Coexistence Measurements and Analysis of IEEE 802.15.4 with Wi-Fi and Bluetooth for Vehicle Networks

Sven Zacharias, Thomas Newe, Sinead O'Keeffe, Elfed Lewis
Optical Fibre Sensors Research Centre, Department of Electronic and Computer Engineering
University of Limerick
Limerick, Ireland
{Sven.Zacharias, Thomas.Newe, Sinead.OKeeffe, Elfed.Lewis}@ul.ie

Abstract—**This paper gives an overview of the channel access methods of three wireless technologies that are likely to be used in the environment of vehicle networks: IEEE 802.15.4, IEEE 802.11 and Bluetooth. Researching the coexistence of IEEE 802.15.4 with IEEE 802.11 and Bluetooth, results of experiments conducted in a radio frequency anechoic chamber are presented. The power densities of the technologies on a single IEEE 802.15.4 channel are compared. It is shown that the pure existence of an IEEE 802.11 access point leads to collisions due to different timing scales. Furthermore, the packet drop rate caused by Bluetooth is analyzed and an estimation formula for it is given.**

Keywords-IEEE 802.15.4; IEEE 802.11; Bluetooth; Vehicle Networks; Wireless Sensor Networks; WSN; Wi-Fi; coexistence; interference

I. INTRODUCTION

The IEEE 802.15.4 standard [1, 2] is the backbone for most Wireless Sensor Networks (WSNs) and the foundation of ZigBee since it provides a simple, low-power stack for the physical and Medium Access Control (MAC) layer. In this paper the term WSN is used as a synonym for the IEEE 802.15.4 standard. WSNs have high potential for Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication, e.g. the recently formed IEEE 802.15.4p Positive Train Control Task Group aims to add functionality to the IEEE 802.15.4 standard to use it for communication between trains and network infrastructure for freight, passenger and rail transit [3]. Although IEEE 802.15.4 is traditionally more suitable for non-safety critical applications, it still has to work reliably. Routing in a wireless mesh network can be used to overcome the problem of metal blocking a direct line of sight communication. Due to the increasing popularity of wireless technologies, the frequency spectrum is crowded. The available spectrum is limited and strictly regulated by local authorities. The IEEE 802.15.4 standard can physically operate in the three free Industrial, Scientific and Medical (ISM) frequency bands offering license free spectrum at 868.0-868.6 MHz in Europe, at 912-928 MHz in North America and at 2,400-2,483.5 MHz worldwide. As the only frequency band available worldwide, the 2.4 GHz band is the most used ISM band and is therefore researched in the following.

The authors identify two technologies as the dominant sources of interference in the 2.4 GHz band for vehicle networks in the near future. First, Bluetooth is a technology widely used for Wireless Personal Area Networks (WPANs), e.g. for wireless headsets used in cars for telephony. Second, Wi-Fi networks based on the IEEE 802.11 standard are either used in the vehicle for connecting mobile devices (e.g. smart phones or laptops) or outside the vehicle as part of some infrastructure. In the following sections these technologies are presented and their coexistence is researched in detail.

The remainder of the paper is structured as follows: Section II gives a literature review. In Section III the features of the communication standards are presented and in Section IV the coexistence of the standards is discussed and the performed experiments are described and analyzed. Finally, the paper is concluded and an outlook is given.

