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On the performance of WLAN and Bluetooth for in-car infotainment systems

Alaa Mourad [a], Siraj Muhammad [b], Mohamad Omar Al Kalaa [b], Hazem H. Refai [b], Peter Adam Hoeher [c]

[a] BMW AG, Munich, Germany
[b] Electrical and Computer Engineering, University of Oklahoma, Tulsa, OK, USA
[c] Information and Coding Theory Chair, University of Kiel, Kiel, Germany

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ABSTRACT

The connected car is ushering in a new era of automotive design. Driven by increasing customer demand for connectivity and advances in electronics, connected cars are now equipped with advanced infotainment systems with a variety of applications. Seamless integration of consumer electronic (CE) devices into car infotainment systems is crucial for mimicking home and office user experience. Because wireless communication is more user-friendly than wired communication, it has become the preferred method for connecting CE devices to car infotainment systems. WLAN[1] and Bluetooth[2] are the most promising technologies for this purpose. Both systems operate in the spectrum-scarce 2.4 GHz unlicensed industrial, scientific and medical (ISM) radio band. The coexistence between WLAN and Bluetooth has garnered a significant amount of attention from both academic and industry researchers. However, the unique features of vehicle mobility and the high density of devices in a limited roadway area necessitate further investigation in the automotive domain.

This paper focuses on the coexistence between WLAN and Bluetooth systems among vehicle infotainment applications, and on WLAN co-channel interference. Performance is evaluated using experimental measurements in real-world scenarios. The mobility effect is studied in detail. Results show that an onboard WLAN network is strongly affected by the surrounding networks. Coexistence duration decreases exponentially with relative speed between automobile networks. WLAN effect on Bluetooth is extremely high when WLAN's non-overlapped channels 1, 6, and 11 are simultaneously occupied. WLAN interference leads to a significant number of clippings in Bluetooth audio signals, especially in high WLAN traffic load situations. An exponential decease in the number of clipping events as a function of speed is observed.

1. Introduction

Connectivity services have gained significant attention in recent years from automotive manufacturers. Advanced infotainment systems with big screens are no longer limited to premium automobile models. According to a report [1] by SBD automotive[3] and GSMA,[4] all new cars will be connected cars by 2025. Automobile communication modules and SIM cards can be either built-in or brought-in. Accordingly, connectivity solutions can be divided into three categories: 1) embedded, 2) tethered, or 3) integrated. In embedded solutions, the communication module and the SIM card are built into the car, allowing connection to a cellular network sans external devices. A typical example of an embedded solution is a navigation system with real-time traffic. A tethered solution utilizes a mobile phone for connecting with an automobile's infotainment system. Music streaming using Bluetooth serves as a typical example of this type of solution. Integrated solutions constitute the newest category of connectivity. An apt example of this type of solution is a mobile phone App integrated in the car

E-mail addresses: alaa.mourad@bmw.de (A. Mourad), sirajmuhammad@ou.edu (S. Muhammad), omarqal@ou.edu (M.O. Al Kalaa), hazem@ou.edu (H.H. Refai), ph@tf.uni-kiel.de (P.A. Hoeher).

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

[2] Bluetooth has been standardized by IEEE as 802.15.1 and is managed by Bluetooth SIG.

[3] Secured by design automotive technology consultancy and research, Milton Keynes, UK.

[4] GSMA, http://www.gsma.com/.

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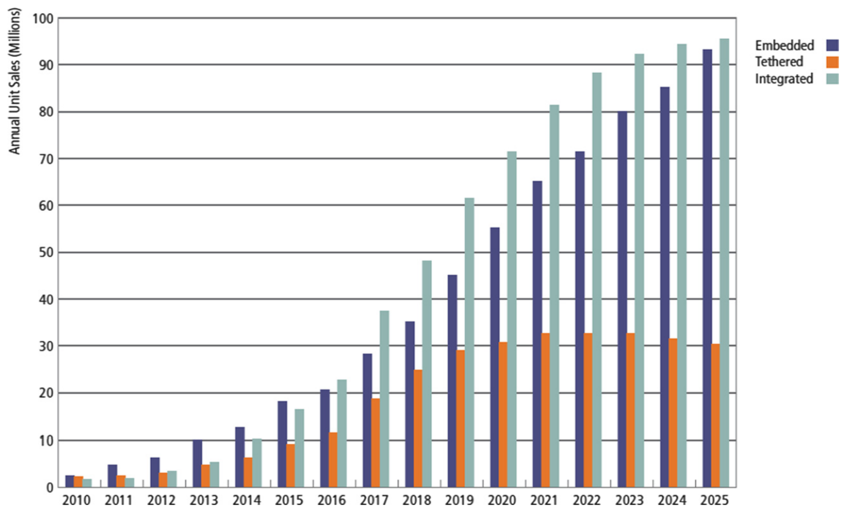

Fig. 1. Sales forecast of connectivity solutions in cars (2010–2025) [1].

infotainment system and an on-board mobile phone. In this way, mobile phone functionality can be accessed via car intelligence, allowing input/output commands, as well as access to the infotainment screen. Google's Android Auto and Apple's CarPlay are examples of widely used integrated solutions. Fig. 1 shows the sales forecast of connectivity solutions for automobiles by 2025. Total sales are projected to increase four fold between 2016 and 2025. Due to customer demand, integrated services are expected to be the most used type by 2025. As mobile phone functionality improves and expands, individuals are becoming ever more attached to their devices and the services they provide. This means that having the same platform and Apps available in an individual's automobile is extremely important to the consumer. By providing such platforms, car manufacturers play an active role in reducing the number of accidents associated with mobile phone usage while driving. Public awareness campaigns have also aided in this effort by highlighting the potential lack of focus when individuals hold their phones while driving. According to a report [2] by the United States National Safety Council, 26% of crashes involve drivers talking and texting on cell phones. This demonstrates the severity of the problem.

While connectivity solutions could be supported by either wired (e.g., via USB) or wireless technologies (e.g., Bluetooth and WLAN), flexibility and ease-of-use make wireless the favored choice. A variety of wireless systems have migrated into the automotive domain, primarily driven by the connectivity revolution. Bluetooth and WLAN are among the most widely used systems for integrating CE devices into car infotainment systems.

Bluetooth is primary used to connect CE devices to a car computer for both tethered and integrated connectivity solutions. Music streaming and hands-free calling are among the most popular Bluetooth applications. Classical Bluetooth operates in the 2.4 GHz ISM band and uses frequency hopping spread spectrum on 79 channels of 1 MHz bandwidth. The minimum number of channels permitted to maintain a connection via Bluetooth specification is 20 [3]. 802.11 systems operate in the 2.4 and 5 GHz ISM bands. Use of 5 GHz for outdoor networks, like in-vehicle applications, is limited due to weather and military radar. For example, in Europe only 100 MHz are available for outdoor usage ranging between 5.725 and 5.825 GHz, and is officially used for short range devices (SRD).[5] WLAN is used for both tethered and integrated connectivity solutions, as well. When compared with Bluetooth, WLAN provides a much higher throughput. This is necessary for applications like CarPlay. In this setup, phones are connected to a car computer using Wi-Fi direct,[6] enabling Wi-Fi devices to connect without an access point (AP). In addition, WLAN provides Internet access (hotspot) using a shared connection to the cellular network. WLAN is also a candidate for vehicle to vehicle (V2V and V2X) applications using 802.11p standard, which operates in the 5.9 GHz licensed band. In this context, 802.11p is resistant to coexistence concerns investigated in this paper. The primary focus, then, for the purposes of our investigation is WLAN infotainment applications.

