Analysis of IEEE 802.11ax High Efficiency WLANs for in-Vehicle Use

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***Abstract*—While the demand for higher throughput is continuously rising, the automotive usage of the Wireless Local Area Networks (WLANs) is emerging. Development of new WLAN standards create the necessity of their evaluation for specific use-cases.**

This paper presents our detailed physical layer (PHY) analysis of the upcoming IEEE 802.11ax standard for in-vehicle use. Basing on our wide-band measurements, we implemented an in-vehicle channel model. End-to-end simulations of IEEE 802.11ax PHY were conducted with this channel model to determine the achievability of the high data rates supported by the IEEE 802.11ax standard for in-vehicle applications. To verify our in-vehicle channel model, we conducted over-the-air (OTA) measurements.

We show that the in-vehicle wireless channel has a much steeper power decay than all IEEE 802.11 channel models and it supports the high data rates defined in the IEEE 802.11ax standard. Our approach to the problem enables realistic evaluation of the upcoming WLAN standards for different use cases before the hardware is available in the market.

I. Introduction

Since the launch of IEEE 802.11 in 1997, WLANs have been gaining popularity and being deployed for several use cases. Today, the use-cases are shifting from static, indoor and low data rate scenarios into mobile, outdoor, high data rate and real-time applications. The demand on higher throughput triggered the evolution of the newer WLAN standards on 2.4 and 5 GHz bands. IEEE 802.11n/ac WLANs use new techniques such as the orthogonal frequency-division multiplexing (OFDM), higher modulation and coding schemes (MCSs), frame aggregation and multiple-input and multiple output (MIMO) [1] [2]. IEEE 802.11ax is the newest WLAN standard on 2.4 and 5 GHz bands and it is going to replace IEEE 802.11n/ac WLANs. Deployment of IEEE 802.11ax WLANs is going to provide higher data rates and more interference-robustness and therefore expand the possible application areas of WLANs.

Automotive domain is one of the newer application areas of WLANs. Main automotive WLAN use-cases are in-vehicle networking, OTA maintenance, inter-vehicle and infrastructure communications. For inter-vehicle use cases such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, IEEE 802.11p standard is available on the 5.8-5.9 GHz dedicated short-range communication (DSRC) band since 2010. On the contrary, for in-vehicle networking common WLAN standards such as IEEE 802.11a/b/g/n/ac are used to enable networking with consumer devices on 2.4 and 5 GHz bands. A common use case of in-vehicle networking is device-to-device video streaming which can have very strict quality-of-service (QoS) requirements. In order to meet these requirements, automobile vendors try to implement systems which support the newest WLAN standards.

The broadening of the application areas of WLANs and the fast evolution IEEE 802.11 standards create the necessity to evaluate new WLAN standards in different environments. Using simulations to perform such evaluations has the benefit of saving significant amount of time, cost and effort. To enable simulations for different environments, the IEEE802.11 standard provides channel models for conventional scenarios like office rooms and large factory buildings [3]. These channel models base on wide-band wireless measurements using a vector network analyzer (VNA). Further channel models for any environment can be developed using the same approach. [4]

In this paper we present the results of our analysis of IEEE 802.11ax WLANs for in-vehicle use. We performed wide-band measurements in a Daimler S-Class car to develop a in-vehicle channel model. This in-vehicle channel model was integrated into MATLAB WLAN System Toolbox and used in end-to-end simulations of IEEE 802.11ax PHY in the baseband. Link budget calculations were done to determine the achievability of the highest data rates in a vehicular environment. To verify the in-vehicle channel model, OTA measurements were conducted and their results were compared with the simulation results. This approach enables us to evaluate an upcoming WLAN standard and estimate maximum achievable data rates for a definite environment.

II. Background

A. IEEE 802.11ax High Efficiency WLANs

Motivation and Timeline:

With the increase in the number of WLAN-capable devices the efficient use of the available spectrum has become a more important problem. Since the number of available channels are limited, multiple devices operate on same frequencies and create interference to each other. If multiple devices transmit at the same time, collisions occur and data may not be correctly recovered at the receiver. To avoid these collisions, IEEE 802.11 standard uses a listen-before-talk mechanism.

Clear channel assessment (CCA) is the functionality which is used to determine if the medium is idle or busy. To determine that the medium is busy, CCA defines the carrier sense threshold (CST) at -82 dBm for IEEE 802.11 signals and the energy detect threshold (EDT) at -62 dBm for non-IEEE 802.11 signals on 20 MHz channels. If the device detects signals above these thresholds, it defers its transmission until the wireless medium is silent again and an additional random backoff time. In a dense deployment scenario, stations can hear signals from several basic service sets (BSS) in the proximity and experience longer delays due to the contention overhead. In dense WLAN deployments, these delays cause significant decrease in the average per-station throughput experienced by the users.

In order to increase the average per-station throughput in dense deployment scenarios, IEEE 802.11 committee has formed the High Efficiency WLAN (HEW) Study Group in 2013. In 2014, IEEE 802.11 committee has approved forming the Task Group ax (TGax) from HEW study group to develop IEEE 802.11ax amendment to IEEE 802.11 Standard. IEEE 802.11ax is to be publicly available in 2020 and aims to improve the spectral efficiency and support at least four times improvement in average throughput per station in a densely deployed WLAN scenario. While providing backward compatibility, IEEE 802.11ax is going to operate on both 2.4 and 5 GHz bands and replace IEEE 802.11n/ac WLANs [5] [6].