II. RELATED WORK

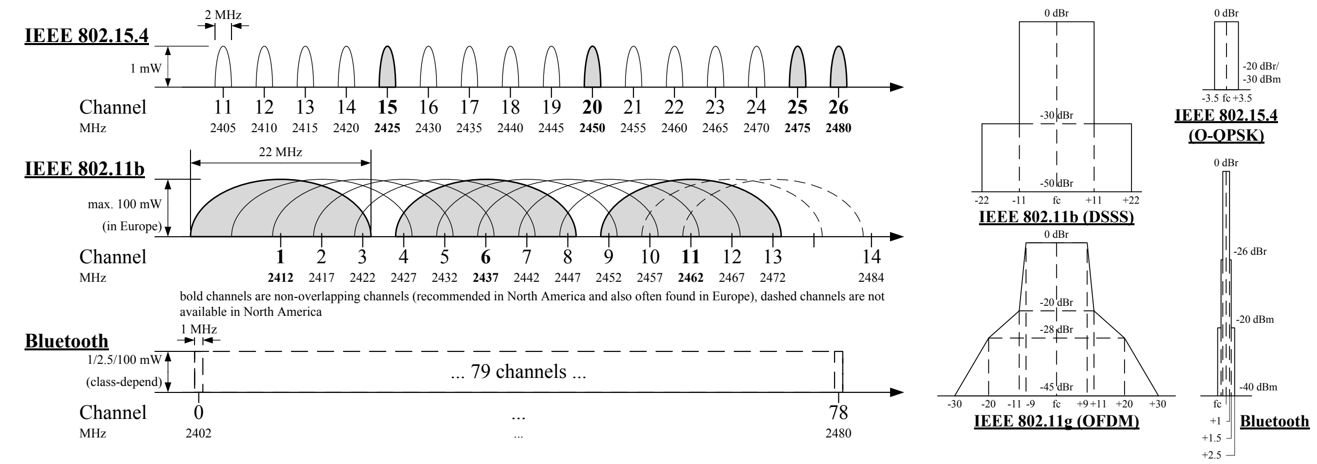
In the IEEE 802.15.4 standard (Annex E), the coexistence with IEEE 802.11b, Bluetooth and IEEE P802.15.3 has been considered by simulations. Overviews of the coexistence of IEEE 802.15.4 with other technologies are also given in literature [4, 5]. Petrova et al. have focused on the interference of Wi-Fi and its different versions on WSNs [6, 7]. Also the coexistence between Bluetooth and Wi-Fi has been analyzed [8] and addressed by the IEEE [9].

Baccour et al. review the link quality estimators in WSNs in general and present some observations: IEEE 802.15.4 is more affected by IEEE 802.11b than vice versa if there is some signal overlap (and signals can spread outside the defined channels); and Bluetooth mostly affects IEEE 802.15.4 and almost not vice versa. Furthermore, experiments and countermeasures are reviewed [10]. Besides empirical studies, many analytical studies have been conducted delivering more or less complex and precise models. A good overview of the effects of coexisting between Wi-Fi and WSNs is given in [11].

Boano et al. use RSSI readings to improve the channel simulation [12] and to recreate interference [13].

Liang et al. present a detailed analysis of WSNs interfered by Wi-Fi and report two regions of coexistence: The symmetric

978-1-4673-3070-1/12/$31.00



(a) (b)

Figure 1. (a) Usage of the 2.4 GHz ISM frequency band by different technologies. (b) Their spectral mask as defined in the standards.

and the asymmetric region. In the first Wi-Fi backs off for WSN traffic and vice versa, while in the latter Wi-Fi cannot detect the WSN traffic anymore. Furthermore they suggest improvements to enhance robustness including the usage of Forward Error Correction (FEC) [14]. In [15], three coexistence regions between 802.15.4 and IEEE 802.11b/g are suggested as part of a coexistence model and their ranges are calculated: A symmetric region, an asymmetric region and a region where neither IEEE 802.11 nor IEEE 802.15.4 can detect each other, but IEEE 802.15.4 is still interfered.

Penna et al. have conducted a measurement campaign with WSNs, IEEE 802.11b/g and Bluetooth. They present the energy distributions and propose a channel selection algorithm for WSNs based on multi-channel scans [16]. Tytagt et al. research the Wi-Fi and WSN channel access mechanisms for coexistence between both technologies. They develop an adopting Clear Channel Assessment (CCA) method, called Coexistence Aware Clear Channel Assessment (CACCA). They assume that the default CCA mode for Wi-Fi is preamble detection instead of energy detection, and therefore Wi-Fi does not back off for WSNs at all [18]. The different CCA modes will be presented later in this work.

