An Experimental Study of Cross-Technology Interference in In-Vehicle Wireless Sensor Networks

Rasool Tavakoli[1], Majid Nabi[1], Twan Basten[1,2], Kees Goossens[1]

[1]Department of Electrical Engineering, Eindhoven University of Technology, the Netherlands

[2]TNO Embedded Systems Innovation, Eindhoven, the Netherlands

{r.tavakoli, m.nabi, a.a.basten, k.g.w.goossens}@tue.nl

ABSTRACT

Wireless in-vehicle networks are considered as a flexible and cost-efficient solution for the new generation of cars. One of the candidate wireless technologies for these wireless sensor networks is the IEEE 802.15.4 standard which operates in the 2.4 GHz ISM band. This is while the number of wireless devices that operate in this band is ever increasing. This broad usage of the same RF band may cause considerable performance degradation of wireless networks due to interference. There is some work on the coexistence of the IEEE 802.15.4 protocol and other standard technologies such as IEEE 802.11 (Wi-Fi) and IEEE 802.15.1 (Bluetooth), but none of it considers the highly dynamic conditions of in-vehicle networks. In this paper, we investigate the interference behavior in in-vehicle environments using real-world experiments. We consider different scenarios and measure the interference on all the 16 channels of IEEE 802.15.4 in the 2.4 GHz band. The measurement data set is available to the public. This real-world data set can be used for realistic and accurate network simulation. To study the effect of interference on in-vehicle networks, we use this data set to evaluate the performance of an IEEE 802.15.4e TSCH link. The simulation results show that the packet error rate for some interference scenarios is considerably high and dynamic over time. This shows the value of the data set and reveals the importance of using adaptive interference mitigation techniques to improve the reliability of wireless in-vehicle networks.

Keywords

Wireless sensor networks; In-vehicle networks; Interference; Wireless co-existence; IEEE 802.15.4e; TSCH

1. INTRODUCTION

Wireless communication is considered as a solution to be used in new generations of cars. This technology provides significant improvement in flexibility and reconfigurability of In-Vehicle Networks (IVNs). It further reduces the manufacturing cost and enables new applications. Based on the requirements of these networks that include low data rate communications, reduced complexity of nodes and low power consumptions, the IEEE 802.15.4 standard [3] is a proper candidate to be used as the physical and Medium Access Control (MAC) layer protocols for these networks. This standard uses 16 frequency channels in the license-free 2.4 GHz ISM band. The 4e amendment [5] of this standard was developed aiming to increase the robustness of wireless communication links through guaranteed medium accesses and channel diversity. In the Time-Slotted Channel Hopping (TSCH) mode, wireless nodes hop over different channels to transmit frames of a single link. This eliminates repeated dropping of packets because of noise on a single channel. Although this standard provides guaranteed access to the medium for the network links, there is no guarantee that it can meet the stringent Quality-of-Service (QoS) requirements of the in-vehicle applications. The main reason is the common usage of the unlicensed 2.4 GHz ISM band by different standards including IEEE 802.11 WLAN [4] and IEEE 802.15.1 Bluetooth [2], which leads to cross-technology interference and packet losses. Fig. 1 shows the frequency usage of these three protocol standards in the ISM band.

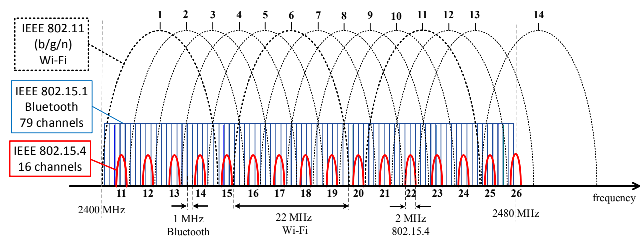


Figure 1: Usage of 2.4 GHz ISM band.

Considering the low transmission power in Wireless Sensor Networks (WSNs), the IEEE 802.15.4 networks are expected to be affected considerably by the other coexisting technologies. Actually there are several experimental and analytical studies on the coexistence of IEEE 802.15.4 and other technologies, but none of them considers the in-vehicle conditions and its effect on the quality of the links in WSNs. Moreover, all of these studies focused on CSMA/CA based MAC modes of the 802.15.4 standard while our study is the first one that investigates the cross-technology interference effect on the TSCH MAC of the 4e amendment.

The cross-technology interference in in-vehicle environments can be categorized into interference of in-car and

MSWiM '16, November 13-17, 2016, Malta, Malta

DOI: http://dx.doi.org/10.1145/2988287.2989141

out-of-car sources. This makes in-vehicle wireless communications more challenging due to (1) high density of in-car wireless devices such as phones and music players that use both Wi-Fi and Bluetooth communications and (2) high dynamism of out-of-car interferers because of the car movements. Furthermore, each coexisting technology behaves differently w.r.t. transmission timings and power. This work is the first one to study the behavior of interference in in-vehicle environments and its effect on TSCH communications.

We investigate the interference behavior in in-vehicle environments using real-world experimental setups. We consider different scenarios and measure the interference power on all the 16 channels of IEEE 802.15.4 in the 2.4 GHz band. The measurement results are used in a simulation framework to analyze TSCH behavior under different interference scenarios. We also provide a public measurement data set for in-vehicle environments. This data set and the simulation scripts are public and available online through https://git.ics.ele.tue.nl/Public/interference-behavior-in-in-vehicle-env.

The paper is organized as follows. The next section gives an overview of related work about wireless coexistence in WSNs. Section 3 presents our measurement setup and scenarios in detail. The measurement result of in-car and out-of-car interference is discussed in Sections 4 and 5, respectively. The performance of TSCH communications under measured in-vehicle interference is studied in Section 6. Section 7 concludes.

2. RELATED WORK

The ever increasing number of the 2.4 GHz ISM band users makes wireless interference of coexisting wireless devices a challenge, especially for low power IEEE 802.15.4 WSNs. The IEEE 802.15.4 standard document [3], provides estimation of packet error rate of this standard under IEEE 802.11b, IEEE 802.15.1, and IEEE 802.15.3 networks using coexistence simulations. Some work has been done on the coexistence of IEEE 802.15.4 with other standard wireless protocols using experiments and analytic modeling. Experimental studies presented in [11, 6, 13], and [18], mainly measure and report the impact of coexistence on the network performance metrics such as Packet Reception Ratio (PRR) and latency. The authors of [16] and [19], provide analytic models of the coexistence of IEEE 802.15.4 under IEEE 802.11 interference, based on the transmission patterns of both technologies. A radio link quality estimation survey in IEEE 802.15.4 WSNs is provided in [7]. The authors present the observation that the external interference of Wi-Fi and Bluetooth has a strong impact on the quality of IEEE 802.15.4 links but the communications of Wi-Fi and Bluetooth are less affected by an 802.15.4 network.