In July 2018, the Draft 3.0 of the upcoming IEEE 802.11ax standard has been approved, and the Draft 4.0, which is going to be the last draft version of the standard, is aimed to be completed in November 2018 [7].

Feature Overview:

Compared to the IEEE 802.11n/ac WLANs, IEEE 802.11ax has several new features in PHY and Medium Access Control (MAC) layers. New features like orthogonal frequency-division multiple access (OFDMA) and BSS color aim to improve the efficiency in dense environments, while the new OFDM scheme and higher MCSs introduced in IEEE 802.11ax enable higher peak data rates [8].

BSS color is a new feature which is introduced in IEEE 802.11ax and is expected provide better interference-handling when there are several overlapping networks in an environment. This feature enables the access points (APs) and stations (STAs) to distinguish between inter- and intra-BSS frames using the BSS color bit inserted into the PHY header. While the legacy CST (-82 dBm) is used for intra-BSS frames, a higher CST can be set for inter-BSS frames to reduce delays caused by the networks in the proximity. IEEE 802.11ax also enables the combination of dynamic CST with transmit power control (TPC) in a proportional rule, which can bring significant increase in spatial reuse [9]. In this case the CST for inter-BSS frames can be increased when a lower transmit power is used. These mechanisms can enable overlapping BSSs to transmit simultaneously and increase the overall throughput.

In order to increase the efficiency in multi-user scenarios, IEEE 802.11ax standard supports uplink- and downlink-OFDMA. OFDMA lets data to be transmitted in smaller resource units (RUs) in frequency domain. It enables the seperation of a 20 MHz channel between up to 9 users and allows an AP to serve several STAs simultaneously. This feature is expected to avoid large delays experienced by the users in WLAN-Hotspot scenarios, in which several clients are served by a single AP.

Besides its interference robustness and multi-user support, IEEE 802.11ax has significant physical layer enhancements which increase the peak data rate for a single user. Two main enhancements are the new OFDM scheme with reduced subcarrier distance and higher MCSs (MCS10 and MCS11) with 1024-QAM. IEEE 802.11ax introduces a new OFDM scheme, which reduces the overhead and increase the throughput. The OFDM subcarrier distance, which is 312.5 kHz in IEEE 802.11a/n/ac WLANs, is reduced to 78.125 kHz in IEEE 802.11ax standard [1], [5]. This reduction in subcarrier distance results in a symbol length of 4 times IEEE 802.11a/n/ac WLANs. While the symbol duration is increased, the standard guard interval (GI) for IEEE 802.11ax is set as 0.8 µs, which is equal to the length of a single long GI or twice the short GI of IEEE 802.11n/ac WLANs. IEEE 802.11ax also extends the range of GI to maximum 0.8 µs to increase robustness against inter-symbol-interference (ISI) in large scale outdoor environments.

Figure 1 displays a brief comparison of IEEE 802.11n/ac and IEEE 802.11ax OFDM symbols in time domain when for all standards the shortest available GI is used. In IEEE 802.11ax, the efficiency is increased by reduced relative length of the guard interval in time domain. Furthermore, IEEE 802.11ax carrier allocation in frequency domain also increases the efficiency by reducing the ratio of the unused edge carriers to the data carriers. Using 1024-QAM also brings significant throughput increase. In IEEE 802.11ac standard the highest MCSs are using 256-QAM, which allows the transfer of 8 coded bits per symbol. With the use of 1024-QAM, IEEE 802.11ax supports the transfer of 10 coded bits per symbol and therefore benefits from 25% additional increase in PHY data rates.

Figure 2 displays a brief comparison of the highest achievable single-input and single-output (SISO) gross data rates (PHY rate) of IEEE 802.11n, IEEE 802.11ac and IEEE 802.11ax WLANs. Using MIMO with multiple spatial streams,

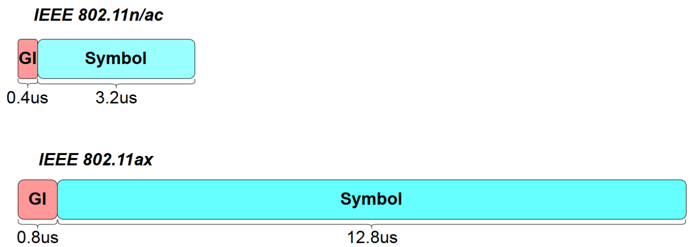

Fig. 1. IEEE 802.11n/ac (short guard) and IEEE 802.11ax OFDM symbols in time domain

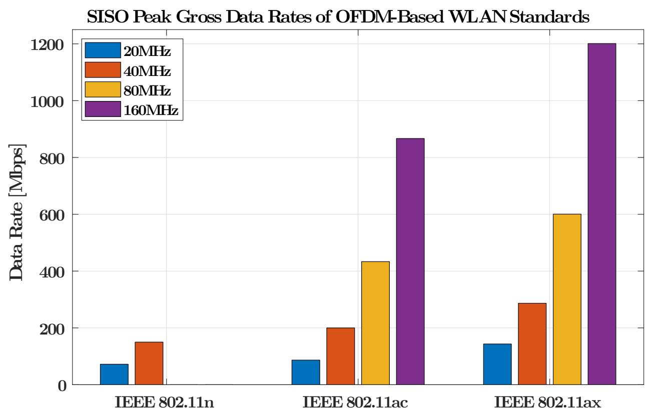

Fig. 2. SISO peak gross data rates of OFDM-based WLAN standards

these data rates can be increased. Note that the IEEE 802.11ac standard and the channel bandwiths of 80 MHz and 160 MHz are only available on 5 GHz band.