III. Overview of Technologies

In the following section the features of WSNs, Wi-Fi and Bluetooth are presented. The potential overlaps of the channels of the different technologies can be clearly seen in Fig. 1 showing a simplified overview of the spectrum on the left and the detailed spectral masks on the right.

A. IEEE 802.15.4 / WSNs

In the 2.4 GHz band, IEEE 802.15.4 uses one of 16 channels with a typical sending power of up to 1 mW in a 2 MHz wide channel, as shown in Fig. 1. The signal is Offset Quadrature Phase-Shift Keying (O-QPSK) modulated. IEEE 802.15.4 supports a theoretical data rate of 250 kb/s. The access to the channel with multiple participants is organized with the help of Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) or Time Division Multiple Access (TDMA). Since WSNs are supposed to be self-organizing and should react fast to network changes, TDMA is seldom used.

CSMA/CA monitors the channel before sending in order to avoid collisions. WSNs can use one of three different CCA modes to check for a free channel [1]:

- CCA Mode 1: Energy above threshold. If the radio detects any energy above a threshold, the medium is considered to be busy.
- CCA Mode 2: Carrier sense only. If the radio detects a signal that has been modulated and spread according to the standard, the medium is considered to be busy.
- CCA Mode 3: Carrier sense with energy above threshold. If the signal modulation and spreading are valid and the received energy is above a threshold, the medium is considered to be busy.

If the channel is busy, normally the transmission is delayed and retried later, but to see the effect of interference in the following, MAC retransmissions are not used. The maximum frame length of a WSN packet is 127 byte, leading to a maximum channel usage of up to 4 ms.

B. IEEE 802.11 / Wi-Fi

Wireless Local Area Networks (WLANs) based on the IEEE 802.11 standard [19] and its amendments [20], also known as Wi-Fi networks, are widespread and used in various environments and devices. Depending on local authority restrictions IEEE 802.11b/g/n supports up to 14 channels in the 2.4 GHz band: 13 in Europe and 11 in North America. Channel 14 is only allowed in Japan for IEEE 802.11b. Due to its 22 MHz spectral width, an IEEE 802.11 channel spreads over the spectral width of four IEEE 802.15.4 channels. The common pattern for using IEEE 802.11 channels to achieve maximum throughput by non-overlapping channels is the usage of channel 1, 6 and 11 (bold channels in Fig. 1). Depending on the version of the standard, different modulations and data rates are available: up to 11 Mb/s for IEEE 802.11b, up to 54 Mb/s for IEEE 802.11g and up to 72 Mb/s for IEEE 802.11n using a single stream on a single channel. IEEE 802.11n introduces wider channels, but here it is assumed that the IEEE 802.11b/g channel pattern with a channel width of 22 MHz is used (as shown in Fig. 1). The modulation used is Direct Sequence Spread Spectrum (DSSS) for IEEE 802.11b and Orthogonal Frequency Division Multiplexing (OFDM) for amendments g and n. Although there is variety, the access point always announces its network with beacon frames. These beacon frames are normally sent with the lowest data rate (1 or 2 Mb/s) for compatibility reasons. Wi-Fi supports the same CCA modes as WSNs.

C. IEEE 802.15.1 / Bluetooth

Bluetooth (IEEE 802.15.1) [21] can use 79 channels in the 2.4 GHz band: each one is 1 MHz wide and adjacent to its predecessor and successor (see Fig. 1). Due to an Adaptive Frequency Hopping (AFH) scheme, the channel is changed 1,600 times a second, which makes Bluetooth devices less interfering with other wireless technologies. Bluetooth will avoid busy channels that are used e.g. by IEEE 802.11. The concept of AFH is shown in Fig. 2. Additionally, Bluetooth supports adaptive power control and channel quality driven data rates to adapt to its wireless environment.

There are three classes of Bluetooth devices differing in their sending power: 1, 2.5 and 100 mW. Bluetooth has been publicized in different versions with slightly changing modulations and abilities: it supports up to 3 Mb/s since Version 2.0 with Enhanced Data Rate (EDR).

