Field Study on the Performance of Wireless Local Area Networks in Automotive Environments

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***Abstract*—Driven by the soaring usage of wireless local area networks (WLANs) in automotive environments, demand for stable, high-throughput connections rapidly grows. Wireless infotainment systems with multiple end devices will soon need to be included in the confined space of a car. Also, the spread of the new LTE standard enhances consumer demand for fast in-car internet, making reliable networks inevitable in the near future.**

We will perform a quantitative analysis of degradation phenomena on mobile WLAN performance.

Realistic use cases and data rate requirements will be discussed. A field study was carried out to examine influencing factors in consideration of regulatory limitations for Europe and the USA. Focusing on moving, real-world scenarios reflecting the challenges of highly mobile WLANs, we will show an overview of the current situation on German and American highways and in cities. Measurements were realized using an Android application running on consumer smart phones. A maximum throughput (worst case) connection with network routers was established. Additionally, available WLANs in the vicinity were monitored and geographically located. Thus, the impact of other data traffic on the used channels can directly be seen depending on the vehicle's position.

***Index Terms*—broadband communication, wireless communication, Wireless LAN, WLAN, Wi-Fi, automotive, throughput, 802.11n, 802.11ac, wireless coexistence, in-car wireless networks**

I. Introduction

A. Automotive Connectivity

In cars, many situations require an exchange of data and therefore some kind of intra-vehicle networking. Typical use cases include multimedia services, information displays, telephony, navigation, or diagnostics and maintenance.

Forecasts see a strong development of connectivity services aboard future vehicles. SBD[1] and the GSM Association[2] estimate a growth from 54 million shipped units in 2016 to 219 million units in 2025 (Fig. 1) [1]. Embedded solutions have a SIM card built in and do not need additional devices to connect to a cellular network; with tethered solutions a SIM card is brought into the vehicle through a mobile phone or tablet device that acts as a modem to the car's intelligence; and integrated solutions bring in another device's SIM card and use their intelligence as well – merely input/output commands and display functions are run on the car's system. Examples would be systems like "Android Auto", "MirrorLink", or "CarPlay". While this forecast includes several connectivity methods, all

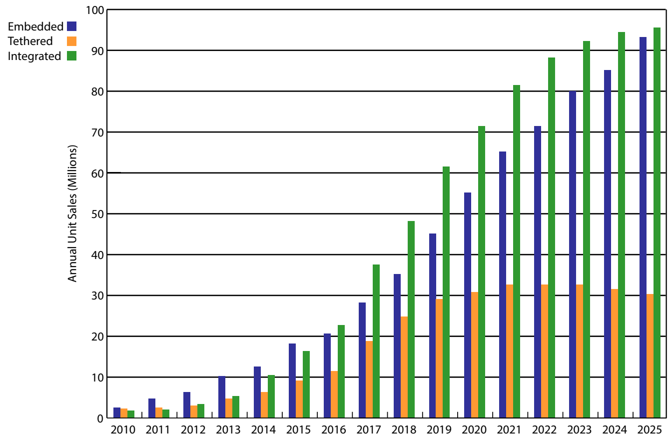

Fig. 1. Predicted annual unit sales for vehicular connectivity solutions [1].

of these solutions almost always require a wireless connection to the user's devices to provide their services. For this, the use of wireless LAN will prevail for its high throughput rates and well-established distribution to date. It is to be expected that data transfer from USB, Bluetooth, and other technologies will shift towards WLAN connections using consumer electronics like smart phones and tablets [2].

B. WLAN Usage in Automobiles

Especially in automotive environments the usage of WLAN as a versatile data exchange network gains importance as high quality infotainment services require stable and high-performance connections. Many scenarios such as intra-vehicle communication, over-the-air (OTA) maintenance, and vehicle to vehicle (V2V) technology are possible fields of application for WLAN. However, most demanding in respect of throughput and latency (real-time) requirements are multimedia applications such as video streaming. For example, for a high-framerate 4K UHD video[3] the video hosting platform YouTube recommends a bandwidth of 53 Mbit/s to 68 Mbit/s [5]. To provide large bandwidths like these to multiple users simultaneously high-throughput wireless networks like WLAN become increasingly important.

Strategy Analytics[4] assesses growing consumer interest in rear-seat entertainment systems and deduces: "OEMs[5] must

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[1]SBD Automotive, Davy Avenue, Milton Keynes, UK.
[2]GSMA Head Office, 25 Walbrook, London, UK.

[3]3840×2160 pixels at 48 to 60 frames per second.
[4]Strategy Analytics Inc., 199 Wells Avenue, Newton, MA, USA.
[5]Original Equipment Manufacturers.

