An Empirical Study of Urban 2.4 GHz RF Noise from the Perspective of a Body Sensor Network

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***Abstract*—In the 2.4 GHz ISM band RF interference is becoming an ever-increasing problem. While there have been several attempts to mitigate the impact of RF interference on (body) sensor networks, e.g. via frequency hopping, it is often unclear how these solutions perform in different interference environments and when they are actually useful. This is not least due to a lack of knowledge about the characteristics of environmental 2.4 GHz RF noise as perceived by a BSN in realistic scenarios. Such knowledge would, for example, help to better understand the communication challenges in a BSN and derive design decisions for interference mitigation techniques.**

Our work targets this underexplored area: we present the results from an urban measurement campaign, in which a mobile BSN collected about half a billion RF noise samples in various urban environments (park, campus, residential area, shopping street, urban transportation system). Our setup captured the entire 2.4 GHz band, on five different body positions simultaneously. Among other things, our results indicate that WLAN was the dominating source of 2.4 GHz RF noise; significant spectrum activity was typically detected during about 5% of the time, but there is a large variation among the scenarios; and, to detect the presence of RF interference the body position is of no of major importance, however, the difference in interference power measured at two different body positions is not negligible.

I. Introduction

In the crowded 2.4 GHz ISM band the transmission power of a IEEE 802.15.4 body sensor network (BSN) is usually two orders of magnitude lower than the output power of competing wireless technologies. Due to their virtual omnipresence, wide spectrum coverage, and comparably high transmit power (20 dBm in Europe) WLANs pose a particular challenge.Despite RF interference mitigation mechanisms like DSSS and "listen-before-talk" incorporated in both standards, it is well established that their mutual interference can result in notable deterioration of packet delivery performance [1].

Lately there have been several attempts to mitigate the impact of 2.4 GHz RF interference on IEEE 802.15.4 sensor networks, e.g. via frequency hopping. On the other hand, Bluetooth has been employing frequency hopping for years. However, it is not clear when the additional overhead introduced by these techniques (discovery, synchronization, etc.) actually pays off. For example, there have been contradicting conclusions, on whether frequency agility in low-power networks is necessary at all ([2] vs. [3]). Such conclusions are obviously dependent on a specific RF interference environment. Unfortunately, there is a lack of understanding about the quality and quantity of 2.4 GHz RF activity in realistic urban environments as perceived by body sensor networks.

Our work targets this underexplored area. We present a mobile BSN measurement setup that allows capturing 2.4 GHz spectrum activity information by five sensor nodes attached to a human body. The nodes continuously perform passive RF energy measurements by sweeping over the entire band (16 IEEE 802.15.4 channels) with an RSSI sampling frequency of 2.2 kHz. Our nodes are connected over an auxiliary wired control channel, which guarantees precise synchronization of the sampling processes. Through a series of 12 experiments in different urban environments we collected a huge dataset. In this paper we present an evaluation of the dataset. Some of our key findings are: significant spectrum activity was typically detected during about 5% of the time, but there is a large variation among the scenarios; an IEEE 802.15.4 intra-BSN link that achieves an RSSI of at least -80 dBm will typically be quite robust against urban RF interference; and it might be promising to take local history information into account when dealing with a certain interference environment.

We believe that our study is an important step towards a realistic assessment of how environmental 2.4 GHz RF noise is perceived by BSNs. In contrast to most previous spectrum measurement studies, we use original BSN hardware and attach several nodes to realistic body positions. Our study can be seen as a continuation of our previous work, in which we studied urban intra-BSN packet loss [1]. However, in contrast to our previous work, for this paper we used a distributed passive setup with more nodes that allow us to better assess spatial RF noise distribution. We also focus exclusively on the analysis and interpretation of the main cause: environmental 2.4 GHz RF noise.

The rest of the paper is structured as follows: Sect. II introduces our measurement setup; our measurement results are reported in Sect. III; in Sect. IV we describe related work and Sect. V summarizes our key findings.