Different WSN operating environments may lead to different coexistence and interference conditions. While some (e.g., [6, 16, 23, 17]) focus on the general coexistence, others consider specific environments such as buildings [11, 14], industrial [8], outdoor [12], and body [13] environments. There are also studies on the wireless coexistence in in-vehicle WSNs. The authors of [24] consider Wi-Fi and Bluetooth as the most likely interferers for IEEE 802.15.4-based IVNs. They provide measurements and analysis for interference of these technologies on a single channel of IEEE 802.15.4, done in an RF anechoic chamber. This makes this work similar to general coexistence studies, skipping the real-world conditions. The authors of [9] do some measurements for a static in-vehicle scenario. They place some IEEE 802.15.4 sensor nodes in different parts of a car, and investigate the performance of different single channel links between them under Bluetooth communications. The results are expressed in terms of Packet Error Rate (PER) and average/peak latency. These studies only addressed the coexistence effect of devices inside a vehicle on single channel IVNs. This is while IVNs (that are operating in single or multiple channels) may also experience interference from devices out of the vehicle There is no measurement study on this.

A channel quality measurement data set for industrial wireless environments is presented in [8]. These kind of public data sets are useful for interference modeling and network performance simulation based on real-world situations. However, the authors of [8] note that these data sets are limited to the office, laboratory, and industrial environments and there is nothing like this for in-vehicle environments.

In this paper, we focus on the multi-channel in-vehicle WSNs and the effect of cross-technology interference on them. Based on real-world scenarios, we perform a set of interference measurements on all the IEEE 802.15.4 channels and provide a public data set for in-vehicle environments that can be used to estimate the performance of wireless IVNs. We also evaluate the performance of a TSCH link under real-world interference using the provided data set and simulations.

3. MEASUREMENT SETUP

To verify the performance of higher layers of a wireless protocol, we need to know about its physical layer conditions in the working environment. In this work, we aim to capture the wireless conditions of all the IEEE 802.15.4 channels in in-vehicle environments. Here we describe the requirements for such a measurement and introduce the used hardware setup for our experiments. Later we present different experiment scenarios to capture different interference behaviors.

3.1 Measurement Requirements

To perform noise measurement on the IEEE 802.15.4 channels, we need to sample each channel continuously. Each channel experiences dynamic energy levels for different periods and durations of time. This is caused by packet transmissions of different coexisting technologies. Wi-Fi and Bluetooth are considered to be two coexisting technologies that have the most impact on 802.15.4 IVNs. The data rate, packet size, and bandwidth usage of these standards vary from each other and even from version to version and application to application. Therefore, the sampling method, rate and duration can have direct impact on the extracted behavior of the wireless channels. Considering these facts, we need to sample the medium continuously and with the highest possible rate. Each sample should reflect the medium quality during the sampling duration.

We select hardware Energy Detection (ED), defined in the IEEE 802.15.4 protocol, to measure the quality of the wireless channels. Based on the IEEE 802.15.4 protocol definitions, an ED is an average of the received signal power within the bandwidth of the channel over 128 μs. Thus, lower values indicate less noisy channels while higher values indicate higher noise on the wireless channel.

3.2 Measurement Hardware Setup

To measure the interference, we used Atmel ATMEGA256-RFR2 Xplained Pro kits [1]. This kit includes an ATMEL ATMEGA256RFR2 SOC which contains an IEEE 802.15.4 compliant wireless transceiver. We assign one Atmel mote to each of the 802.15.4 channels to measure the noise level of that channel and stream the measurement results to a laptop. In the Atmel chip, each ED is done by averaging RSSI values over this period and has a value in the range of [-90, -10] dBm.

We use 16 AVR kits to measure the noise level of all the 16 IEEE 802.15.4 channels on the 2.4 GHz ISM band at the same time. All the AVR kits are placed next to each-other under the back window of a car. Since one Wi-Fi transmission can affect 3 to 5 IEEE 802.15.4 channels, we should synchronize all the samples of different channels to correctly extract the interference behavior. Clock drifts of different AVR chips make a one-time initial synchronization useless. We use wired signaling between kits to synchronize them at the beginning of each sampling interval. One of the kits works as master and triggers an output pin at the start of each sampling interval. Other nodes get this signal as input and start each sampling period when it is triggered. We set the sampling period to 500 μs which is enough to do an ED and send the results to the computer. On the computer side, we use Matlab to collect the sampling data that is sent by individual kits.

3.3 Measurement Scenarios

We categorize the interference sources for wireless IVNs into in-car and out-of-car sources. For each category we perform several measurements using different real-world scenarios. For in-car interference sources, each scenario is designed to investigate the effect of one type of interference sources and/or applications. In this case, we picked up three measurement scenarios to study the behavior of Wi-Fi and Bluetooth transmissions. The three scenarios are 1) Bluetooth connection of a mobile phone and a music player device with an audio streaming application, 2) Bluetooth connection between two smart phones with a file transfer application which requires more bandwidth and handshaking than that of scenario 1, and 3) Wi-Fi connection between two smart phones with a file transfer application.

The out-of-car interference is caused by the devices that are operating out of the car along the roads or in other cars. We defined four scenarios in this case; 1) Driving along a route near some apartments; 2) Driving along an office area in downtown; 3) Driving in a suburb area; 4) Driving along a highway with no buildings around.

4. IN-CAR INTERFERENCE MEASUREMENT

To study the interference behavior of in-car sources, we parked the car in an open space area with no construction within 0.5 kilometer. Using sniffers, it was confirmed that the selected environment has negligible external interference on the 2.4 GHz ISM band. We pick three measurement scenarios to study the behavior of in-car interferers (including Wi-Fi and Bluetooth devices). Each measurement is performed for 5 minutes which leads to 600k samples per channel. In the following, we discuss the result of each measurement in detail.