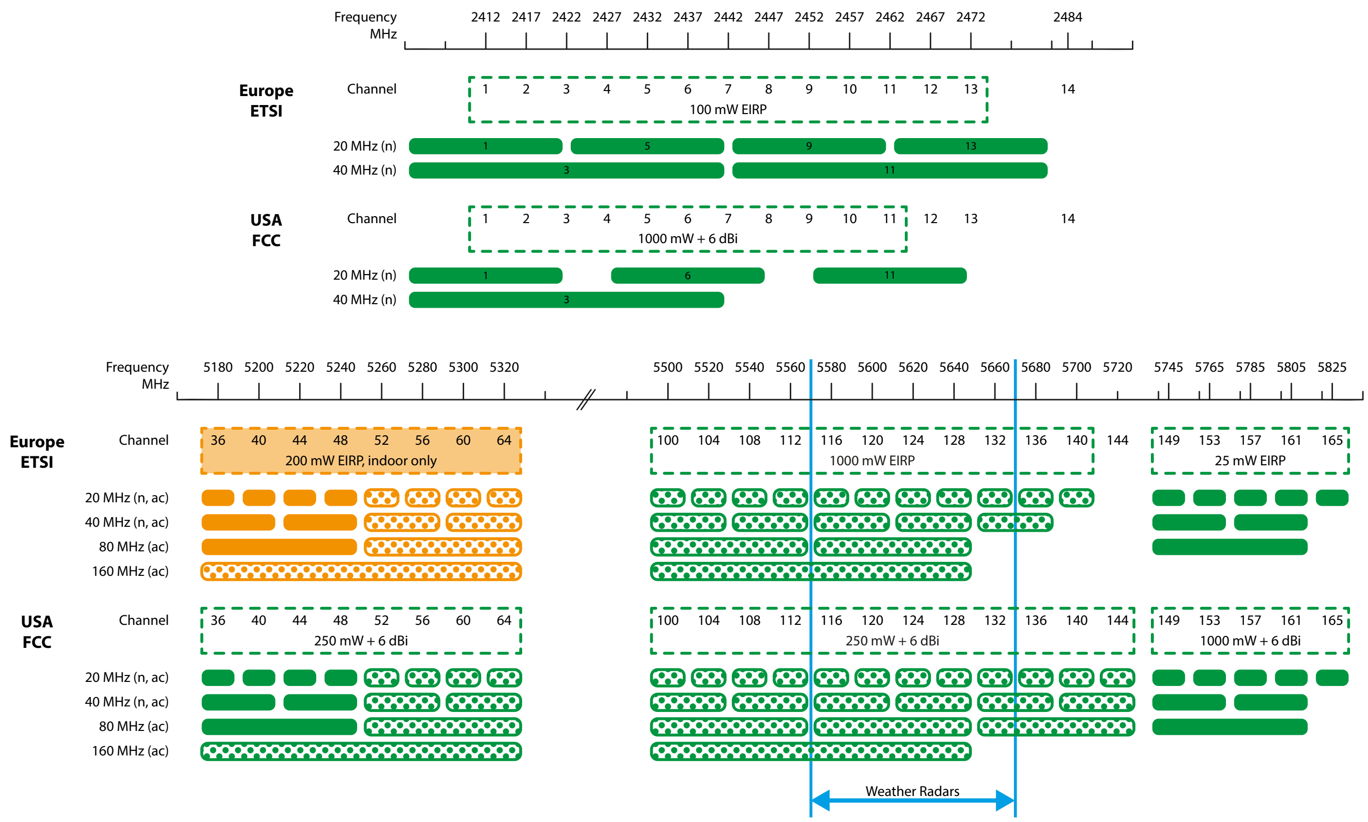


Fig. 2. Permitted WLAN channels for automotive use in the 2.4 GHz- and 5 GHz-band. Possible overlap-free channel widths are shown as well as the standards using them. Dotted channels require the use of dynamic frequency selection (DFS) [3], [4].

consider the inclusion of reliable and fast on-board connectivity a ‘must-have’ in future models for a variety of reasons, and the increased usage of streaming media for rear-seat entertainment is certainly one of them” [6], [7].

Users are getting used to fast, LTE-based internet on their smart phones and will demand that quality of service in their cars as well. Consumer behavior shifts from single, simple website browsing towards multi-device video streaming. Providing and distributing high data rates like those of the next generation LTE standard to multiple stations wirelessly will remain a major challenge in the near future.

C. *Hypothesis*

Continuing the WLAN examinations from 2014 (see [8]), this study takes the next step from a stationary to a moving situation. A field study on the performance behavior of WLAN under real-world conditions was carried out to inspect city and highway scenarios, as well as other influences. Concerns regarding the quality of service of WLAN in automotive environments mostly include interference with other WLAN traffic and wireless services operating on the same frequencies.

This paper will evaluate the likelihood of declining throughput in typical scenarios and with respect to the regulations and current realizations of automotive WLAN. We will mainly see interference in city scenarios with many household WLANs, but we predict a similarly occupied frequency situation on highways in the near future.

II. Theoretical Model

A. *WLAN Frequency Spectra*

Frequencies for WLAN operation are regulated in Europe by the European Telecommunications Standards Institute (ETSI) and the Federal Communications Commission (FCC) in the USA respectively. In Europe the maximum equivalent isotropically radiated power (EIRP) is limited by law; in the USA the maximum conducted output power given an antenna with a 6 dBi maximum gain is confined. For easier diction and management overlapping WLAN channels that are spaced 5 MHz apart in the 2.4 GHz-band[6] and non-overlapping 20 MHz-channels in the 5 GHz-band were agreed on ranging from 1 to 165. Fig. 2 shows the frequency situation for non-overlapping channels in the 2.4 GHz- and 5 GHz-band.

