Bluetooth and IEEE 802.11n System Coexistence in the Automotive Domain

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***Abstract*—Connected cars have telecommunication services similar to those found in homes and offices. Passengers have come to expect efficiently using time spent in their cars working and engaging in entertainment. Fulfilling this desire requires advanced infotainment systems with a variety of capabilities and functions similar to mobile phones. As people become more attached to their mobile phones, seamless integration of phones into the car computer becomes more crucial. Bluetooth and IEEE 802.11 systems are often used to connect mobile phones to car computers. Both technologies operate in the 2.4 GHz unlicensed industrial, scientific and medical (ISM) radio bands. However, since early development of standards governing the ISM band, coexistence among devices sharing the band have been under close scrutiny. An increased use of Bluetooth and 802.11 systems in the automotive domain and the logistics of having extremely small distances between devices makes coexistence a challenging task.**

This paper presents performance evaluation of both WLAN[1] and Bluetooth for typical automotive domain applications (i.e., music streaming and hands-free calling). Focused attention is paid to a scenario in which all three non-overlapped WLAN channels are used. The effect of traffic load and WLAN power level are investigated. Results demonstrate that Bluetooth channels 71 to 78 are critical to maintain acceptable Bluetooth connectivity. Hands-free calling is more sensitive to interference than music streaming. Bluetooth effect on WLAN is small.

***Index Terms*—Bluetooth, WLAN, Wireless coexistence, Automotive domain, 2.4 GHz ISM band, Intra-vehicle interference, IEEE 802.11, Hands-free calling**

I. Introduction

Driven by customer demand, car manufacturers have recently invested tremendous effort into their automobiles infotainment systems. Most new cars have large screens and a variety of connectivity services. These features are rapidly becoming decision points for choosing between car models [1]. Furthermore, the automotive domain has recently attracted the interest of big technology companies like Apple and Google, which have developed special platforms for cars, CarPlay and Android Auto, respectively.

Manufacturers have employed a number of wireless technologies to facilitate car connectivity and support various functionalities. Bluetooth[2] and WLAN, in addition to Kleer [2] are among the most widely recognized that operate in the 2.4 GHz unlicensed ISM band.

While Bluetooth and WLAN are often used to provide wireless connection between the phone and car computer, Kleer is often utilized to stream high quality music. Bluetooth is usually used for music streaming, hands-free calling, and transferring contact information. WLAN is primarily used to provide Internet access for passengers, given a shared connection to the cellular network. WLAN is also used for applications like screen mirroring using Wi-Fi direct[3]. It is expected that CarPlay and Android Auto may also utilize Wi-Fi direct to provide high speed wireless data connection to car computers.

As mentioned above, Bluetooth and WLAN operate in the 2.4 GHz unlicensed ISM band. These technologies are rather compatible than competitor to each other, although coexistence between them is not completely avoidable at all times in all places (e.g., homes and offices). Since Bluetooth and WLAN were introduced, a tremendous amount of work has been invested to find ways to improve coexistence in various scenarios. The IEEE 802 community has initiated a task group (TG2) to study coexistence between WLAN (802.11b) and wireless personal area network (WPAN, 802.15). Advisement from this task group was submitted in 2003 and became recommended practice [3].

The most widely adapted technique in this regard is adaptive frequency hopping (AFH) for Bluetooth systems. The Bluetooth physical layer is based on frequency hopping spread spectrum (FHSS), which was mainly chosen to allow coexistence between multiple Bluetooth systems operating in the same location. FHSS systems coexist inefficiently with other systems that use static bandwidth allocation, like Wi-Fi. Thus, in the event of randomly chosen hops, there is a high probability that a Bluetooth system hops to frequencies within the bandwidth of Wi-Fi. AFH avoids interference by choosing hoping frequencies, depending on channel quality. As such, frequencies used by other systems will be avoided,

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

[2]It was standardized by IEEE as 802.15.1, now it is managed by Bluetooth SIG

[3]Called also Wi-Fi P2P, it enables Wi-Fi devices to connect directly

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dramatically improving Bluetooth performance and reducing the effect on other systems.