IEEE 802.11ax features such as 1024-QAM and reduced subcarrier distance introduce new challenges to WLAN hardware. For 1024-QAM (MCS 10 and 11), the maximum tolerable error vector magnitude (EVM) is -35 dB, which is 3 dB lower than the requirement for 256-QAM [10]. Due to the reduced OFDM subcarrier distance, IEEE 802.11ax suffers from more severe performance degradation when residual carrier frequency offset (CFO) is present at the receiver [11]. Furthermore, the orthogonality of the new OFDM scheme is more sensitive to the hardware impurities such as phase noise. These hardware challenges and other new features defined in PHY and MAC layers make IEEE 802.11ax WLANs more difficult to implement compared to IEEE 802.11n/ac WLANs.

B. In-Vehicle WLAN Usage

Automotive WLANs are regarded as outdoor usage by many country regulations and therefore, they are subject to additional limitations. In some countries like Japan, there is not any available spectrum for automotive usage on the 5 GHz band. In Europe, lower channels of the 5 GHz band recently became allowed for in-vehicle use.

The limited number of available channels results in an increase in the number of users in a channel in an automotive scenario. In-vehicle WLANs are subject to interference created by nearby vehicular and static networks in an urban environment. Due to higher range of signals and higher number of wireless devices, the interference situation is more critical in the 2.4 GHz band than in the 5 GHz band. Even though the signal-to-interference ratio (SIR) of an in-vehicle WLAN is expected to be high due to high received signal strength and shielding provided by the vehicle body, transmission delays will be experienced because of the CCA mechanism defined in the IEEE 802.11 standard. Theoretically, on the 2.4 GHz band the signals from nearby networks within a range of 76 m can exceed the CST of -82 dBm and cause transmission delays. In [12], 30% throughput degradation of an in-vehicle WLAN was observed while driving in an urban environment. By using infrared-shielding car glass, additional attenuation can be introduced to the external signals and the experienced interference can be reduced [13].

In-vehicle deployment of IEEE 802.11ax WLANs is expected to provide a number of benefits, including robustness against the interference created by nearby networks. Enhanced user experience will be possible by better interference handling and higher peak data rates which IEEE 802.11ax WLANs provide. The BSS color feature defined in the IEEE 802.11ax standard can limit the unnecessary delays caused by the neighbor networks such as the other in-vehicle WLANs in the proximity and increase the probability that the users benefit from the highest data rates defined in the standard.

For in-vehicle use, a brief comparison of the highest achievable WLAN data rates can be done by taking the channel availability for this scenario into account. Since the 2.4 GHz band has a more severe interference problem than the 5 GHz band, it is common to use 20 MHz channels on the 2.4 GHz band and 80 MHz channels on the 5 GHz band for in-vehicle WLANs. IEEE 802.11ax supports SISO gross data rates up to 143 Mbps on 20 MHz and 600 Mbps on 80 MHz channels. Compared to the closest WLAN standards IEEE 802.11n and IEEE 802.11ac, IEEE 802.11ax has the potential of increasing the peak gross data rate by 98.6% for 20 MHz channels on 2.4 GHz and by 38.6% for 80 MHz channels on 5 GHz bands. But this increase in data rate happens only when the highest MCS is used. 1024-QAM has relatively close constellation points and therefore has strict signal-to-noise ratio (SNR) and EVM requirements and only works under favorable channel conditions. If the highest MCSs are not achievable in an environment, the benefits of IEEE 802.11ax would be limited to its interference handling mechanisms and the throughput increase provided by the new OFDM scheme. This situation creates the necessity to investigate if the highest data rates defined in IEEE 802.11ax are achievable in the use cases of interest. The availability of the highest data rates depends on the wireless channel conditions and therefore a detailed study of the in-vehicle wireless channel is necessary.

C. IEEE 802.11 Channel Models

The IEEE 802.11 standard describes six different channel models A to F, most of which are based on indoor measurements [3]. Models B-F are multi-path channel models which are based on a cluster approach first used by Saleh and Valenzuala [14]. These models differ in the impulse

TABLE I
CHANNEL MODELS [2]

Model	RMS Delay Spread[ns]	# Clusters	Enviroment
A	0	1	N/A
B	15	2	residential
C	30	2	small office
D	50	3	typical office
E	100	4	large office
F	150	6	large space

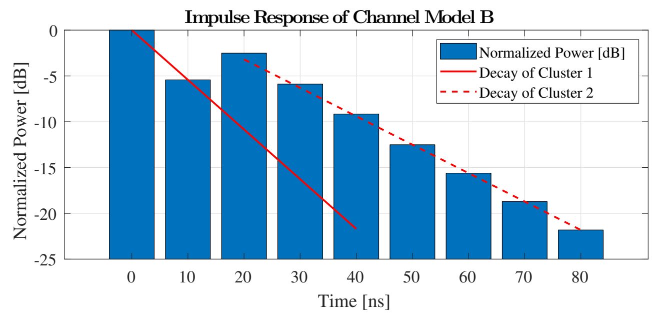

Fig. 3. Impulse response of IEEE 802.11 channel model B with two clusters

response and they represent rooms of different sizes [2]. A brief overview is given in table I. The larger the size of the environment is, the higher are the delay spread and number of clusters.