While in the 2.4 GHz-band only four 20 MHz-channels in Europe and three 20 MHz-channels in the USA do not overlap, the 5 GHz-band offers 24 and 25 non-overlapping channels respectively. However, constraints upon outdoor operation and the use of dynamic frequency selection (DFS) are partly imposed. These are necessary to enable better coexistence with other technologies in this spectrum such as satellite communication systems, weather radars, and military radars. Typically, in-car WLAN is classified as an outdoor application which will limit the number of available channels in the 5 GHz-band even more. Furthermore, DFS is extremely difficult to

[6] With the exception of channel 14 which is 12 MHz apart from channel 13.

implement in a dynamic car situation as the environment is constantly changing [8]. This leaves five 20 MHz-WLAN channels (149 to 165) in Europe[7] and nine channels (36 to 48, and 149 to 165) in the USA available to the use in automotive environments. For very high throughput networks operating on larger channel widths even less channels are left for mobile use: in Europe two 40 MHz-channels, and one 80 MHz-channel; in the USA four 40 MHz-channels, and two 80 MHz-channels.

Still, the high number of radio frequency transceivers operating in the 2.4 GHz-band (see IV-C) encourages the utilization of the 5 GHz-band in vehicles.

B. Radio Propagation Model

To calculate the propagation and range of wireless LAN electromagnetic waves a modified free space model based on geometric optics is used[8]. Neglecting multi-path propagation – only the direct path is considered – the electromagnetic power at the receiver $P_{RX}(d,f)$ in [dBm] at distance d in [m] and on frequency f in [Hz] can be estimated as [8]

$$P_{RX}(d,f) = P_{TX} + G_{TX} - L(d,f) + G_{RX}, \qquad (1)$$

with the transmit power P_{TX} in [dBm], transmit antenna gain G_{TX} in [dBi], path losses $L(d,f)$ in [dB], and receive antenna gain G_{RX} in [dBi].

Path losses $L(d,f)$ consist of losses in free space $L_{FS}(d,f)$ and at obstacles L_{OB}. Furthermore, the dual-slope, empirical TGn channel model [9] considers a breakpoint distance d_{BP} after which losses increase quicker than with the plain free space model to account for different environments so that [10]

$$L(d,f) = \begin{cases} L_{FS}(d,f) + L_{OB} & d \le d_{BP} \\ L_{FS}(d_{BP},f) + 35\log_{10}\left(\frac{d}{d_{BP}}\right) + L_{OB} & d > d_{BP}. \end{cases} \qquad (2)$$

This model was developed for the IEEE 802.11n standard. Logarithmic free space attenuation is given by [10]

$$L_{FS}(d,f) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c_0}\right), \qquad (3)$$

where c_0 is the speed of light in [m/s]. Attenuation due to atmospheric water vapor and other atmospheric gases is relatively small compared to $L(d,f)$ and therefore neglected here.

In a typical large office environment[9], a transmission over $d = 76.4$ m at $f = 2412$ MHz (channel 1) with additional losses L_{OB} due to one non-infrared shielding car window $L_{win} = 1$ dB [8] and one car environment $L_{car} = 13$ dB [8] ($L_{OB} = L_{win} + L_{car} = 14$ dB) experiences a path loss of

$$L(76.4\,\text{m}, 2412\,\text{MHz}) = (60 + 31 + 14)\text{dB} = 105\,\text{dB}.$$

[7]It is to be noted that those channels do not have a specific approval for WLAN; merely a generic and very restrictive regulation for short range devices (SRDs) exists.

[8]This model is a coarse estimation of the real-world situation and not an actual physical model. Still, it remains useful to show the general relations.

[9]For channel model "D" breakpoint distance $d_{BP} = 10$ m [9].

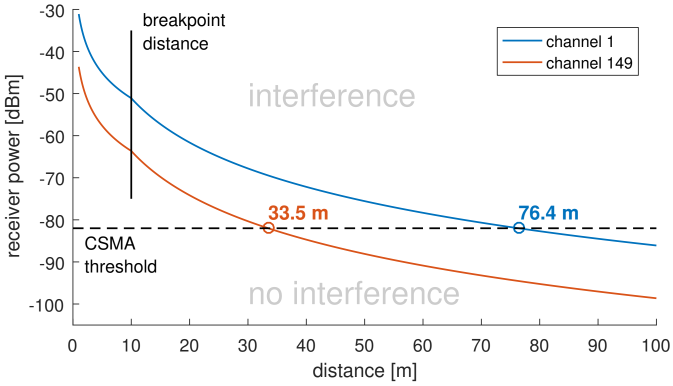


Fig. 3. Theoretical range of interference with a passing car for 2.4 GHz- and 5 GHz-office WLANs at respective German regulatory limits and receiver antenna gains.

Sending with $P_{TX} + G_{TX} = 20$ dBm(EIRP), the regulatory limit in Germany, a receiver with an antenna of $G_{RX,2412\,\text{MHz}} = 3$ dBi detects a power level of

$$\begin{aligned} P_{RX}(76.4\,\text{m}, 2412\,\text{MHz}) &= 20\,\text{dBm(EIRP)} - 105\,\text{dB} + 3\,\text{dBi} \\ &= -82\,\text{dBm}. \end{aligned}$$

This is the minimum power level $P_{min} = -82$ dBm that WLAN hardware has to be able to detect according to standard IEEE 802.11 (see II-C) [11]. Therefore, distance $d = 76.4$ m can be taken as the maximum WLAN range of this setup at $f = 2412$ MHz.

