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Experimental Study of the Impact of WLAN Interference on IEEE 802.15.4 Body Area Networks *

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Abstract. As the number of wireless devices sharing the unlicensed 2.4 GHz ISM band increases, interference is becoming a problem of paramount importance. We experimentally investigate the effects of controlled 802.11b interference as well as realistic urban RF interference on packet delivery performance in IEEE 802.15.4 body area networks. Our multi-channel measurements, conducted with Tmote Sky sensor nodes, show that in the low-power regime external interference is typically the major cause for substantial packet loss. We report on the empirical correlation between 802.15.4 packet delivery performance and urban WLAN activity and explore 802.15.4 cross-channel quality correlation. Lastly, we examine trends in the noise floor as a potential trigger for channel hopping to detect and mitigate the effects of interference.

Key words: Body Area Networks; IEEE 802.15.4; Interference

1 Introduction

Body Area Networks (BANs) allow monitoring of the human body with detail and pervasiveness that is opening new application opportunities in domains ranging from personalized health-care and assisted living to sport and fitness monitoring [1]. In these domains the wireless telemetry was traditionally based either on proprietary communication technologies or on standardized solutions with significant licencing overhead and limited geographic availability. With the introduction of the IEEE 802.15.4 standard [8] and its focus on low data rates, low power consumption, reduced complexity and device size, an alternative emerged that matches the specific requirement of a BAN platform quite well.

Although 802.15.4 technology has rapidly matured and become the basis of several commercial products, there is still a level of uncertainty whether it can meet the stringent QoS requirements typical for some BAN applications under more challenging operating conditions. These concerns especially pertain to the coexistence with other major users of the unlicensed 2.4 GHz ISM band, notably

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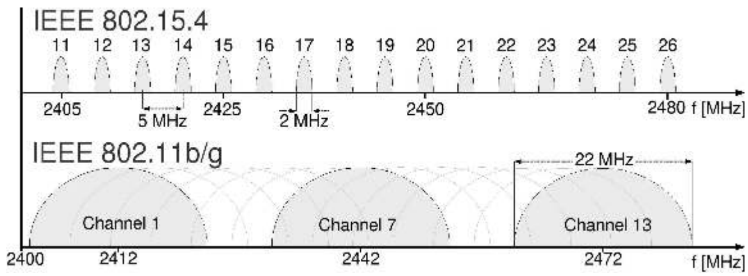


Fig. 1: IEEE 802.15.4 and 802.11 spectrum usage in the 2.4 GHz ISM band. The availability of channels is regulated per country.

IEEE 802.11 (WLAN) [10] and IEEE 802.15.1 (Bluetooth) [9]. Due to their virtual omnipresence and comparably high transmit power (20 dBm in Europe) WLANs pose a particular challenge.

Fig. 1 shows the spectrum usage of the two technologies in the 2.4 GHz ISM band. Despite interference mitigation mechanisms like DSSS and "listen-before-send" incorporated in both standards, it is well established that their mutual interference can result in notable deterioration of packet delivery performance. Although previous studies have treated this problem both from analytical and experimental side (Sect. 6), none of them has taken into consideration the specific characteristics and operational features of the BAN domain in terms of topology configuration, mobility and radio duty cycle under *realistic interference scenarios* in typical urban environments.

Our work targets this unexplored area. We present a measurement setup that allows capturing of a large subset of the parameter space with detail that was previously not reported. It supports mobile long-term monitoring of interference effects using symmetric communication and variable transmit power on all sixteen IEEE 802.15.4 channels in the 2.4 GHz band. We (1) report on multi-channel measurements from a controlled environment as well as from different urban environments, (2) demonstrate empirical correlation between 802.15.4 packet delivery performance and "real-life" WLAN activity and (3) explore 802.15.4 cross-channel quality correlation and trends that may be used as a potential trigger for channel hopping.

We believe that our study is an important step towards a realistic assessment of how WLAN interference can affect IEEE 802.15.4 BANs and towards the development of schemes for interference detection and mitigation.

The rest of the paper is structured as follows: in Sect. 2 we describe our experimental setup and provide a definition of the relevant metrics. We present the results of a set of baseline experiments in Sect. 3 and report on a representative sample of our dataset from an urban environment in Sect. 4. In a "first cut" evaluation we analyze in Sect. 5 the empirical traces for cross-channel quality correlation and trends in the noise floor. In Sect. 6 we discuss related work and present our conclusions and plans for future work in Sect. 7.

2 Experimental Setup

This section introduces our measurement platform and provides a definition of the relevant metrics.