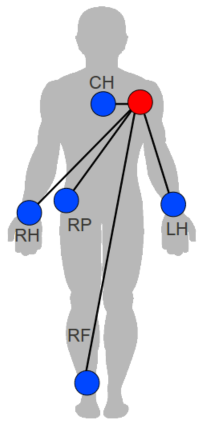

Figure 1. Node positions: blue nodes monitor RF noise, the red node (shoulder) synchronizes them via digitial I/O cabling.

II. Measurement Setup and Scenarios

This section introduces our measurement setup and the scenarios in which we performed the measurements.

A. Measurement Setup

Our measurement setup consists of six Shimmer2 [4] nodes attached to the human body at the positions marked in Fig.1. Shimmer2 is a wearable sensor platform designed for medical applications that capture various physiological parameters through optional sensorboards (ECG, GSR, EMG, etc.). Like the popular Telos platform, Shimmer2 integrates the Texas Instruments MSP430 MCU and the IEEE 802.15.4-compliant CC2420 radio for wireless communication. Our setup is completely passive: the main task of the nodes is to continuously perform RF noise measurements by *sweeping* over the entire 2.4 GHz ISM band (16 IEEE 802.15.4 channels). Each *sweep* consists of taking one RSSI (Received Signal Strength Indicator) sample on each of the 16 channels, where each sample represents the ambient RF noise power averaged over a window of 128 μs.

Our setup introduces an auxiliary wired channel to synchronize the sampling processes of the individual nodes in time. This synchronization is performed over digital I/O signals via pins exposed on the Shimmer2 expansion connector: with a set of dedicated shielded cables we interconnect each of the nodes with a central master node (carried in the right chest pocket of the subject). The master node is responsible for two tasks: it signals the beginning of a new sweep to the five nodes attached to it via cables; and it collects and stores location information obtained through a GPS sensorboard. The master node does not take part in RF noise measurements, because this would interfere with maintaining precise impulses over the digital I/O connection. Our setup thus effectively consists of one node that monitors GPS information and five other nodes that continuously and simultaneously sample ambient RF noise power in the 2.4 GHz band.[1] Each node stores the data on its SD card and after an experiment we collect the SD cards and extract the data. Note that we do not postprocess (calibrate) the RSSI data among the different nodes before we use it in our evaluation, because the noise floors of our particular nodes are very similar[2] and previous work has shown that differences in CC2420 RSSI readings are due to a linear offset [5], which can be determined through a noise floor measurement.

In our setup the duration of a sweep over the set of 16 channels is 7 ms; this includes the time for storing the RSSI samples on the SD card. We thus achieve a sweep frequency of 142 Hz resulting in an RSSI sampling frequency of 2.2 kHz. This performance can easily compete with commercial low-cost spectrum analyzers, such as the Wi-Spy 2.4x [6] USB spectrum analyzer. However, in contrast to a spectrum analyzer, our mobile setup allows to perform distributed spectrum measurements on multiple body positions in parallel, using realistic BSN radio technology.

B. Scenarios

We had one subject who performed 12 experiments in different urban environments. We selected three categories to classify these scenarios: environment (park, campus, residential area, shopping street, urban transportation system); degree of subject mobility (static, mobile or mixed); and indoor vs. outdoor. Table I describes the experiments and their classification. Some of the mobile experiments covered a certain path multiple times, e.g. a series of walks around the same blocks in a certain neighbourhood. For these experiments Table I shows the number of such iterations. Each experiment typically lasted for about one hour, resulting in a total experiment time of 13 hrs, in which we collected about half a billion RSSI samples.