Since Bluetooth and WLAN technologies were introduced, their coexistence in limited spectrum resources has been the source of extensive investigation. The TG2 task group [4] coalesced from the IEEE 802 community in hopes of proposing solutions for coexistence, which they define as "The ability of one system to perform a task in a given shared environment where other systems have an ability to perform their tasks and may or may not be using the same set of rules."

Primary factors affecting system coexistence are time, frequency, and space. Time is related to medium utilization. For example, if two systems utilize the medium 50% of the time and maintain perfect synchronization, neither will affect functionality of the other (i.e., channel access methods). Frequency is related to required bandwidth for each system relative to overall available bandwidth. If adequate frequency separation between the two systems is achieved, neither will cause interference. This equilibrium is difficult to achieve in the unlicensed bands, however, due to limited available spectrum and the large number of systems operating in this band. Space is related to spatial separation between the systems so that signal-to-interference-plus-noise ratio (SINR) at the desired receiver is sufficiently high. This factor is directly related to propagation characteristics in a given environment and transmission power. For example, if two systems operate at very low power and/or are positioned at a sufficient distance from one another to ensure ample SINR, the systems can safely coexist. Furthermore, directional antennas utilize spatial domain to reduce coexistence conflicts between systems by ensuring the beam is tightly focused and directed toward the desired receiver.

Adaptive frequency hopping (AFH) for Bluetooth was implemented to mitigate coexistence concerns between Bluetooth and WLAN. Because WLAN uses a fixed channel with 20–22 MHz bandwidth, Bluetooth avoids occupied WLAN channels by altering its

[5] Some mobile phones like Nexus 6 do not support this band for WLAN so far, status 01/2017.

[6] Called also Wi-Fi P2P.

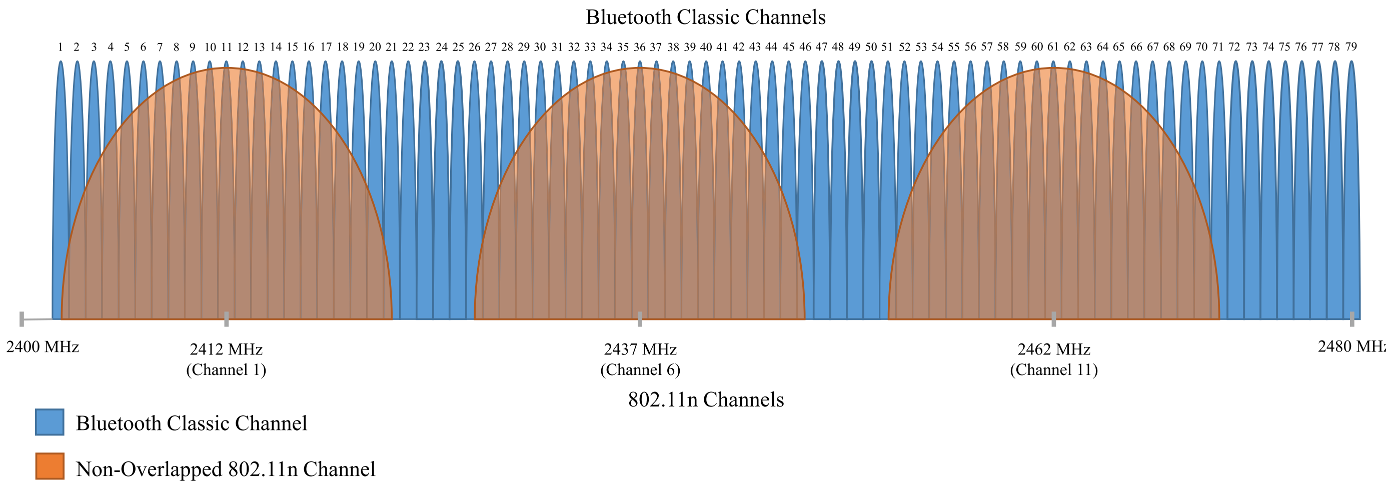

Fig. 2. Bluetooth channels and WLAN non-overlapped channels (1, 6 and 11).

hopping sequence based on measured channel quality. Doing so dramatically improves Bluetooth performance and reduces coexistence effects on other systems, like WLAN.

2. Motivation and contribution

To reiterate, this paper focuses on WLAN and Bluetooth technologies used for vehicle infotainment applications. Growth in this area is expected to be significant. Automobile mobility and high device density in a small area make the roadway environment dramatically different from a building environment. While walls strongly attenuate signals, the body of a car causes extremely low attenuation. According to [5,6], path loss in the 2.4 GHz band will not exceed 80 dB at 50 m distance between cars. Consequently, interference between neighboring cars is likely and could potentially be very high.

2.1. WLAN/WLAN co-channel interference

High density overlapped basic service sets (OBSSs) cause significant interference between neighboring cars. In the event of an increasing number of cars (e.g., during a traffic jam), throughput of each network will be appreciably degraded. Given a limited number of WLAN channels, the probability of co-channel interference becomes extremely high. The forthcoming IEEE 802.11ax standard [7] focuses on high density deployment 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." Coexistence is improved by differentiating between inter-BSS and intra-BSS frames using the new BSS color field in the frame [7]. Unfortunately, the new standard does not consider the effect of mobility, thus this serves as the impetus to better understand this effect on WLAN performance.

2.2. Bluetooth/WLAN interference

Bluetooth effects on WLAN are relatively low due to differences in medium access control and transmission power for each system [8]. However, the opposite is not true. Bluetooth performance can be heavily degraded by WLAN interference. Power difference between the two technologies, as well as WLAN traffic load, are important determining factors in this regard. Only three non-overlapped WLAN channels, namely 1, 6, and 11, are available in the 2.4 GHz ISM band. As expected, these channels are frequently used. In the near future most cars are expected to be equipped with onboard WLAN, making it highly probable that all three channels will remain busy. It is likely that automobiles will also be affected by WLAN signals coming from widely deployed outdoor hotspots, especially in city center areas. Fig. 2 shows three non-overlapped WLAN channels in tandem with Bluetooth channels. Given that all three WLAN non-overlapped channels are used, the remaining channels for Bluetooth are less than 20, which, according to the standard, is the minimum required. Consequently, depending on WLAN traffic load, collision will occur. In busy situations, AFH achieves little or no benefit. This technology was proposed to mitigate WLAN static channel allocation. Due to mobility, changes in WLAN frequency allocation coupled with the unpredictable nature of WLAN traffic makes AFH ineffective.