2.1 Measurement Platform

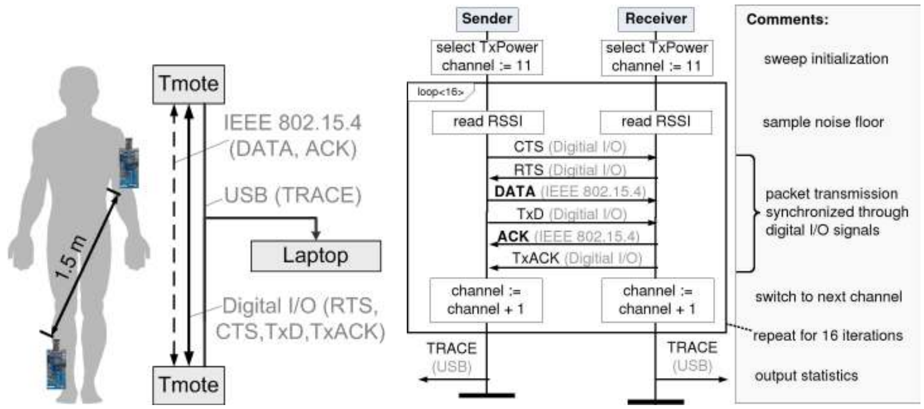
Our measurements are performed with Tmote Sky [13] (Telos Rev. B) sensor nodes, which are equipped with the IEEE 802.15.4-compliant Texas Instruments CC2420 transceiver [2]. The CC2420 operates in the 2.4 GHz ISM band, uses O-QPSK modulation and has a data rate of 250 kbps. A packet can be transmitted on one of 16 channels which are spaced 5 MHz apart and occupy frequencies 2405 MHz - 2480 MHz as shown in Fig. 1.

Our setup consists of two nodes, each node is placed in a thin plastic enclosure and strapped to a person: one to the left upper arm, the other on the right shin just above the ankle, resulting in a relative distance of about 1.5 m (Fig. 2a, left). When the person stands still both nodes have the same alignment and both surface areas are facing in the same horizontal direction. However, in all experiments, the test person is walking at an even speed of about 1.2 m/s (common walking speed). Our setup introduces two auxiliary wired channels: one to synchronize the transmissions on the IEEE 802.15.4 channel; and a second for streaming measurement results to a laptop. This is schematically shown in Fig. 2a (right) and explained in the following.

Packet Transmission Our measurement software accesses the CC2420 radio directly, there is no MAC layer involved and all packets are sent immediately (without clear channel assessment, CCA). Both nodes continuously iterate over the 16 channels, exchanging one `DATA` and acknowledgement (`ACK`) packet per channel. We call an iteration over all 16 channels – involving 32 packets – a *sweep*. During a sweep the roles of the nodes are fixed: one node sends the `DATA` packets, the other node sends the `ACK` packets; after every sweep the roles are swapped. We use acknowledgements, because this is common to many IEEE 802.15.4 networks, and we let the nodes swap roles, because this allows us to (better) evaluate link (a)symmetry.

The CC2420 supports different transmission power levels, the datasheet documents 8 discrete levels ranging from -25 dBm to 0 dBm [2]. The relevant `TXCTRL` register of the radio, however, accepts 32 different values. The radio manufacturer confirmed to us that all 32 values are valid, however, "the relation between the register setting and the output power is not linear". We experimentally determined an output power of roughly -42 dBm when the `TXCTRL.PA_LEVEL` is set to the value of 2.[1] In our study we then used three different output power levels of -10 dBm, -25 dBm and -42 dBm, alternating every sweep. The MSC in Fig. 2b shows the sequence of operations performed during a sweep.

[1] We chose 38 sender/receiver combinations from a batch of 10 Tmote Sky nodes and measured RSSI for different documented as well as the undocumented register



(a) Node placement and schematic measurement setup. The laptop is carried in a backpack.

(b) MSC describing a sweep. Note that only DATA and ACK packets are exchanged over the wireless channel.

Fig. 2: Measurement setup and Message Sequence Chart (MSC) for a single sweep.

Synchronization Whenever a packet is transmitted by one node, the other node's radio is in receive mode, both nodes have tuned to the same channel, and they use the same level of transmission power for the `DATA` and `ACK` packet. This requires very careful synchronization. One option is to perform synchronization through the arrival times of `DATA` and `ACK` packets, but since our experiments are conducted in an environment of possibly strong RF interference we rejected such "in-band" synchronization, because it would require unknown (conservative) guard times to counter the clock drift in case of successive packet losses. Instead we perform synchronization over digital I/O signals through pins exposed on the Tmote Sky expansion header: with a shielded cable we interconnect the two microcontrollers via four digital I/O ports. To increase robustness we use differential signalling (complementary signals sent on two separate wires) and thus allow four different signals, which is sufficient to synchronize the transmission of `DATA` and `ACK` packets. The sequence of exchanged digital I/O signals is shown in Fig. 2b, the vocabulary of messages and signals is listed in Table 1.

Data Logging During our study the sensor nodes collect large amounts of statistics that, due to limited memory, cannot be stored on the nodes themselves. Instead the nodes are connected and continuously output the results to a laptop through the USB interface of the Tmote Sky, which also serves as their power

settings in a low-interference environment based on a fixed node placement. Assuming a linear relationship between output power and RSSI, we used the documented values in combination with the measured average RSSI as anchors for a linear regression to determine the unknown transmission power level based on the corresponding measured RSSI value.

Table 1: Messages and signals exchanged during the measurements.

Message/ Signal	Channel	Description
DATA	802.15.4	DATA packet (MPDU of 36 byte)
ACK	802.15.4	ACK packet (MPDU of 5 byte)
RTS	Digital I/O	Sender requests to send a DATA packet
CTS	Digital I/O	Receiver is ready to receive DATA packet
TxD	Digital I/O	Sender has sent a DATA packet
TxACK	Digital I/O	Receiver has sent an ACK packet
TRACE	USB	Measurement results for a sweep over 16 channels

supply. The laptop is carried in a backpack by the same person that wears the two sensor nodes and is also used to monitor 802.11b/g traffic on selected WLAN channels during the experiments.