From the 5 multi-path channel models defined in IEEE 802.11 standard, the model B is the closest one to an in-vehicle environment. Figure 3 displays the impulse response of the channel model B. Each tap is represent as a bar and represents the receive power at a certain discrete delay time. The lines are the two clusters defined in the channel model. The first cluster represent the line-of-sight (LoS) and the second cluster represents a multi-path. The angle-of-arrival (AoA) and power angular spread are therefore the same within a cluster [3]. The received power in the clusters decreases logarithmically with time, which corresponds to the increasing attenuation due to higher path length. The two clusters partially overlap and the power in each tap results from the summed power of the individual clusters at the respective discrete time. In-vehicle wireless channels are not included in the IEEE 802.11 channel models so far. An in-vehicle environment is much smaller than the residential environment on which the channel model B is based on. In [15], measurements are conducted to characterize the wireless channels in different types of vehicles. While the results are vehicle-dependent, it is stated that a shorter delay spread than IEEE 802.11 channel models is observed and no clustering effect was seen.

III. In-Vehicle Wireless Channel

A. Measurement Setup and Procedure

In order to characterize the in-vehicle channel, we performed S-parameter measurements in the frequency domain using a VNA. The measurements were conducted in a frequency range of 1-6 GHz. In this range the frequency response

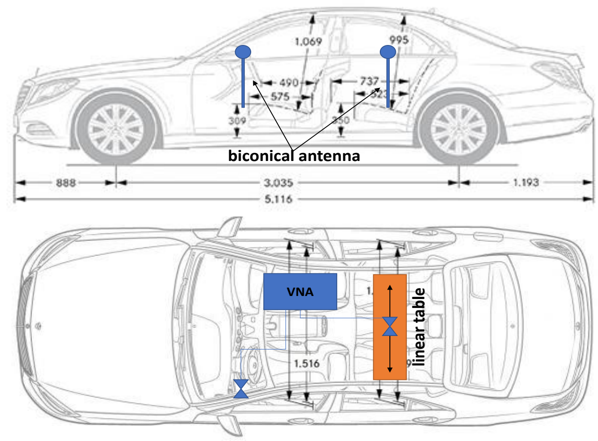

Fig. 4. Measurement Setup to characterize inside vehicle channel

of the channel was determined from the S-parameters. Due to the short measurement time, the channel can be assumed to be static during one S-parameter measurement. The frequency response also carries the path-loss information within the measured range. Averaging over the WLAN channels, we extracted path-loss information from the channel frequency response. The channel's impulse response was calculated from the frequency domain data using the inverse Fourier transform (IFT).

The measurements were carried out in an S-Class W222 from Daimler. The interior including trunk has a length of approximately 3 m and a width of 1.5 m and is therefore smaller than the typical environments included in the IEEE 802.11 channel models. Biconical antennas (Schwarzbeck SBA 9199-108) were used to achieve an isotropic transmit- and receive-characteristic in azimuth and simultaneously high bandwidths. As figure 4 presents, the transmit antenna was positioned near the A-pillar on the driver's side. This corresponds to a possible antenna position which is already used in some vehicles. The receiver antenna was mounted on the back seat of the car.

To measure the influence of the antenna position to the impulse response, the receiver antenna was mounted on a linear drive and the channel measurement was performed at multiple positions along the backseat, as shown in figure 4. Using methods of digital beamforming (DBF), the direction-of-arrival (DoA) of the waves from the transmitter antenna in the front to the backseat could be determined.

Lastly, the measured impulse response and DoA information were combined to determine the channel coefficients with tap delays and corresponding powers. These coefficients were used to model the in-vehicle wireless channel in MATLAB.

B. In-Vehicle Wireless Channel Model

Figure 5 presents distribution of the measured path-losses in WLAN bands for the sweep over all receiver antenna positions on the back seat. The distribution on both bands is similar and the path-loss on the 5 GHz band is higher. The 90th percentile of the path-loss is 51.6 dB on the 2.4 GHz band and 59.7 dB on