2.3. IEEE 802.19 task group 2

High demand from automobile manufacturers and a steady increase in the number of wireless systems installed in automobiles have drawn increasing attention to wireless coexistence among automobiles. The IEEE 802 community has responded by forming the Wireless Automotive Coexistence (WAC) task group under the IEEE 802.19 working group. Individuals serving on WAC have been charged with developing practice guidelines for IEEE 802 wireless and Bluetooth device parameter settings in hopes of enhancing performance. The work highlighted in this paper supports this activity by assessing WLAN and Bluetooth performance using off-the-shelf commercial devices to measure real-world performance.

The contributions of this work are twofold:

- Investigate WLAN co-channel interference in both static and mobile setup environments. The effect of mobility on an onboard WLAN network operating among neighboring cars is explored in conjunction with a roadside WLAN network. The relationship between coexistence duration and relative speed between the two networks is investigated.
- Evaluate Bluetooth performance of an in-car application under interference from bursty WLAN traffic. Lab measurements are recorded for a Bluetooth connection supporting music streaming relative to WLAN networks operating on non-overlapped WLAN channels 1, 6, and 11 with various traffic loads and power levels. The effect of mobility is also studied with real-world measurements of three WLAN networks – two roadside

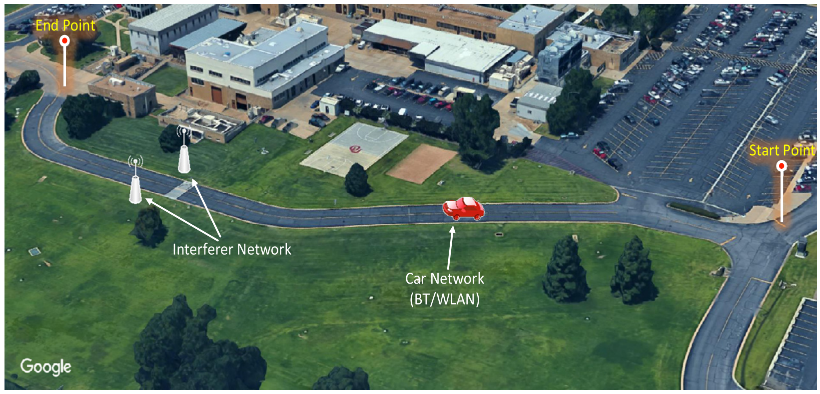

Fig. 3. Test location.

and one onboard – in addition to active Bluetooth connection in a car. The relationship between degradation of audio quality and speed is developed.

The remainder of this paper is organized as follows. Section 3 reviews the related work. Section 4 describes the measurement setup and equipment used, and Section 5 discusses the measurements results. In Section 6, solutions are proposed. Finally, Section 7 concludes the paper.

3. Related work

Although research about vehicular wireless communication is well developed, few papers focus on infotainment applications. Instead, most work focuses on VANET in conjunction with safety and traffic management applications. Because the investigation reported in this paper is experimental, only aligned related work is presented. In [9], 802.11p standard performance was evaluated in real-world scenarios using off-the-shelf devices. Results demonstrate that communication with moving vehicles is sometimes unstable. However, data was transmitted at distances exceeding 300 m with data rates up to 8 Mbps. Drive-thru Internet access and vehicular Wi-Fi offloading [10–12] have gained increased attention with a focus on using already deployed APs to provide Internet access for car passengers. Effective and fast handover is problematic for such solutions. In [11], a new handover approach is proposed for improvements in data rate and connection time. A survey investigating barriers and solutions of vehicular Wi-Fi offloading is presented in [12]. However, such solutions will exacerbate the coexistence problem in the automotive environment due to limited available spectrum and an increased number of vehicles using WLAN for other purposes (e.g., screen mirroring [13]). In our previous work [14], test drives were performed to evaluate the effect of surrounding networks on an onboard WLAN network. Measurements revealed that the interference effect is extremely high in a city environment wherein a sizable number of either public or private APs are deployed. This is in sharp contrast to highway environments. Although much work has been done on the coexistence between Bluetooth and WLAN, neither mobility effect or Bluetooth applications in the automotive domain have been considered. In [15], Bluetooth low energy (BLE) for inter-vehicular communication was investigated. Results show that communication is plausible up to 100 m however, a robust connection can be achieved only up to 50 m. Notably, WLAN interference will strongly affect performance, especially when all three non-overlapped WLAN channels are used [16]. Coexistence between 802.11g and Bluetooth was studied in [17]. Bluetooth performance was shown to be strongly affected under WLAN interference. AFH and space-time block coding (STBC) using a two-element antenna array were found to improve the packet error rate (PER). In [18], a method to evaluate the Bluetooth performance degradation by a single and arbitrary 802.11b interferer was presented. 802.11b traffic load served as the decisive factor for Bluetooth performance degradation. Depending on path loss in a given environment, Bluetooth connection range for a relatively high 802.11b traffic load was strongly reduced. Testbed results detailing interference between Bluetooth and 802.11b in [19] showed that Bluetooth performance degradation depends on distance of Bluetooth link, distance to interferer, orientation of antennas, and traffic load of IEEE 802.11b. Furthermore, voice links are more likely to suffer when compared to data links.

4. Measurement setup

System measurements were performed on the University of Oklahoma, Schusterman campus in Tulsa, Oklahoma. Fig. 3 shows the measurement path and general test setup. The environment is characterized as a two-way street measuring 5 m in width. During all measurements, there were no other active WLAN or Bluetooth connections in the same area. This was confirmed by a spectrum sweep using National instrument PXIe-1075 chassis equipped with a PXIe-5663 vector network analyzer [20].

Mikrotik Wi-Fi router boards (RB953G) equipped with R11e-2HPnD radio cards were utilized. Notably, these boards are fully configurable. The 802.11n – most recent WLAN standard operating in the 2.4 GHz band – with single antenna was chosen. User datagram protocol (UDP) traffic was transmitted between two boards – one acting as an access point (AP) and the other one as a station. A Microchip RN52 evaluation board and Samsung Galaxy Note 3 cell phone were used for Bluetooth connection. The RN52 chip acts as a carkit, supporting both music streaming and hands-free calling, which are two of the most used profiles for car applications. Bluetooth traffic was captured using a Bluetooth sniffer from Frontline. Traces and data were imported to MatLab for post-processing. Measurement equipment are summarized in Table 1. Two coexistence scenarios were considered: WLAN/WLAN co-channel interference and BT/WLAN coexistence. BT/BT coexistence was not studied, as Bluetooth uses frequency hoping, which allows efficient coexistence of multiple piconets. Also, Bluetooth transmission power is relatively low, which limits radiation to neighboring cars.

4.1. WLAN/WLAN

4.1.1. Static case

Two cars were parked parallel to one another with 1.5 m separating them, as shown in Fig. 4. This replicates when two cars are parked closely together or when there is a traffic jam. To simulate a real-world scenario, the study used a 2003 Toyota Camry and a 2016 BMW X6. A WLAN network was established in each

Table 1
Measurement parameters.