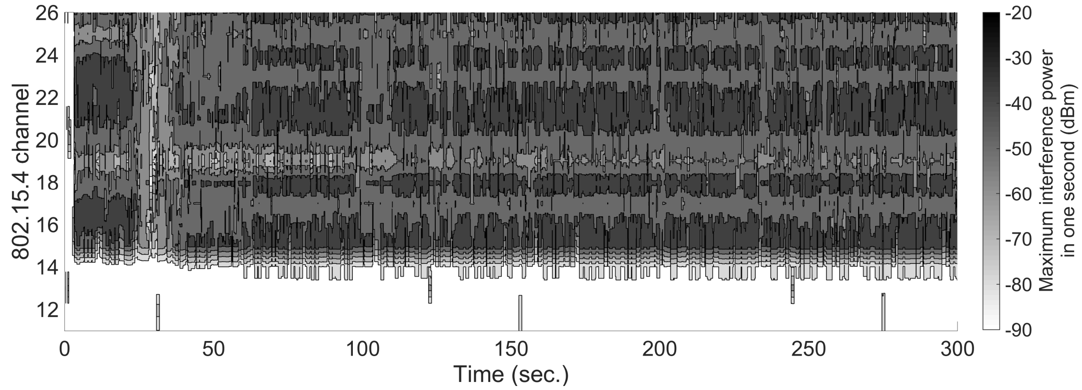
4.1 Bluetooth Audio Streaming

In this scenario, we use a mobile phone to stream audio to the audio system of the car using Bluetooth version 4.0. We placed the phone on the dashboard of the car, with 2.5 meters distance from the interference measuring motes. Fig. 2 depicts the captured Bluetooth interference over time on different IEEE 802.15.4 channels. Fig. 2(a) uses a contour plot to show the distribution of interference power over different channels. Each color in the plot reflects the maximum power of the captured Bluetooth signal on a channel during a period of one second. In contour plots, the width of the samples' color on the horizontal line shows the repetition of samples with that power level in that channel over time.

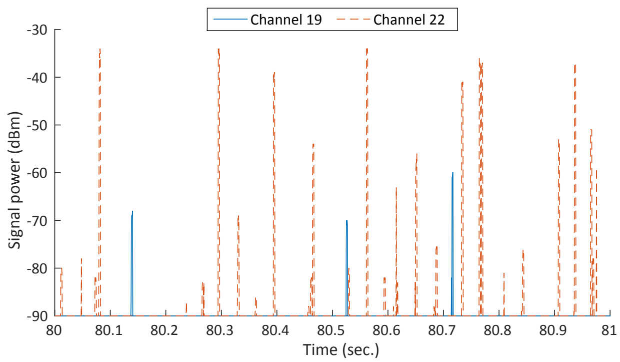
The first observation about Fig. 2(a) is that in this scenario there is no Bluetooth interference on the first four IEEE 802.15.4 channels in the 2.4GHz ISM band. This may be because of the blacklisting method that is used by the Bluetooth channel hopping module. It should be considered that this blacklisting method may be different in different Bluetooth devices, from version to version, and vendor to vendor. The Bluetooth channel hopping module can also be pre-programmed to not use some parts of the frequency band to prevent cross-technology interference with in-range devices. The second observation about Fig. 2(a) is that the usage of different parts of the frequency band by Bluetooth is not uniform. For instance, some of the channels, such as channel 22, experience higher power Bluetooth interference (darker parts of the plot) while some others, such as channel 19, experience lower power Bluetooth interference. To make it clearer, Fig. 2(b) shows the measured noise on channels 19 and 22 during one second. We can see that channel 22 experiences interference of more that 20 Bluetooth transmissions during this period. Channel 19 only experiences interference of 3 Bluetooth transmissions. This shows that the Bluetooth interference is not uniform over different channels, and some channels may be occupied more than others. Furthermore, the measured power of the interference signal on channel 22 is considerably higher than on channel 19. A possible reason is the cross channel interference and distance between center frequency of the Bluetooth operating channels and the measured IEEE 802.15.4 channel. Thus, different adjacent Bluetooth channels can cause interference with different signal powers on an IEEE 802.15.4 channel.

We have a more detailed look at the Bluetooth interference behavior considering the application of audio streaming that is used in this scenario. Fig. 2(c) depicts the Bluetooth interference measured on the IEEE 802.15.4 channels in a 100 ms time period in this scenario. The measured interference follows a periodic behavior with intervals of around 30 ms with each transmission lasting for 3 ms, which is the transmission time of a Bluetooth packet with the maximum size. It shows that the audio streaming application sends periodic packets that require a bandwidth of around 10% of the available Bluetooth bandwidth.

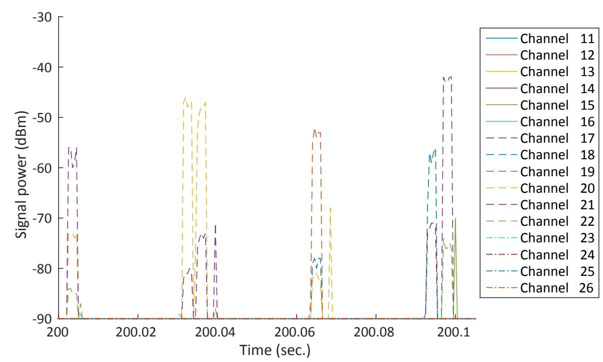
Fig. 3 shows the measured interference of one complete Bluetooth packet transmission. In this case, we can say that the first Bluetooth packet transmission fails because it is not followed by the receiver's acknowledgement. Thus, the transmitter sends the packet again within a short interval, and in this try, it is followed by an acknowledge packet. As mentioned before, the difference between measured signal powers on different IEEE 802.15.4 channels for a single (or multiple) Bluetooth transmission(s) can be because of



(a) Interference behavior over 300 s using contour plot.



(b) Measured interference power on channels 19 and 22 over 1 s.



(c) Measured interference power on all channels over 100 ms

Figure 2: Effect of Bluetooth audio streaming on IEEE 802.15.4 channels

the different distance between center frequency of the Bluetooth operating channels and the measured IEEE 802.15.4 channels. For instance, the first Bluetooth packet transmission in Fig. 3 generates interference on both the IEEE 802.15.4 channels 17 and 18 with different powers.

As a conclusion, voice streaming over Bluetooth produces periodic transmissions that lead to non-uniform interference for IEEE 802.15.4 channels. Thus some IEEE 802.15.4 channels may experience less interference than other channels (as shown in Fig. 2(a)). This behavior is caused by the channel hopping of Bluetooth which follows a pseudo-random hopping sequence. The power level of this interference on each channel is often stable over substantial periods of time.

4.2 Bluetooth File Transfer

To study the Bluetooth interference on IEEE 802.15.4 channels when Bluetooth is under higher load, we use two mobile phones to transfer a large file using a Bluetooth connection. The transmitter phone was placed on the back seat of the car near the interference measuring motes. The receiver phone was placed on the dashboard with 2 meters distance from the transmitter phone. As Fig. 4(a) shows, as for the audio streaming scenario, some of the channels experience more interference than others. Furthermore, the power level of the interferer signal on a single channel varies over time (compare interference power on channel 14 at $t = 100$ and $t = 200$).

