bluetooth are in the scope in addition to other non IEEE 802 systems (like Kleer) working in the same bands. The target of the group is to attract the attention to this important domain and evaluate the need for a new IEEE 802.11 standard, suitable for intra-car wireless systems.

To our knowledge, there is no similar measurements in the open literature.

III. IEEE 802.11 SYSTEMS

The different IEEE 802.11 systems [11]–[15] provide wireless connectivity for the different portable devices to the wireless LAN. The standards define both the MAC layer specification and the physical layer techniques. Table I shows the different IEEE 802.11 standards with the year of release. The IEEE (Institute for Electrical and Electronics Engineers) approved a standard for wireless local area networks called 802.11 in 1997, with the target of using the air interface instead of cables with the advantages of low cost, easy management and installation and mobility of the end devices. The first standard uses the 2.4 GHz ISM band providing data rates up to 2 Mbps. In 1999, two new extensions were approved, 802.11b and 802.11a, working in 2.4 GHz and 5 GHz ISM bands, respectively. More details about physical layer and MAC layer are available in [11]–[13].

TABLE I: IEEE 802.11 Standards

Standard	Description	Status
IEEE 802.11	2.4 GHz, up to 2 Mbit/s	Finished 1997
IEEE 802.11b	2.4 GHz, up to 11 Mbit/s	Finished 1999
IEEE802.11a	5 GHz; up to 54 Mbit/s	Finished 1999
IEEE802.11g	2.4 GHz, up to 54 Mbit/s	Finished 2003
IEEE802.11n	2.4 GHz and 5 GHz, up to 600 Mbit/s, MIMO	Finished 2009
IEEE802.11ac	5 GHz, up to 1300 Mbit/s	Finished 2013
IEEE802.11ax	2.4 GHz and 5 GHz, OFDMA, MIMO	Task group active

In 2003, a new standard 802.11g was approved. It works in the 2.4 GHz band providing data rates up to 54 Mbit/s. The physical layer is based on orthogonal frequency division multiplexing (OFDM). The multiple input multiple output (MIMO) technique was first introduced to the standard 802.11n which was approved in 2009. It provides a data rate up to 600 Mbit/s, an operation in the 5 GHz band is optional. The physical layer is also based on OFDM.

The most recent standard 802.11ac, which was approved in 2013, provides a data rate up to 1300 Mbit/s in the 5 GHz band with some improvement on the physical and MAC layers [15].

The standard 802.11ax [9] is still under development, it is expected to be finished by 2019. It improves the coexistence and spacial reuse by differentiate between Inter-BSS and Intra-BSS frames using a new field in the frame, named as BSS color. However, it will take some years before the consumer electronic devices will support this new standard.

In the 2.4 GHz band, the spectrum ranges from 2.4 to 2.4835 GHz in most countries; 83.5 MHz bandwidth is available. Additionally, the 5 GHz band ranges from 5.035 to 5.835 GHz, but the available channels depend on regulations in different countries. In most countries, most of the channels are restricted to the indoor environment or require dynamic frequency selection (DFS) to avoid interfering with the weather radar for example. The car environment considers outdoor, in addition DFS is not possible in a moving car which explains that moving to the 5 GHz band will solve the coexistence problem only partly (for example with Bluetooth). The overlapped BSS will still affect the achieved throughput. For example in Europe, the available spectrum for WLAN in the cars in the 5 GHz band is from 5.735 to 5.825 GHz, however this range is licensed for short range devices (SRD) as well. The 5 GHz is more attractive for cars, because the interference to the surrounding environment is less compared to the 2.4 GHz band due to the increased path loss at higher frequency.

In the 2.4 GHz band, there are fourteen 22 MHz channels with only three non-overlapping channels 1, 6 and 11, which are mostly used. Fig. 1 illustrates the fourteen channels.