WLAN boards	Mikrotik router boards (RB953GS) with R11e-2HPnD radio cards
WLAN standard	802.11n
WLAN channel width	20 MHz
WLAN traffic type	UDP traffic
WLAN scenario	Downlink only
WLAN antenna gain	4 dBi
Cell phone	Samsung Galaxy Note 3
Bluetooth evaluation Board	Microchip RN52
Bluetooth version	3.0
Bluetooth Tx power	4 dBm
Bluetooth Sniffer	ComProbe BPA 500 Dual Mode Bluetooth Protocol Analyzer
Power measurement hardware	PXIe-1075 chassis equipped with a PXIe-5663 vector network analyzer

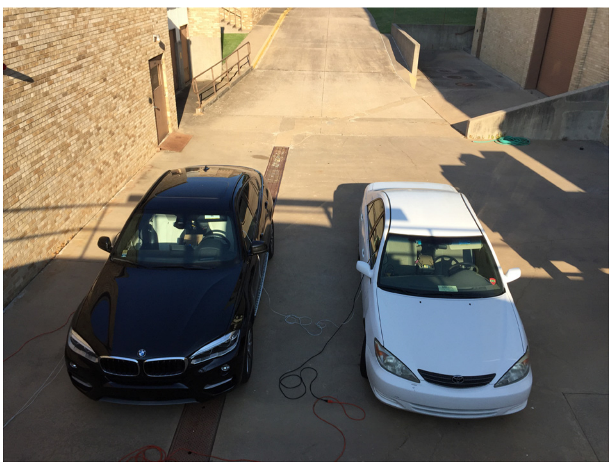

Fig. 4. The WLAN/WLAN static test setup.

car, as described above. The station was positioned on the back seat, and the AP was positioned in two places: the middle console and the driver's footwell. To study co-channel interference, both networks were configured on WLAN channel 6. As reported in [5], footwell position is the preferred choice for minimizing radiation to a neighboring car. Although this coexistence problem is quite general and not restricted to an automotive environment, density of the OBSSs is extremely high and attenuation between cars is very low in this domain. Furthermore, network planning is not possible, as APs are not fixed, and they are managed by different operators (i.e., automobile manufacturers).

4.1.2. Mobility case

Two WLAN networks operating on channel 6 were established: one in the car and the other on the road side, as shown in Fig. 5. The AP was positioned on the middle console in the car, and the station was located on the middle back seat. Test path is shown in Fig. 3. The car was driven at different speeds ranging from 5 to 35 mph with a 5 mph step size. Measurements were repeated 10 times at each speed, and results were averaged. The number of repetitions was sufficient to obtain a low standard deviation. The test scenario emulates a car with WLAN coexisting with another WLAN network, either from a neighboring car or an outdoor network (e.g., house or office).

4.2. Bluetooth/WLAN

4.2.1. Static case

The main purpose of this work was evaluating Bluetooth performance under simultaneous interference from three WLAN networks operating on the non-overlapped channels (i.e., channels 1,6 and 11). Because it is nearly impossible to position all devices in a controlled environment in a car, as some devices will have line-of-sight (LOS) conditions; others will have non line-of-sight (NLOS) conditions, depending on their position, the test was performed in a lab, as shown in Fig. 6. The influence of different WLAN power levels and traffic loads was studied. In the figure, BT2 represents the mobile phone and BT1 represents the RN-52. Music stored in the phone was played using music streaming Bluetooth profile, namely A2DP (advanced audio distribution profile). A2DP uses asynchronous connection-less (ACL) logical transport, which is a packet-switched connection [21].

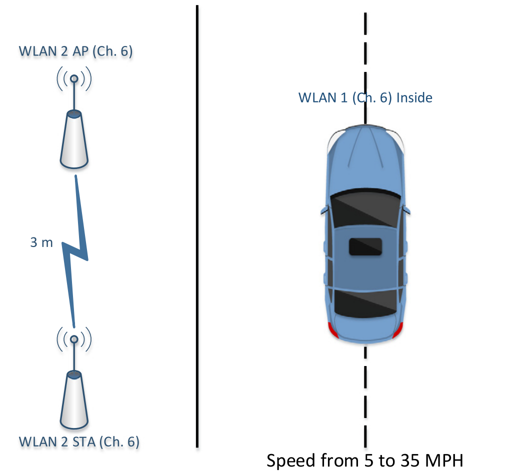

Fig. 5. WLAN/WLAN mobility case setup diagram.

4.2.2. Mobility case

A test setup was established to investigate the mobility effect (see Fig. 7). The mobile phone was positioned on the back seat, and the RN52 was positioned on the dashboard. In addition, a WLAN network was set in the car with AP on the dashboard, and a station was position on the middle back seat. Two additional WLAN networks were set up on the roadside – one on each side with 3 m distance between the AP and station. The car network was configured on channel 6, while the roadside networks utilized channels 1 and 11. The car was driven at speeds ranging from 5 to 35 mph with a 5 mph step size. In such scenario, mobility effect can be studied when all three non-overlapped WLAN channels are simultaneously occupied in the presence of an active in-car Bluetooth connection. Fig. 8 shows a typical real-world example.

5. Measurements results

Results for both scenarios – WLAN/WLAN and BT/WLAN – are presented in this section. A discussion follows. Although results might vary given different measurement equipment and alternative cars, findings should be representative of available commercial devices that implement both WLAN and Bluetooth standards.

5.1. WLAN/WLAN results

When two WLAN networks operating with maximum traffic load are co-located within sensing range of one another, throughput of each network is nearly equal. The sum of both nearly equals maximum achieved throughput when each network operates independently [22]. Given a static scenario, transmission power is the primary factor affecting throughput. Relative speed between the two networks plays an additional role in the mobility scenario. Let us define coexistence duration CD as the time-period in which the throughput of both networks is affected by interference. Given that

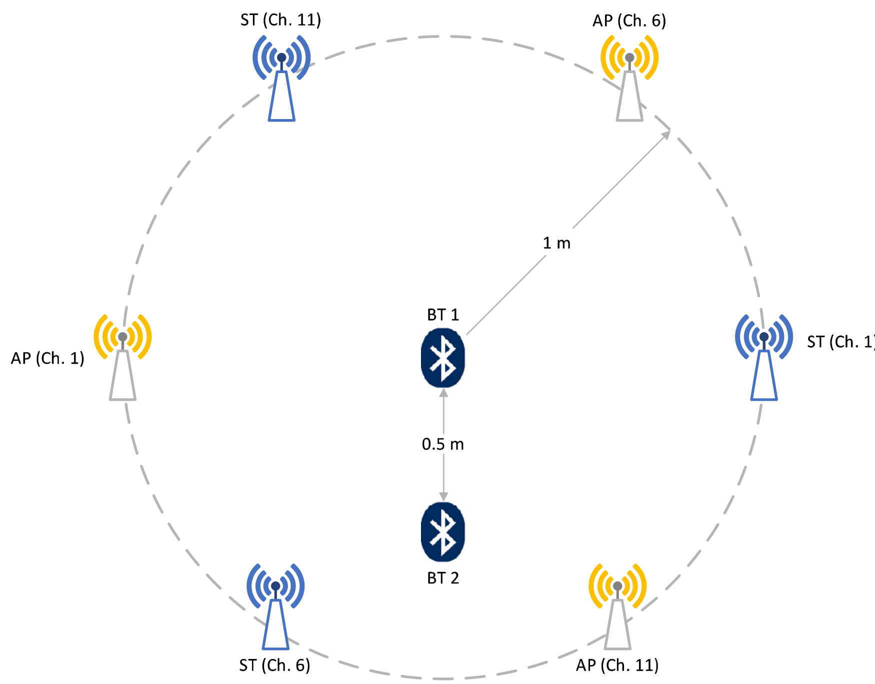

Fig. 6. BT/WLAN test setup in the lab.