Fig. 4(b) shows the measured Bluetooth interference in channels 14 and 25 at $t = 200$ for half a second. This figure shows that the number of interferer signals and their power in channel 14 is considerably higher than in channel 16. This is while Bluetooth uses its full bandwidth to transfer data in this scenario (see constant transmissions in Fig. 4(c)). Considering the results of the first scenario, we can conclude that Bluetooth causes a non-uniform interference over IEEE 802.15.4 channels for different applications with different data transfer rates. The important point here is that the power of Bluetooth interference on each channel is almost stable over substantial periods of time.

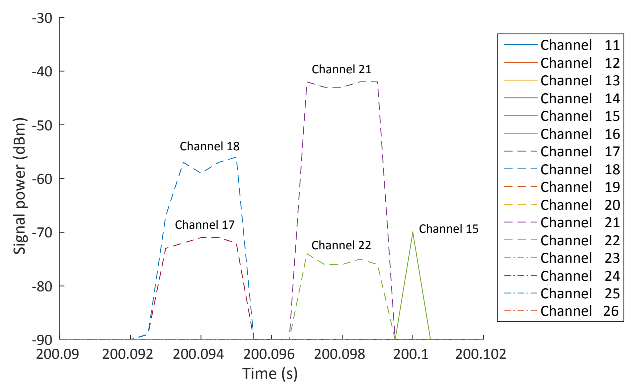
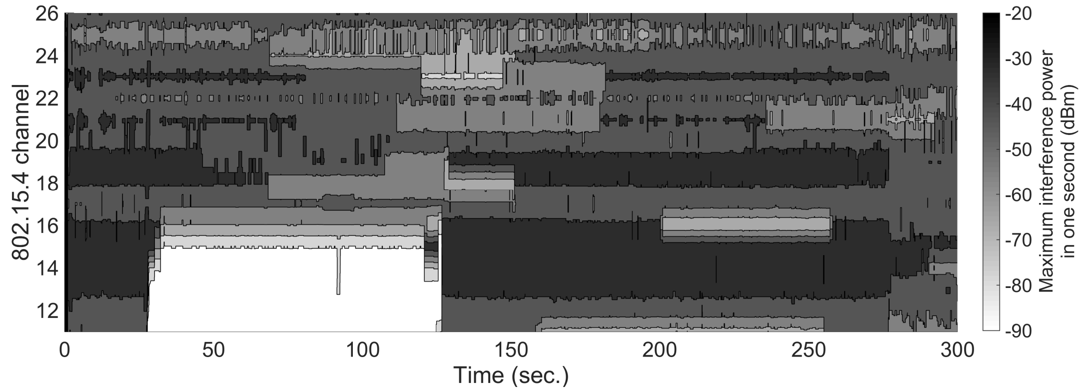
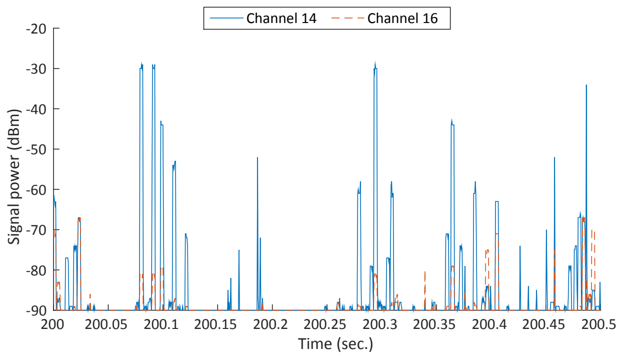


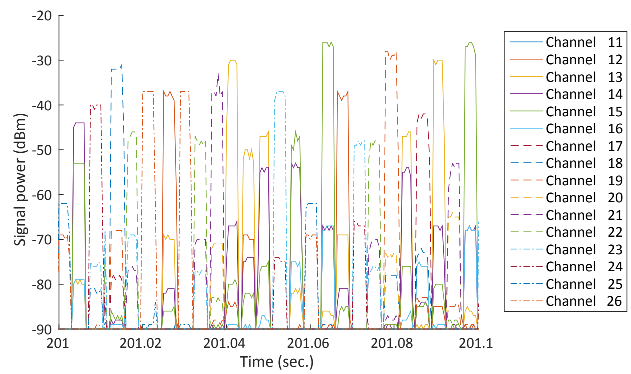
Figure 3: Interference of one Bluetooth packet transmission, one retransmission, and one acknowledgement on IEEE 802.15.4 channels



(a) Interference behavior over 300 s using contour plot.



(b) Measured interference power on channels 14 and 16 over 0.5 s.



(c) Measured interference power on all channels over 100 ms.

Figure 4: Effect of Bluetooth file transfer on IEEE 802.15.4 channels

4.3 Wi-Fi Connection

In this scenario we are interested in the amount of interference from Wi-Fi communication within the vehicle on the IEEE 802.15.4 channels. To study this effect, we connect two smart phones using *Wi-Fi direct* and use this connection to transfer some large files. One of the phones is used as the transmitter and another one as the receiver of the files. During the experiment, two phones are placed in different places inside the cabin by two passengers (one passenger at the driver seat and another at one of the rear seats). We logged the generated interference of this Wi-Fi connection on the IEEE 802.15.4 channels for 300 seconds.

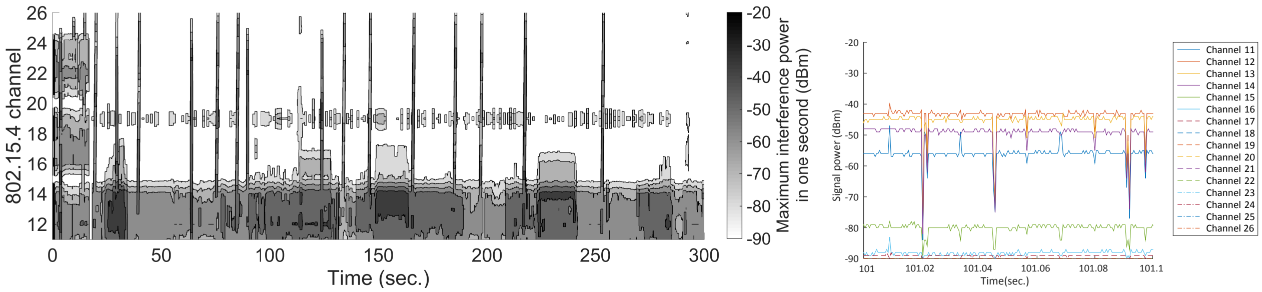
Fig. 5(a) shows the interference behavior over time and channels, using a contour plot. It shows that the Wi-Fi interference mostly affects a number of adjacent IEEE 802.15.4 channels and the power of this interference decreases by going far from the center frequency of the Wi-Fi operating channel. This plot also shows some transmissions at other frequencies than the frequency channel used for the mentioned Wi-Fi connection. These are probe requests (to perform active scans) and beacons (to advertise a P2P Group) that are done on so-called social channels, namely channels 1, 6 or 11 in the 2.4 Ghz band, by *Wi-Fi direct* devices [22].