Related work about wireless coexistence has a wide scope and is generally divided into three categories, depending on the type of investigation: analysis, simulation, and experimental. Because the work detailed herein is experimental, only aligned related work is provided. In our previous work [4], test drives were performed to assess interference from surrounding WLANs to the network inside the car. Results demonstrated a dramatic effect, especially in the city center. Effectiveness of Bluetooth low energy (BLE) for inter-vehicular communication was studied in [5]. BLE performance was analyzed under interference from 802.11g and found very resilient to interference. In [6], interference between IEEE 802.11b and Bluetooth is empirically investigated. Minimum signal-to-interference level required to meet PER requirements in Bluetooth standard was investigated. In [7], a method to study the effect on Bluetooth by single and arbitrary 802.11b interferer was developed. Given low 802.11b network load, the effect on Bluetooth was extremely weak. For moderate to high 802.11b network load, Bluetooth connection range was reduced, depending on path loss in a given environment. Testbed results in [8] showed that Bluetooth performance under interference from IEEE 802.11b depends on distance of Bluetooth link, distance to interferer, orientation of antennas, and IEEE 802.11b traffic load. In addition, voice links are more likely to suffer when compared to data links. Researchers in [9] studied coexistence between 802.11g and Bluetooth systems in indoor environments. AFH and space-time block system coding (STBS) using two-element antenna array for Bluetooth was found to improve PER performance.

II. Motivation and contribution

Although much work has been done on how to improve coexistence between WLAN and Bluetooth, only small contributions have been made in the context of the most recent 802.11n standard. 802.11n uses a number of new techniques (e.g., MIMO, packet aggregation, block acknowledgment, channel bonding [10]), that could impact Bluetooth communication. In [11], the mutual impact of 802.11n and Bluetooth devices are investigated through empirical experiments. Only file transfer profile (FTP) for Bluetooth was considered. Results show that both networks are highly impacted, especially when devices operate in close proximity to one another. This scenario is typical of what could occur in the automotive domain, as distance between devices is less than 2 m. Some car manufacturers have designed more than two access points for various applications. Note, however, that coordination between them is not possible due to their position and complexities of car design. Furthermore, path loss in the automotive domain is different than in an indoor environment, where strong signal attenuation occurs due to walls. Simulations and measurements in [12] and [13], respectively, show that path loss from inside the car to the surrounding space is extremely low; this is different from indoor environments. Notably, any kind of network planning will not help in interference reduction, because these WLANs in the cars are mobile and with different speeds.

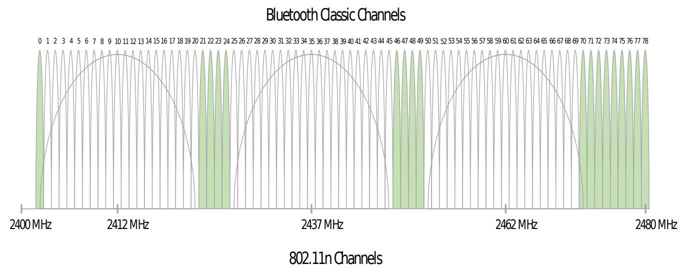

Fig. 1: Bluetooth channels and WLAN non-overlapped channels (1, 6 and 11)

The IEEE 802 community has recently recognized coexistence issues in the automotive domain that have been driven by car manufacturer demands. Consequently, a new study group [14] was formed under the wireless coexistence working group. The goal of this group is to optimize both WLAN and Bluetooth parameter settings to enhance coexistence.

