Coexistence of WBAN and WLAN in Medical Environments

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***Abstract*— In this work, we present a coexistence study for wireless body area networks (WBAN) and wireless local area networks (WLAN). The aim is to evaluate the feasibility of WBAN systems in realistic medical environments, assessing their robustness to interference. We focus on the evaluation of the impact of a collocated IEEE 802.11g WLAN interferer on the performance of IEEE 802.15.4/ZigBee transceivers, through a combination of physical (PHY) layer simulations and experimental interference tests in a hospital room. In order to have a better understanding of the underlying communication model, we have also conducted channel measurements, channel modeling and power spectrum measurements. The performance of ZigBee for different system configurations and node topologies is shown, providing insights into the main factors that affect the system performance in a hospital room. In addition, recommendations for high performance operation are provided.**

I. Introduction

Over the past years, advances in electronics and wireless communications have enabled the rapid development of small-size low-power wireless sensors, which are expected to increase the functionality of lifestyle and healthcare devices to gradually match the needs of society. An important application of these wireless sensors is to collect, monitor and transport vital signs and other medical information for the user. The sensors have very low power budget, and they often need to send critical data that require extremely reliable communications.

In wireless coexistence scenarios, two or more collocated devices transmit data sharing the available time and frequency resources. At the receiver side, due to the broadcast nature of the wireless channel, the intended signal and the interfering signals may be superimposed, thus degrading the system performance. An example of coexistence of wireless body area network (WBAN) and wireless local area network (WLAN) in a hospital room scenario is given in Figure 1. A WBAN network is represented by the nodes in orange, whereas the nodes in blue represent WLAN devices. The WBAN consists of sensors on the patient operating in 2.4 GHz ISM band (devices colored in orange), e.g. using ZigBee/IEEE 802.15.4 [1]. Collocated with this WBAN is a WLAN also transmitting at 2.4 GHz (devices colored in blue), e.g. using Wi-Fi/IEEE 802.11g [2]. Figure 1 also shows the generic coexistence environment considered in this study. A WBAN receiver Rx_1 experiences interference from a collocated WLAN device transmitting, Tx_{N+1}, represented by the lower dashed link. On the other hand, WBAN transmitting nodes, $Tx_1, \ldots, Tx_N$, interfere with a collocated WLAN receiver, Rx_2. In this study, we uniquely consider the impact of the lower interfering link, originated at Tx_{N+1}.

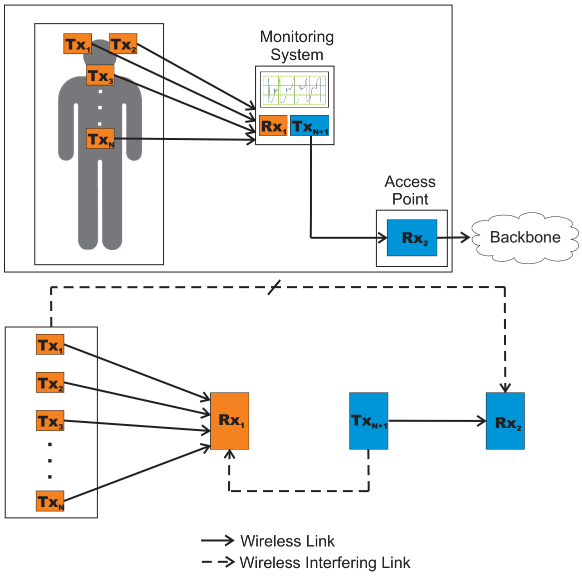

Fig. 1. Example of network topology in monitoring application at hospital room (above), and schematic of generic coexistence environment considered (below).

In the research literature, to the best of the authors' knowledge, there are no available coexistence studies for WBAN and WLAN in realistic medical environments. In this work, we provide a coexistence study for WBAN and WLAN devices operating in the 2.4 GHz ISM band. We focus on the performance evaluation of 802.15.4 devices with 802.11g interference in a hospital room, through a combination of simulation and experimental studies. The main objectives of this work are summarized as follows

- Assess the feasibility of WBAN systems in realistic medical environments.
- Evaluate the impact of the system parameters and environmental factors on mutual interference and system performance.
- Give recommendations to design and optimize WBAN systems robust to interference.

This paper presents the performance results obtained in the simulation and experimental studies. In order to have a better understanding of the underlying communication model, we have also carried out power spectrum measurements, channel measurements, and channel modeling. We provide performance results obtained from experimental coexistence tests and from a calibrated coexistence simulator, which incorporates our proposed channel models and measured spectrum characterization.

