Interference of Wireless Technologies on BLE Based WBANs in Hospital Scenarios

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***Abstract*— Bluetooth Low Energy (BLE) devices are becoming common in hospital scenarios. This technology is widely employed to collect patients' vital signs, to provide wireless connectivity to medical equipment, and to enable communications between devices carried by hospital personnel, patients and visitors. This paper presents a mathematical model to evaluate the impact of the interferences, from different wireless technologies, on the performance of a BLE-based body area networks operating over the 1 Mbit/s physical layer (PHY). The interfering technologies addressed are ZigBee (802.15.4), Wi-Fi (802.11), and the newly introduced BLE version 5.0 (coded PHY). The results for the latter are supported by real-life measurements, which are reported in this paper, thus giving some insight into the practical performance of this new technology. The presented numerical results provide guidance on how to manage these various technologies to minimize the packet error rate (PER) of the communications emanating from the on-body BLE enabled devices.**

***Index Terms*—Bluetooth low energy, BLE v5, coexistence, wireless body area network, BLE range extension.**

I. Introduction

The use of wireless devices in all aspects of life is continuously increasing worldwide. The medical field is not an exception to this rule. Nowadays it is very common to find in hospitals wireless devices monitoring patients' vital signs, and helping to locate doctors, nurses, and medical equipment. In addition, patients, visitors, and hospital personnel continuously connect their mobile phones and tablets to the available wireless local area network (WLAN). At the same time, the deployment of wireless body area networks (WBAN), whose function is to continuously monitor the vital signs of a human body, is rapidly increasing.

In a recent survey of wireless technologies in medical scenarios [1] it was noted that Bluetooth Low Energy (BLE) is by far the dominant technology for on-body devices such as pulse oximeters, electrocardiogram (ECG) sensors, and heart and lung monitoring devices. These devices operate in the 2.4 GHz band of the industrial, scientific, and medical (ISM) region of the spectrum. By their very nature, BLE devices are supposed to operate with low duty cycles, sufficiently fast rates and low transmission power. These same features are also important to be able to use these devices close to a human body in a continuous mode. Unfortunately, these features also make BLE-enabled devices very susceptible to interference from other wireless technologies present in a hospital. In this paper, we then investigate and analyze the effects that various wireless technologies may have on BLE-based communications.

The addressed scenario is as follows. The affected BLE-based BAN, operating with the traditional BLE 1 Mbit/s frequency hopping PHY, is assumed to be on a patient in a hospital room. The other wireless devices, operating in the 2.4 GHz band, and using various wireless technologies are located within the patient's room as well as in the nearby rooms and spaces, causing interferences. As interfering wireless technologies, we consider ZigBee (IEEE Std. 802.15.4), Wi-Fi (IEEE Std. 802.11), and the new BLE version 5.0 with coded PHY. The latter has been introduced in the most recent version (v 5.0) [2] of BLE specification in December 2016 and adds the capability of extending the communication range by using error correcting coding and higher transmitting power. Due to its novelty, not much information about the BLE v 5.0 is available. Therefore, to obtain the necessary data for this paper, an experimental study in a four-story building using a commercially available BLE v 5.0 device was conducted. The results of this study are briefly reported and used in the analyses.

II. Hospital Scenario

The scenario is a typical patient room in a future hospital currently under construction in Finland as illustrated in Fig. 1. A single patient equipped with a BAN is located in one room. The electromagnetic interference includes wireless signals within the room and the ones emanating from the neighbors' rooms and corridors. Note, that BLE and ZigBee interference from rooms located directly above and below the patient's room are also considered in this study. The analysis presented in this paper focuses on the 2.4 GHz band since, as pointed out in [1], that band is most susceptible to interference in a hospital environment due to the number of available wireless technologies. It is assumed the presence of BLE, ZigBee, and Wi-Fi enabled devices. The interference calculations are done for the worst-case scenario of multiple devices located in proximity of each other and transmitting often. The analyzed setup is summarized below:

In each patient's room:

- Five BLE-based WBAN devices. From the patient's perspective, the performance of this WBAN is the most critical and is considered in this study as the wireless victim technology.
- Five BLE devices being used by medical personnel, visitors, and/or attached to equipment(s) in the room. At least one of these devices has a Wi-Fi interface to relay BLE data.
- Five ZigBee nodes dedicated to the room environment and hospital logistics system
- Continuous Wi-Fi traffic in the 2.4 GHz band

In the corridor next to the patient room:

- 20 BLE nodes
- Ten ZigBee nodes
- Wi-Fi base station and traffic in the 2.4 GHz band

In addition, one BLE v 5.0 device on the corridor or patient room depending on the analyzed scenario.

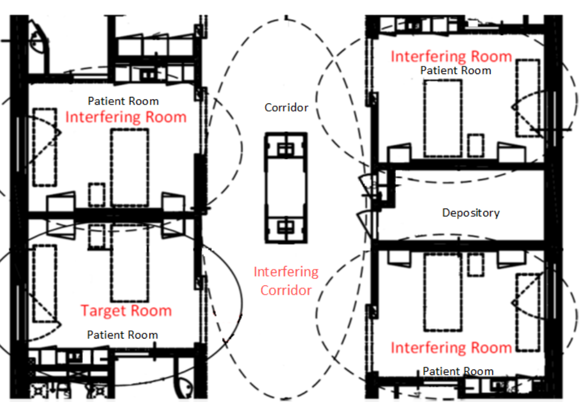

Figure 1. Illustration of the hospital room scenario.