Sweep-time Performance In our setup the time required for a sweep over 16 channels is about 87 ms, which results in around 12 sweeps (384 packets) per second including streaming the measurement results over USB. This is achievable because we increase the Tmote Sky CPU frequency to the maximum of 8 MHz and because synchronization over digital I/O is very fast. We took particular care to minimize the impact of streaming the statistics over the USB on the actual measurement and its periodic workflow: most operations related to the transmission of 802.15.4 packets and synchronization occur in interrupt context, while sending serial packets over USB is divided in many small blocks of code that are executed in non-interrupt context. All outgoing/incoming packets are timestamped. After the measurement we use the hardware generated timestamps of successful transmissions as anchors, perform a linear regression to cancel out the clock drift, and obtain precise timing information to verify that in our setup 802.15.4 data packets are indeed transmitted periodically with an average interarrival time of around 5.5 ms. For example, in the experiment described in Sect. 4.1 we determine an average interarrival time of 5.43 ms (maximum: 6.45 ms, minimum: 4.39 ms).

2.2 Additional Hardware

We use a portable *Wi-Spy 2.4x* USB spectrum analyzer to verify that the baseline measurements are conducted in an environment of negligible external RF interference. The two laptops that generate controlled 802.11b traffic (Sect. 3.2) use Intel PRO/Wireless 2100 network interface cards. In some of our measurements we also monitor 802.11b/g traffic using a PC card based on an Atheros chipset plugged into the laptop that collects the measurement results.

2.3 Metrics

In our study all 802.15.4 `DATA` packets are acknowledged and a transmission is defined as *successful* if both, `DATA` and `ACK` packet, were received without errors. Correspondingly, a transmission has *failed* if either `DATA` or `ACK` packet (or both) were corrupted (CRC check failed). Whenever we report on moving averages, the average is calculated over either 10 or 100 transmissions for a particular channel and transmission power level. Because a sweep takes about 87 ms and we use three different transmission power levels alternating every sweep, this corresponds to a time window of about 2.6 s (10 transmissions) or 26 s (100 transmissions).

The CC2420 radio adds to every received packet the Receive Signal Strength Indicator (RSSI) level and a Link Quality Indication (LQI) value. We use the formula in the CC2420 datasheet [2] to convert the exported RSSI value to dBm. The LQI value from the CC2420 "represents a measurement of correlation between the received [and the determined] chip"[2] and we always report the raw LQI values ranging from about 110 (maximum quality) to 50 (worst quality). In addition to per-packet RSSI and LQI we measure the noise floor in between transmissions by reading the CC2420 RSSI register, which we hereafter call SSI_{noise}.

3 Baseline Measurements

We begin our study with a set of baseline measurement conducted outdoors in a large park, an environment of negligible external RF interference, as verified with the help of a portable spectrum analyzer. The results are intended to give some confidence in the performance of our setup, to reveal that — at least in this environment — the effects of mobility are virtually negligible and to show possible effects of 802.11b interference on 802.15.4 link quality.

3.1 Low Interference

In our first measurement the test person takes a 35 minute walk while the BAN measures packet loss, noise floor, RSSI and LQI over the 16 different channels. Out of the total 390.096 transmission only 2 failed (one at −42 dBm, the other at −25 dBm). This is negligible and indicates that with our setup a transmission power of −42 dBm is in principle sufficient in this kind of environment. We observe only small variance in RSSI, the maximum standard deviation for RSSI on any channel for any out of three given transmission power was 1.54 dBm. However, at −42 dBm transmission power the RSSI is usually around −88 dBm, which is close to the −94 dBm sensitivity threshold specified in the CC2420 datasheet. LQI varies a little more, in particular at −42 dBm transmission power, where we observe a maximum standard deviation of 3.10 for channel 11 on one node. The noise floor was very stable at −99 dBm on both nodes.

[2] One 802.15.4 symbol is mapped to a sequence of 32 chips resulting in a nominal chip rate of 2.0 Mchip/s.

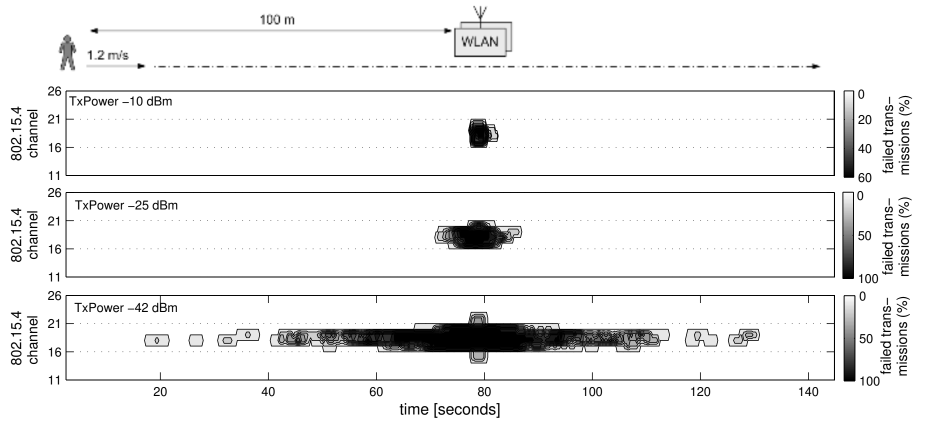


Fig. 3: Failed 802.15.4 transmissions while walking past two 802.11b stations transmitting at maximum rate on 802.11 channel 7. For every 802.15.4 channel the transmissions are averaged over a window of 10 transmissions, and 802.15.4 packets are transmitted with either −10 dBm (top), −25 dBm (middle) or −42 dBm (bottom) transmission power, alternating every sweep. The total distance covered is 180 m, the 802.11 network is located at 100 m distance from the starting point.