The channel access mechanism is based on the coordination function. There are two functions which are defined in the 802.11 standards: distributed coordination function (DCF) and a point coordination function (PCF). The latter is optional in the standard. The DCF is based on the carrier sense multiple access/collision avoidance (CSMA/CA) channel ac-

cess method. The station starts the transmission only if it senses the medium free for a period longer than a short time calls inter frame space (IFS). The receiving stations sends an acknowledgment to the transmitter after receiving the packet. If the transmitting station does not receive an acknowledgment after a certain period, it will repeat the transmission up to a maximum number of times before deferring the transmission; the packet will be lost. If a station wants to send a new packet after sending another one, it waits for an IFS period, then it listens to the channel and initialize a counter, called a random back off interval counter. The station starts the transmission when the counter reaches zero. If the station senses another transmission, it stops decrementing the counter, waits for the end of current transmission and then waits for IFS period and next decrements the counter from the point which had left. This procedure is called a back-off procedure. It assures the fairness between the stations in accessing the medium [14].

IV. MEASUREMENT SETUP

The measurements have been done using a BMW 7th series, in cooperation between BMW AG and Qualcomm. A WiFi link is established in the car using a WLAN router (ASUS RT-AC68U; only one antenna was used, the other ports were terminated using 50 Ohm terminators) and a WLAN USB stick (TP-Link WNTL722N). Each device has been controlled by a laptop, as can be seen in Fig. 2. The positions of the devices in the car under test are shown in Fig. 3.

The network testing tool IPerf [16] has been used to measure the TCP throughput of the WLAN link. The router has been configured as a server and the stick as a client. The transmitting power of the router is set to maximum according to the regulation in Germany 80 mw (19 dBm), and the used WLAN channel was changed depending on the test setup. The wireless mode was set to 802.11n.

Two test scenarios were performed. In the first one, test drives in and around Ingolstadt (a city in Germany) were done. The throughput was continuously measured during the test drives. In the second scenario, the car was parked in the lab, and an adjustable WLAN-like signal was transmitted from an antenna in different positions around the car using a test transmitter (Rohde & Schwarz SFE100). The target is to check the effect of the direction of the interferer on the link inside the car. The duty cycle of the signal is 50%. A horn antenna with a gain of 10.7 dBi was used. The power and the frequency of the generated signal are adjustable. Fig. 4 shows the spectrum of the generated signal.

V. MEASUREMENTS RESULTS

In order to obtain a reference for the achieved throughput without interference using our test devices, the same WLAN link between the two devices was established in an anechoic chamber. The distance (around 0.75 m) between the two devices was similar to the setup in the car. Fig. 5 shows the measured TCP throughput. The achieved value is around 95 Mbit/s most of the time. This value is higher than the