In this experiment, the center frequency of the Wi-Fi operating channel is between channels 12 and 13 of IEEE 802.15.4. As Fig. 5(a) shows, the interference strength changes over time. These changes are due to the movement of two phones which changes the distance between interferer and sensor nodes and also due to the movement of passengers in the car that affects the path-loss of the interferer signal. Compared to Bluetooth, the observed interference on each channel is more stable over time. This is because Wi-Fi devices do not use channel hopping and a connection normally uses a fixed channel for communications.

Fig. 5(b) depicts the interference of Wi-Fi transmissions on the IEEE 802.15.4 channels over 100 ms. According to this plot, channels 11 to 14 are within the main 22 MHz bandwidth of the Wi-Fi operating channel, while channels 15 and 16 are on the sidebands of the Wi-Fi operating channel. Because the file transfer application uses the full bandwidth of the Wi-Fi connection, the captured interference on each channel is almost constant during the transmission period of a file.

4.4 In-car Interference Conclusion

In this section, we investigated the behavior of two main sources of in-car interference for wireless IVNs. The experiments show that the distribution of interference on different IEEE 802.15.4 channels is not uniform. Depending on the interferer protocol and the used application, the power of interference on each channel is almost stable over substantial periods of time. The minimum period of changes in the power of the interferer signal, that is more visible for Bluetooth, is in the order of a few seconds. We may conclude that the non-uniform interference over different channels suggests the need for a proper channel whitelisting (or blacklisting) mechanism. These mechanisms should also cope with the possible changes in the quality of each channel over time.



(a) Interference behavior over 300 s using contour plot. (b) Wi-Fi transmissions over 100 ms.

Figure 5: Interference of in-car Wi-Fi communications on the IEEE 802.15.4 channels.

5. OUT-OF-CAR INTERFERENCE MEASUREMENT

To study the interference behavior of out-of-car sources, we drove the car in different environments with different density of interferer sources. During these measurements, all the in-car interferers were turned off and the car was driven with allowed speed in that district. Four scenarios are considered that include apartment area, downtown, suburb, and highway. Considering the higher transmission power of Wi-Fi compared to Bluetooth devices, we expect that the Wi-Fi devices at sides of the roads be the main source of out-of-car interference. By using a Wi-Fi analyzer application on a mobile phone, we found that the density of Wi-Fi devices in these four scenarios is decreasing from apartment areas to downtown, suburb, and highways. We take a 5 minute drive in each of the environments while the interference measuring motes measure the noise level of all 16 channels. Fig. 6 shows the captured interference in different environments using a contour plot. To make these plots more clear, for each point in the plots we show the maximum observed interference level over a window of 2000 samples (1 s) in that time.

Fig. 6(a) shows the interference behavior while driving near apartments with speed in a range of 10 to 25 kmph. As it was expected, the interference power and density in apartment areas is more than in other environments. In this figure, there are lots of overlapping ovals with a high power at their centers (some of which are marked by red ellipses). This is because when the car is in the range of one Wi-Fi device and moving toward it, the interference power will be increased and vise versa. Thus the interference of one Wi-Fi device is only visible for a few seconds. The figure shows that any time the car is in the interference range of a number of Wi-Fi devices, which they can even overlap in operating channels, each one can affect 2 to 3 IEEE 802.15.4 channels. On the other hand, some of the IEEE 802.15.4 channels are noise free over different periods of time; this can be seen as white spaces on the contour plots.

The downtown scenario (Fig. 6(b)) has two specific properties. First, the speed of the car is determined by the traffic load of the streets and the traffic lights and is in a range of 0 to 30 kmph. This affects the time that a car will be in the range of a stationary interferer and thus affects the dynamism level of the interference. For example, around time 0s to 30s in the Fig. 6(b), the car has been waiting for a traffic light and the interference is not dynamic on channels 12 and 18. This is while from time 250s to 300s, the car has been moving along the street and the observed interference is relatively more dynamic. The second property is that the car moves next to other cars in the street in the same or opposite direction. These neighbor cars may carry some devices that are operating in the 2.4 GHz ISM band (Bluetooth, Wi-Fi, etc.). This may lead to long or short term interference. The vertical bars in Fig. 6(b) may be because of such interferences. These bars can be due to Bluetooth transmissions in the neighbor cars which affect most parts of the frequency band because of the fast channel hopping of the Bluetooth protocol. The interference of Bluetooth devices in neighbor cars is normally very short term. This is because of the low transmission power that is used in Bluetooth devices which leads to interference only when two cars are in a distance of few meters.

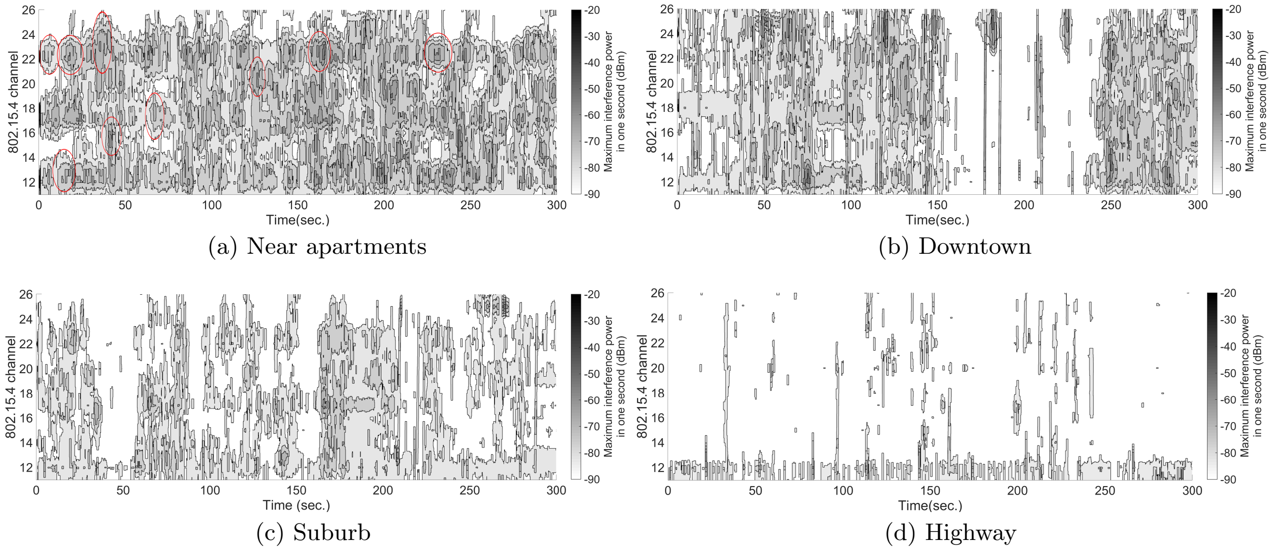
In the third scenario, the test car is moving in a quiet street in a suburb area with an average speed of 40 kmph. As it is clear in Fig. 6(c), the interference level in this area is less than apartment and downtown areas and there is more noise-free area left in the channel-time space. This is because of lower density of houses in suburb areas which leads to lower density of interferers. This also causes longer distances between stationary interferers and the car, which reduces the power of the observed interferer signal.