3.2 Controlled 802.11b Interference

We are interested in how a nearby 802.11 network can affect the link quality of the 16 different 802.15.4 channels. In this experiment we set up two laptops to form an 802.11b ad-hoc network and start a large file transfer from one to the other. Both laptops are placed close to each other on the ground, and generate heavy traffic on 802.11 channel 7 at 11 Mbit/s. The experiment is simple: our test person first stands 100 m away from the 802.11 network, at time $t = 0$ s starts walking on a straight line towards it, passes 1 m by the two laptops (at about $t = 80$ s) and continues walking on the same straight line. The BAN measures the number of failed 802.15.4 transmissions, the changes in noise floor and per-packet RSSI and LQI. After the experiment we sort the measurement results by the transmission power level, and produce a contour plot, respectively, showing failed transmission averaged over a window of 10 transmissions (2.6 s) for each channel. The result can be seen in Fig. 3.

The 802.11b network temporarily caused significant packet loss: at −10 dBm transmission power transmissions failed only at close distance (a few meters), at −25 dBm losses occurred within about ± 10 m, and at −42 dBm the first transmissions failed at more than 75 m distance. However, packets were lost only on channels that are close to 2442 MHz, the center frequency of 802.11 channel 7, that is mainly on 802.15.4 channels 17 to 20 (compare Fig. 1). According to the 802.11 standard, at ± 11 MHz from the center frequency, the radiated energy must be 30 dB lower than the maximum signal level; still, when the 802.15.4

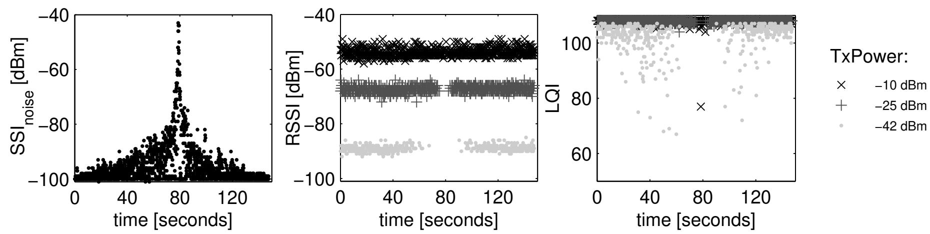


Fig. 4: Noise floor (left), RSSI (middle) and LQI (right) on channel 18 over time, extracted from the traces belonging to the experiment shown in Fig. 3.

network transmitted at −42 dBm even channels 15, 16, 21 and 22 suffered short-term losses at close distance.

The results can be interpreted in line with the SINR model: from the perspective of the 802.15.4 BAN the 802.11b laptops generate interference, which decays (non-linearly) with distance. When approaching the interferers, at a certain distance the ratio of received power in the 802.15.4 signal to the power of the interference is too low for the CC2420 radio to correctly decode the symbols and packets are lost.

Fig. 4 shows the dynamics in the noise floor, RSSI and LQI. The figure only shows the results for 802.15.4 channel 18, because it was one of the most affected by packet loss. Naturally RSSI and LQI are only available for received packets, but the respective graphs (middle and right in Fig. 4) give some first insight in temporal trends around the losses.

As expected, the noise floor increases with smaller distance to the 802.11b network; however, even at very close distance (around $t = 80\,\mathrm{s}$), we see a range of different SSI_{noise} values, some as low as −99 dBm. A possible explanation is that the 802.11 stations are not permanently transmitting. For example, there are at least short Inter-Frame Spaces (IFS) between 802.11 packets during which the channel is idle. The CC2420 averages a single SSI_{noise} reading over $128\,\mu\mathrm{s}$, and it can thus happen that a sample is taken while the channel is (partially) idle. This indicates that a single SSI_{noise} value is rather unreliable for determining presence of an interferer.

RSSI seems almost unaffected by the 802.11 traffic, but LQI shows higher variance as distance to the 802.11 network decreases, especially at −42 dBm transmission power. This is understandable since LQI represents a measure of correlation between 802.15.4 chips: single chips may be corrupted by 802.11 interference while the symbols are still correctly decoded.

4 Urban Measurement Campaign

We made measurements in three different environments in the city of Berlin, Germany: at a shopping street, in a central residential area and in an office area. During all measurements the test person was walking outdoors on the