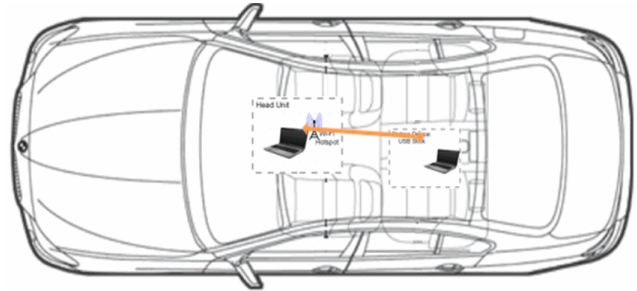


Fig. 2: Test setup in the car

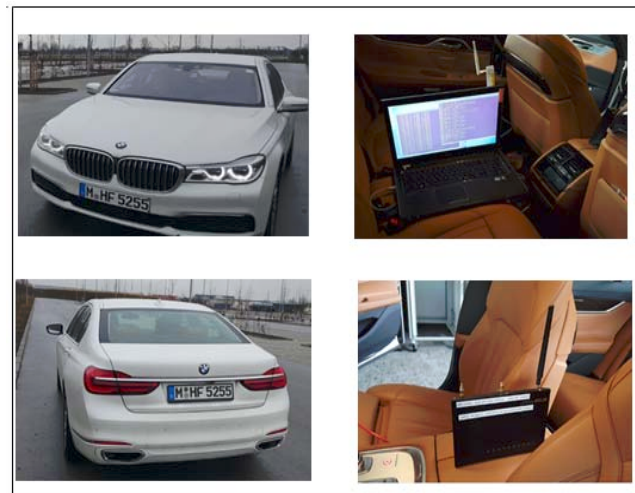


Fig. 3: Test devices positions in the car under test

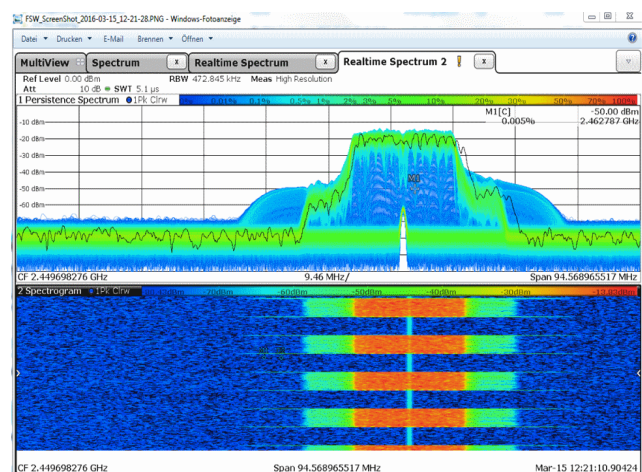


Fig. 4: The spectrum of the WLAN generated signal

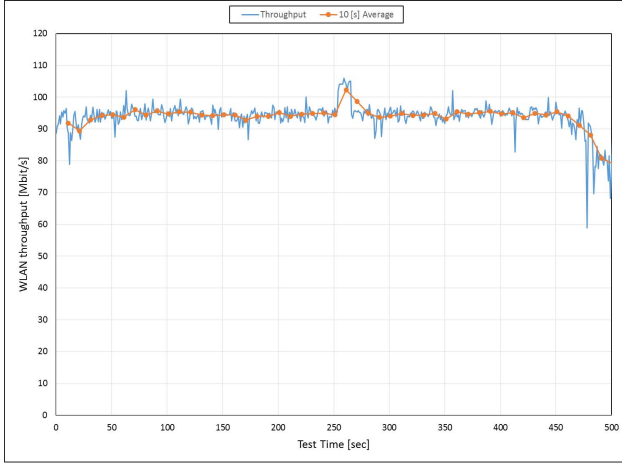


Fig. 5: WLAN throughput measured in the anechoic chamber

maximum (65 Mbit/s) expected for 802.11n with one stream, but similar results were achieved with two other routers. The effect of the opened door is clear at the beginning and at the end of the measurements.

A. Scenario I

Many test drives with different WLAN channels were done in order to have an impression on the effect of the interference from the surrounding on the link inside the car. Only the most interesting test drives will be presented due to limited space. Fig. 6 shows the results of the test drive (on channel 6), which takes around 40 minutes. The test drive took place in rural area, highway and in the city center of Ingolstadt. The GPS location was recorded during the test drive. Fig. 7 shows the throughput in different position, color mapping was used as described in Fig. 8.

From Fig. 6 and Fig. 7, it is clear that the throughput on the highway and rural areas is higher than the achieved value in the city. A maximum throughput of 100 Mbit/s was observed on the highway [300-600 sec]. The average throughput was around 55 Mbit/s in the city as can be seen [1300-1700 sec]. A significant drop to 20 Mbit/s is clear at around 1400 sec, which is related to the dense deployment of WLAN in the city center, either public Hotspots or private ones in homes. This drop was near to the main train stations of Ingolstadt.

In one test drive on channel 11, the achieved throughput was under 10 Mbit/s for more than 10 sec near to the main train station, where a lot of public Hotspots are deployed. However it is clear that the achieved throughput is changing strongly in the same position at different times. As the main effect on the throughput will be when the WLAN is in use, because in this case the medium is shared between the different access points based on the CSMA/CA mechanism.