Several Bluetooth applications have recently migrated into the automotive domain, Music streaming and hands-free calling are among the most used. The main contribution of this work is to assess the performance of music streaming and hands-free calling using Bluetooth profiles, namely Hands-free Profile (HFP) and Advanced Audio Distribution Profile (A2DP). A typical, real life scenario was considered: three WLAN networks operating on three non-overlapping channels, each with different power levels and traffic loads. The mutual effect of these three networks and a Bluetooth connection was examined. This set up emulated a typical real-life scenario wherein all three non-overlapped channels were occupied. Of particular interest was how Bluetooth would perform under said conditions, especially taking into account that the AFH is active. According to Bluetooth specification [15], the minimum required number of Bluetooth RF channels should be 20. Fig. 1 shows 79 Bluetooth channels alongside three non-overlapped WLAN channels. Thus, if Bluetooth channels between Wi-Fi non-overlapped channels are used, 20 channels will not be available. Furthermore, side-lobes of WLAN channels could measure high in the event of significant interference power. Performance of both systems in such a scenario is quite interesting. To the best of our knowledge, a similar study in the open literature is not available.

The remainder of this paper is organized as follows. Section III describes the measurement setup, and Section IV displays measurement results. Section V highlights results. The paper is concluded in Section VI.

III. Measurement setup

Measurements are performed in an underground room, where no other networks are active in the 2.4 GHz ISM band; room status was confirmed via a spectrum sweep prior to testing. Justification for choosing an indoor room, as opposed to a car, is that it is nearly impossible to position all measurement devices in a controlled manner within a car, as some devices will have line-of-sight (LOS) conditions and others will have non line-of-sight (NLOS) conditions, depending on their position. Analyzing results is a difficult task. Measurements in [16] suggest that an intra-car channel model is similar to indoor channel models in terms of small scale variation, though delay spread is much smaller than in indoor environments (depending on room size). Thus, the effect of multi-path propagation on inter-symbol interference (ISI) is negligible.

Used Wi-Fi boards are Mikrotik router boards (RB953G) equipped with R11e-2HPnD radio cards. The boards are fully configurable, allowing power level and traffic load adjustment. Six boards were used in the test, with two of each operating on a different WLAN channel (1, 6 and 11); one serves as an access point and the other as a station. Downlink user datagram protocol (UDP) traffic is continually generated as part of the measurements. The standard 802.11n with a single antenna were used. Samsung Galaxy Note 3 and Microchip RN52 evaluation boards were leveraged for Bluetooth connection. RN52 acts as a Bluetooth car kit, supporting both music streaming and hands-free calling. A Bluetooth sniffer from Frontline (ComProbe BPA 500 Dual Mode Bluetooth Protocol Analyzer) was used to capture Bluetooth traffic. WLAN boards were mounted on the circumference of a circle with 1 m radius, as illustrated in Fig. 2. The purpose of this setup was to study received Bluetooth signal under interference from three WLAN signals (i.e., channels 1,6 and 11) with equal power levels. This configuration is extremely helpful for analyzing results. Measurement setup was static, meaning that distances and device positions remain constant throughout the test. Bluetooth power was not changed; both devices supported class 2 (i.e., maximum power level of 4 dBm). For Wi-Fi boards, power was changed from 0 to 24 dBm with 3 dB step size. For each power level, offered throughput was tuned from 10 to 50 Mbps with 10 Mbps step size, in addition to the maximum achieved throughput. Maximum achievable value was maintained at 66 Mbps without interference. In this way, the effect of both interference power and traffic load on Bluetooth could be studied. With regard to music streaming, BT1 represents RN52, and BT2 represents the cell phone (the receiver). A song stored in the cell phone was continually streamed. With regard to hands-free calling, BT1 represents the cell phone, and BT2 represents the RN52 board. A recorded speech was played continuously on a computer with speaker output connected to the RN52 microphone input. Speech was transferred to the cell phone using Bluetooth hands-free profile (HFP). The Bluetooth sniffer was mounted near BT1, and collected data before exporting it to MatLab for post processing. Music streaming uses asynchronous connectionless (ACL) link, while hands-free calling uses synchronous connection oriented (SCO) link [17].