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TABLE I

CC2520 AND LINKSYS WRT54G SPECIFICATION SUMMARY

Device	Frequency	Occupied Band-width	Data Rate	Nominal Output Power	Modulation	Receiver Sensi-tivity
CC2520 ZigBee 802.15.4	2.4 GHz	2 MHz	250 kbps	Up to 5 dBm	DSSS and OQPSK	-98 dBm
Linksys WRT54G 802.11g	2.4 GHz	16.6 MHz	6,9,12,18 24,36,48, 54Mbps	18 dBm	OFDM and PSK/QAM	-67 dBm at 54Mbps

II. CASE STUDY: TECHNOLOGIES AND MEDICAL ENVIRONMENT

The present wireless coexistence study between WBAN and WLAN focuses on the impact of 802.11g interference on the performance of an 802.15.4 link in the 2.4 GHz ISM band. A simple network is considered, involving the following 3 nodes

- 802.15.4/ZigBee transmitter (T).
- 802.15.4/ZigBee receiver (R).
- 802.11g/Wi-Fi interferer (I).

The 802.15.4 node is Texas Instruments' second generation of ZigBee transceivers, CC2520 [3]. The chosen interferer is Linksys Wireless-G broadband router, model WRT54G [4], which is one of the most common Wi-Fi devices in the market. The main specifications of these technologies at PHY level are summarized in Table I. 802.11g uses a wide spectrum for transmission, approximately 16.6 MHz in practice, while 802.15.4 devices occupy around 2 MHz. Most 802.11g devices transmit at high power, around 20 dBm, 15 dB higher than the highest output power option at CC2520.

In 802.15.4, a total of 16 channels can be selected, ranging from channel identifier 11 to 26, with a spacing of 5 MHz between center frequencies. Channel 11 is centered at 2405 MHz, and channel 26 is centered at 2480 MHz. On the other hand, the frequency channel plan for 802.11g starts at a center frequency of 2412 MHz and goes up to 2462 MHz, with 5-MHz steps between selectable channel center frequencies, which correspond to channel identifiers 1 to 13. In addition, channel 14 is available for transmission in Japan, centered at 2484 MHz. Figure 2 shows the frequency plan for 802.11g with non-overlapping channels, which in the United States and Canada can only be obtained when using channels 1, 6 and 11. The overlap with 802.15.4 channels is also depicted in the figure. The medical environment considered in this coexistence study is a patient room in a hospital, where both channel measurements and interference tests were conducted. Hospital rooms tipically have metallic structures and high ceilings not present in regular bedrooms, which significantly change the propagation characteristics. In the room used during the tests, a long metallic rack is embedded on the wall, right next to the head part of the bed, used for connecting various medical equipments. The patient's bed is also quite different from a regular bed, since it is built on a cumbersome metallic frame. The bedside table is also fully metallic.

In this work, we focus on a PHY-layer study and the impact that interference has at this level. We assume that in the scenarios of interest the system performance is limited by the effect of interference, rather than by the signal attenuation (path loss) induced by a patient near an 802.15.4 transmitting

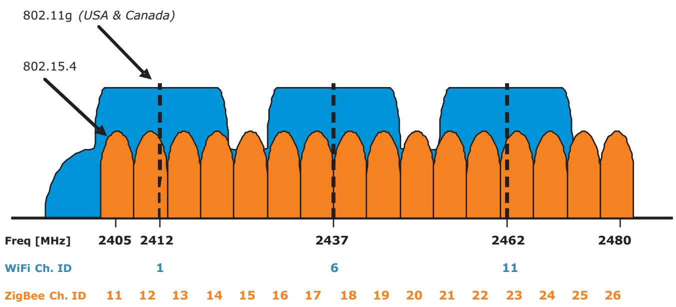

Fig. 2. Frequency channel plan for IEEE 802.11g and IEEE 802.15.4.

node. In practice, the effect of human body would result in higher attenuation for the transmitter-receiver link, while the attenuation at the interferer-receiver link would remain practically unchanged for the coexistence topologies considered. Hence, in this study, we focus solely on the effect of interference. We consider a coexistence scenario in which all devices are continuously transmitting, with disabled channel sensing features. Thus, once the transmitter-receiver link is established between the 802.15.4 devices using a certain frequency band, the channel remains fixed even with an interferer occupying the same band. Hence, the proposed PHY-layer study reflects a worst case scenario, with transmitted signals overlapping in time and frequency (subject to a certain offset between carrier frequencies). In the experimental tests, this is attained by performing an FTP file transfer between 802.11g nodes at an arbitrarily high duty cycle in overlapping frequency bands, appropriately choosing the data rate. The second 802.11g node is located far outside the room and only transmits control packets, thus minimizing its impact on the performance study.