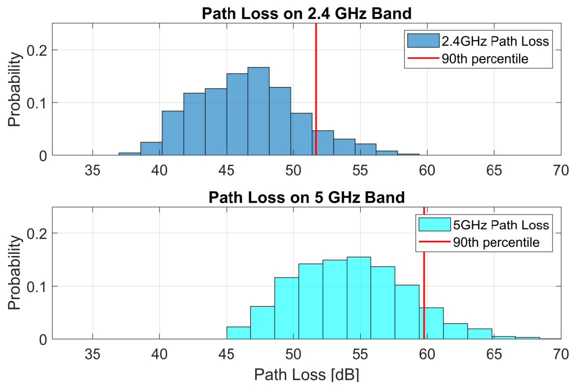

Fig. 5. Path-loss on 2.4 and 5 GHz WLAN channels in vehicle

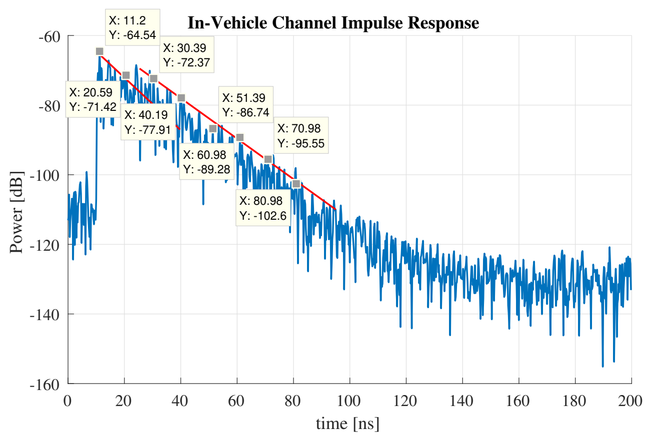

Fig. 6. Impulse response of the in-vehicle wireless channel

the 5 GHz band, respectively. For the link budget calculations in the next section, we are going to use the 90th percentile of the path-loss values to make a worst-case approximation.

The frequency response we obtained by the measurements is a frequency-selective channel. The channel impulse response which was calculated using IFT is presented on figure 6. The decrease in reception power is faster than that in all IEEE 802.11 multi-path channel models. In the DoA measurements two clusters were observed at some but not all reception positions. Also the channel impulse response was dependent on the position of the receiver antenna.

To create an in-vehicle channel model with discrete taps from the obtained impulse response, relevant data points were chosen with a delay of approximately 10 ns between each other. The yellow markers in figure 6 show the position and power of these data points. The red lines represent the power decays of both clusters. These were line fitted through the measurement data.

IEEE channel model B has also two clusters and therefore was chosen as the basis for our in-vehicle channel model. The number taps, the values for power angular spectrum (PAS), i.e. angle of arrival, were taken from this channel model. Using the data which is presented in figure 6, the power of each tap for the in-vehicle channel model was determined.

TABLE II
DECAY OF POWER (ΔP) AND DELAY OF FIRST TAP OF THE IN-VEHICLE WIRELESS CHANNEL MODEL COMPARED TO THE IEEE 802.11 CHANNEL MODEL B

Model	Cluster 1		Cluster 2	
	Delay [ns]	ΔP [dB/ns]	Delay [ns]	ΔP [dB/ns]
In-Vehicle	0	0.9	20	0.61
B	0	0.54	20	0.31

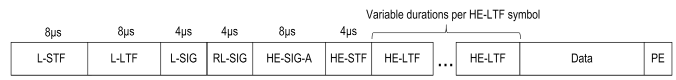

Fig. 7. IEEE 802.11ax PPDU Structure [5]

Table II compares the decay of power (ΔP) for each cluster in the channel model B to the in-vehicle channel model. The in-vehicle channel model has a much steeper power delay profile. Possible reasons of this difference are the shorter signal paths due to the small size of the vehicle interior and the high signal absorption caused by the seats, console etc.

The channel impulse response is expected to be vehicle-dependent, since the size of the vehicle would determine the signal paths and delay spread.

IV. Simulations of IEEE 802.11ax PHY

MATLAB WLAN System Toolbox provides necessary functions for IEEE 802.11 PHY baseband waveform creation and reception [16]. These transmitter and receiver functions are IEEE 802.11 standard compliant, therefore they can be also used for OTA measurements. Performing packet waveform creation and packet reception in a loop, there are end-to-end simulation examples available with additive white Gaussian noise (AWGN) or IEEE 802.11 multi-path channel models which are available in MATLAB WLAN System Toolbox. We integrated the in-vehicle channel model into the set of multi-path channel models and conducted end-to-end simulations of IEEE 802.11 PHY.

A. Simulation Structure

We conduct simulations of IEEE 802.11ax PHY under the assumption that there are not any impurities coming from the hardware. Figure 7 displays the IEEE 802.11ax packet structure which is used in the simulations. In each iteration of the simulation, IEEE 802.11ax packets are created with a given length containing random bits in the payload. Single packet waveforms are passed through the channel model. This channel model can be pure AWGN, an IEEE 802.11 multi-path channel model or our in-vehicle channel model. If a multi-path channel model is used, AWGN is added at the output of the multi-path channel model. Then the receiver operations such as packet detection, time and frequency synchronization, channel estimation, equalization, demodulation and decoding are performed using the functions of MATLAB WLAN System Toolbox [16]. As last, the decoded bits at the receiver are compared to the bits at the transmitter to check if the packet