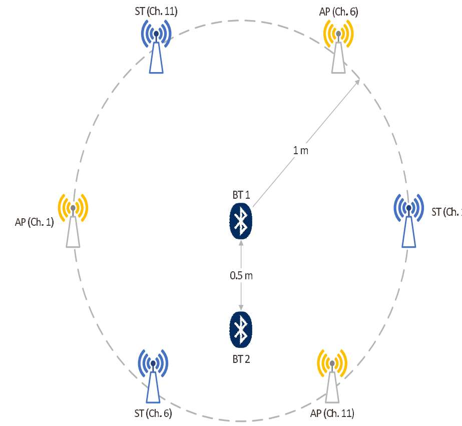

Fig. 2: Measurement setup diagram

IV. Measurements results

Results for both profiles are presented in this section and then discussed in the next. Measurements were repeated 20 times. Mean value is represented in the figures. Notably, results could vary given an alternative hardware implementation scheme than the one used in our setup. However, our results should be regarded as representative of available commercial devices implementing Bluetooth and Wi-Fi standards.

Let's define PER_{BT} as Bluetooth packet error,

$$PER_{BT} = \frac{N_{PE} + N_{HE}}{N_{Tot}} \tag{1}$$

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 as observed by the Bluetooth sniffer. The packet with both header error and payload error is counted as header error only.

In addition, RR is the retransmission rate out of correctly received packets, given by:

$$RR_{BT} = \frac{N_{Re}}{N_{Ok}} \tag{2}$$

where N_{Re} the number of successfully received packets with retransmissions and N_{Ok} total number of successfully received packets. In this work, only SCO links are used for hands-free profile as the eSCO link is not supported by the cell phone employed in this test. As such, the test is considered a worst-case scenario.

For Bluetooth effect on WLAN, linear model was used due to the linear relationship between the set and get throughput in case of no interference. Therefore, Bluetooth effect can be easily quantified. Achieved throughput is given by:

$$\Theta_g = \alpha \Theta_s + \beta \tag{3}$$

where Θ_s and Θ_g are the set and get throughput, respectively; α is the slope; and β is the intercept. In the event that there is no effect on WLAN, $\alpha = 1$ and $\beta = 0$. Linear regression was used to find both coefficients based on all measurement points (i.e., 20 measurement results).

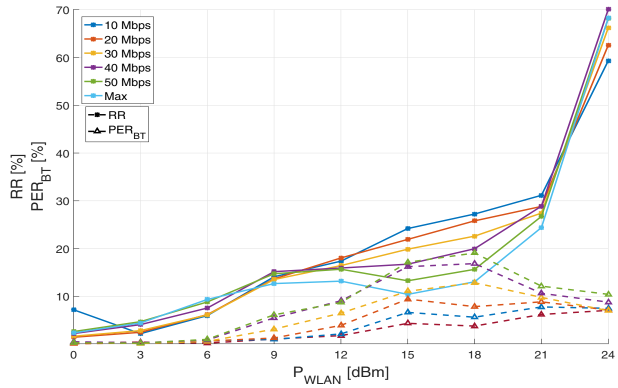

Fig. 3: Bluetooth packet error rate and retransmission rate as a function of WLAN power level; music streaming

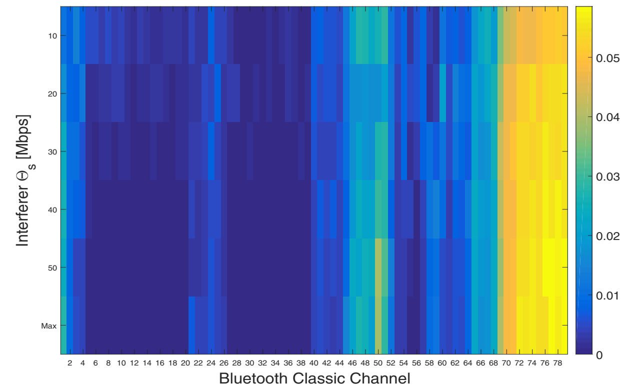

Fig. 4: Bluetooth channels histogram as a function of WLAN traffic load at power level of 18 dBm; music streaming

Music and speech quality was evaluated by five raters who listened to multiple measurements; quality was classified as good, fair, or poor (incomprehensible). In the event that results varied by rater, the majority opinion was used.