III. COEXISTENCE ANALYSIS METHODOLOGY

In this section, we provide an overview of the methodology used in this coexistence study. After the selection of applications and scenarios, described in the previous section, the study is divided in 3 main parts:

- Simulation study.
- Experimental study.
- Model validation and calibration.

A PHY-layer coexistence simulator has been developed in MATLAB for the technologies under study.

Three different types of measurements have been performed. First, radio channel measurements have been carried out with a vector network analyzer in the hospital room, for the purpose of channel modeling. The result is a complete characterization of the radio channel. The second set of experimental tests consists of wireless coexistence measurements in the hospital room for the selected WBAN technology in the presence of WLAN interference. This gives the actual performance of the chosen WBAN technology in a coexistence environment for different topologies and system parameters. Finally, power spectrum measurements of the wireless devices under evaluation have been performed, for the purpose of characterizing their RF properties accurately.

Parameter extraction from the radio channel measurements have been fed back to the coexistence simulator. Similarly, the resulting power spectrum measurements have also been

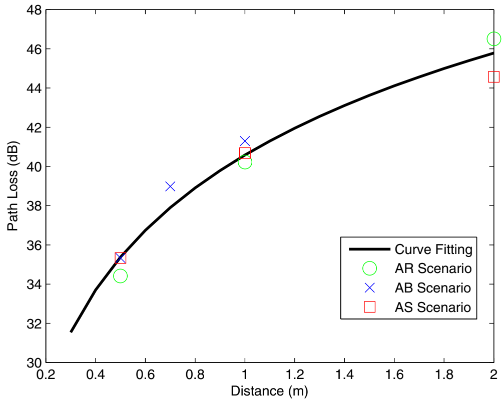

Fig. 3. Path losses for different LOS scenarios and the obtained curve fitting.

incorporated to the simulator. Hence, the proposed methodology, which feeds experimental results back to simulation models, has allowed us to obtain validated communication and propagation models from measurements.

IV. Channel measurements and modeling

A typical channel measurement technique used in indoor propagation is the frequency domain channel sounding [5][6]. This technique uses a vector network analyzer to measure the frequency domain channel. The measured frequency domain channel is then converted to the time domain channel by using the inverse discrete Fourier transform. In our measurements, the R&S ZVL6 vector network analyzer was used. The measured frequency range was set from 2 to 3 GHz. We consider three line-of-sight (LOS) scenarios and one non-line-of-sight (NLOS). These three LOS scenarios include the transmission across the room (AR), transmission along the front board of the bed (AB), and the transmission along the side of the bed (AS). The NLOS scenario considers the cases where transmission is blocked by the bed.

A. Large-scale path loss and small-scale fading

The average large-scale path loss is usually characterized as a log-distance path loss model, which is given by [6],

$$PL(d) = PL(d_0) + 10n \log d/d_0 \qquad (1)$$

where n is the path loss exponent that indicates the rate at which the path loss increases with distance, d_0 is the reference distance at which the reference path $PL(d_0)$ loss is measured. Here the path losses are represented in dB. A typical method to estimate n and $PL(d_0)$ from measured path losses is the linear least squares curve fitting. Based on our measurement, we find that a single model suffices to represent path losses for all the three considered LOS scenarios. With this method and setting $d_0 = 1$, we obtain $n = 1.7287$, and $PL(d_0) = 40.5805$ dB. The measured path losses and the corresponding curve are shown in Figure 3. For the NLOS scenario, we obtain $n = 2.4519$ and $PL(d_0) = 50.5637$ dB.

The variability of the signal strength in close spatial proximity to a particular location is called the small-scale fading, which is caused by the multipath effect. In the described patient room, the worst case scenario in terms of multipath propagation delays corresponds to the case of NLOS, with an approximate distance of 2m. From channel measurements, we find that most of the energy in the power delay profile (PDP) is concentrated on a very small temporal span, i.e. within 30ns.