III. Measurement Results

In this section we analyze the data collected in the previously described experiments (we used MATLAB for data processing/evaluation). For our analysis we define two reference thresholds: -94 dBm, which is the sensitivity threshold of the radio below which RF interference is irrelevant, because packet reception rate will fail anyway (the CC2420 requires an SNR of about 1-2 dB); and -85 dBm, which can be considered the RSSI of an intermediate link ("gray area"). Fig. 2 gives a first impression of the capabilities of our setup: it shows a one second snapshot of the intensity of 2.4 GHz RF noise measured simultaneously by nodes located on the left and right hand of the subject.

[1]Note that our hopping pattern, i.e. the order in which the 16 channels are covered during a sweep, is randomized, in order to not accidentally miss periodic signal sources (WLAN beacons, etc.). All nodes follow the same pattern as they use the same seed to initialize the pseudo-random number generator.

[2]Max. 2 dB difference in interference-free environment over all channels.

Table I
EXPERIMENT SCENARIOS

expt. no.	environment	description	subject mobility	duration
1	campus (indoor)	sitting at an office desk, working in front of a laptop	static	40 min
2	campus (indoor)	walking through campus buildings (5 iterations, 3.5 min each)	mobile	17.5 min
3	park (outdoor)	walking in an urban recreational park (10 iterations, 6 min each)	mobile	1 hr
4	residential (outdoor)	walking around a suburban residential block (15 iterations, 5 min each)	mobile	75 min
5	residential (indoor)	inhouse activities (kitchen work, watching TV, cleaning, ...)	static/mobile	66 min
6	residential (indoor)	like expt5, but in a different apartment	static/mobile	70 min
7	residential (indoor)	like expt5 (same apartment)	static/mobile	73 min
8	shopping street (outdoor)	walking an urban shopping street repeatedly (15 iterations, 6 min each)	mobile	90 min
9	shopping street (outdoor)	sitting outdoor in a suburban coffee bar (+few minutes walking)	(mostly) static	90 min
10	shopping street (outdoor)	walking from apartment to supermarket (few minutes inside) + return	mobile	48 min
11	shopping street (indoor)	sitting indoor in a suburban coffee bar (+few minutes walking)	(mostly) static	77 min
12	transportation system (indoor)	using the public transport system (urban railway, underground, tram)	(mostly) static	75 min

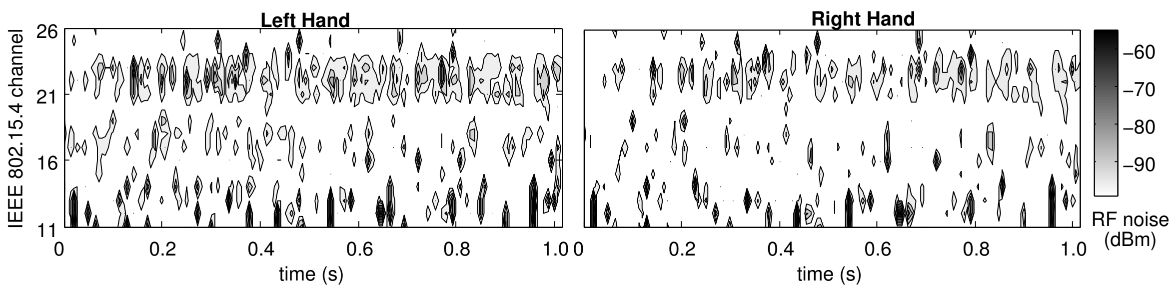

Figure 2. Example 2.4 GHz RF noise trace captured on the left hand and right hand simultaneously in expt7.

For the majority of time no significant activity is detected, however, when there is significant activity (≥ -94 dBm), it often correlates in frequency and time. Furthermore, there is already strong visual evidence that the data captured on the two different body positions simultaneously is correlated. In the rest of this section we will explore the data along the dimensions power, frequency, space and time.