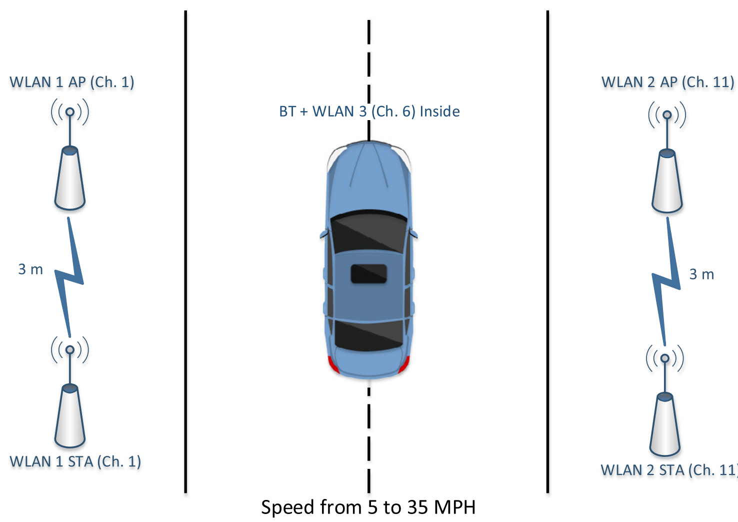

Fig. 7. BT/WLAN mobility case setup diagram.

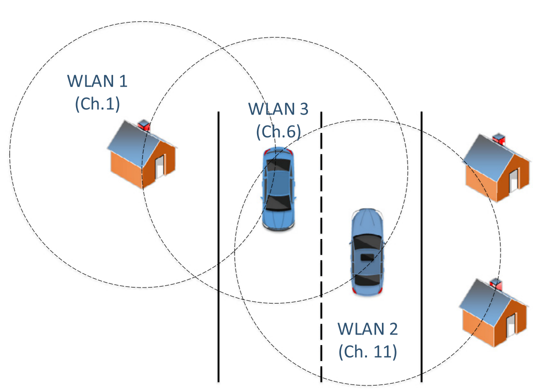

Fig. 8. Example scenario.

the power of both networks is fixed, relative speed V between the two networks is the primary factor affecting coexistence duration. Given low mobility, channel time-variance is of negligible influence. $CD(V)$ is calculated using throughput time derivation to determine the time difference between positive and negative peaks, as described in (1):

$$CD(V) = \left| t|_{\theta_V = max\left(\frac{\delta\theta}{\delta t}\right)} - t|_{\theta_V = min\left(\frac{\delta\theta}{\delta t}\right)} \right|, \quad (1)$$

where $\theta(t)$ is WLAN network throughput as a function of time. Fig. 9 provides an example of calculating interference duration for the on-road network at a speed of 20 mph, in other words $CD(V = 20\text{ mph})$.

5.1.1. Static case

Transmission power was changed from 0 to 16 dBm in 2 dB steps. Fig. 10 shows network throughput for both AP positions. Measurements were repeated 15 times, which was ample to obtain a low standard deviation. Average and standard deviation values are represented in the figure. Maximum achieved through-

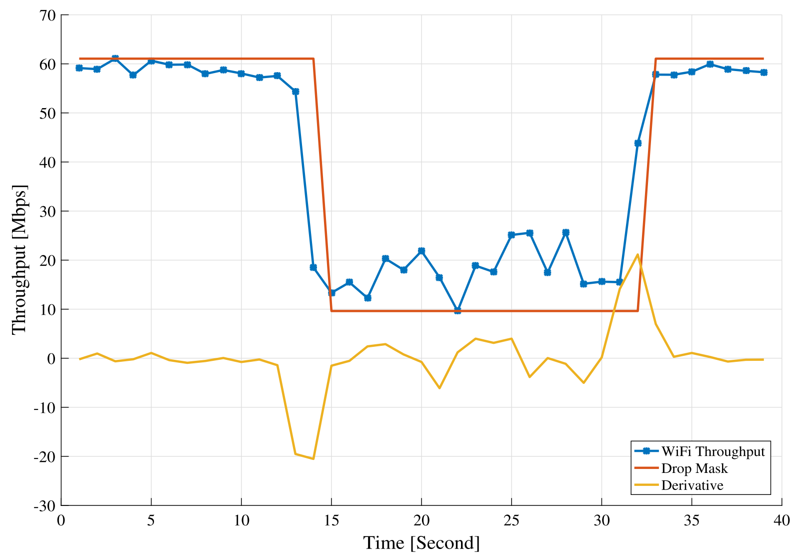

Fig. 9. Coexistence duration for the road side network at $V = 20$ mph.

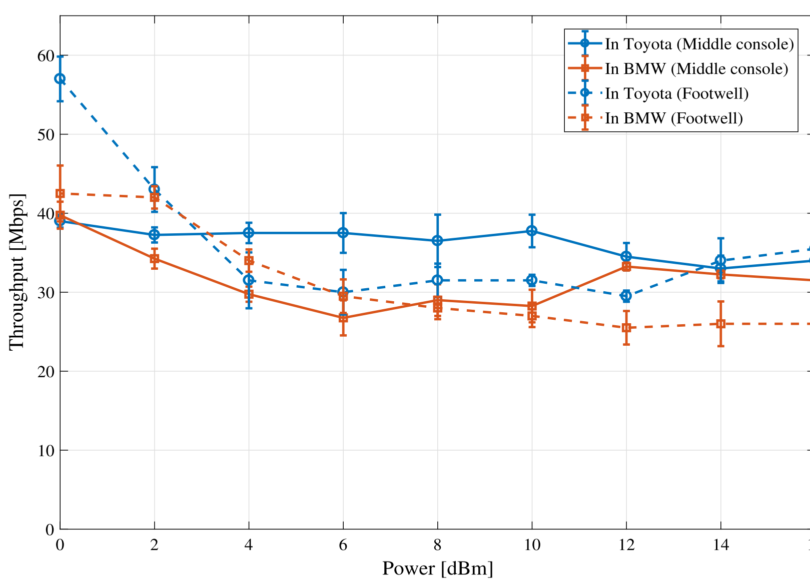

Fig. 10. Throughput as a function of power for both AP positions. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

put using these boards is approximately 66 Mbps [23]. For high transmission power conditions, the networks share the medium evenly and, therefore, only approximately half of maximum achievable throughput is reached. This behavior continues as the power decreases until the power is so diminished that neither network senses the other. At this point, network throughput for both starts to increase. Given the footwell position, throughput starts to rise at a higher power level (e.g., approximately 4 dB difference) when compared with the middle console position. The reason for this can be explained by the fact that in the middle console scenario, the majority of signals propagate through windows, which have low attenuation at this frequency. More details can be found in [23]. Notably, a power level of 16 dBm is not the maximum allowed power level. The number differs depending on country regulations. For example, 19 dBm is the maximum allowed in Germany, demonstrating the severity of the coexistence problem in the automotive domain. Most cars are expected to have WLAN for infotainment applications in near future. Note that the interfering network could either be in a neighboring car or from a fixed AP in homes or offices. Interestingly, the performance of the fixed APs will also be affected by networks in cars in the vicinity. These results could be generalized based on work presented in [22]. When multiple cars are stopped near each other (e.g., traffic jam), throughput will theoretically be divided by the number of cars.