Fig. 6(d) shows the observed interference on a highway while the car is moving with a fixed speed of 115 kmph. In this scenario, the stationary interferers play the least role (only near the gas stations). The interferer devices in neighbor cars cause low level and short term interference too. The reason is the short time and high distance adjacency of cars in a highway.

Considering the mentioned observations of the out-of-car interference behavior, it can be concluded that in-vehicle wireless sensor communications may face serious problems in city environments if the operating channels and transmission power are selected blindly. In the next section, we study the effect of such interferences on the performance of the TSCH protocol by using probabilistic communication models and the collected interference database.

6. IVN SIMULATION UNDER REAL INTERFERENCE DATA SET

In this section, we propose a simulation framework that uses the measured interference data set to evaluate the performance of IEEE 802.15.4 WSNs. As a case study, we study the effect of dynamic in-vehicle interferences on the performance of multi channel wireless IVN communications.



(a) Near apartments (b) Downtown

(c) Suburb (d) Highway

Figure 6: Behavior of out-of-car wireless interference in different city environments.

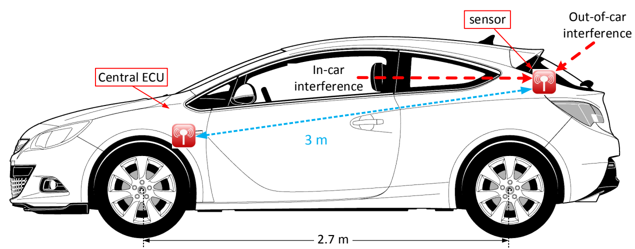


Figure 7: Interference model for packet reception probability computation.

Time Slotted Channel Hopping (TSCH) is one of the operation modes of the IEEE 802.15.4e [5] protocol standard. It uses channel hopping to eliminate blocking of wireless links caused by external interference on some frequency channels. This technique improves the reliability and connectivity of the wireless links compared to single channel communications [21]. This is the first work in the literature on the evaluation of TSCH performance under interference of in-vehicle environments. To investigate the effect of channel whitelisting, we also evaluate ETSCH [20], one of the enhancements to the TSCH protocol that uses channel whitelisting based on the interference condition of all channels. The main conclusions of [20] are confirmed, but the savings are less for the realistic scenarios, compared to the lab tests of [20].

We use a simple model to extract the communication behavior of a single wireless link in a car (shown in Fig. 7). In this model, there is an Engine Control Unit (ECU) inside the dashboard of the car which is connected, through a wireless link, to a wireless sensor node placed exactly where we placed the interference measuring motes. Considering a direct wireless link from the central ECU to the sensor node, the received signal power (P_{rx}) at the sensor node can be computed as:

$$P_{rx}[dBm] = P_{tx}[dBm] - PL(d)[dB] \tag{1}$$

where P_{tx} is the power of the signal at the transmitter (central ECU) and $PL(d)$ is the path loss at distance d. We use the path loss model (Eqn. 2) introduced in [3] for short range communications at 2.4 GHz band.

$$PL(d)[dB] = \gamma\ [20.1 + 10\log(d)] \qquad d \leq 8m \tag{2}$$

where γ is the path-loss exponent, which has a value equal to (for free space) or greater than 2.0 (other environments).

The receiver node in our framework experiences interference from sources inside and outside the car. The probability of successful communication is related to the Signal-to-Noise Ratio (SNR) [15]. Here we focus on the effect of interference from co-existing devices and ignore other kinds of noise. Thus, the SNR is given in decibel as:

$$SNR[dB] = P_{rx}[dBm] - P_{intf}[dBm] \tag{3}$$

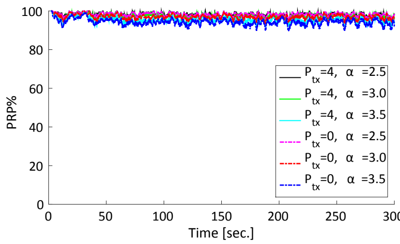
where P_{intf} is the interference power at the receiver point within the same bandwidth as P_{rx}. Considering that the distance between the transmitter and receiver in our model is 3 meters, the SNR for the given link can be presented as:

$$SNR[dB] = P_{tx}[dBm] - 24.87\gamma - P_{intf}[dBm] \tag{4}$$

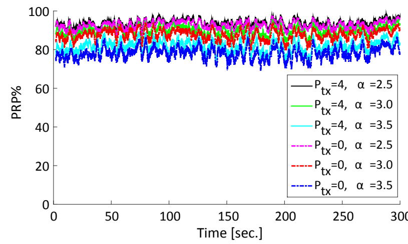
For a given SNR, the expected Bit Error Rate (BER) of an IEEE 802.15.4 link can be extracted using the BER model provided in the IEEE 802.15.4 standard (Annex E part 4.2) [3]. Thus, we can compute the expected Packet Reception Probability (PRP) for a given packet length and interference level during the transmission of that packet.

We perform our simulations with $P_{tx} = 0$ dBm that is the default transmission power of the protocol and also with a higher power of $P_{tx} = 4$ dBm that is the maximum transmission power of our ATMEL wireless motes. The path-loss exponent is expected to be dynamic in an in-vehicle environment because of the dynamism in the car (e.g., number of passengers and their position). We pick 3 values of $\gamma = 2.5$, 3.0, and 3.5 for our simulations to investigate the effect of environment changes on the performance of the given wireless link. Therefore, we simulate the performance of the TSCH link for 6 different (P_{tx}, γ) combinations under all different interference scenarios.