A. Power

To gain a first insight in how severe 2.4 GHz environmental RF noise is perceived in body sensor networks, we examined the amount of samples exceeding either of two thresholds, -94 dBm or -85 dBm, per experiment. Or stated differently, the empirical probability that an RSSI sample was larger or equal than the given threshold for each experiment. The result is shown in Fig. 3. In several experiments significant spectrum activity occurred for about 5 % of the time, but there is quite a fluctuation: one experiment has a value well below 1 % (expt3), others more than 10 % (expt4+5) and up to 20 % (expt8). When applying a -85 dBm threshold the amount of samples decreases considerably: in this case none of the experiments showed more than 5 % of activity. This indicates that the power of environmental RF noise is often moderate, with values below or around -90 dBm. On the other hand, for the IEEE 802.15.4 an SNIR (signal-to-noise-and-interference ratio) of a few dB

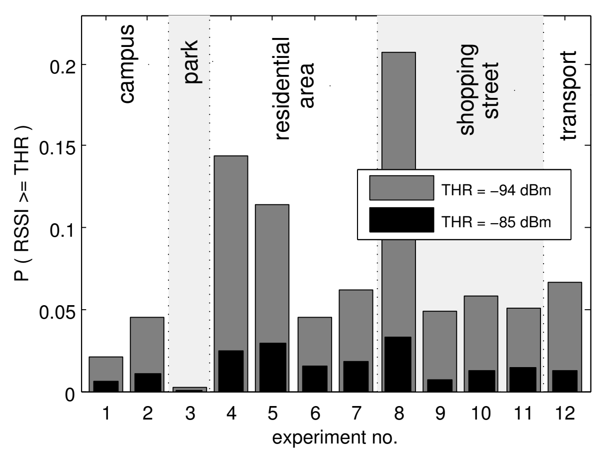

Figure 3. Empirical probability for RSSI samples being larger or equal than a threshold THR (-94 dBm or -85 dBm) per experiment. A distinction between channels, node position or sampling time is not made.

already results in good reception probability. Therefore, if an IEEE 802.15.4 intra-BSN wireless communication link achieves an RSSI of at least -80 dBm, it will typically be quite robust against urban RF interference.

Based on Fig. 3, no obvious trend with respect to our scenario classification is noticeable: the experiment with highest RF noise activity (expt8) was carried out in a

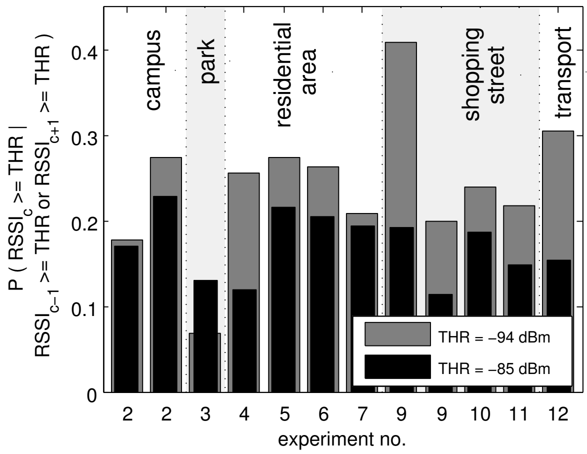

Figure 5. Conditional probability for RSSI samples being larger or equal than a threshold THR (-94 dBm or -85 dBm), given that the RSSI of a neighbouring channel (± 1 channel) was larger or equal than that threshold during the same sweep.

shopping street; yet, other experiments in different shopping streets rendered much less activity. It is more likely that results are influenced by momentary WLAN traffic, which - at least from our perspective - is quite arbitrary. But since expt8, for example, was an experiment that involved multiple consecutive iterations (6 min. each), we were able to analyze the continuity of the environmental conditions in more detail (Sect. III-D).