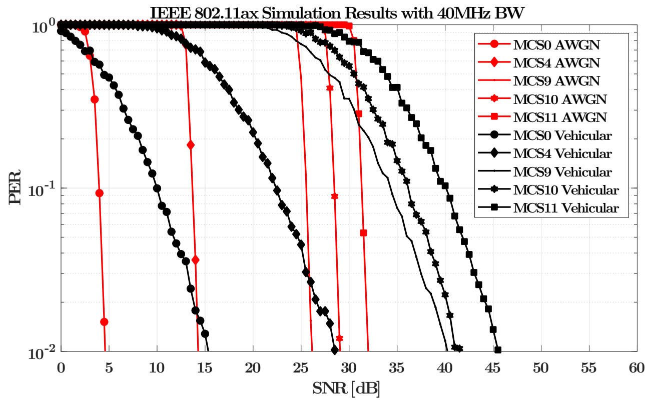

Fig. 8. IEEE 802.11ax simulation results with AWGN and in-vehicle channel models

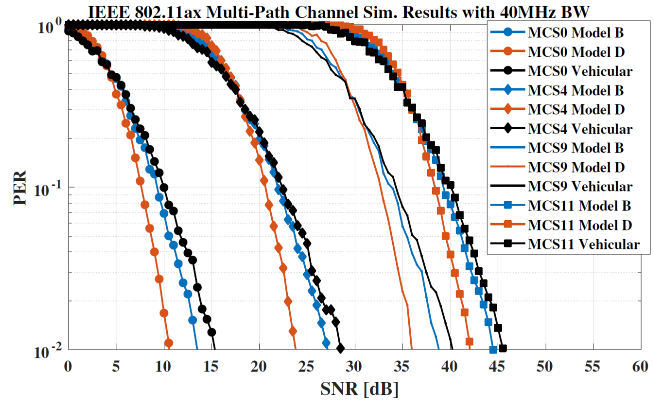

Fig. 9. IEEE 802.11ax simulation results with in-vehicle channel model and IEEE 802.11 channel models B and D

is received correctly. During our simulations, we increment SNR in 0.5 dB steps and observe the relationship between SNR and packet error rate (PER) for each MCS defined in IEEE 802.11ax standard. Lastly, we interpolate between the simulation results to determine the minimum acceptable SNR supporting a PER less than 10%, which is the threshold defined by the IEEE 802.11 standard.

B. Simulation Results

Figure 8 displays the comparison of SISO simulation results using AWGN and in-vehicle channel models. In these simulations, 40 MHz channel bandwidth and 1024 Byte PPDU length were used. For a PER of 10%, around 8 dB higher SNR is required with the in-vehicle channel model in comparison to the AWGN channel, in which there are not any multi-path effects are present. MCS11 (1024-QAM R=5/6) requires 40.1 dB SNR with the in-vehicle channel model and 31.3 dB SNR with the AWGN channel. MCS10 (1024-QAM R=3/4) requires 36.2 dB SNR with in-vehicle channel model. On both channel models, the required SNR is approximately 6 dB higher for MCS11 in comparison to MCS9 (256-QAM R=5/6), which is the highest MCS defined in IEEE 802.11ac standard.

Further simulations were carried out with IEEE 802.11 multi-path channel models B and D and their results were compared to the previous simulation results with the in-vehicle channel model. As displayed in figure 9, the SNR requirements of three different multi-path channels for 10% PER differ from each other by less than 2 dB.

C. In-Vehicle Link Budget

As presented in the simulation results, higher MCSs require higher SNR at the receiver. The reachability of high SNR values such as 40.1 dB for MCS11 in a vehicular environment can be determined by a link budget calculation.

At the receiver the signal gets distorted by thermal noise ($\mathrm{N_{thermal}}$), which depends on the bandwidth and temperature. The thermal noise power in Watts is equal to $k_\mathrm{B} \cdot B \cdot T$, where B is the bandwidth in Hz, k_B is the Boltzmann constant and T is the temperature in Kelvin. Further distortion is caused by receivers noise figure (NF). The required received signal power ($P_\mathrm{RX,req}$) to reach a definite SNR at the receiver can be calculated as shown in equation 1.

$$P_{\mathrm{RX,req[dBm]}} = SNR_{\mathrm{req[dB]}} + \mathrm{N_{thermal[dBm]}} + \mathrm{NF_{[dB]}} \quad (1)$$

The signal power at the receiver depends on the equivalent isotropically radiated power (EIRP) at the transmitter, signal attenuation caused by the environment (L_path), cable losses at the receiver (L_RX), and the receiver antenna gain (G_RX) as shown in equation 2.

$$EIRP_{\mathrm{req[dBm]}} = P_{\mathrm{RX,req[dB]}} + L_{\mathrm{path[dB]}} + L_{\mathrm{RX[dB]}} - G_{\mathrm{RX[dBi]}} \quad (2)$$

On a 20 MHz wide channel, the thermal noise power is -100.8 dBm at room temperature. Doubling the channel bandwidth results in a 3 dB increase of the noise power. We assume that the noise figure, cable losses and the antenna gain are 3 dB each at the receiver. As path-loss we use the 90th percentile of the measurement results from the previous section, which are 51.6 dB for the 2.4 GHz band and 59.7 dB for the 5 GHz band, respectively. Inserting these values into equations 1 and 2, we calculate the worst-case EIRP requirements for the highest MCSs.

TABLE III
REQUIRED EIRP FOR IEEE 802.11AX MCS11 (1024-QAM, R=5/6) ON 2.4 GHZ AND 5 GHZ BANDS WITH 20, 40 AND 80 MHZ BW

		$\mathrm{EIRP_{req}}$[dBm]	
Bandwidth [MHz]	$\mathrm{SNR_{req}}$[dB]	2.4 GHz	5 GHz
20	40.4	-5.8	2.3
40	40.1	-3.1	5.0
80	38.4	-	6.3

Table III presents the required EIRP values on 2.4 and 5 GHz bands with 20, 40 and 80 MHz channel bandwidths according to our simulation results with the in-vehice channel model. The use of 80 MHz channels are not permitted on the 2.4 GHz band. The highest EIRP requirement occurs on the 5 GHz band when channel bandwidth is 80 MHz. Even