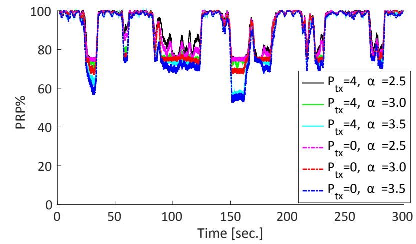
We implemented our simulation framework in Matlab according to the communication timings of the TSCH protocol. Time is divided into $10ms$ timeslots. After an offset at the beginning of each timeslot, we compute the BER for every bit using Eqn. 4 and the measured interference sample at that time on the operating channel. We considered a packet



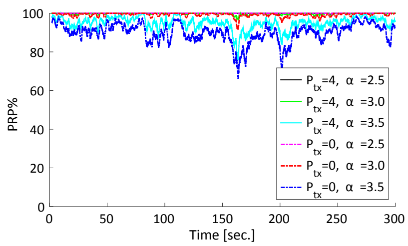
(a) Bluetooth mp3 streaming



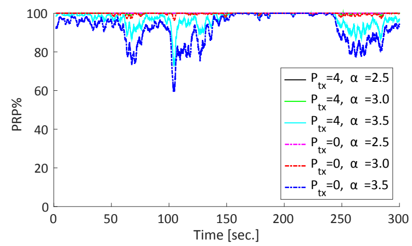
(b) Bluetooth file transfer



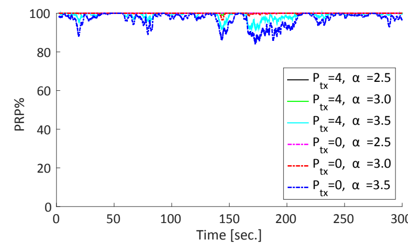
(c) Wi-Fi connection



(d) Near apartments



(e) Downtown



(f) Suburb

Figure 8: Average PRP of TSCH communications over time for different interference scenarios and transmission parameters.

length of 133 bytes which is the maximum physical layer packet length in the IEEE 802.15.4 protocol. By the start of the next timeslot, we hop to the next channel according to the TSCH hopping algorithm. We use all 16 available channels for the hopping sequence.

In our interference measurements, the radio sensitivity of the used devices was -90 dBm. Considering our worst case scenario with $P_{tx} = 0$ dBm and $\gamma = 3.5$, the PRP for $P_{intf} =$ -90 dBm is more than 99.99%. Thus we can be sure that our simulations only show the effect of existing interference. Measured interference values of -90 dBm, at the radio sensitivity limit, have no effect on the results.

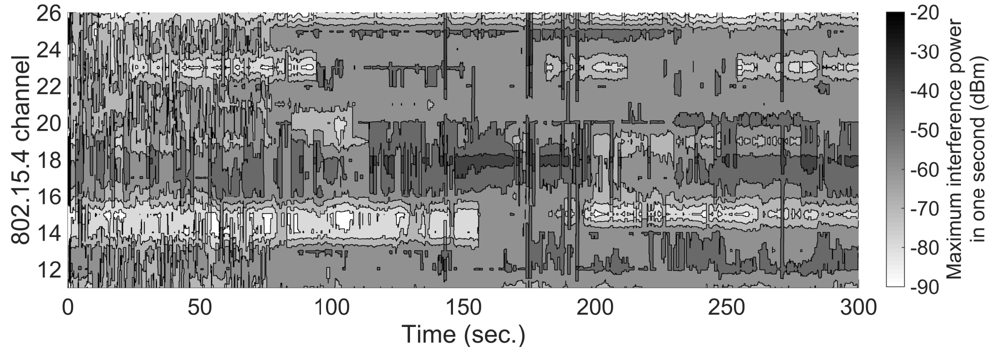
Fig. 8 shows the PRP for different scenarios. We skipped results of the highway scenario because for all the different sets of parameters, the PRP is close to 100%. We used a moving average function with a window of 2 s (200 transmissions) to show the average PRP over time. This is an approximation of the PRR in real-world communications.

A general observation from different scenarios in Fig. 8 is that the path-loss exponent, which is a parameter of the environment conditions, considerably affects the communications. Since this parameter is not a controllable parameter in the real-world, higher transmission powers may be a solution to increase the PRP. But WSNs are limited in power sources and thus, transmission power should be decreased as much as possible. The effect of generated interference to the neighbor networks due to this increase in transmission power should also be taken into account.

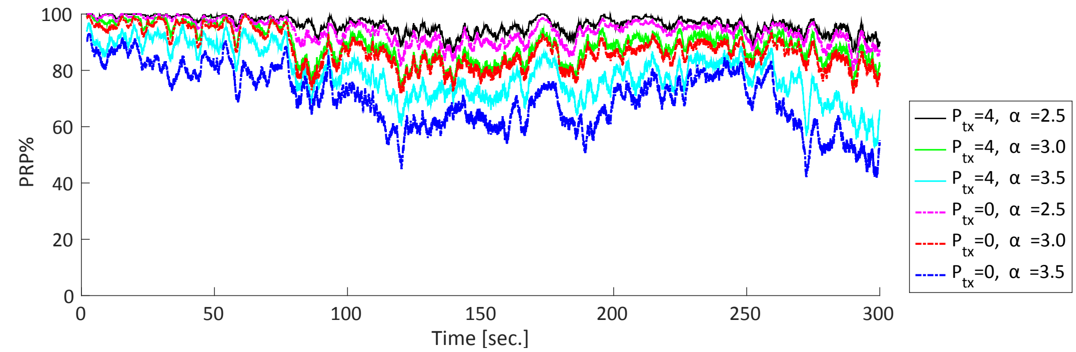
Another observation is that for almost all different (P_{tx}, γ) combinations in in-car interference scenarios (Fig. 8(a-c)), interference decreases the PRP even for a small value. In out-of-car scenarios (Fig. 8(d-f)), the impact of interference on PRP is considerably higher for $(P_{tx}, \gamma) = (4, 3.5)$ and $(0, 3.5)$ combinations, but for other combinations of (P_{tx}, γ), interference has almost no effect on the PRP. The reason is that different in-car interferers normally produce high power interference on a set of channels (due to a low distance between interferer and the wireless node in the car) and less or even no interference on other channels (Fig. 2(a),4(a), and 5(a)). Therefore even for (P_{tx}, γ) combinations with higher P_{tx} and lower path-loss exponents, the 802.15.4 link cannot overcome this high power interference on some channels and PRP will be decreased even with low values. On the other hand, in the out-of-car scenarios the interference power is usually weaker (compared to in-car interference) but distributed over most of the channels (Fig. 6). For higher P_{tx} and lower path-loss exponents, this low power interference has almost no effect on the PRP because the SNR is high enough. This is while for lower P_{tx} and higher path-loss exponents, the SNR decreases and even low power interference can affect the PRP. Because multiple channels in urban scenarios may experience interference at the same time (Fig. 6(a), (b), and (c)), packet transmission may fail in a set of channels and thus PRP decreases considerably.