B. Frequency

To get a better understanding of the distribution of RF noise in the frequency domain, we created kernel density plots showing the density of significant spectrum activity in the band for each experiment individually as well as considering the entire dataset. Fig. 4 shows the results: the shaded area represents the entire dataset; it clearly shows peaks at IEEE 802.15.4 channel 13, 17 and 22. These channels happen to be very close to the popular WLAN channel 1, 6 and 11 center frequencies.[3] Furthermore, the shape of the peaks resembles the PSD of 802.11 DSSS signals, which is strong evidence that WLAN is indeed the major source of 2.4 GHz activity.

We were interested in the correlation of activity on (neighbouring) channels. Such information is a first indicator for the designer of a frequency hopping algorithm, about "where (not) to hop". Fig. 5 shows the empirical conditional probability for significant activity on a channel, given that at least one of the two neighbouring channels showed significant activity during the same sweep.[4] With a threshold of -94 dBm the average probability is around 20 %, which is roughly a factor 4 increase compared to the average 5 % probability for detecting significant activity (Fig. 3). A threshold value of -85 dBm results in an increase of up to an order of magnitude. These results indicate that there is a significant correlation of activity on neighbouring channels.

C. Space

The example snapshot shown in Fig. 2 already indicated a strong visual correlation between the RF noise samples captured simultaneously on different body positions. To gain a deeper insight, we computed the difference between two RSSI samples taken simultaneously at two different node positions, whenever any of the two nodes had detected significant activity (≥ -94 dBm). Fig. 6 shows a CDF that summarizes the results for all node pair combinations computed over our entire dataset. Roughly speaking, on average every second sample taken by two nodes simultaneously had a difference of 5 dB or less. In about 80 % of the cases the difference was no more than 10 dB. Fig. 7 renders a different perspective: it shows the empirical probability of a node detecting RF activity (above -94 dBm, or -85 dBm), given that another node detects the activity in parallel. The probability is more than 50 %, regardless of the particular node pair combination.

This indicates that for the practical task of *binary* interference detection, i.e. the detection if interference is present or not, the results will be similar for different body positions. However, the difference in interference power measured at two different body positions is not negligible, it may vary up to 10 dB or more.

D. Time

Fig. 3, which was introduced above in Sect.III-A, had shown quite a large fluctuation in the amount of significant RF noise detected in different experiments, even if they belonged to the same type of environment. As described in Table I some of the experiments consisted of the subject following a certain path multiple times, e.g. a series of walks around the same blocks in a certain neighbourhood. For such experiments (in total 4), we were interested in a comparison of the individual iterations, e.g. comparing the results of two subsequent walks around the same block. Because these iterations were carried out immediately after another, such a comparison can give some insight in the temporal dynamics of urban 2.4 GHz RF noise. To this end, we compared the relative amount of samples exceeding -94 dBm for the individual iterations of experiments 2,3,4 and 8, which all included an iterative path.

The outcome can be seen in Fig. 8. Experiment 8, which had been the one with the most significant RF noise activity (Fig. 3), shows very stable iterations, all close to the average 20 % value. The situation for experiment 4 is almost analogous. For these two experiments the RF noise conditions thus did not change significantly over the

[3] Although the measurements were performed in Europe, the recommended European configuration (1,7 and 13) does not seem to be common. This might be due to a default U.S. configuration of WLAN AP equipment.

[4] In this analysis we omitted channels 11 and 26 as they only have a single neighbouring channel.