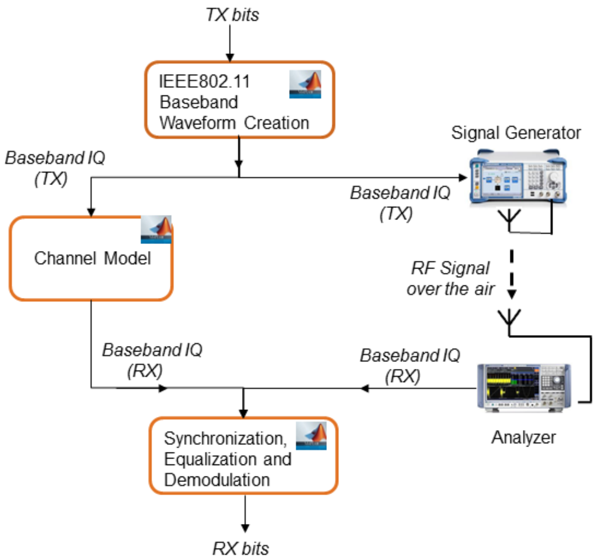

Fig. 10. IEEE 802.11 simulation (left side) and OTA measurement (right side) structure

though the 90th percentile of path-loss values were used for the calculations, all EIRP requirements are much lower than 14 dBm, which is the highest allowed EIRP in Europe on the 5 GHz band. On the 2.4 GHz band, the required EIRP levels are much lower and the margin to 20 dBm, which is the highest allowed EIRP in Europe on this band, is significantly large. This large margin to the regulatory limits may compensate additional distortions caused by the hardware impurities and may allow MIMO deployments especially on the 2.4 GHz band.

V. Over-the-Air Measurements

OTA measurements with IEEE 802.11ax PHY are conducted to verify the in-vehicle channel model. For these measurements, we break the simulation loop and and send the baseband waveform to a vector signal genarator as shown in the figure 10. There the baseband signal is upconverted to 2.4 or 5 GHz RF band. This RF signal reaches through a coaxial cable to the antenna, and there it is transmitted over the wireless channel. The signal received by the receiver antenna is downconverted to baseband at the spectrum analyzer. The baseband signal is sent to the laptop over an Ethernet connection and analyzed in MATLAB similar to the simulation process.

A. Methods

In the following, we present two different methods we used to evaluate the in-vehicle wireless channel for WLAN applications.

Exhaustive Method:

The exhaustive way of evaluating the in-vehicle channel for different antenna positions is to transmit WLAN packets with random data coded by a given MCS and then reduce the

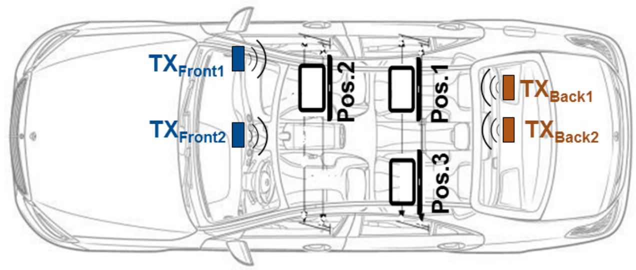

Fig. 11. TX antenna and laptop (RX) positions for in-vehicle WLAN Measurements

transmit power in small steps until the 10% PER limit is no more achieved. The result is the necessary EIRP for a definite antenna configuration and packet type. If the required transmit power is less than the regulatory limits, the given antenna configuration and wireless environment can be assumed to allow the given MCS. In order to determine if 10% PER is reached for a given antenna configuration and a transmit power, a meaningful amount of packets should be transmitted with these settings. Then these measurements should be repeated for different antenna positions representing several use-cases. Consequently the measurement duration is quite long in this approach.

Channel Sounding Method:

In order to reduce the measurement duration, we developed a channel sounding method combining the simulations and over-the-air measurements. In this method, null-data-packets (NDPs) are transmitted through the in-vehicle wireless channel. The preamble of the received packets are analyzed and the channel state information (CSI) is extracted. This channel estimate is extended by extrapolation to cover the channel spectrum edges and interpolated to cover the DC carriers and provide higher resolution in frequency domain.

After several CSI examples are collected in an environment, simulations are conducted using this data. Baseband WLAN packet waveforms are created with random data similar to the previous simulations. These data packet waveforms are converted into frequency domain via fast Fourier transform (FFT), multiplied with the frequency domain channel response and then converted into the time domain using inverse fast Fourier transform (IFFT). Then AWGN is added to these waveforms in 1 dB steps to determine the required SNR to achieve a PER smaller than 10% for the given scenario. With this approach, first the estimated channel responses can be collected and then the simulations can be conducted for any kind of WLAN packets using the same CSI set. Therefore, it is not necessary to iterate over the transmit power during the OTA measurements. The measurement duration in-vehicle is significantly reduced in this method.