The maximum range for this setup at $f = 5745$ MHz (channel 149) is $d = 33.5$ m. Additional losses are $L_{OB} = L_{win} + L_{car} = 2\,\text{dB} + 13\,\text{dB} = 15\,\text{dB}$ [8], regulatory EIRP limit is $P_{TX} + G_{TX} = 14$ dBm(EIRP), and receiver antenna gain $G_{RX,5745\,\text{MHz}} = 5$ dBi.

$$\begin{aligned} L(33.5\,\text{m}, 5745\,\text{MHz}) &= (68 + 18 + 15)\text{dB} = 101\,\text{dB and} \\ P_{RX}(33.5\,\text{m}, 5745\,\text{MHz}) &= 14\,\text{dBm(EIRP)} - 101\,\text{dB} + 5\,\text{dBi} \\ &= -82\,\text{dBm}. \end{aligned}$$

These theoretical ranges (Fig. 3) and the media access control method described in II-C show that both 2.4 GHz- and 5 GHz-office WLANs have a non-negligible range for interfering with passing cars. Automotive WLANs show similar behavior and ranges so that interference with other in-car WLANs is just as likely. This impact can be diminished considerably by using infrared-shielding car glass [8]. Following the traffic jam calculations from [8] the maximum number of other cars in WLAN range in a traffic congestion on a three lane motorway would be 70 for 2.4 GHz-WLAN and 30 for 5 GHz-WLAN[10]. Given the worst case situation of every car being equipped with in-car WLAN, dense traffic would cause a crowded frequency spectrum and a significant degradation of WLAN performance. The fact that the 2.4 GHz-range of influence is more than twice as wide as the 5 GHz-range is a strong argument to use those higher frequencies in cars.

[10]Non-infrared shielding windows are assumed.

C. WLAN Collision Avoidance

In the CSMA[11] media access control 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. Requirements for the CCA mechanism are specified in the IEEE standard. It differentiates between two cases for a 20 MHz-channel bandwidth [10], [11]:

- Signal detect CCA threshold: At or above −82 dBm receiving power the WLAN hardware has to be able to detect the start of a valid OFDM[12] packet with a probability of more than 90 % within 4 µs and hold the channel busy for the duration of the packet.
- Energy detect CCA threshold: If no valid OFDM signal is detected, the channel has to be held busy for any signal at or above −62 dBm within 4 µs.

These two requirements were specified for the OFDM physical layer (802.11a). With the 802.11n amendment and the support of 40 MHz-operation, additional specifications were needed. The primary channel has the same requirements as the OFDM physical layer and the secondary channel is limited to the energy detect CCA requirement. In the 802.11ac amendment, the signal detect CCA threshold was adapted for a 40 MHz-VHT PPDU[13] at or above −79 dBm, for 80 MHz-VHT PPDU at or above −76 dBm, and for 160 MHz at or above −73 dBm. For more details concerning the CCA mechanism the reader is referred to the 802.11 standard [11].

The aforementioned CCA thresholds for the signal detect correspond to the minimum sensitivity level defined in the 802.11 standard and do not depend on the transmission power. This requirement is understandable and necessary to ensure a proper function of WLAN connections when access point (AP) and station (STA) are located far away from each other. However, in in-car situations AP and STA are located close to each other and usually have a strong receiving signal. Yet 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 CCA threshold defined in the IEEE standard is not depending on the transmitting power, a power reduction of the vehicle's transmission is not beneficial for the own performance – not before the surrounding networks are also reducing their transmitting power [8].

III. Methodology

Over the course of twelve months[14] measurements were carried out. Aiming for representative results, the setups were slightly varied to gain insight into the most relevant parameters of a WLAN connection. Quality and reproducibility of the study were ensured by controlling as many parameters of the environment as possible.

[11] Carrier sense multiple access.

[12] Orthogonal frequency-division multiplexing.

[13] Very high throughput PLCP (physical layer convergence protocol) protocol data unit.

[14] October 2015 to September 2016.

(a) Network router on back seat. (b) Mobile devices in front.

Fig. 4. In-car measurement setup: a connection is established between access point (4a) and station (4b). Additionally, other WLAN networks are monitored with a second device (4b).

To measure the impact of other wireless signals on in-car WLAN connections, a worst case scenario was created by constantly sending or receiving the maximum possible data rate from an AP to a STA in the car. Measurements were carried out between different consumer smart phones (see Fig. 4b) and network routers (see Fig. 4a) to best represent typical use cases. To monitor the existence of other WLANs in range a passive WLAN scan over all permitted frequencies was performed on another mobile device. This was done using a built-in scanning function of the Android operating system. Also, all measurements were geographically logged via coordinates acquired through the phones' GPS modules to georeference the data in the subsequent analysis.