There are two different types of connections: Synchronous Connection-Oriented (SCO) links, which strictly use the channel hopping pattern, and Asynchronous Connection-Less (ACL) links that can use one, three or five time slots without changing the channel (see Fig. 3). Bluetooth performs TDMA instead of CSMA/CA to access the medium and therefore there is no need to check the channel with a CCA.

IV. COEXISTENCE

The effects of Wi-Fi and Bluetooth on WSN traffic are shown in the following section by measurements in a Radio Frequency (RF) anechoic chamber and their theoretical analysis. For the WSN, retransmissions have been turned off in the MAC, thus lost packets are not resent. In real deployments they would be resent resulting in a decreased throughput and increased energy consumption. Also for the analysis a packet collision is set equal to a lost packet, which is a suitable assumption since the theoretical packet drop rate corresponds to the measured results.

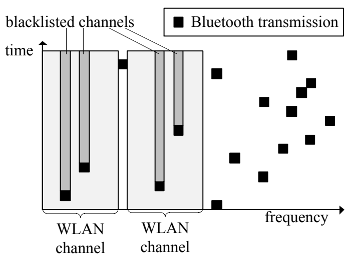


Figure 2. Principle of Adoptive Frequency Hopping (AFH): After each transmission, the channel changes according to a pseudo-random pattern. If a channel is already busy, AFH will avoid using this channel for a predefined time in future.

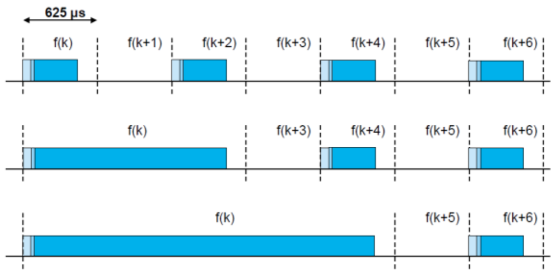


Figure 3. Single- and multi-slot packets used by Bluetooth. The top row shows the frequency hopping pattern for a unidirectional single-slot communication. Both rows below show multi-slot packets [21].

A. Measurement Setup

To research the effect of interference, measurements have been conducted in an RF anechoic chamber. Thereby external interference and multipath propagation are eliminated. The setup in the chamber can be seen in Fig. 4. Two Tmote Sky sensor nodes [22] are positioned 3 m away from each other. In the middle between them, a laptop (including an Intel(R) WiFi Link 5300 AGN network card and a Dell Wireless 370 Bluetooth Mini-card) and the second device are placed. The second device varies during the experiments to be a Samsung WEP-470 headset for Bluetooth Audio Streaming, a Motorola Razr v3i mobile phone for a Bluetooth File Transfer Protocol (FTP) connection or a Linksys WRT150N Wireless-N Home Wi-Fi router. The Tmote Sky sensor nodes are equipped with IEEE 802.15.4 compliant CC2420 radios [23] and run ContikiOS 2.5 [24]. For errorless RSSI readings, the peak detectors in-between the amplifier stages are activated [13]. To determine the packet drop rate, 2,000 packets have been sent, one every second and each 32 bytes long. The sending power is -25 dBm. Each experiment has been repeated three times. The packet drop rates can be seen in Table 1. Without interference, all packets arrived at the base station.

For creating Fig. 5, 7, 8 and 9, the Received Signal Strength Indication (RSSI) value of the Tmote Sky was used.

Fig. 5 shows the power density of Wi-Fi and Bluetooth, each operating isolated. Due to the long measurement time of over 1,600 seconds at 8,192 Hz, the histogram of the RSSI values is assumed to be identical with the power density function. For Fig. 7, 8 and 9, a second of sampling at 8,192 Hz is done, using the default CCA energy detection threshold of the CC2420 radio (-77 dBm) to decide if the channel is used. After the sampling period, the results are sent to the laptop and a new sampling period starts.