5.1.2. Mobility case

In Fig. 11, coexistence duration $CD(V)$ is shown as a function of speed for both networks, where all measurement points (i.e., 10 datasets) are presented. Results for both networks are quite similar, as is the observed behavior. Coexistence duration decreases exponentially with the speed. Given an extremely low speed ($V = 5$ mph), coexistence duration could reach 60 s. This is not acceptable, especially when multiple cars share the same channel. For higher speeds ($V \geq 35$ mph), like automobiles traveling in city center, CD becomes very short: $CD(V) < 15$ s. However, this length is still not negligible. The relationship between coexistence duration and speed can be modeled by an exponential relationship:

$$CD(V) = a \times e^{(b \times V)}, \tag{2}$$

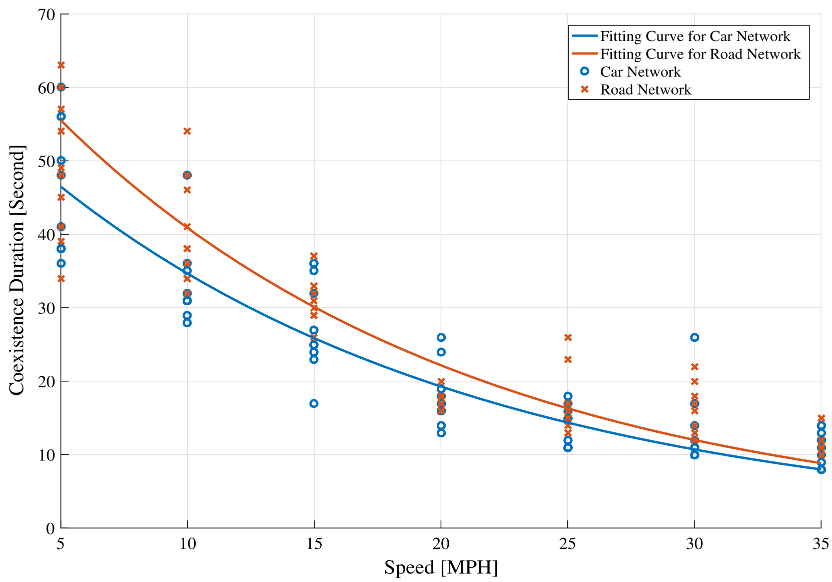

Fig. 11. Coexistence duration as a function of speed for both networks. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

Table 2
Parameters of coexistence duration model.

	Parameters	
	a	*b*
Car network	19.27	−0.5111
Road network	22.15	−0.5331

Table 3
Statistics of coexistence duration model.

	Statistics	
	RMSE	R^2
Car network	5.8796	0.8049
Road network	5.6029	0.8469

where V is the relative speed between the two networks. The coefficients for both networks – car and road – are shown in Table 2. Mean, standard deviation and correlation between the model and measurement values are shown in Table 3.

5.2. Bluetooth/WLAN results

In our tests, the audio signal was captured by a Bluetooth sniffer, and then extracted and imported to MatLab for post-processing. Bluetooth ACL supports retransmissions to account for transmission errors. However, when the number of errors is very high, retransmission and buffering will not help. This results in a high distortion in the audio signal due to clipping, which occurs when the amplitude of a digital audio signal exceeds the maximum supported level. In this work, the evaluation of audio quality is based on the number of clipping events in the audio signal. Clipping events with five or more clipping samples were considered; primarily because events with less than five samples were not clearly recognized when listening to music. Both left and right channels were considered in the analysis.

Let us define PER_{BT} as Bluetooth packet error,

$$PER_{BT} = \frac{N_{PE} + N_{HE}}{N_{Tot}}, \tag{3}$$

where N_{PE} is the number of packets with payload errors, N_{HE} is the number of packets with header errors, and N_{tot} is the total number of packets observed by the Bluetooth sniffer. A packet with both header error and payload error was counted as header error only.

In addition, RR is the retransmission rate from correctly received packets, given by

$$RR_{BT} = \frac{N_{Re}}{N_{Ok}}, \tag{4}$$

where N_{Re} is the number of successfully received packets with retransmissions and N_{Ok} the total number of successfully received packets.

5.2.1. Static case

The purpose of this setup was to study received Bluetooth signal under interference from three WLAN signals on channels 1, 6, and 11 at equal power levels. This configuration facilitates analyzing results. Bluetooth transmission power was fixed, while WLAN power changed between 0 and 24 dBm in 3 dB steps. Also, WLAN traffic load was tuned from 10 to 50 Mbps with a 10 Mbps step size, in addition to maximum achievable throughput. Fig. 12 shows the number of clipping events per second in the music for various WLAN traffic loads as a function of WLAN power level. Bluetooth retransmission rate and packet error rate are shown in Fig. 13. For WLAN power level below 3 dBm, the effect on Bluetooth is negligible, even for a high WLAN traffic load. This means that even in a collision scenario, the SINR remains high enough for a Bluetooth receiver to successfully decode the data. PER is zero, and RR is very small. As the WLAN power level increases, the number of clipping events increases. This is the result of an increase in RR and PER. The number of clipping events per second reached 0.23 for a power level of 15 dBm and traffic load of 10 Mbps. Surprisingly, for a high WLAN traffic load, the number of clipping events is lower than for a low traffic load at this power level. This is explained by the fact that given higher retransmission rate at low throughput (25% for 10 Mbps) when compared to high throughput (10% for maximum throughput), there is a correlation between RR and the number of clipping events. For low traffic load, some channels might be classified as acceptable by Bluetooth due to low WLAN medium utilization. However, collisions could still occur during transmission. As a result, additional retransmissions are required for a lower WLAN traffic load. PER remains smaller than during high WLAN traffic load. For high WLAN power level (e.g., 24 dBm), the number of clipping events is very high, reaching one clipping per second for a maximum traffic load. RR increases