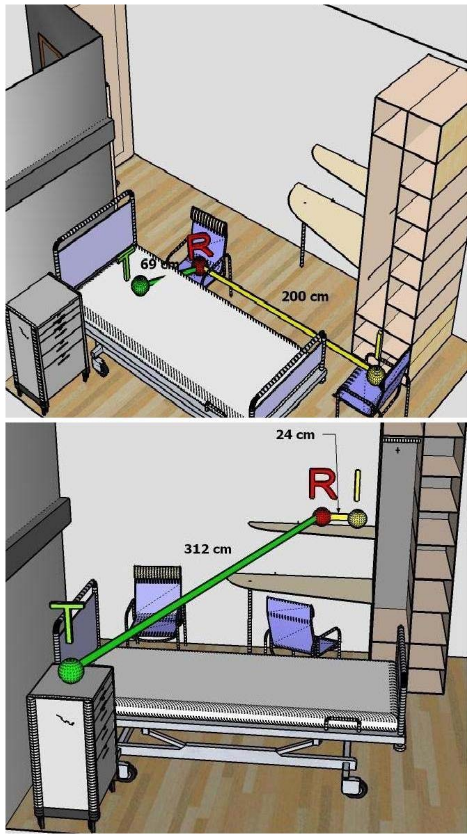

Fig. 4. Node Topology A (above) and node Topology B (below). LOS channel between transmitter and receiver, and also between interferer and receiver.

Note that most of the current commercialized low power wireless systems in 2.4GHz are narrow band. For example, the chip duration of an 802.15.4 system is 500ns, which is much larger than the largest delay spread (i.e. 30ns). As most of the energy is concentrated on a delay spread of 30ns, we can model the channel as a flat-fading channel. The statistical varying nature of the received envelope of a flat-fading channel typically obeys the Rayleigh distribution or the Ricean distribution [6]. Unlike the large-scale path loss where a single log-distance path loss model is sufficient to characterize three different LOS scenarios, the Ricean factors are different in these three scenarios. We find that a wall close to the transmit and receive antennas significantly influences the variation of signal strength in LOS scenarios such that signal strength has a Rayleigh distribution instead of a Ricean distribution. Further details can be found in [7].

V. Experimental and simulation coexistence tests

In this section, we present experimental and simulation results on the performance of an 802.15.4 link in a hospital room in the presence of an 802.11g interferer. The purpose of the study here presented is to investigate the role of topological and communication parameters.

A. Node topologies

In the present coexistence study, different node topologies have been considered, placing at different locations in the room the 802.15.4 transmitter, 802.15.4 receiver and 802.11g interferer. Each topology reflects a different LOS/NLOS situation for T-R and I-R links, or different distances between T-R and I-R. In this paper, for the sake of brevity, we focus on the topologies that resulted in the best and worst 802.15.4 link performances, depicted in Figure 4. For each of these topologies, different system configuration parameters were selected, as we discuss in detail in the next section. In the first case, topology A, we show the performance of an 802.15.4 link with a line of sight between transmitter and receiver, located near from each other (69 cm). The interferer is placed far from the 802.15.4 receiver (200 cm) also with a LOS. As we show later on in the paper, this situation is a good scenario for 802.15.4 communication. A topology with a NLOS between interferer and receiver does not provide significant performance gains and thus is not shown in this study. In topology B, we study the performance of an 802.15.4 link with a line of sight between transmitter and receiver, located far from each other (312 cm). The interferer is placed at a very near distance (24 cm) with a line of sight to the 802.15.4 receiver. The devices are distributed within the room as depicted in Figure 4.

B. Procedure for coexistence tests

Several tests have been performed for each topology. In each coexistence test, the 802.15.4 transmitter sends 10000 data packets, each with a payload size of 10 Bytes, to the 802.15.4 receiver. Concurrently with the ZigBee data transmission, 802.11g interference is generated. A Linksys WRT54G router is placed in the room, sending a large file through FTP transfer protocol to a laptop placed far outside the room. This second laptop sends control packets at low rate, and thus the impact on CC2520 ZigBee performance is almost negligible. The Linksys interferer acts as FTP server (uploading the file), while the laptop outside the room, equipped with an 802.11g wireless card, acts as FTP client (downloading the file). Since the purpose of this study is to evaluate the performance of 802.15.4 at PHY level, we intend to generate 802.11g interference at high duty cycle, which practically corresponds to continuous 802.11g interference. This is done by selecting a data rate of 6 Mbps at the WLAN link, which yields long packets and ensures a high flow of data. This gives in practice an approximate interference duty cycle of 87%, which is taken into account in the simulations. The output power of Linksys is fixed, which corresponds to a nominal transmit power of 18 dBm, although in practice the measured power is around 19.5 dBm (depending on the frequency band used).