A. *Music Streaming*

1) Bluetooth performance: Fig. 3 shows the PER_{BT} and RR_{BT} as a function of WLAN power levels for various WLAN traffic loads. For WLAN power levels between 0 to 6 dBm, the effect on Bluetooth connection was negligible for all traffic loads. This result can be explained by the fact that $SINR_{BT}$ was sufficiently high, and therefore packets were correctly decoded, even when collisions occurred. Given that the WLAN power level increased, PER_{BT} also increased until it reached around 19% at interference level of 18 dBm with the maximum offered throughout. The effect of interferer traffic load is clear at all power levels: the lower the WLAN throughput, the greater chance for Bluetooth to jump inside WLAN channels. As such, collisions occur less often. For high WLAN power level (i.e., 21 to 24 dBm), the effect of traffic load becomes smaller. Interestingly, PER_{BT} at interferer power level of 24 dBm is smaller than at power level of 18 dBm. The reasons for this phenomenon are related to retransmissions used in the event of ACL link [17]. If the CRC check fails, packet is retransmitted, so retransmissions could lead to successful reception of packets plagued with long delays and lower throughput. This could affect music quality. For power level 18 dBm, music quality was acceptable. For interference power level of 24 dBm, music quality was extremely poor with incomprehensible words. The scores by raters are shown in Table I. Clearly, retransmissions rate at the power level 24 dBm is much higher than at power level of 18 dBm. The RR_{BT} is approximately $60 - 70\%$.

Fig. 4 shows a histogram of Bluetooth hopping channels as a function of WLAN traffic load at WLAN power level of 18 dBm. It demonstrates that given low traffic load, Bluetooth can jump inside the WLAN channels. As traffic load increases, Bluetooth avoids WLAN channels, and the majority of packets are sent between WLAN channels– in addition to the last eight Bluetooth channels $(71 - 78)$, see Fig. 1. WLAN medium

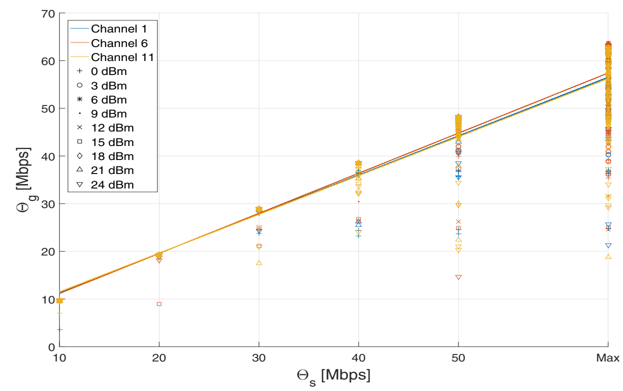

Fig. 5: WLAN throughput with Bluetooth music streaming

utilization reaches 97% for maximum 802.11n throughput [18], which shows that medium sharing is nearly impossible in this case. At 24 dBm, interference power level is extremely high and leads to corruption of Bluetooth packets in the event of a collision. As such, most of packets are sent on the channels $(71 - 78)$, and few are sent on channels $(46 - 49)$.

2) WLAN Performance: Fig. 5 shows a scatter-plot of WLAN throughput for music streaming. Linear regression results are summarized in Table II. Results show that Bluetooth interference causes a reduction in WLAN throughput, especially at high offered traffic load. Goodness of fit (R^2) is approximately 0.92 for all three channels, which indicates a high correlation between 20 dataset measurements points. The effect on all three WLAN channels is quite similar, although the effect on channel 11 is slightly higher.