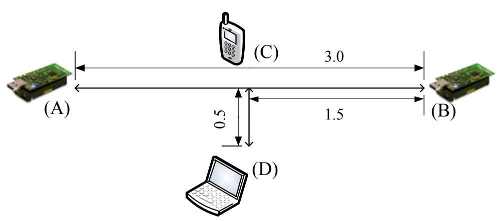


Figure 4. Experimental setup in Radio Frequency (RF) anechoic chamber: (A) and (B) are the positions of sensor nodes, the laptop is positioned at (D) and a Bluetooth device or Wi-Fi router is placed at (C).

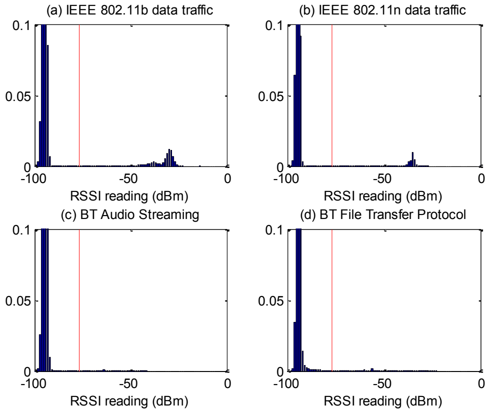


Figure 5. Power density of measured RSSI values. The technologies operated isolated without a WSN in range. The red line shows the CCA threshold (-77 dBm).

B. Coexistence of Wi-Fi and WSNs

The coexistence between Wi-Fi and WSNs is complex due to the variety of IEEE 802.11 standards, channels, data traffic types, number of participants, etc. But Wi-Fi sends with most energy of the here presented technologies. In literature different numbers for the effect of Wi-Fi in different setups are given and packet drop rates over 80% are reported [4, 7, 16]. In the following, Wi-Fi channel 11 (2,462 MHz) is used. It spans over the WSN channels 21 (2,455 MHz), 22 (2,460 MHz), 23 (2,465 MHz) and 24 (2,470 MHz). The WSN operates on channel 22 and is therefore in the middle of the used Wi-Fi channel.

In Fig. 5 (a) and (b) local maxima from the data traffic are clearly identifiable in the power density measured by the sensor node. On the other hand, Wi-Fi can detect WSN traffic if the sender is close. Yuan et al. state that an IEEE 802.15.4 transmitter sending with 0 dBm can be detected by IEEE 802.11b within a radius of 22 m and by IEEE 802.11g within a radius of 32 m. The path loss with a wave length (λ) of 2,460 MHz and a small distance (d) of 1.5 m is

$$\mathrm{PL(d)} = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (1)$$

resulting in roughly 44 dB. With a sending power of -25 dBm, symmetric detection is thus still possible [15]. This calculation has been proven by a simple experiment, where the sending sensor node was set to the transmitter test mode and generated a modulated spectrum. As a result, the Wi-Fi connection failed.

The simplest and least interfering case to study is the traffic generated by beacons sent by a Wi-Fi access point. A Wi-Fi

TABLE I. PACKET DROP RATE UNDER INTERFERENCE.

Scenario	Packet Drop Rate [%]		
	Repeat 1	*Repeat 2*	*Repeat 3*
IEEE 802.11n beacons	2.50	2.75	2.50
Bluetooth, Audio Streaming (SCO link)	2.85	2.55	3.10
Bluetooth, File Transfer Protocol (FTP) (ACL link)	7.45	6.20	6.60

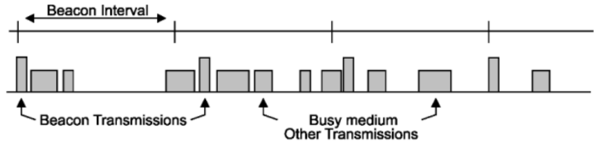


Figure 6. Beacon delay due to data traffic blocking the channel [19].

beacon is sent periodically to announce the network and its features to potential new participants. It is normally more than 100 bytes in length (depending on the features supported by the access point). With more traffic on the channel, the beacons can be delayed, because the standard does not provide reserved time slots for the beacons (see Fig. 6). In the experiments conducted for this work, the beacon frame is 275 bytes long and is sent with 1Mb/s. This low data rate enables maximum compatibility and is the default of the used access point. The beacons are sent at 10 Hz by default. To be more precise, they are sent with 9.77 Hz, every 102.4 ms instead of every 100 ms. The IEEE 802.11 standard uses the time unit (TU), which is equal to 1.024 ms. This base-2 number is easier to implement. Unfortunately, there is a common misconception that a time unit is exactly 1 ms and many Wi-Fi router setup interfaces use wrong units.