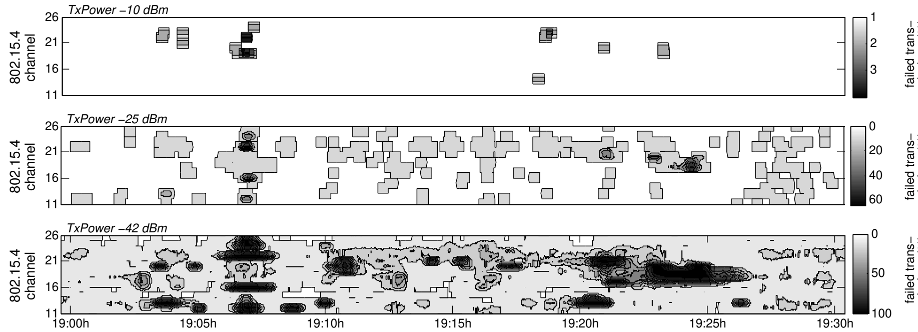


Fig. 5: Failed 802.15.4 transmissions while walking along an urban shopping street. For every 802.15.4 channel the transmissions are averaged over a window of 100 transmissions (26 s), and packets are sent with three different transmission power levels: −10 dBm (top), −25 dBm (middle) or −42 dBm (bottom), alternating every sweep.

urban streets using the same setup as described previously. A single measurement typically lasted around 30 minutes. As a case study in this section we report on one such measurement in detail, in the next Sect. 5 we present an evaluation of the empirical traces from all measurements.

The measurement described in the rest of this section was made at a central urban shopping street. Buildings were located on either side of the roughly 30 m wide street, which was moderately frequented by cars and other pedestrians on a weekday evening at 7 p.m. The test person took a 30 minute walk outdoors along the pavement passing by shops, coffee bars and offices as well as other pedestrians. The walk was one-way and close to straight-line at even walking speed (stopping only at red traffic lights).

4.1 Transmission Failures

Fig. 5 shows failed 802.15.4 transmissions averaged over 100 transmissions per channel (about 26 s) sorted by transmission power.

The losses for −10 dBm transmission power (top) are negligible, even at −25 dBm (middle) we never see more than 60 % loss within a window of 26 s on any channel. At −42 dBm (bottom) transmissions failed more frequently and some channels were temporarily completely blocked. The figure suggests that losses were not completely random. Instead they showed some correlation in time and frequency, sometimes lasting for a few tens of seconds up to multiple minutes and spanning over multiple consecutive 802.15.4 channels.

Fig. 6 shows a 2 minute excerpt of the bottom Fig. 5 at around 19:03 h. In this figure transmissions are averaged over a window of 10 transmissions (2.6 s) as in the baseline measurement shown in Fig. 3. When comparing these two figures we find that in Fig. 6 the pattern at around 19:03 h to 19:04 h on channels 13 closely resembles the 802.11b “footprint” in Fig. 3, which suggests that these losses might have been caused by 802.11 traffic.

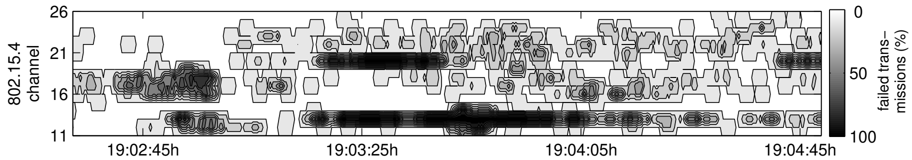


Fig. 6: Two minute excerpt from bottom Fig. 5, averaged over 10 transmissions.

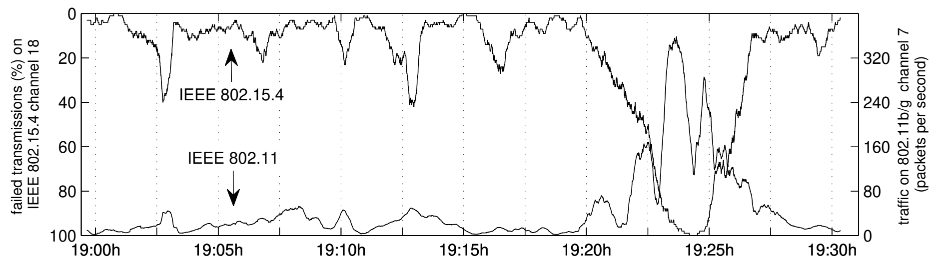


Fig. 7: 802.15.4 transmission failures on channel 18 using transmission power −42 dBm (left Y-Axis) and 802.11b/g traffic on WLAN channel 7 (right Y-Axis) averaged over a window of about 26 s.

4.2 Correlation with 802.11b/g Traffic

During the experiments the 802.11b/g card of the laptop that collected the statistics from the nodes was set to passive monitoring mode so that all 802.11 traffic on a given channel was captured. We tuned the card to 802.11 channel 7, because it is one of the most commonly used. In this way we measured two things in parallel: 802.15.4 failures on all channels and 802.11b/g traffic on 802.11 channel 7.

In Fig. 7 one can see both, failures on 802.15.4 channel 18 using transmission power −42 dBm and the number of received 802.11 packets on channel 7, averaged over 100 transmissions in the 802.15.4 network (26 s). As shown in Fig. 1, 802.11 channel 7 completely overlaps with 802.15.4 channel 18. The results appear (negatively) correlated both, visually and statistically. The empirical correlation coefficient is r = -0.89, which when squared is 0.79 and describes the proportion of variance in common between the number of 802.15.4 failures and received 802.11 packets when averaged over a window of 26 s. This suggests that in this experiment 802.11 was indeed the cause for considerable packet loss, at least on channel 18.

When we repeated the measurement at other locations we observed less correlation (correlation coefficients around r = -0.4). It must be noted, however, that the correlation coefficients indicate only linear dependency and that the number of received 802.11 packets is a rather coarse metric because it does not take, for example, packet size or signal strength into consideration.