In order to clearly see this effect, one test drive with the same route was repeated many times. In addition, the position of the router was changed in order to check the effect of the positions on the achieved throughput. In the first test drive,

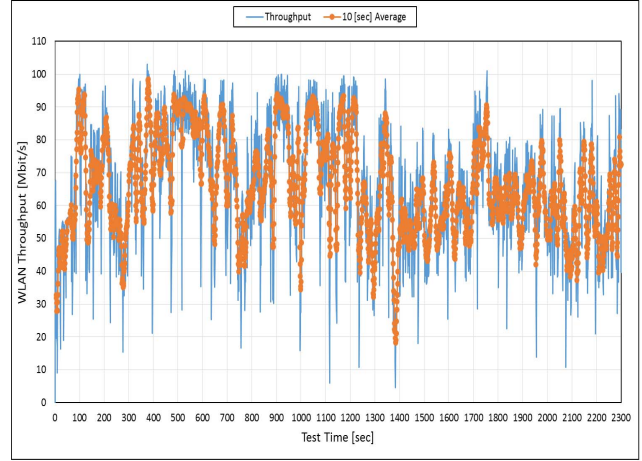


Fig. 6: Throughput for the test drive in and around Ingolstadt as a function of time



Fig. 7: Throughput for the test drive in and around Ingolstadt as a function of position

Color code	Throughput [Mbit/s]	
	from	to
Red	> 0	10
Orange	10	20
Yellow	20	30
Light Green	30	40
Green	40	50
Dark Green	50	60
Teal	60	70
Blue	70	80
Dark Blue	80	90
Purple	90	100
Light Purple	> 100	
White	= 0	

Fig. 8: The used color mapping for the throughput

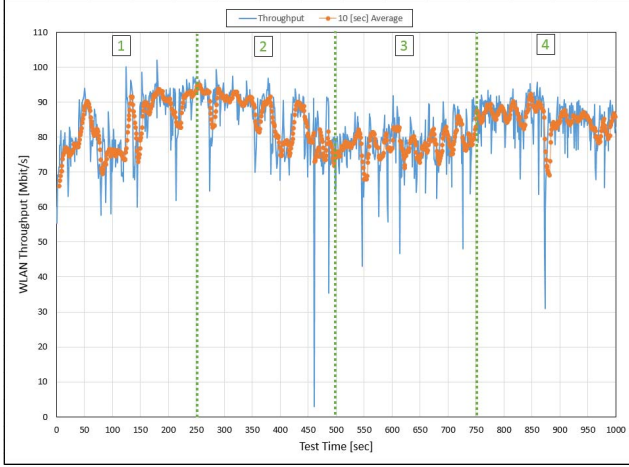


Fig. 9: Throughput for the test drive around the shopping area as a function of time (router position on the middle console)



Fig. 10: Throughput for the test drive around the shopping area as a function of position (router position on the middle console)

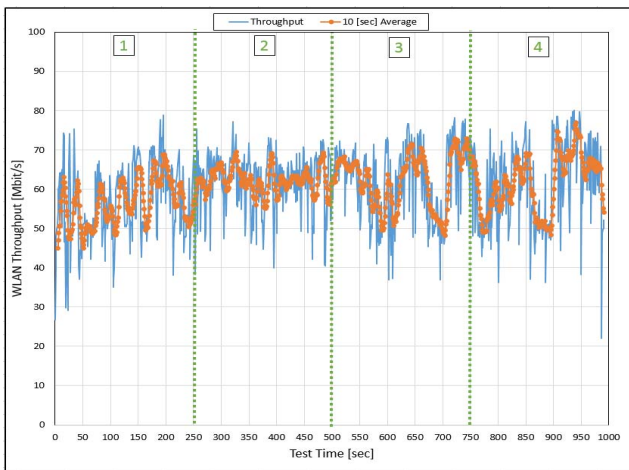


Fig. 11: Throughput for the test drive around the shopping area as a function of time (router position in the footwell)



Fig. 12: Throughput for the test drive around the shopping area as a function of position (router position in the footwell)

the position of the devices was as presented in Fig. 3. In the second one, the router was positioned near to the driver feet (footwell). The route was around a shopping center where a lot of WLAN APs are deployed.

Fig. 9 and Fig. 10 show the results of four rounds (on channel 6) around the shopping center for the first case (the router is on the middle console). We started from an empty parking place (left), where we got a value around the maximum 90 Mbit/s, which shows that the car environment does not affect the achieved throughput. Each round takes around 250 sec.