Hence, the assumption is not true that a WSN packet (sent with 1 Hz) and Wi-Fi beacons (sent with ~10 Hz) should not lead to any collisions because there is enough time between the beacons. Due to the additional 2.4 ms every second, the WSN frame is hit with a chance of approximately 2.4% (the precise probability depends on the packet and beacon lengths). This effect of the different timings is shown in Fig. 7. The apparently changing position of the WSN packets between the Wi-Fi beacons is due to the fact that the timing intervals differ by the rounding error of the binary system. As shown in Table 1, the packet drop rate observed in experiments is around 2.6%.

Data traffic in Wi-Fi networks is very variable and its modeling is beyond the scope of this paper. Bianchi has established a widely used, simple, yet accurate model to compute the distributed coordination function [25].

Basically, with higher data rates, the time a packet blocks the channel is reduced and thus the chance of collisions decreases. Fig. 8 gives an impression of the channel usage under data traffic. The beacons can be clearly seen in subfigure (c) as periodically appearing channel usage (ten times), for the lower data rates the beacons are harder to distinguish from the data traffic. This data traffic was collected while streaming a

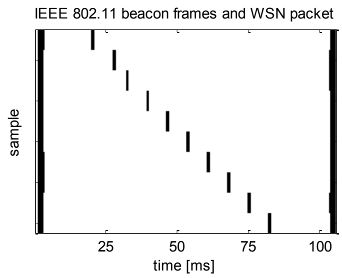


Figure 7. Changing position of a WSN packet relative to beacon frames due to different reference times. At the borders at roughly 2 ms and 104 ms, the Wi-Fi beacons are transmitted.

video, thus traffic occurs in bulks, whenever the buffer runs low. In the figure such reload bulks of data are shown. But depending on the applications running on the higher layers, the traffic pattern can change completely. More detailed experiments for the effect on traffic can be found in [16].

C. Coexistence of Bluetooth and WSNs

The coexistence of Bluetooth and WSNs has less different cases than the coexistence with Wi-Fi. Due to Bluetooth's channel hopping, the maximum power and channel usage duration are limited and data traffic has less effect. In Fig. 5 (c) and (d), it is shown that there is no clear effect on the average power measured on the channel over time due to the short transfer bursts of Bluetooth. In Fig. 9 (b) and (c), the channel usage can be seen in the time domain. For SCO links, the channel is changed regularly and slots are alternatively reserved for master and slave. Assuming that the channels are used totally randomly (which is not necessarily the case because AFH can blacklist channels), the chance of Bluetooth using a 2 MHz wide WSN channel is 2 × 1/79.

Depending on the length of the WSN packet, there are multiple chances of collisions as shown in Fig. 10. The 32 byte WSN packet can cover up to parts of three Bluetooth slots. Note that it is unlikely to have a collision in the first slot, since a slot has not to be used fully, only the transmission must start at the beginning of the slot.

Since it is a unidirectional transmission, the second slot is not used. Thus there is a low chance (< 2/79) of a collision in slot 1 and a 2/79 chance of a collision in slot 3. Other timings as an overlap of only two Bluetooth slots mean even less chances of collisions. In Table 1, results of the experiments for a unidirectional SCO audio transfer are shown: They indicate a packet drop rate slightly higher than 2/79 ≈ 2.53%.