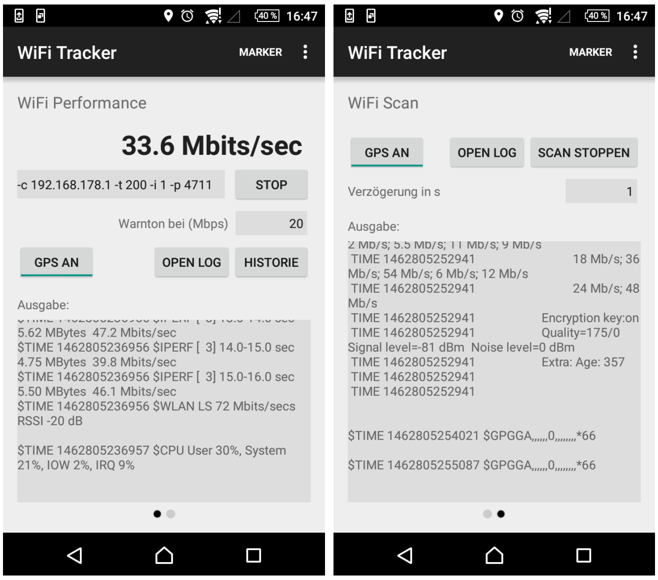
A. Station and Scan Setup

All Android phones (STAs) used for measuring the throughput performance and scanning for networks were the European version of the model running their manufacturers' unaltered operating system. Devices of different brands and varying age were used. They mainly differ in their built-in WLAN chipset, number of installed antennas, and Android version. Their WLAN modules support different standards and frequencies depending on their age and country code. The quantity of antennas determines the number of simultaneous data streams[15]. Some WLAN functions are only available at higher versions of Android – mainly, tethering in the 5 GHz-band is only available since version 6.0 ("Marshmallow"). Because WLAN modules for automotive environments oftentimes derive from chips of the mobility sector, this measurement setup represents a typical in-car user scenario well.

Due to the regulatory situation in Europe that restricts the usage of channels 149 and above to an EIRP of 25 mW, many manufactures opt to not use and scan those channels at all[16]. Hence, with the DFS requirements for the use of 5 GHz-channels lower than 149 in Europe, most mobile phones currently do not monitor the only available channels for 5 GHz in-car WLAN.

[15] Single input single output (SISO), single stream 1×1, versus multiple input multiple output (MIMO), e.g. two streams 2×2.

[16] Known to us, only recent European versions of the Apple iPhone, Sony Xperia, Goodle Nexus, and various Laptops support these channels natively.



(a) iPerf-mode. (b) Scanning-mode.

Fig. 5. Screenshot of the Android application “WiFi-Tracker” (v0.8).

B. Android Application “WiFi-Tracker”

An Android application (Fig. 5) was developed to run an instance of iPerf[17] as well as accessing the network scanning function of Android. In iPerf-mode, network throughput can be measured via iPerf in both directions (up- and downstream) on multiple WLAN frequencies. Simultaneously, the CPU load and battery temperature of the device are logged to monitor internal influences and several metadata[18] are saved for further analysis.

The measurements are carried out with iPerf because it can provide a worst case situation by attempting to send as much TCP-data as possible per interval. This way any influences on the transmission can easily be made visible. Especially the CSMA method can clearly be seen when active.

In scanning-mode, available networks from Android’s network list are logged frequently with all their additional information[19]. This scanning is done passively on the WLAN chip. However, only the networks’ beacons, as specified in the IEEE 802.11 standard, are being detected. The presence of network beacons does not necessarily coincide with the actual WLAN data traffic occurring in the scanned networks.

In both modes, the device’s GPS information is logged to associate the information geographically. Usually, the GPS location data’s horizontal delusion of precision lays within 3 m [13], [14]. Nonetheless, for the localization of other networks nearby the typical range for WLANs of 76.4 m for 2.4 GHz and 33.5 m for 5 GHz has to be considered (see II-B).

[17]iPerf is a tool for active measurements of the maximum achievable bandwidth on IP networks [12].

[18]Model no., Android version, link speed, received signal strength indicator (RSSI), MAC address, service set identifier (SSID), and used port.

[19]Channel, RSSI, MAC address, SSID, encryption, and beacon age.

C. Access Point Setup

For the AP setup, too, mainly consumer hardware was chosen. Network routers in general were chosen because of their many options to adjust transmission channel and IEEE standard. Different routers[20] as well as a custom-built evaluation board were tested and compared. Their main difference lays in their integrated WLAN chipset and installed operating system. For instance, the custom firmware DD-WRT on the Netgear R6300v2 router allows for networks on channels 149 and above, whereas the European version of FRITZ!Box’s operating system FRITZ!OS – similar to most European mobile devices – restricts the use of the 5 GHz-band solely to channels 36 to 140.

D. Vehicles and Environment

Throughout the measurements cars of different age and size were used. They differ in their installed connectivity services and their usage of infrared-shielding windows.

For this field study different regions in Germany and the Midwestern USA were investigated ranging from spacious, rural environments to dense, city scenarios. Special attention was given to areas with public WLAN access, industrial areas vs. residential areas, tunnels, traffic jams, and other cars or buses in the vicinity that might have WLAN aboard.

IV. Measurement Results and Interpretation

In the following, results from 100 h of overall measurements are shown and interpreted. Examples were selected to show the most relevant phenomena. Measurements were carried out mostly on channels 6 and 36 because most network interference ought to be expected there. Even though this 5 GHz-situation is not realizable as of the current regulatory limitations in Europe, this setup reproduces a busy traffic situation on channels 149 and above the best.

A. Station and Access Point Limitations

The used hardware, even though current to date, cannot cope with the highest data rates possible in IEEE standards 802.11n and 802.11ac. Therefore, measurements could not be conducted at 100 % performance where highest interference would have occurred.

Biggest limitation for STAs was found to be heat. Constricted space, high CPU load, multi-antenna use, and possibly protective cases make heat flow difficult. The strong correlation of WLAN throughput and battery temperature can be seen in Fig. 6 and is assumed to be due to internal safety policies that prevent overheating or power saving mechanisms. These effects were found in all phones to a variable extent.

APs are mostly limited in their processing power; especially with two or more streams CPU limitation was clearly visible. Even though all routers offer multi-stream, dual-mode[21]

[20]AVM FRITZ!Box 3490 (QCA9558-AT4A + QCA9880-AR1A), Netgear R6300v2 (BCM4331 + BCM4360), and Netgear R8500 (three BCM4366).