Transmission in the 802.15.4 link is done in channel 20, centered at 2450 MHz. The operating frequency of the WLAN link is selected for each test, thus modifying the frequency offset between CC2520 and Linksys carrier frequencies. The following communication parameters are selected in each test

- 802.15.4 transmit power. The power options used are -18 dBm, -4 dBm, 0 dBm and 5 dBm.
- Frequency offset between 802.11g and CC2520 carrier frequencies. Obtained by setting the carrier frequency at the 802.11g interferer:
  - Channel 9 (2452 Mhz) → 2 MHz frequency offset
  - Channel 7 (2442 Mhz) → 8 MHz frequency offset
  - Channel 5 (2432 Mhz) → 18 MHz frequency offset

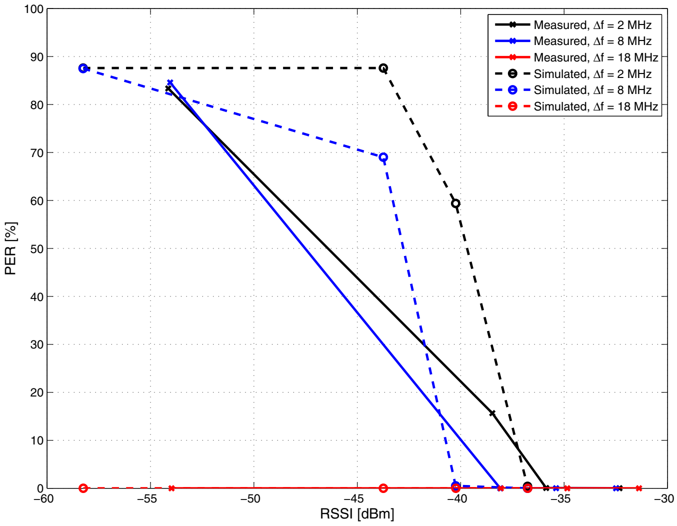

Fig. 5. Node TOPOLOGY A. PER as function of RSSI for different 802.11g carrier frequency offsets.

The following parameters are obtained from each test.

- Received Signal Strength Indicator (RSSI): This value is calculated by the radio device and indicates the strength of the signal at the RF pins.
- Packet Error Rate (PER): This value is the ratio of successfully received packets without CRC errors to the number of packets transmitted by the ZigBee node.

C. Coexistence test results

Figure 5 shows the link performance for topology A. The highest power option available at the transmitter (5 dBm) provides good performances for 2 and 8 MHz of frequency offset between ZigBee and the Wi-Fi interferer. Since the interferer is located far from the ZigBee receiver, the 0 and -4 dBm power options at the ZigBee transmitter also provide good performances for an 8 MHz frequency offset, while 0 dBm is enough for a 2 MHz frequency offset. The simulated performance fits reasonably well the measured results. Note that due to the fact that the measured PER vs. RSSI have low resolution in the power domain (4 points have been used), the curves appear quite steep. Here, slightly different simulated RSSI values result in simulated intermediate PER values between the actual measured PER values.

Figure 6 shows the PER as function of RSSI for topology B, for different frequency offsets between transmitter and interferer. We can observe in this scenario that low performances are exhibited for 2 and 8 MHz frequency offsets, even for the highest CC2520 power options available. For 18 MHz, only 5 dBm of transmit power ensure good performance. Note that in this topology the measured performance is notably worse than the predicted by simulations using an AWGN channel and a mean path loss component, except for 2 and 8 MHz frequency offsets. This is due to the fact that the topology contains aspects which are difficult to capture by the proposed PHY-layer coexistence simulator. The channel model for this particular case is quite different to other LOS situations due

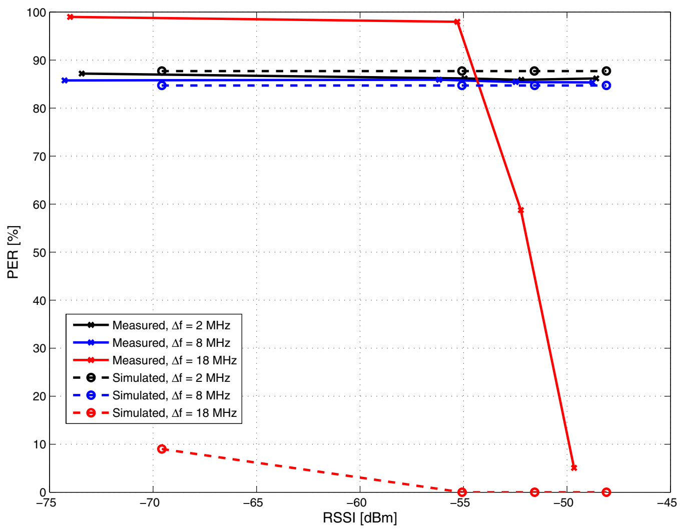

Fig. 6. Node TOPOLOGY B. PER as function of RSSI for different 802.11g carrier frequency offsets.