B. Measurement Setup and Procedure

Figure 11 shows the positions of the transmitter antennas and the laptop, which was used as the receiver. The transmitter

TABLE IV
COMPARISON OF THE SNR REQUIREMENTS FOR IEEE 802.11AX WITH 20 MHZ BW OBTAINED BY EXHAUSTIVE AND CHANNEL SOUNDING METHODS

Laptop Position	$SNR_{over-the-air}$[dB]	$SNR_{channel\ sounder}$[dB]
1	33.5	32.0
2	33.2	32.0
3	32.8	32.1

antennas were patch antennas placed in front or back side of the car. Four positions for the transmitter antennas were used. While the transmitter antennas in the front (TX_{Front1} and TX_{Front2}) were not covered with any material, the antennas at the back (TX_{Back1} and TX_{Back2}) were separated from the vehicle interior by a thin panel. A laptop whose WLAN antennas were separated from its WLAN-Adapter was used to receive the WLAN signals. The measurements were carried out with three positions of the laptop. From three positions, the position 2 had LoS to the transmitter antennas in the front. Since the laptop has two antennas, we switched between them to during the measurements on each position to test different scenarios for the wireless channel.

Verification of the Channel Sounding Method:

Firstly, the exhaustive method and the channel sounding method were used for the same settings to perform a verification of the channel sounding method. During the verification process we switched between the antennas at the back for all three positions of the laptop.

Table IV presents results of the verification of the channel sounder method with 20 MHz channel bandwidth. The mean required SNR levels obtained by the exhaustive result are compared to the values obtained by the channel sounding method. During the OTA measurements with the exhaustive method, approximately 33 dB SNR was required to achieve less than 10% PER with MCS11 for all three receiver positions. When the channel sounding method was used, the required SNR for all three receiver positions was approximately 32 dB. These results show that the channel sounder method can be used to reproduce an approximation of the wireless channel, while it is slightly tend to underestimate the required SNR and deliver optimistic results.

Channel Sounding Measurements:

After the accuracy of the channel sounder method was verified this method was used for further analysis and the verification of the in-vehicle channel model we developed. For these measurements the channel bandwidth was set to 40 MHz, which was the highest supported bandwidth by the spectrum analyzer. IEEE 802.11ax NDPs were transmitted over the in-vehicle wireless channel. Several CSI samples were collected using packet preamble analysis. These CSI samples were collected using the transmitter antennas TX_{Front1} and TX_{Front2} for all receiver positions. At each receiver position the laptop was shifted a couple of centimeters to both sides several times and the channel sounding procedure was repeated to obtain a larger variety of CSI. At least 800 samples of channel estimates were saved for each receiver position. Simulations were conducted with these estimates to observe the distribution of the SNR requirements.

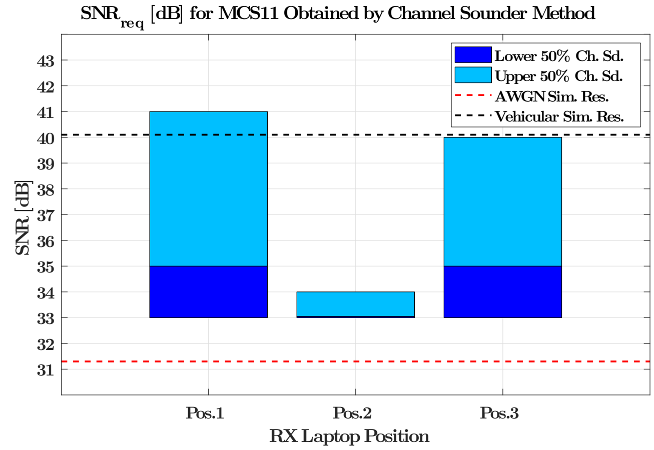

Fig. 12. Required SNR [dB] for IEEE 802.11ax MCS11 obtained using the channel sounder method with 40 MHz bandwidth

C. Results and Interpretation

Figure 12 presents the measurement results using the channel sounder method. The distribution of SNR requirements for each receiver position is plotted in bars, in which the color transition indicate the median value. The red and black dashed lines show the SNR requirements according to the simulation results with AWGN and in-vehicle channel models, respectively. The SNR requirements for the laptop position 2 have a lower median and a much smaller variance than the other receiver positions. This difference stems from the fact that the received signal had a very strong LoS component on the position 2. With a very strong LoS path, the multi-path characteristic of the channel may be negligible and the frequency response of the channel becomes relatively flat. On the contrary, the receiver positions 1 and 3 are expected to be subject to stronger multi-path effects which can create deep fades in the channel frequency response. The OTA measurement results for these positions therefore show a larger variance. Almost all results lie between the simulation results conducted with AWGN and vehicular channel models. Therefore, our in-vehicle channel model can be regarded as a worst-case approximation of an in-vehicle environment.

VI. CONCLUSION

We performed a detailed analysis of IEEE 802.11ax PHY for in-vehicle use. Using wide-band measurements in a Daimler S-Class car, we developed an in-vehicle channel model basing on IEEE 802.11 channel model B and used it in end-to-end simulations of IEEE 802.11ax PHY. Using the simulation results, we estimated the required EIRP for MCS11 on 2.4 and 5 GHz bands in a vehicular environment. Lastly, the simulation results were verified by OTA measurements.

The in-vehicle channel model we developed in this study has a much steeper power decay in time domain compared to the IEEE 802.11 channel model B. The results of our channel measurements, simulations and link budget calculations show that the highest SISO data rates defined in IEEE 802.11ax standard are achievable on both 2.4 and 5 GHz bands for in-vehicle applications. On the 2.4 GHz band, the required EIRP values are much lower than the regulatory limits. According to the OTA measurement results, our in-vehicle channel model can be regarded as a worst-case approximation of the multi-path channel in a vehicle. Our methods can be used to evaluate specific environments and new WLAN standards without the commercial WLAN hardware.

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