It is observed that there is no periodic pattern in the achieved throughput as expected, although the laps were done immediately after each other. The throughput was between 70 and 93 Mbit/s.

In the second case, the router was positioned near to the driver feet. Fig. 11 and Fig. 12 show the results for this case. In contrast to the first case, there is no line-of-sight (LOS) between the router and the stick. Therefore, the throughput dropped by 20% on average compared to the first case. The throughput was between 45 and 77 Mbit/s.

The throughput still fluctuates, although the router was positioned in the footwell. This could be due to the position of the WLAN stick. This interesting observation makes the problem more complicated, so even if the WLAN antenna is positioned in the footwell, the devices of the passengers might be located everywhere in the car. This means that the interference from outside will not be reduced. Furthermore, significant drop of throughput is observed, which could be due to absence of LOS propagation.

B. Scenario II

In order to have a controllable interference environment, a test transmitter was used. The horn antenna was positioned in four different locations around the car as seen in Fig. 13. The distance between the antenna and the car is shown in Table II. The WiFi link inside the car and the generated WLAN-like signal were set to the same channel (6). The achieved throughput without the interferer was relatively constant at 54 Mbit/s, as the surrounding is not changing. Fig. 14 shows the achieved throughput under different levels of interference for the four different positions around the car. As mentioned above, the used antenna has a gain of 10.7 dBi.

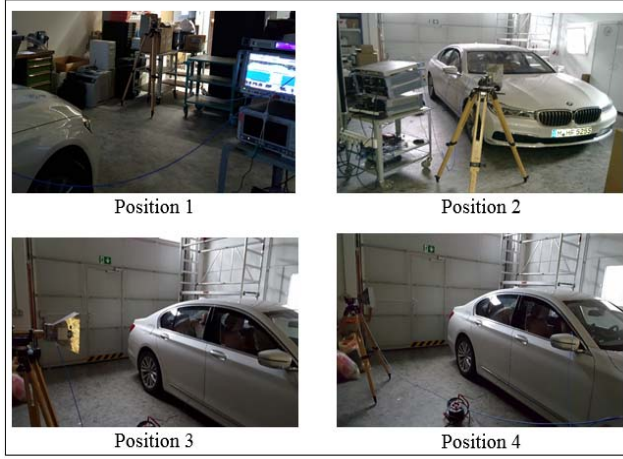


Fig. 13: Measurement setup in the lap employing different antenna positions

TABLE II: Transmit antenna positions overview

Position	Description	distance
1	Front	2.1 m
2	Front right	1.75 m
3	Middle right	1.75 m
4	Rear right	1.75 m

As can be seen from Fig. 14 the throughput decreases very fast in proportion to the power of the interferer, especially in positions 2 and 4. Position three (middle right) is the least critical one. These results depend on the type of car and the positions of devices inside the car. But it emphasizes on the idea that the interference from neighboring cars will affect the WLAN link inside the car, especially in case of high power transmission.