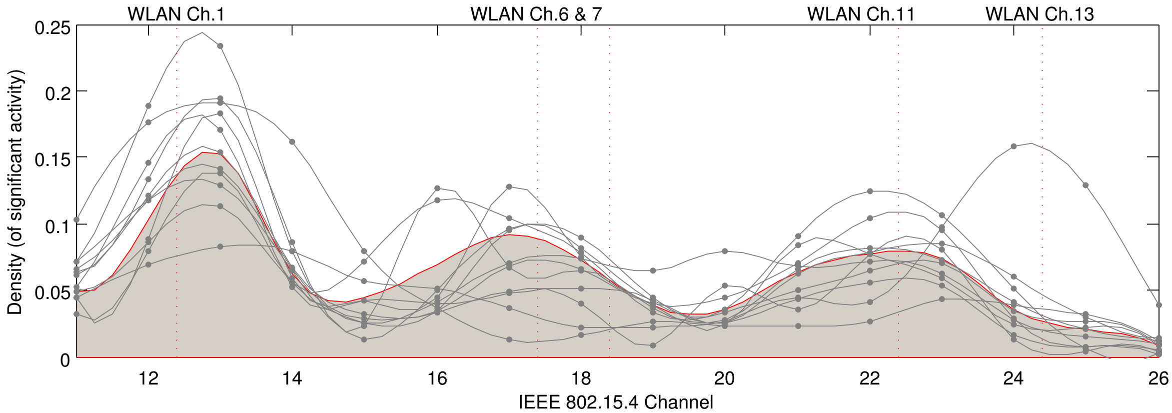

Figure 4. Kernel density plot of significant spectrum activity (≥ -94 dBm) for all experiments (shaded area) and individual experiments (gray graphs). Overlapping WLAN frequencies are shown as red vertical dotted lines.

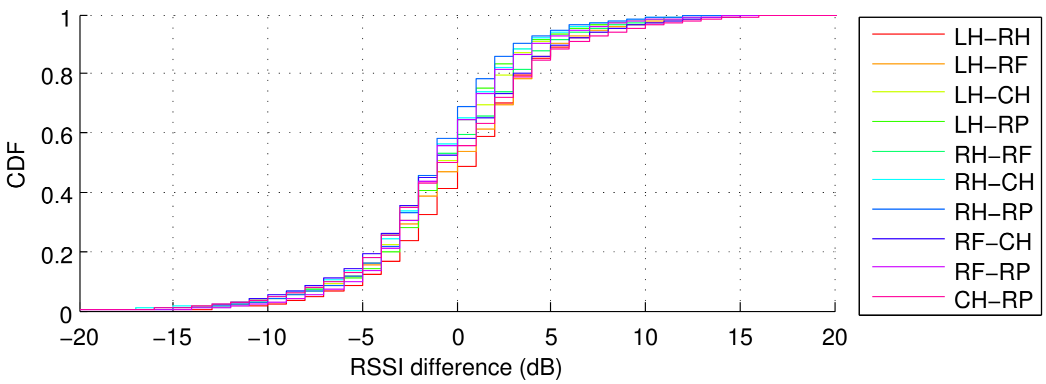

Figure 6. CDF of the instantaneous RSSI difference between different node position pairs (c.f. Fig 1 for notation).

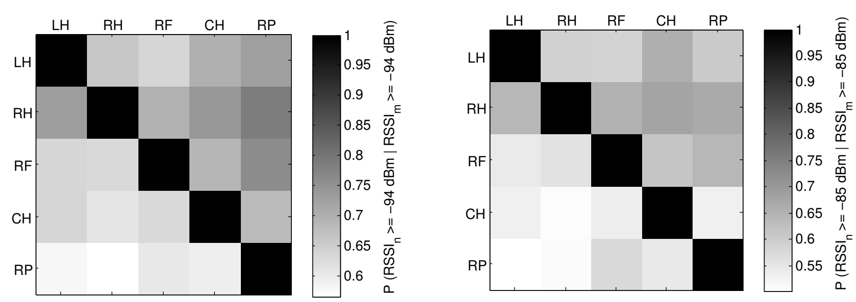

Figure 7. Conditional probability for an RSSI sample being larger or equal than a threshold THR (-94 dBm or -85 dBm), given that the simultaneously sampled RSSI on another node was larger or equal than that threshold (c.f. Fig. 1 for notation).