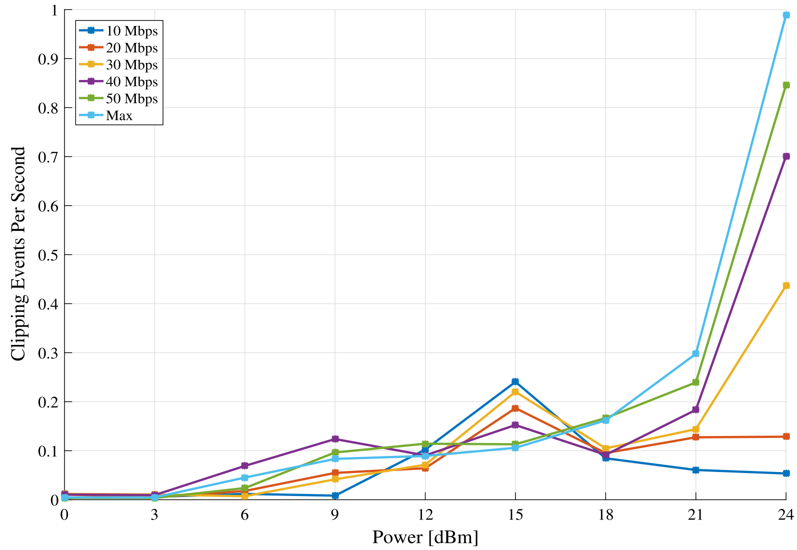

Fig. 12. Number of clipping per seconds for different traffic load as a function of WLAN power level. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

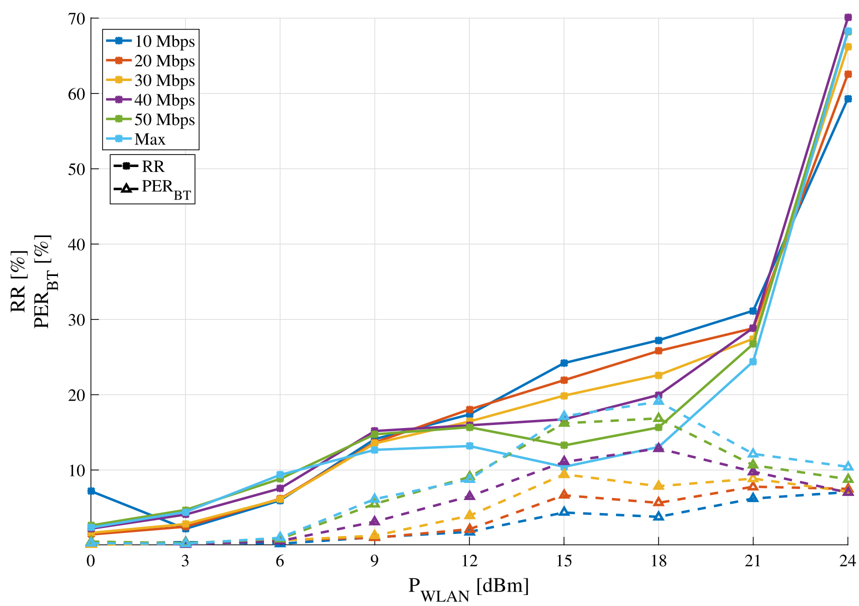

Fig. 13. Bluetooth packet error rate and retransmission rate as a function of WLAN power level. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

tremendously, reaching 69% for a maximum WLAN traffic load. PER is smaller when compared to an 18 dBm power level for a high WLAN traffic load. This phenomenon is related to the channel quality classification procedure for a Bluetooth master device. It is interesting to note how AFH copes with such WLAN interference and how Bluetooth channels are selected under this type of coexistence scenario. Fig. 14 and Fig. 15 illustrate the histogram of Bluetooth channels as a function of WLAN traffic at WLAN power levels of 18 and 24 dBm, respectively. Both figures show the importance of channels 71–78 for Bluetooth operations in such scenarios. Theses channels were primarily used for all WLAN traffic loads and power levels. Given low WLAN traffic loads, even channels within WLAN channels could be used by Bluetooth. When comparing the two figures at maximum WLAN traffic load, Bluetooth channels 50–70 are used more often at a WLAN power level of 18 dBm. This explains why PER is higher at a WLAN power level of 24 dBm.

5.2.2. Mobility case

Fig. 16 shows the number of clipping events per second as a function of speed, where all measurement points (i.e., 10 datasets) are presented. For extremely low speeds ($V = 5$ mph), the number of clipping events per second can reach 0.36. Mean value of the complete measurement set is 0.17, which is unacceptable, especially given that this speed is typical during traffic jam conditions. As speed increases ($V = 35$ mph), which is a typical speed in city centers, the number of clipping events decreases until it reaches approximately zero. Notably, speed represents relative speed between the two networks. Therefore, when driving at a much higher speed, a significant number of clipping events might occur when the relative speed between two networks is not high enough. Curve fitting of the data sets was performed so that the relationship between the number of clipping events per second and the speed can be described by:

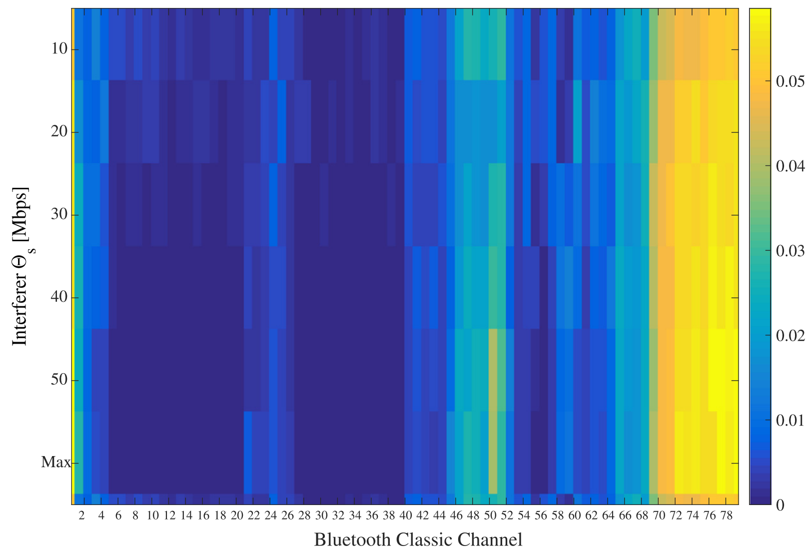

Fig. 14. Bluetooth channels histogram as a function of WLAN traffic load at power level of 18 dBm. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