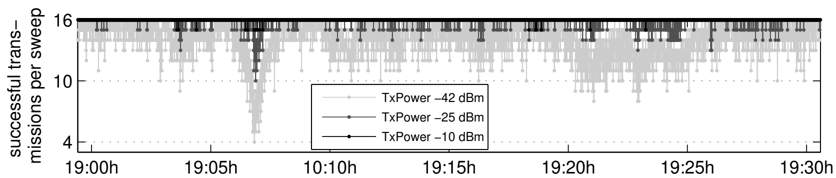


Fig. 8: Successful transmissions per sweep for the measurements described in Sect. 4.1.

5 Evaluation of Selected Aspects

The measurement results from three different urban environments provided us with a large dataset to explore. In the following we analyze this dataset to determine (1) the interrelation of the transmission quality on different channels at a given point in time, and (2) whether trends in the noise floor can indicate a (future) decrease of transmission quality. The first helps understanding to what extent channel hopping could improve transmission quality, the second gives insight in a potential (dynamic) trigger for channel switching.

Our evaluation is an important starting point, but also has its limitations: it is trace-driven and therefore the results are applicable only for the particular environments, the specific mobility pattern and node placement. Our measurement setup also allows us to abstract from many practical issues such as scheduling periodic noise sampling so that transmissions of other nodes do not interfere.

5.1 Cross-channel Quality Correlation

We are interested in the correlation of transmission failures over different channels at (roughly) the same time. Little correlation would mean that they share little variance and thus there is a greater probability that a “good” channel is available at a given point in time. In the following we first examine the fraction of good channels over time, then report on the empirical correlation between the channels and finally evaluate post factum how many hops an ideal frequency hopping scheme would have required to achieve 0 % transmission failures.

Fig. 8 shows the number of successful transmissions per sweep over time for the measurement described in Sect. 4.1 (it was the environment where we observed most transmission failures). At −10 dBm and −25 dBm transmission power for the majority of time the transmissions succeeded on almost all channels. Even for −42 dBm the number of good channels rarely dropped below 10, only at around 19:07 h temporarily 13 out of the 16 available channels were blocked. This means that in principle there were enough good channels at any point in time.

From the figure one cannot conclude how much variance the different channels have in common. We calculated the empirical correlation coefficients for the number of failed transmissions over time between all channels and found that they are often very low (typically around zero). For example, for −42 dBm transmission power the maximum correlation coefficients for any two channels

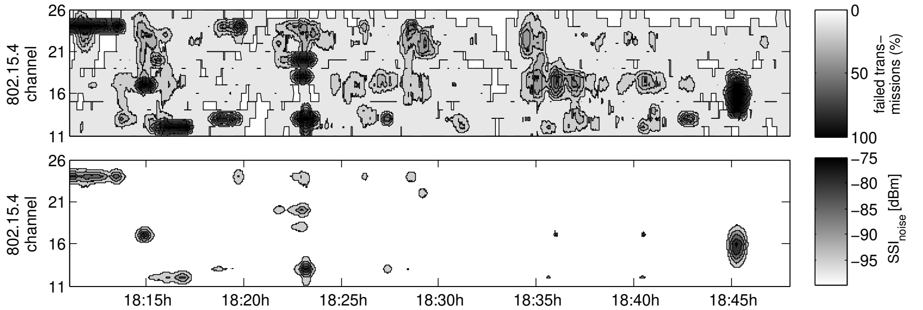


Fig. 9: Failed 802.15.4 transmissions at −42 dBm transmission power while walking through a central urban residential area (top). The bottom figure shows the noise floor measured during the same experiment. The results are averaged over a window of 100 transmissions per channel (26 s).

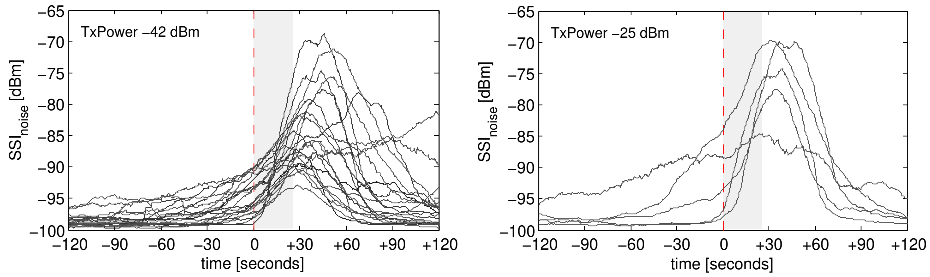
in the three measurements were $r^2 = 0.1844$, $r^2 = 0.1052$, and $r^2 = 0.0336$, respectively.

We are interested in the minimum number of channel switches that would have been required to achieve 0 % transmission failures. In other words, the minimum number of hops that an ideal channel hopping scheme with precise knowledge of the future channel conditions would have taken to guarantee that all transmissions succeeded. We implemented a simple greedy algorithm that replays the empirical traces, starting from the first transmission and proceeding in time. The algorithm examines all transmissions and chooses the channel that provides 0 % transmission failures for the maximum time ahead. It proceeds in time on this channel until a transmission failure occurs and switches the channel during this very sweep, again by choosing the channel that provides 0 % transmission failures for the maximum time ahead (from the previous evaluation we know that there is always a "good" channel). It repeats this step until it reaches the end of the empirical trace and then outputs the overall (minimum) number of channel switches (hops).