B. *Hands-free calling*

1) Bluetooth performance: Fig. 6 shows the PER_{BT} as a function of WLAN power level for various traffic loads. Unlike music streaming– and even for low interference power (0-6

TABLE I: Music evaluation

Power level	0-18 dBm	21 dBm	24 dBm
Score	good	fair	poor

TABLE II: Linear regression results

	WLAN Channel	α	β	R^2
Music	Ch. 1	0.82014	3.2115	0.91893
	Ch. 6	0.8408	2.7546	0.92201
	Ch. 11	0.81395	3.3481	0.92112
Call	Ch. 1	0.91644	1.0886	0.99101
	Ch. 6	0.89974	1.4819	0.97402
	Ch. 11	0.92521	0.80493	0.98733

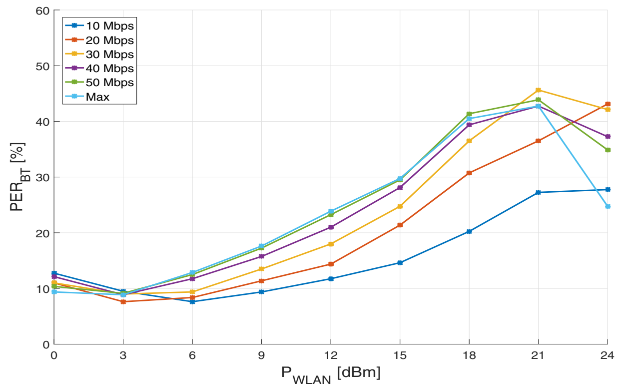

Fig. 6: Bluetooth packet error rate as a function of WLAN power level; hands-free calling

dBm)– PER_{BT} is around 10%. PER_{BT} increases as power increases, reaching nearly $(28 - 45\%)$, depending on WLAN traffic load. SCO link does not offer any retransmission [17], thus, given corrupted packets, packet error rate will increase. Speech quality was quite acceptable at interference level of 18 dBm. For interference level 21 dBm and 24 dBm, quality was extremely poor, and the speech was not understandable. The scores by raters are shown in Table III. Strange behavior was observed at WLAN power level 24 dBm. For traffic load higher than 30 Mbps, PER_{BT} decreased rather than increased, even though WLAN utilized the medium more. This could be explained by the histogram of Bluetooth hopping channel. Fig. 7 shows a histogram of Bluetooth hopping channels for various WLAN traffic loads at WLAN power level 24 dBm. At low traffic load, WLAN utilizes channels less often; thus, Bluetooth could classify channels as acceptable. However, during transmission, collisions occur and due to high WLAN power, collided packets cannot be decoded. For high WLAN throughput, Bluetooth avoid WLAN channels completely, and only guard bands are used.

2) WLAN Performance: Fig. 8 presents a scatter-plot of throughput for all three WLAN channels relative to hands-free calling. Fitting accuracy is higher than music streaming; achieved values are 0.99, 0.97, and 0.98 for channels 1, 6, and 11, respectively. Achieved slopes are higher than those associated with music streaming, which demonstrates that the call has less effect on WLAN than the music streaming.

TABLE III: Call evaluation

Power level	0-18 dBm	21-24 dBm
Score	good	poor

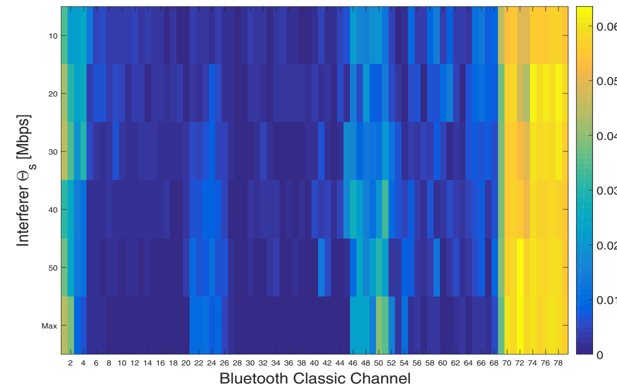

Fig. 7: Bluetooth channels histogram as a function of WLAN traffic load at power level of 24 dBm; hands-free calling