Fig. 8 also shows that PRP in in-car scenarios (Fig. 8(a-c)) is almost uniform over time. This is because the user applications in in-car interferers are normally invariant and running for a long time. Thus, wireless medium usage and generated interference is almost uniform over time. For the Wi-Fi scenario in which we transmitted some files with random intervals, the uniform behavior is visible for each file transfer (the periods with reduced PRP). Due to the movement of the interferers inside the car in this scenario, each file transfer leads to different interference power and thus different levels of PRP. For the out-of-car scenarios (Fig. 8(d-f)), because of the car movements, different interferers (with different user applications) may come into range during time and even in some periods there may be no interferer in the range. Therefore, the effective interference and thus the PRP is very dynamic over time.

It should be considered that in real-world scenarios, out-of-car interference may be mixed with in-car interference, which may cause a bigger impact on the performance of a in-vehicle WSN. For example, a moving car in a downtown area may carry a mobile phone that is connected to the audio system of the car by Bluetooth to answer a phone call and at the same time a kid on rear seats may play an online video on a tablet which is connected to internet through



(a) Interference behavior over 300 s using contour plot.



(b) Average PRP of TSCH communications over time.

Figure 9: Effect of the mixed interference scenario on the IEEE 802.15.4 channels.

a Wi-Fi hotspot link on a mobile phone. Since there can be a scenario with lots of interferers that block communications on all the channels, discussing about the possible worst case interference scenario is pointless. We consider the mentioned situation as an example real-world scenario (named mixed scenario) with multiple sources of interference for an in-vehicle WSN. Fig. 9 shows the captured interference of this scenario together with the simulation results of average PRP of TSCH communications. As it can be seen, in such a scenario the PRP of the TSCH protocol may be reduced more than 50% in some points. This makes in-vehicle WSNs an unreliable candidate for in-vehicle networks.

There are some solutions such as ATSCH [10] and ETSCH [20] to overcome packet errors (due to interference) in TSCH networks. All of these techniques dynamically pick a subset of less noisy channels for channel hopping purposes, instead of using all available channels. The ETSCH technique uses part of the offset at the beginning of each timeslot for interference measurement (one sample in our experiments) on 2 to 3 channels and assigns a quality value to each channel based on the results. In every predefined time-interval, this technique selects a subset of the best quality channels as the hopping sequence list for the network. We implemented the functionality of this technique on top of our simulation framework in Matlab to evaluate its performance under real-world interference. In our simulations, one second time-intervals are used to update the hopping sequence list of size 6. As the interference input for our simulations, we picked the scenario of Bluetooth file transfer, Wi-Fi file transfer, driving near apartments, and the mixed scenario with multiple interference sources. In the Wi-Fi scenario,

Table 1: Average PRP of TSCH and ETSCH

	P_{tx}	TSCH	ETSCH
Bluetooth file transfer	0 dBm	78.02	87.31
	4 dBm	81.86	90.01
Wi-Fi file transfer	0 dBm	74.77	99.75
	4 dBm	76.14	99.81
Driving near apartments	0 dBm	89.90	97.01
	4 dBm	94.92	98.72
Mixed interference scenario	0 dBm	70.36	84.76
	4 dBm	78.97	91.16

the connection was idle between consecutive file transfers and those periods do not reflect the effect of Wi-Fi transmission on TSCH communications. Thus in our calculations of this scenario, we only take the file transmission periods into consideration.

Table 1 shows the average PRP over 300 seconds for both TSCH and ETSCH. We only show the results for the $(P_{tx}, \gamma) = (0, 3.5)$ and (4,3.5) combinations that led to the worst PRP results in TSCH simulations. As the results show, interference of a Wi-Fi connection reduces the average PRP of TSCH protocol about 25%, but ETSCH can reduce this negative effect to less than 1%. This is because of the static channel usage by the Wi-Fi protocol. For other scenarios, which experience more dynamic interference over frequency and time, ETSCH is still able to reduce the effect of interference more than 50%. This shows the importance of using such a technique for in-vehicle WSNs to improve the reliability of the network for both dynamic out-of-car and strong in-car interferences.

To the best of our knowledge, currently there are no models for simulating interference in in-vehicle environments. In this section we showed that the logged data set can be easily used to perform realistic simulations for in-vehicle WSNs under interference of different types of sources. In these simulations, there is no need to dive into the detail of the behavior of the protocols that are used by interference sources. Moreover, the logged data set can be used in the future for developing and tuning interference models for in-vehicle environments.

7. CONCLUSION

This paper studies the cross-technology interference behavior in in-vehicle environments using real-world experiments. Different scenarios for both in-car and out-of-car interference are considered. Each measurement simultaneously captures the noise power on all the IEEE 802.15.4 channels in the 2.4 GHz band. The measurement data set is available online and can be used for research in this domain by the community. Use of this data set provides more accurate analysis than lab data and simulated data. Moreover, there is no interference model available for in-vehicle environments and data sets as the one presented in this paper can be used to develop such models.

The measurement results show that both in-car and out-of-car interference affect most of the IEEE 802.15.4 channels at the same time and the maximum power of interference on each channel typically is stable over substantial periods of time. The measurement data set is used as an input for a packet transmission model to study the behavior of the TSCH protocol under interference of different scenarios. The results show that interference of in-car sources leads to effective and almost uniform probability of packet errors over time. For out-of-car interference sources, the probability of packet errors can be highly dynamic over time. An enhanced version of the TSCH protocol [20] that uses a channel whitelisting technique is simulated using the real interference data set. The results show that this technique almost completely overcomes the less dynamic interference caused by in-vehicle Wi-Fi devices. The technique also reduces around 50% of the effect of dynamic interference caused by different sources. This result shows the importance of using such techniques for in-vehicle WSNs to improve their reliability and it illustrates the value of the collected data set.

8. ACKNOWLEDGMENTS

The research from the DEWI project (www.dewi-project.eu) leading to these results received funding from the ARTEMIS Joint Undertaking under grant agreement n° 621353.

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