When the algorithm replayed the traces from the three measurements the total number of channel switches for −10 dBm transmission power was zero for all three empirical traces, which means there was at least one channel on which no failures occurred, respectively. At −25 dBm transmission power two or three hops were required. And at −42 dBm the measurement described in Sect. 4.1 required 50 hops (note that Fig. 5 shows moving averages over 100 transmissions), resulting in an average hopping frequency of about 2 Hz. The empirical results from the residential and office area corresponded to 27 and 38 channel switches, respectively.

5.2 Prediction of the Link Quality Degradation

A brief examination of the measurement results revealed that a substantial increase in noise floor is typically accompanied by heavy packet loss, in particular



(a) −42 dBm transmission power: between 0 s and 26 s ≥ 90 % transmissions failed.

(b) −25 dBm transmission power: between 0 s and 26 s ≥ 50 % transmissions failed.

Fig. 10: Noise floor within a window of ±2 minutes around heavy transmission failures (starting at 0s). SSI_{noise} is arithmetically averaged over the past 26 s (prior moving average).

at −42 dBm transmission power. For example, Fig. 9 shows failed transmissions over time (top) together with a contour plot of the noise floor (bottom) averaged over 100 transmissions; this measurement was made in an urban residential area on a Friday afternoon.

We are interested in the dynamics of SSI_{noise} around the point in time when the quality of a communication link experiences significant degradation. For −42 dBm transmission power we define the threshold as ≥ 90 % transmission failures within 100 transmissions on a given channel, that means ≥ 90 % failures within 26 s. An analysis of the empirical traces reveals 8 (shopping street), 11 (residential area) and 2 (office area) = a total of 21 occurrences of significant link quality degradation. For every occurrence we extract SSI_{noise} on the given channel within a window of ±2 minutes (roughly 1000 noise floor samples and corresponding to a SSI_{noise} sampling frequency of 4 Hz). Note that in our analysis we count only the first occurrence per channel (otherwise there was a total of 26 occurrences) and we ignore channels that already had significant losses at the beginning of the measurement, because for them the previous 2 minutes are not available.

Fig. 10a shows the results for −42 dBm transmission power. Since we are interested in general trends independent of the environment or a particular channel it includes the results from all measurements, one graph for every occurrence of link quality degradation. Each graph is aligned relative to the *beginning* of significant link quality degradation, which is represented by the vertical dashed line at time $t = 0$ s. This means, starting from $t = 0$ s the next 90 or more out of 100 transmissions failed, respectively. SSI_{noise} is arithmetically averaged over the *past* 26 s (prior moving average). A single point on one of the 21 graphs thus includes the current as well as the history of 99 previous noise floor samples.

At −25 dBm output power transmission failures were less frequent and we therefore reduced the threshold to ≥ 50 % transmission failures within a window of 26 s. This resulted in a total of 5 occurrences of link quality degradation as shown in Fig. 10b.

Discussion The graphs show similar trends: at time $t = -120$ s the average (past) noise floor is typically below −95 dBm, respectively. Between $t = -120$ s and $t = 0$ s it increases slightly and the most substantial increases are observable around and especially short after $t = 0$ s, which is also the *start* of significant transmission failures. Right-shifting the dashed line by 13 s as well as left-shifting the noise floor graphs by 13 s, respectively, establishes temporal alignment between the moving averages. It is then clearly observable that significant link quality degradation corresponds with a *simultaneous* increase in average noise floor, which strongly suggests that external RF interference is indeed causing the packet loss. The graphs are typically bell-shaped, which is likely a result from walking past a stationary interferer (for example, a WLAN access point).

The results suggest also that (the history of) noise floor observations may be valuable input to a link estimator. Especially at lower transmission frequency trends in the noise floor may be observable before a communication link experiences significant degradation. Increasing the noise floor sampling frequency and using more elaborated statistical techniques than a simple moving average are likely to have better predictive quality. We consider these topics part of our future work.

6 Related Work

The problem of coexistence between IEEE 802.11 and IEEE 802.15.4 networks has received significant interest from the research community. Most early work concentrated on developing probabilistic models that capture the dependence of interference-related packet loss in a 802.15.4 network based on frequency overlap and duty cycle, transmit power and distance of an 802.11 interferer [18]. Others analyzed the reverse problem, that is the impact of 802.15.4 networks on 802.11 devices [7], concluding that it is little to non-existing. A recent experimental study comes to a different conclusion, reporting that 802.15.4 devices may cause significant packet loss in an 802.11 network under specific conditions [16]. Prior work assessing the impact of WLAN interference on static 802.15.4 networks in lab environments typically reported on severe packet loss at small distances between the interfering devices [5].

Recently several 802.15.4 radio chip manufacturers have published guidelines to mitigate interference effects between the two technologies [11, 17, 4], for example, through minimal frequency offset of 20 MHz , spatial separation of 2 m and the use of the complete protocol stack (using ARQ to translate losses into latency) [17]. Acknowledging the problem, the IEEE 802.15 Task Group 4e currently investigates how to incorporate frequency hopping in the MAC layer. Meanwhile, recent revisions of standards that build on top of the 802.15.4, already incorporate simple frequency agility methods like periodic random channel hopping [19, 6].