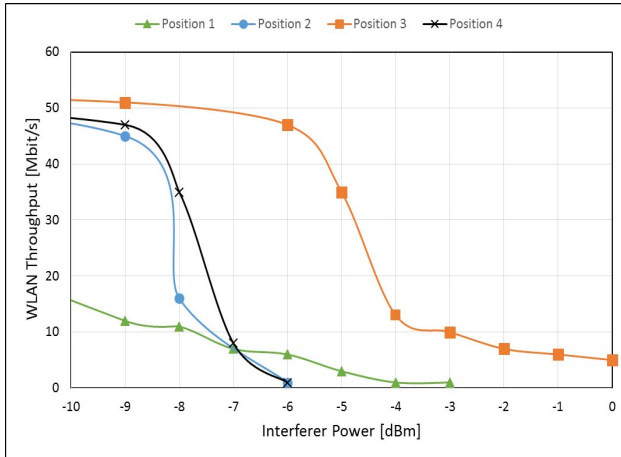


Fig. 14: WLAN throughput in the car against external interference

VI. DISCUSSION

The main target of our work is to attract attention to the coexistence problem in the automotive domain. As the measurements show that the interference from the surrounding environment will strongly effect the WiFi link in the car, this will affect the QoS of different applications which use WLAN. The interference of the surrounding could come from fixed or mobile Hotspots which are densely employed everywhere nowadays. On the other hand, WiFi in the cars will also affect the Hotspots, which could lead to very bad performance in case of tens of cars around one Hotspot. Therefore this problem is not only related to the automotive domain. Especially, the performance of outdoor public Hotspots, which are widely used, will be heavily affected. Even on highways, for example where there are no deployed Hotspots, the interference could come from other cars, which have WLAN AP, as expected in the near future. In this case video streaming or Miracast [17] will not work properly which is not acceptable for car customers especially in case of traffic jam situations.

As observed in the measurements, in contrast to indoor environments, where the walls attenuate strongly the signals, the car body and windows have small attenuation in the 2.4 GHz ISM band [8]. Additionally due to limited non-overlapping available channels in this band, the OBSS cannot be avoided. Better types of windows like heat absorbing glass could reduce this effect significantly, however the cost of such windows is still very high. Interestingly, the car manufactures are trying to make the cars lighter using different kind of materials (like carbon fiber). These materials have low attenuation making the interference more pronounced.

In addition, these WLAN APs could not be managed by one operator, because they are managed by the car manufactures, which makes any cooperative mechanism for interference management not doable.

One solution could be by offloading some traffic to the 5 GHz ISM band, however the available channels in the 5 GHz band are still limited for outdoor use. Additionally, the interference with LTE-U (LTE in unlicensed spectrum) could affect the WLAN performance when it will be widely deployed. The IEEE 802 and 3GPP communities work closely to check the possible impact of LTE-U on WLAN, in order to guarantee the fairness in sharing the medium.

The car manufactures should pay more attention to the antenna positions. The antennas should be positioned as low as possible in order to reduce the radiation to the outside. On the other hand the antenna radiation characteristics play an important role as well. However, the passengers devices might be located anywhere in the car, so mounting the antenna very low in the car will reduce the problem only partially.

MIMO techniques could help in improving the quality of wireless systems in the vehicles [18], [19], nonetheless the improvement in case of interference degradation need more investigations.

Transmission power control (TPC) is the most promising

technique to limit the interference effect in this domain. The transmitted power could be adjusted depending on the users positions. Even so the TPC will provide improvement only in case of all surrounding networks using it as well, which is difficult to guarantee. This requires cooperation between the cars manufactures, as this will improve the performance for everyone.

VII. CONCLUSION AND FUTURE WORK

In the near future, it is expected that most of the cars will support WLAN, so millions of unmanaged uncoordinated WLANs will make the spectrum scarcity problem more difficult.

In this paper test drives and measurements in the lab are presented in order to test the performance of WiFi links in the 2.4 GHz ISM band in the automotive environment. The measurements show that the influence of the surrounding networks on the link inside the car is quite high. In one position near the main train station, the throughput was dropped by 80% compared to the case without interference, which shows the severity of the problem. Although this drop of throughput was observed only in one position and only in one test drive out of 20, this is expected to happen when most of the cars will have WiFi in the near future; some cars could have multiple WLANs for different applications as well. The measurements in the lab show that in case of WLAN interference signal with duty cycle of 50%, the throughput could be reduced by 80% in case of interferer power larger than -7 dBm (plus 10.7 dBi antenna gain) for most positions around the car; the interferer was positioned around 1.75 m from the car. It must be noticed that generalization is not possible because the effect depends totally on the car type and the positions of the transmitter and receiver inside it.

As this topic is relatively novel, the possible future work is quite wide. The coexistence between Bluetooth and WiFi in the automotive domain is quite interesting due to very small distances between the devices in the car. The hands-free calling using Bluetooth plays a big role in reducing accidents. An interesting question will be if Bluetooth will survive between tens of WLAN access points which cover the whole 2.4 GHz band. In addition, the coexistence between WiFi and LTE-U has recently gained great importance. A study of the performance of both systems in the automotive domain is desirable.

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