[21]Operating a 2.4 GHz- and a 5 GHz-network at the same time.

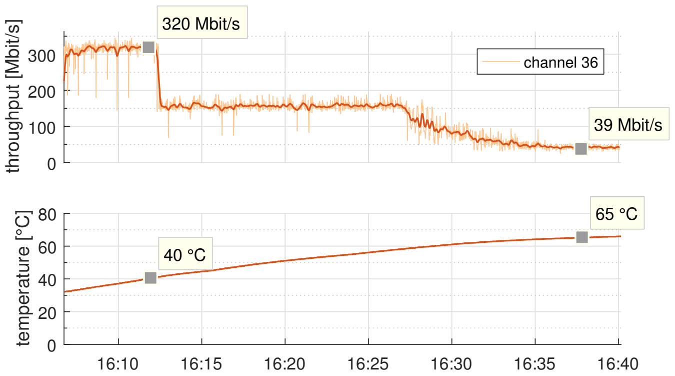


Fig. 6. Throughput degradation due to a heated mobile device. Measured on a Samsung Galaxy S5 (BCM4354, 2 × 2, Android 5.0.2) in SISO-ac-mode. An increase in temperature of 25 °C caused a decline of throughput performance by 88 % (281 Mbit/s).

network compatibility, neither can supply the necessary processing power to handle six[22] or even twelve[23] simultaneous data streams at maximum load. In consequence, for MIMO-measurements in the 2.4 GHz- and 5 GHz-band two APs were used instead of a single router's dual-mode option. Most reliable and repeatable measurements were obtained in SISO-mode. Therefore, to get a test system with optimum efficiency, the least amount of limitations, and to best see interference with other transceivers, a SISO-setup was chosen ultimately.

With the AVM FRITZ!Box 3490 set on 20 MHz channel width (2.4 GHz), interference with out-of-channel frequencies was found. Disrupting senders outside of the 20 MHz-width but inside a 40 MHz-width have significant influence on the channel performance.

Highest WLAN throughput was achieved between a Samsung Galaxy S6 (BCM4358, 2 × 2, Android 6.0.1) and a Gigabyte BRIX computer utilizing an automotive WLAN adaptor[24] (BCM89359, 2 × 2).

B. Net versus Gross Data Rates

TABLE I
NO-INTERFERENCE MAXIMUM DATA RATES
SISO, GUARD INTERVAL 400 NS

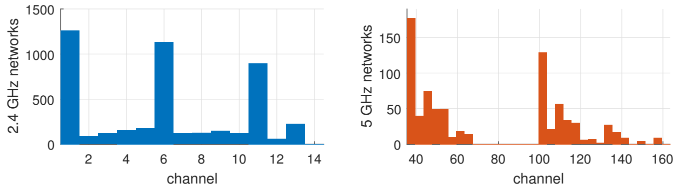
WLAN Standard	802.11n	802.11ac
Channel Bandwidth	20 MHz	80 MHz
Modulation	64-QAM	256-QAM
Coding	5/6	5/6
Gross Rate	72.2 Mbit/s	433.3 Mbit/s
Max. Throughput	63 Mbit/s	322 Mbit/s
Efficiency	87 %	74 %

Investigations in an electromagnetic-shielded environment were done to evaluate maximum non-interference data rates on the used hardware. Measurements were carried out on a Samsung Galaxy S6 and a Gigabyte BRIX computer (see IV-A).

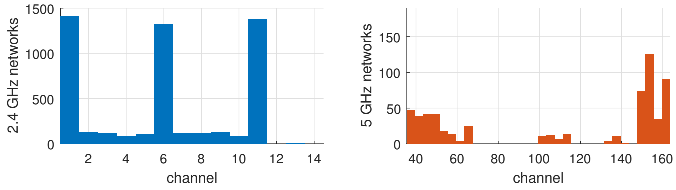
[22]Dual-mode, 3 × 3, AVM FRITZ!Box 3490 and Netgear R6300v2.

[23]Tri-mode, 4 × 4, Netgear R8500.

[24]Provided by Cypress Semiconductor Corporation, 198 Champion Court, San Jose, CA, USA.



(a) Germany: 4640 networks in 2.4 GHz-band; 785 networks in 5 GHz-band.



(b) USA: 4997 networks in 2.4 GHz-band; 615 networks in 5 GHz-band.

Fig. 7. Comparison of the WLAN channel usage in Germany and the USA. Histograms of the cumulative network occurrences over 26 h of measurements in mixed environments (highway and city) and during different times of day.

Maximum net data rate for a 802.11n-connection with link speed 72.2 Mbit/s was 63 Mbit/s yielding an efficiency of 87 %. Highest rate for a 802.11ac-connection with link speed 433.3 Mbit/s was 322 Mbit/s yielding an efficiency of 74 %. These maximum rates (Tab. I) were taken as reference for all field campaigns.

There are several reasons for the lower-than-100 % net rate: Firstly, the CSMA method requires idle times in which the sender waits for a transmission slot and physically does not transmit yet – even when there is no other transceiver in range [15]. Secondly, on MAC layer a header containing metadata is added to the frame followed by the actual data unit and terminated with a frame check sequence for verification [16]. This is overhead data that does not contribute to the measured iPerf-throughput. Thirdly, since a TCP-connection was established through the iPerf measurement tool, also TCP-overhead adds to the losses in net data rate. Lastly, IEEE 802.11 protocol requires management[25]- and control[26]-frames being sent additionally to data frames [17]. Those, too, take up available bandwidth.