If ACL links are used, the alternation between master and slave is overridden and thus more collisions are possible, up to 3 × 2/79 ≈ 7.59% as seen in Table 1 for the FTP transfer. If AFH has blacklisted channels, the chance of collision changes from 3 × 2/79 to:

3 × 2 / (number of available Bluetooth channels) (2)

Generalizing (2) leads to a worst case collision probability for a WSN with Bluetooth of:

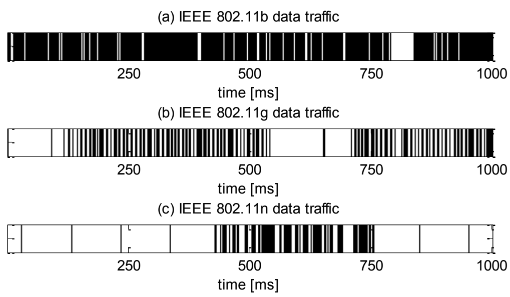


Figure 8. Clear channel monitoring: (a) IEEE 802.11b data traffic (b) IEEE 802.11g data traffic (c) IEEE 802.11n data traffic (CCA threshold is -77 dBm, channel used is drawn in black).

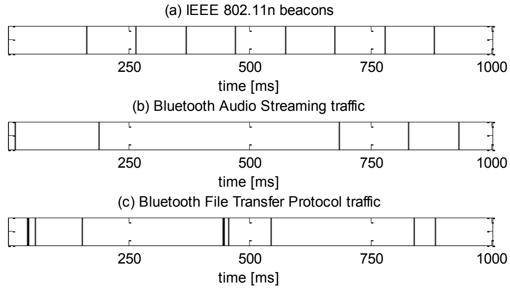


Figure 9. Clear channel monitoring: (a) Bluetooth, Audio Streaming (SCO link) (b) Bluetooth, File Transfer Protocol (FTP) (ACL link) (c) IEEE 802.11n beacons (CCA threshold is -77 dBm, channel used is drawn in black).

$$P_{max}(\text{Collision}) = \left(ceiling\left(\frac{T_{WSN\,Tx}}{T_{BT\,Slot}}\right) + 1\right) \times \frac{2}{C_{BT}} \quad (3)$$

where $T_{WSN\,Tx}$ is the duration of the transmission of a WSN packet (in the conducted experiment this is 1 ms) and $T_{BT\,Slot}$ is the duration of a Bluetooth slot, which is the maximum time a channel can be used by Bluetooth (0.625 ms). Further, C_{BT} is the number of available Bluetooth channels, in an isolated setup it equals 79 channels. The few packet collisions caused by the WSNs should not lead Bluetooth to blacklist the two channels and to avoid them in the hopping scheme, although the standard does not strictly define an algorithm to decide if a channel is blacklisted, but states that at least 20 channels have to be available for hopping.

V. Conclusion and Outlook

This paper gives an overview of the most likely interferers for IEEE 802.15.4 based WSNs in vehicle networks: Wi-Fi and Bluetooth. The authors provide measurements of channel usage by these technologies, done in an RF anechoic chamber. The coexistence between Wi-Fi and WSNs is complex and this work shows that even the simplest and least interfering case, an access point without clients, leads to inter-system packet collisions. The different timing foundations give an explanation for these collisions. The effects of Bluetooth on WSNs are also experimentally researched and a formula is derived to estimate the maximum packet drop rate. Further experiments will be conducted to quantify the effects of different scenarios and to deliver robust estimation rules for the coexistence of wireless vehicle networks in the near future.

Acknowledgment

The authors wish to thank the following for their financial support: The Embark Initiative and Intel, who fund this research through the Irish Research Council for Science, Engineering and Technology (IRCSET) postgraduate Research Scholarship Scheme.

Figure 10. A 32 byte WSN frame can stretch over up to three Bluetooth slots. Examples for transmission are shown in gray.

REFERENCES

[1] *IEEE Standard 802.15.4™-2003*, IEEE Computer Society Std., 2003.

[2] *IEEE Standard 802.15.4™-2006*, IEEE Computer Society Std., 2006.

[3] C. Backof, "Connections: From macro to micro [from the editor]," Vehicular Technology Magazine, IEEE, vol. 7, no. 2, p. 3, June 2012.

[4] A. Sikora and V. Groza, "Coexistence of IEEE 802.15.4 with other systems in the 2.4 GHz-ISM-band," in *Instrumentation and Measurement Technology Conference*, vol. 3, May 2005.