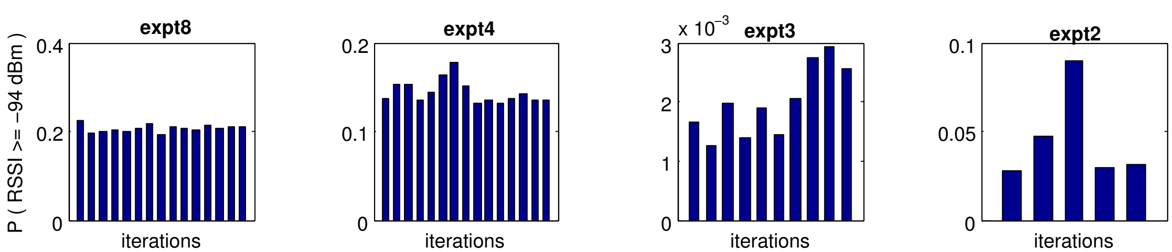

Figure 8. Empirical probability for RSSI samples being larger or equal than -94 dBm for the individual iterations of those experiments which included a path that was covered multiple times (e.g. during a series of walks around the same block).

individual iterations. This indicates that it was not temporary heavy WLAN traffic or a microwave oven that caused the peak in Fig. 3; possibly it was a longer-lasting WLAN file downloads from inside the buildings that our subject passed repeatedly. The results for the park environment (expt3) show more variance, but are not very representative due to the limited amount of significant RF noise samples collected during this experiment. Also the campus experiment (expt2) shows large fluctuations, likely caused by irregular usage of the university WLAN infrastructure. However, the analysis of expt8 and expt4 revealed that it might be promising to take local history information (past RF noise data for a given location) into account when designing interference mitigation techniques. An evaluation of the time dimension in more detail is omitted due to lack of space.

IV. Related Work

Several studies have reported on urban 2.4 GHz RF spectrum utilization. For example, in 2004 an urban power spectrum measurement campaign in the San Fransisco Bay Area showed "significant levels of the man-made signals regardless of time and location proving the proliferation of unlicensed devices in ISM 2.4 GHz" [7]. It has also been reported that in urban residential areas 2.4 GHz RF activity is often complex, (temporal) patterns are not obvious and there exists non-negligible noise from non-802.11 devices [8]. On the other hand, high utilization of the 2.4 GHz band is often contrasted by only sporadically utilized licensed frequency bands above or below the 2.4 ISM band, which might be utilized via cognitive radio concepts [9]. These previous studies have, however, not taken the specific characteristics of BSNs into account as they were conducted with static equipment at a single specific site. Closer to our work is an experimental study on the impact of RF interference from multiple BSNs in an indoor office environment [10]: the authors' main conclusion is that distance is not a good indicator for the received interference power, because it is dominated by random variations in signal power. Finally, in a previous article [1] we have reported on wireless communication performance in a BSN using an active measurement setup (with 2 nodes). However, only in this article we have been able to show results from a large number of different urban scenarios; furthermore, to the best of our knowledge it is the first study that converted a medium-sized (5 node) body sensor network into a highly synchronized, distributed spectrum analyzer that allows to evaluate the spatial distribution of RF interference based on realistic BSN-hardware.

V. Conclusions

In this paper we have described and interpreted the results from an urban RF noise measurement campaign, conducted with a set of five body sensor nodes that synchronously collected a total of half a billion 2.4 GHz RF noise samples in various urban scenarios. Our key findings are: (1) there is strong evidence that WLAN is the major source of 2.4 GHz activity; (2) in many experiments significant spectrum activity occurred for about 5% of the time, but there is a large variation among the scenarios; (3) an IEEE 802.15.4 intra-BSN link that achieves an RSSI of at least -80 dBm will typically be quite robust against urban RF interference; (4) there is a significant correlation of the simultaneous activity on neighbouring channels; (5) for binary interference detection the body positions is of no major importance, but the difference in interference power measured at two different body positions is not negligible; and (6) it might be promising to take local history information into account when designing interference mitigation techniques.

Acknowledgment

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