C. WLAN Scanning Analysis

To analyze the prevalence of WLANs to date multiple scan drives were carried out. After 26 h of scan measurements in both Germany and the USA respectively the current situation can be described as shown in Fig. 7. The preferred use of the overlap-free channels 1, 6, and 11 can clearly be seen in the 2.4 GHz-band. Additionally, in Germany regulations allow the usage of channels 13 and 14 (see II-A). In the 5 GHz-band no distinct channel preference is visible in Germany except that channels 149 and higher are basically not used due to their low power restrictions[27]. In the USA channels 149 to 165 (power limitation: 1000 mW + 6 dBi) are clearly favored over all other channels (power limitation: 250 mW + 6 dBi).

[25]e.g. association request, beacon, authentication.

[26]e.g. request to send (RTS), clear to send (CTS), acknowledgment.

[27]Because of their short range those channels might also not be seen properly by the scanner unit from inside the car.

TABLE II
ANALYSIS OF 26 H OF SCANNING FOR NETWORKS

	Germany	USA
Car	Audi (31)	Volvo (1)
	Daimler (21)	
	Volkswagen (7)	
	BMW (2)	
	Porsche (1)	
	Volvo (1)	
Bus	Flixbus (5)	
	DB Bus (3)	
	Postbus (3)	

Also, an avoidance of the DFS channels 52 to 144 can be recognized. Statistically, 2.4 GHz-networks make up 86 % of all WLANs in Germany and 89 % in the USA. 14 % of all German networks are in the 5 GHz-band; 11 % of all American networks.

Based on their SSID and MAC address some networks could be classified as vehicular network[28] or related to a bus company[29]. A quantitative overview of these is shown in Tab. II. Only one assignment could be made for WLANs in the USA. All automotive networks were exclusively found in the 2.4 GHz-band.

D. Infrared Shielding Measurements

To test the influence of infrared-shielding windows the same 2 min-test run through a business park was done with a Mercedes-Benz W222. Once with all side windows rolled down; once up. With open side windows 20 WLANs were scanned in the vicinity; with the shielding windows in place only 9. This proves that infrared shielding has a considerable effect on the influence of other networks on in-car WLANs. However, only very few vehicles to date are equipped with these windows.

The impact of infrared-shielding windows was also examined in [8] showing a car window attenuation of $L_{win} = 12\,\text{dB}$ in the 2.4 GHz-spectrum and an attenuation of $L_{win} = 25\,\text{dB}$ at 5 GHz-frequencies.

E. Highway Scenario

Fig. 8 shows an exemplary measurement run from the city of Freising over highways A 92 and A 9 into the city of Munich. This route displays differences between in-city environments and highway scenarios well. A histogram of all scanned network during this campaign is shown in Fig. 9.

Looking at the time plot shown in Fig. 10, from 22:25 to 22:45 the measurement took place on highways. To date, almost no WLANs are present when traveling on highways; and hence, no interference with other transceivers was found in the 5 GHz-band and only very little on the 2.4 GHz-channels. Only few mobile WLANs were seen and none of them caused any notable degradation in throughput performance. In average

[28] e.g. "Audi_MMI_5465", "MB WLAN 56841", "VW_WLAN_6290".
[29] e.g. "FLIXmedia", "DB IC Bus WLAN 1111", "Postbus".

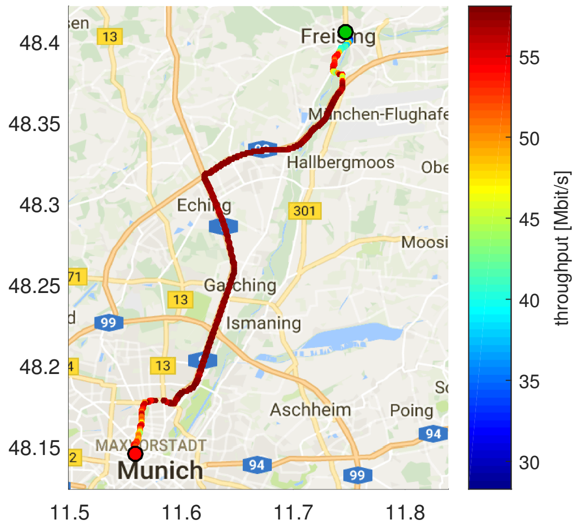


Fig. 8. Measurement run from Munich suburb to downtown Munich. First in urban environment, then on two highways until entering the city of Munich. The scatter plot shows the 2.4 GHz-WLAN throughput from Fig. 10.

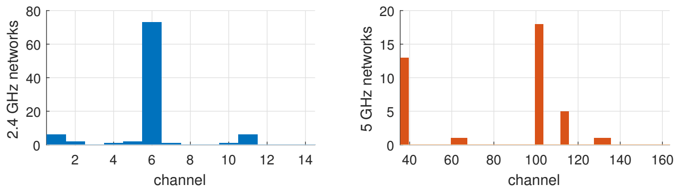


Fig. 9. Histogram of the exemplary 40 min measurement run. 92 networks in 2.4 GHz-band; 40 networks in 5 GHz-band.

90 % (57 Mbit/s) of the maximum data rate from IV-B were achieved on channel 6 (802.11n) and even 96 % (309 Mbit/s) of the maximum net rate were reached on channel 36 (802.11ac).