to close reflections on the wall, as discussed in Section 5. On the one hand, the interferer and the receiver are very close to each other (24 cm), both located along the wall. This seems to have important distortion effects on the 802.11g spectrum received at the ZigBee receiver side. This effect is not captured by the simulator, which assumes that the transmit 802.11g spectrum is attenuated equally at all frequencies (frequency flat channel). In addition, a back wall on the transmit-receive link may also produce random phase rotations, becoming in some cases similar to a Rayleigh fading channel as discussed in Section IV.

VI. Conclusions and Recommendations

In this paper, a coexistence study has been carried out to evaluate the impact of an 802.11g interferer on the performance of a point-to-point 802.15.4 link in a hospital room. The work here presented has been focused on PHY layer evaluation, with overlapping interference and 802.15.4 signals both in frequency and time domain.

A. Conclusions on PHY-layer performance

The performance of ZigBee point-to-point links with the devices used in this test, CC2520, was very good in the absence of interference for all the studied topologies. The obtained packet error rates (PER) were below 0.1% regardless of the power option selected at the ZigBee transmitter (even for the -18 dBm option). In the presence of an 802.11g interferer, high performances are achieved in most topologies when the frequency offset between 802.15.4 and 802.11g is 18 MHz. However, in the case with a wall behind the transmitter-receiver link and a close interferer, the impact of interference seems much stronger even for large frequency offsets. In this worst case scenario, 5 dBm are needed to provide 5% PER for 18 MHz offset. In cases with LOS between transmitter and receiver and no back wall, 5 dBm of transmit power provide good performance for all frequency offsets, and even 0 or -4 dBm in some cases. For other topologies, however, communication seems difficult for frequency offsets of 2 and 8 MHz, even with 5 dBm of output power at the transmitter. The most favorable case for transmission with an interferer in the room corresponds to a LOS between transmitter and receiver in the middle of the room, without back wall reflections, exhibiting very low packet error rates.

B. Recommendations for high-performance operation

As discussed in Section 2, the available 802.11g channels range from carrier frequencies at 2412 MHz (channel 1) to 2462 MHz (channel 11) in the United States and Canada. This means that at most 3 non-overlapping 802.11g networks may coexist in a worst case interference scenario for ZigBee, using carrier frequencies at 2412 MHz, 2437 MHZ (channel 6) and 2462 MHz. If 802.15.4 links are established in the frequencies between them (2425 and 2450 MHz), the resulting frequency offset becomes either 12 or 13 MHz to each interfering 802.11g network. In the United States and Canada, using channel 26 (centered at 2480 MHz) for 802.15.4 transmission ensures a frequency offset of 18 MHz between 802.11g and 802.15.4. However, besides an 18-MHz frequency offset, the highest power option at the CC2520 transmitter, 5 dBm, is necessary to ensure good performances in all topologies, which may be too power-consuming in some applications. Particularly, a topology with interferer and receiver very close to each other, or a receiver near the wall, have a strong impact on the system performance as we have shown. In Europe and China, Wi-Fi channels 12 (2467 MHz) and 13 (2472 MHz) are also available, which means that at most 8 MHz offset can be ensured with channel 26. On the other hand, in Japan, ZigBee networks in channels 11-23 ensure a frequency offset greater than or equal to 19 MHz.

Therefore, we can conclude the following. In general, an 802.15.4 point-to-point link provides very good performance in a hospital room in the absence of interferers. However, in the presence of an 802.11g interferer inside the room, the 802.15.4 link can not ensure high performance operation for all situations relying solely on the physical layer. In order to provide high quality communications in a hospital room, the system performance must be improved by combining smart channel selection, as well as higher layer MAC and networking mechanisms. In addition, 802.11g access points that are part of the hospital infrastructure may be configured to operate at lower transmission power and in a limited number of channels, controlling further the impact of interference on ZigBee systems.

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