There is not so much experimental work on the specific challenges and opportunities of 802.15.4 BANs. Some recent studies have examined the performance of mobile 802.15.4 person-to-person communication, as well as with static receivers [3, 12]. This work targets the impact of the human body on an inter-BAN communication link under specific mobility patterns, rather than external RF interference. Despite their static setup, the study presented in [14] is closest to our work: it focuses on detecting and mitigating the WLAN interference impact on 802.15.4 networks in an office setting. Targeting stationary networks, their measurement setup is optimized for more stable interference configurations, which is also reflected in the significantly higher duration of the sweep time compared to our setup (1.6 s vs. 85 ms). Their results confirm the correlation between 802.15.4 packet loss and 802.11 activity, as well as the suitability of noise-based predictors of WLAN interference.

7 Conclusions and Future Work

The effects that we observed in the isolated baseline measurements could, to some extent, also be recognized in the urban environments: transmission failures sometimes span over multiple consecutive 802.15.4 channels, are often correlated in time and substantial losses are typically accompanied by an increase in the noise floor. This suggests that external interference, in particular the virtually omnipresent WLAN, can be a major cause for substantial packet loss in IEEE 802.15.4 body area networks. However, in our configuration this is true only for the very low-power regime: already at -10 dBm transmit power transmission failures were negligible.

An obvious conclusion for the design of BAN protocols is to use higher transmission power (the IEEE 802.15.4 default is 0 dBm). On the other hand, there are several arguments for using low transmission power in BANs: less interference for other networks; less absorption of electromagnetic energy by the human body; less energy spent by the transceiver and thus longer lifetime (especially important for implanted sensors); less susceptibility for eavesdropping.

Adaptive transmission power control seems a promising approach to unite these requirements. Investigating the overhead of more effective interference evasion mechanisms, more intelligent noise "probing" approaches, combined with learning algorithms, as presented in [15], seem to be another promising direction of research that warrants experimental validation.

References

1. G.-Z. Yang, editor. *Body Sensor Networks*. Springer Verlag, 2006.
2. Texas Instruments. CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver. `http://www.ti.com/lit/gpn/cc2420`, Apr. 2002.
3. J. Espina, T. Falc, and O. Mülhens. *Body Sensor Networks*, chapter Network Topologies, Communication Protocols, and Standards, pages 145–182. Springer Verlag, 2006.

4. Freescale Semiconductor. Mc1319x coexistence - application note. `http://www.freescale.com`.
5. N. Golmie, D. Cypher, and O. Rébala. Performance analysis of low rate wireless technologies for medical applications. *Computer Communications*, 28(10):1255–1275, 2005.
6. HART field communication protocol specifications: TDMA data link layer specification. *HCF_SPEC-75*, 2008.
7. I. Howitt and J. Gutierrez. IEEE 802.15.4 low rate - wireless personal area network coexistence issues. *Wireless Communications and Networking, 2003. WCNC 2003. 2003 IEEE*, 3:1481–1486 vol.3, March 2003.
8. IEEE standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks specific requirements part 15.4: wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs). *IEEE Std 802.15.4-2003*, pages 1–670, 2003.
9. IEEE standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements. - part 15.1: Wireless medium access control (MAC) and physical layer (PHY) specifications for wireless personal area networks (WPANs). *IEEE Std 802.15.1-2005 (Revision of IEEE Std 802.15.1-2002)*, pages 1–580, 2005.
10. IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements - part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)*, pages C1–1184, 12 2007.
11. Jennic Ltd. Co-existence of IEEE 802.15.4 at 2.4 GHz - application note. `http://www.jennic.com/`.
12. E. Miluzzo, X. Zheng, K. Fodor, and A. T. Campbell. Radio characterization of 802.15.4 and its impact on the design of mobile sensor networks. In *Proc. of 5th European Workshop on Wireless Sensor Networks (EWSN)*, Bologna, Italy, Jan. 2008. Springer.
13. Moteiv Corporation. Tmote sky datasheet. `http://www.sentilla.com/pdf/eol/tmote-sky-datasheet.pdf`.
14. R. Musaloiu-E. and A. Terzis. Minimising the effect of WiFi interference in 802.15.4 wireless sensor networks. *Int. J. Sen. Netw.*, 3(1):43–54, 2008.
15. S. Pollin, M. Ergen, M. Timmers, A. Dejonghe, L. van der Perre, F. Catthoor, I. Moerman, and A. Bahai. Distributed cognitive coexistence of 802.15.4 with 802.11. *Cognitive Radio Oriented Wireless Networks and Communications, 2006. 1st International Conference on*, pages 1–5, June 2006.
16. S. Pollin, I. Tan, B. Hodge, C. Chun, and A. Bahai. Harmful coexistence between 802.15.4 and 802.11: A measurement-based study. *Cognitive Radio Oriented Wireless Networks and Communications, 2008. CrownCom 2008. 3rd International Conference on*, pages 1–6, May 2008.
17. G. Thonet, P. Allard-Jacquin, and P. Colle. ZigBee - WiFi coexistence, white paper and test report. Technical report, Schneider Electric, 2008.
18. D. G. Yoon, S. Y. Shin, W. H. Kwon, and H. S. Park. Packet error rate analysis of IEEE 802.15.4 under IEEE 802.11b interference. *Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd*, 3:1186–1190, May 2006.
19. ZigBee Alliance. ZigBee specification. *ZigBee Document 053474r17*, 2008.