[5] Jennic, "Co-existence of IEEE 802.15.4 at 2.4 GHz," Technology for a changing world, Application Note Revision 1.0, February 2008.

[6] M. Petrova, J. Riihijärvi, P. Mähönen, and S. Labella, "Performance study of IEEE 802.15.4 using measurements and simulations," in *Wireless Communications and Networking Conference*, 2006. WCNC'06. IEEE, vol. 1, April 2006, pp. 487 –492.

[7] M. Petrova, L. Wu, P. Mähönen, and J. Riihijärvi, "Interference measurements on performance degradation between colocated IEEE 802.11 g/n and IEEE 802.15. 4 networks," in *Networking*, 2007. ICN'07. 6th International Conference on. IEEE, 2007, pp. 93–93.

[8] A. Conti, D. Dardari, G. Pasolini, and O. Andrisano, "Bluetooth and IEEE 802.11b coexistence: Analytical performance evaluation in fading channels," *Selected Areas in Communications, IEEE Journal on*, vol. 21, no. 2, pp. 259 – 269, February 2003.

[9] *IEEE Standard 802.15.2™-2003*, IEEE Computer Society Std., 2003.

[10] N. Baccour, A. Koubâa, L. Mottola, M. Zúñiga, H. Youssef, C. Boano, and M. Alves, "Radio link quality estimation in wireless sensor networks: A survey," *ACM Transaction on Sensor Networks*, 2011.

[11] D. Yang, Y. Xu, and M. Gidlund, "Wireless coexistence between IEEE 802.11- and IEEE 802.15.4-based networks: A survey," *International Journal of Distributed Sensor Networks*, Article ID 912152, p. 17, 2011.

[12] C. Boano, K. Römer, F. Österlind, and T. Voigt, "Demo abstract: Realistic simulation of radio interference in cooja," in *Proceedings of the European Conference on Wireless Sensor Networks (EWSN)*, 2011.

[13] C. Boano, T. Voigt, C. Noda, K. Römer, and M. Zúñiga, "Jamlab: Augmenting sensornet testbeds with realistic and controlled interference generation," in *Information Processing in Sensor Networks (IPSN), 10th International Conference on*, April 2011.

[14] C.-J. M. Liang, N. B. Priyantha, J. Liu, and A. Terzis, "Surviving Wi-Fi interference in low power ZigBee networks," in *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, SenSys. New York, NY, USA: ACM, 2010.

[15] W. Yuan, X. Wang, and J. Linnartz, "A coexistence model of IEEE 802.15.4 and IEEE 802.11 b/g," in *Communications and Vehicular Technology in the Benelux, 14th IEEE Symposium on*. IEEE, 2007.

[16] F. Penna, C. Pastrone, M. Spirito, and R. Garello, "Measurement-based analysis of spectrum sensing in adaptive WSNs under Wi-Fi and Bluetooth interference," in *Vehicular Technology Conference. IEEE 69th*, April 2009.

[18] L. Tytgat, O. Yaron, S. Pollin, I. Moerman, and P. Demeester, "Avoiding collisions between IEEE 802.11 and IEEE 802.15.4 through Coexistence Aware Clear Channel Assessment," *EURASIP Journal on Wireless Communications and Networking*, pp. 137 - 152, 2012.

[19] *IEEE Standard 802.11™-2007*, IEEE Computer Society Std., 2007.

[20] *IEEE Std 802.11n™-2009*, IEEE Computer Society Std., 2009.

[21] *Bluetooth Specification Version 2.1+EDR*, Bluetooth SIG, Inc. Std., July 2007.

[22] M. Corporation, *Tmote Sky - Ultra low power IEEE 802.15.4 compliant wireless sensor module*, 2006.

[23] *CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver*, Chipcon, June 2004, datasheet.

[24] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki-a lightweight and flexible operating system for tiny networked sensors," in *Local Computer Networks. 29th Annual IEEE International Conference on*. IEEE, 2004.

[25] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 3, pp. 535 –547, March 2000.