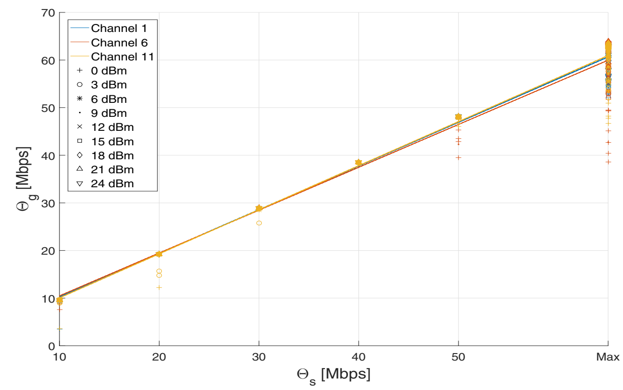

Fig. 8: WLAN throughput with Bluetooth hands-free calling

The reason behind this is that needed throughput for music streaming is much higher than for hands-free calling. As such, music streaming utilizes the medium much more, leading to significantly more collisions with WLAN packets.

V. Discussion

This work focuses on coexistence of WLAN and Bluetooth. Performance is studied for two widely used Bluetooth profiles in the automotive domain. A real life scenario is considered when all three non-overlapped WLAN channels are utilized with different traffic loads. WLAN networks could be operating in the same car, neighboring car or a fixed Hotspot. Results show that HFP is more sensitive to interference than music streaming, as HFP transfers real-time speech. Results also show that effect is higher for WLAN with higher traffic load. Notably, it is rare to find WLAN operating at the maximum data rate, although it could be that multiple networks share the same channel, which would increase channel utilization. Bluetooth channels 71 to 78 are very important for successful transmission given coexistence with Wi-Fi. This work demonstrates the importance of using only the three, non-overlapped channels, namely 1, 6, and 11. Channels 12 or 13 should not be used by car manufacturers. Adhering to this practice will greatly affect Bluetooth performance. Results indicate that Bluetooth effect on WLAN is low, particularly for hands-free calling. Only a small decrease in throughput was observed when networks operate with high throughput.

The automotive domain is different than other domains (e.g., buildings environments). First, distance between the devices is very short, and it is possible that many devices could be concentrated in a dense volume of devices. Second, path loss between cars in the 2.4 GHz band is extremely low [13], causing severe interference between cars. Third, due to mobility effect, WLAN interference have bursty traffic on different channels for short time, this makes AFH inefficient in such scenario. As expected, in the near future most new cars will have WLANs, meaning that millions of new mobile overlapping basic service sets (OBSSs) will be added to current fixed ones. A typical example is a highway traffic jam. In this scenario, Bluetooth performance will be strongly affected by an enormous amount of surrounding Hotspots. Different car manufacturers will implement Hotspots in a variety of ways, thus handicapping cooperation. This paper demonstrates that power limitation is crucial in the automotive domain to reduce interference among cars in close proximity. Regulation offices should take note of such suggestions.

VI. Conclusion and Future Work

Connected cars are poised to be the next milestone in the automotive domain evolution. Car manufacturers have responded to consumer demand and have turned their attention to enhancing connectivity services. Bluetooth and WLAN are among the mostly used wireless systems. Both utilize the 2.4 GHz ISM band. Although WLAN applications are still evolving, Bluetooth functionality is mainly focused on hands-free calling and music streaming. Enabling reliable hands- free calling is a proactive step toward reducing the number of accidents related to cell phone usage while driving.

This work highlights coexistence issues between Wi-Fi and Bluetooth in the automotive domain. Results indicate that music streaming and hands-free calling performance is greatly affected when all non-overlapped WLAN channels are used. Such a scenario is widely expected as a typical scenario for automobile usage in the near future. Music streaming is more resilient than HFP to WLAN interference as a result of retransmissions. The Bluetooth effect on the WLAN is insignificant. Only a small decrement in throughput is observed when networks function with high throughput. The mobility effect on Bluetooth performance is left for future work due to its importance and uniqueness in this domain.

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