Low prevalence of household and office WLANs and only few automotive networks are the main reason for good throughput performance on highways. Stronger attenuation effects on the 5 GHz-frequencies cause even less interference on the high, 5 GHz-channels.

F. In-City Scenario

The main difference in a city compared to on a highway is the existence of many household and office WLANs in range. Also, due to lower driving speeds the device remains longer in the radius of one single network making it more likely to experience interference through collision avoidance.

The results of a typical in-city measurement are shown in Fig. 8 and Fig. 10. In the beginning, from 22:17 to 22:25, and in the end, from 22:45 to 22:57, the route led through urban environment. During these times noticeably more networks were scanned on all channels. In the 2.4 GHz-band mean net data rates drop to 44 Mbit/s (Freising) and 52 Mbit/s (Munich) with minima of 18 Mbit/s and 37 Mbit/s. This corresponds to lows at only 32 % of the average highway data rate and 29 % of the non-interference net data rate at 2.4 GHz. Certain throughput fluctuation can be explained with different activity levels in the monitored WLANs. Only when the surrounding

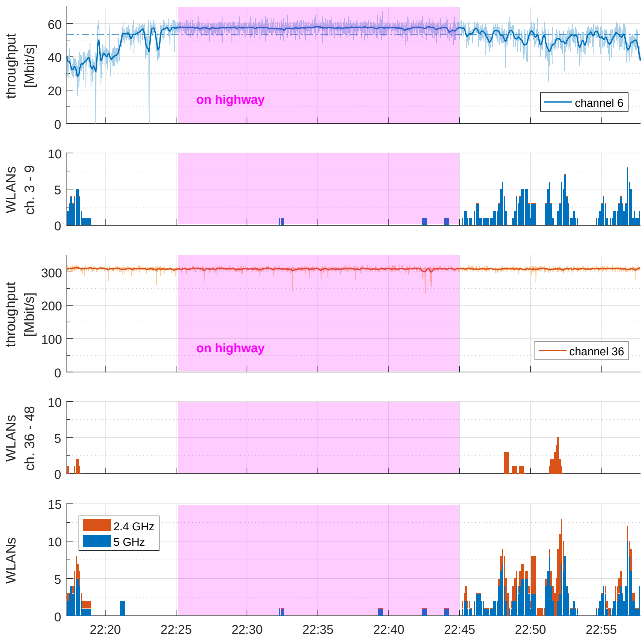


Fig. 10. WLAN throughput performance on channels 6 and 36 while driving on a highway and in-city. WLAN occurrences on relevant interfering channels (ch. 3 - 9 and ch. 36 - 48) are displayed as well as all scanned WLANs. See Fig. 8 for exact route. Measured on two Samsung Galaxy S6 and a Gigabyte BRIX computer in SISO-mode (see IV-A).

networks are actively sending data, the CSMA mechanism is reducing the vehicular throughput rate and causes performance degradation.

Throughput rates in the 5 GHz-band did not decline noticeably in city environments. This can be attributed to stronger dampening and less networks in general on 5 GHz.

In all measurements, the strongest interference phenomena could be observed in the 2.4 GHz-band, especially on channel 6. This is due to the larger range of 2.4 GHz-networks compared to 5 GHz-networks and also because channel 6 is one of the most popular non-overlapping channel in that band. These results can be transferred as follows: due to the expected growth of 5 GHz-WLAN applications the crowded traffic situation on channel 6 can be taken as a prediction of the 5 GHz-channels in the future. With more and more vehicles offering high-speed connectivity services the occupancy of the 5 GHz-band will soon look similar to that of the current 2.4 GHz-band. However, the shorter range of 5 GHz-networks will still lessen the interference problems of those networks. Furthermore, the slow in-city driving reflects the situation of a highway traffic jam. In that situation wireless entertainment systems with good performance are crucially important to the user.

V. Conclusion

In summary, WLAN performance depreciation in automotive environments today only occurs in the 2.4 GHz-band. Strongest interference with other WLANs was noticed on the popular 2.4 GHz-channels in cities. This is due to the high number of active household and office networks and their large range of influence. Vehicular WLANs that cause coexistence problems were found in the 2.4 GHz-band on highways as well.

In the higher 5 GHz-frequency range strongly alleviated degradation effects were found in cities and no interference occurred on highways. However, there are strong indicators for a quick populating of the 5 GHz-band in automotive environments. More allocated channels – especially the availability of high-throughput 80 MHz-channels – and a shorter physical range of influence (stronger attenuation) promote those higher frequencies. Multi-user video streaming for instance is only possible when transmitting on the IEEE 802.11ac standard. Also, the ongoing penetration of the market of automotive connectivity solutions accelerates the growth of mobile wireless networks. Therefore, vehicular WLANs are expected to shift towards the 5 GHz-band in the future increasing the likelihood of interference phenomena in cities and on highways in equal measure. To date, the regulatory situation in Europe and the partly pending phone manufacturers' adaptation to SRD-channels 149 and above are a major barrier. Furthermore, the CSMA control method is not suited well for short-range utilization in mobile scenarios. Infrared-shielding car windows minimize interference effects with external sources considerably.

Ongoing research is done to evaluate the probability of other (non-WLAN) disruptive transceivers such as radar motion detectors or traffic guidance systems interfering on the SRD-channels in the 5 GHz-band.

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