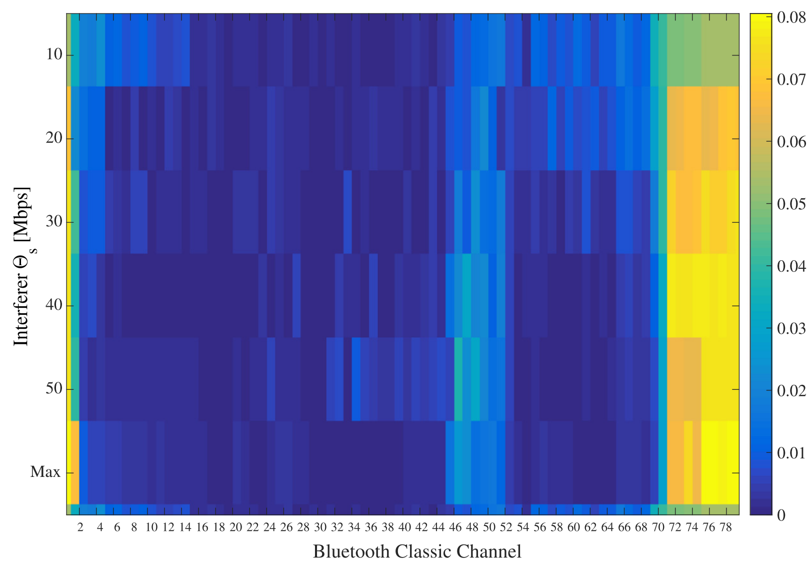

Fig. 15. Bluetooth channels histogram as a function of WLAN traffic load at power level of 24 dBm. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

$$N_{clipping} = a \times e^{(b \times V)}, \quad (5)$$

where $a = 0.3338$; $b = -0.1318$; and V is the relative speed between the two networks. RMSE and R^2 are given by 0.0140 and 0.9717, respectively.

6. Discussion

A possible solution for the coexistence problem between Bluetooth and WLAN is offloading WLAN traffic to the 5 GHz ISM band using the 802.11ac standard [24]. In addition, this frequency band provides more channels for WLAN, which significantly increases the supported data rates in dense deployment scenarios. The 5 GHz ISM band is also used by meteorological and military radars, which adds dynamic frequency selection (DFS) [25] restriction on WLAN for outdoor use. Although the difference between outdoor and indoor environments is not well defined by regulations, the car environment is most likely considered outdoors due to very low attenuation of car bodies [5]. The number of WLAN channels for outdoor usage without DFS requirement is very limited. For example, in Germany there are no official channels for WLAN without DFS. The 5.725–5.825 GHz band, which is officially used for SRD, could be used for WLAN in outdoor operations with 25 mW maximum transmission power. On the other hand, DFS with mobility is quite challenging, as the radar detection mechanism might not perform well in such cases. Due to FCC requirements, when a radar signal is detected, the corresponding channel should be blocked for a minimum of 30 min. This leads to a reduction in the number of available channels. More research is needed in this area. An effective power control mechanism should be used to reduce interference in the surrounding environment. Transmission power should be high enough to guarantee acceptable coverage inside the car. It is important for the power control to be standard among automobile manufacturers to guarantee fairness in medium sharing [23]. Regulatory bodies should take action in this regard.

Multiple input multiple output (MIMO) techniques could be used for in-car WLAN to boost data rates [23]. Channel utilization for MIMO is smaller than single input single output (SISO) at the same date rate, which leads to improved coexistence with Bluetooth. It is recommended that only non-overlapped WLAN chan-

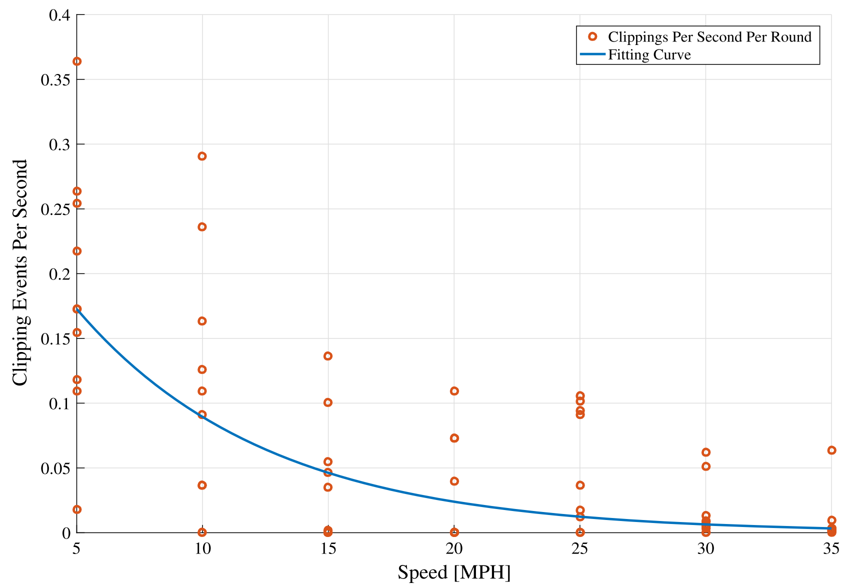

Fig. 16. Number of clipping events per second for different speeds. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

nels 1, 6, and 11 are used in automobiles, leaving a number of free Bluetooth channels between the WLAN channels, in addition to Bluetooth channels 72–79, as shown in Fig. 2.

It is important to mention that due to their popularity in this domain, the focus of this work was merely on Bluetooth and WLAN. There are many other systems (e.g., ZigBee) operating in this band. This could escalate the coexistence problem. Furthermore, the long term evolution (LTE) system operates in the 2.3 GHz band in some regions, which could cause interference to systems operating in the neighboring 2.4 GHz band.

WLAN standard 802.11ad is a possible candidate for solving the coexistence problem in this domain. Because attenuation in the 60 GHz band is very high, radiation to the outside is significantly minimized. Moreover, an efficient beamforming technique is easy to implement in this band; this assures acceptable coverage inside the car. It is unclear when CE devices will support this band. Also, the cost of an antenna module is very high.

7. Conclusion

Connected cars are growing at a rapid pace. All new cars are expected to be connected cars by 2025. This trend is driven by increased customer demand and improvements in consumer electronics. WLAN and Bluetooth are among the most used technologies in the 2.4 GHz unlicensed ISM band for automobile infotainment applications. Low insertion loss between cars and the high density of devices in a small area make wireless coexistence challenging. Furthermore, mobility effect is unique in the automotive environment.

Two main scenarios were investigated in this work: WLAN/WLAN co-channel and BT/WLAN coexistence. Lab measurements and road measurements were performed. Results for WLAN/WLAN indicate that a car WLAN network is greatly affected by surrounding networks, either in neighboring cars or fixed WLAN networks. Decreased duration in throughput could reach 60 s for extremely low speeds (e.g. traffic jam conditions). This attribute affects a variety of applications, especially when multiple networks share the same channel. In the BT/WLAN scenario, results indicate that Bluetooth performance is greatly affected when non-overlapped WLAN channels 1, 6, and 11 are used, especially given high WLAN traffic load. Real-world examples using a car traveling at various speeds were studied. The effect is not negligible, especially during low speeds.

8. Future work

Although it is difficult to generalize findings based on the conducted measurements, we believe that this work will increase the attention given to the coexistence problem in this domain. It will also open the door for further studies, especially those focusing on the connected vehicle revolution. The spectrum for future work is broad. A study on required throughput for WLAN applications in vehicles is extremely important for understanding whether or not the effect of interference not only reduced throughput but also affects the QoS of various applications. Solutions for improving Bluetooth quality in this domain are needed and should be investigated. Without additional research, impairment to Bluetooth performance could be significant, especially when an increasing number of vehicles are equipped with WLAN.

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