III. Mathematical Model

To compute the packet error rate (PER), and other performance metrics, the steps proposed in [3] are followed here. These steps are described in the following subsections.

A. Geometric Model

Unlike other studies, e.g. [3] and [4], where the affected wireless network (AWN) and the interfering wireless network (IWN) each have only two nodes, the geometry is richer for the cases studied in this paper, i.e., there are several IWNs which can include multiple nodes. Figure 2 illustrates the scenario considered. In Fig. 2 the red ellipses show the affected wireless links and the dashed black ellipses show the interfering links. Dashed lines represent the walls between the rooms. The locations of the nodes are assumed to be typical for a hospital environment. It is expected that the medium access protocol (MAC) of the BLE and ZigBee networks ensure that only one node of their corresponding network can transmit at any given time, i.e., only one BLE and ZigBee link can be active at the same time in each room and in the corridor (e.g., the respective nodes are on one piconet). In the target room the ZigBee / BLE 5 nodes and links are explicitly shown since they have the most effect on the interference calculations. Without significantly affecting the results, the location of the BLE and ZigBee nodes in the adjacent patients' room are assumed to be identical. The hospital has three floors with similar architecture and thus it is expected that wireless devices in the upper and lower rooms create interfere to the target room. These interferers are not shown in Fig. 2 for simplicity sake.

B. Path Loss Models

There are several path loss models (2.4 GHz) proposed for indoor environments, such as the one described in the IEEE Std. 802.15.2 recommendation [5]. A model specifically developed for a hospital environment is proposed in [6] where line-of-sight (LOS) and a non-line-of-sight (NLOS) equations are provided for different types of hospital rooms outlined in Table 1. For LOS scenarios the path loss equation is

$$PL(d) = PL_0 + 10n\log_{10}\left(\frac{d}{d_{h0}}\right), \quad (1)$$

where n is the path loss exponent and d_{h0} (assumed to be 1 m in [6]) is the reference distance at which the reference path loss PL_0 is measured. For the channel model (CHM) type 2a a more accurate equation is

$$PL(d) = PL_0 + \alpha_0\left(\frac{d}{d_{h0}}\right). \quad (2)$$

Values for PL_0, n, and α_0 are shown in Table 1.

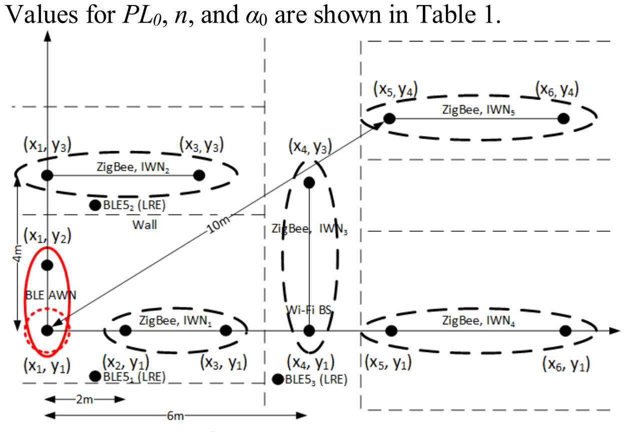

Figure 2. Geometric model.

Table 1. Parameters for hospital path loss model.

CHM	Scenario	PL_0 [dB]	PL_c [dB]	n	α_0
1	LOS room	48.5		1.20	
2a	LOS corridor (no back wall)	48.2			0.41
2b	LOS corridor (with back wall)	47.7		1.21	
3	LOS intensive care unit (ICU)	43.7		1.90	
4	NLOS room <-> hall / ICU		53.2	2.11	
5	NLOS room <-> corridor		55.5	2.57	
6	NLOS corridor <-> hall / ICU		34.0	3.92	

Table 2. Definition of the parameters in Equation 3.

Parameter	Definition
L_c	Constant loss arising from multi-wall curve fitting
L_W	Loss of (plaster) wall
L_{CL}	Loss of (concrete) column
L_{CA}	Loss of ICU cabinet
L_D	Loss of door
N_W	Number of penetrated walls
N_{CL}	Number of penetrated columns
N_{CA}	Number of penetrated ICU cabinets
N_D	Number of penetrated doors

For NLOS hospital scenarios the proposed equation in [6] is

$$PL(d) = PL_c + 10n\log_{10}\left(\frac{d}{d_{h0}}\right) + L_{MW}, \quad (3)$$

where $L_{MW} = N_W L_W + N_{CL} L_{CL} + N_{CA} L_{CA} + N_D L_D$ and $PL_c = PL_0 + L_c$. These parameters are defined in Table 2.

In this study Eq. 3 is revised by adding a term that takes into account the attenuation across different floors using values obtained from a recent BLE measurement campaign detailed in the following section. In this work Eqs. 3 and 5 are used to model the path loss of the interfering signals.

For the WBAN the path loss model used is the one proposed in [7] and given by

$$PL(d) = -10\log_{10}(P_0 e^{-m_0 d} + P_1) + \sigma_p. \quad (4)$$

This model represents the exponential decay with distance expected with diffraction around a cylindrical body, followed by a flat saturation point due to the energy received from multipath reflections off nearby scatterers. The maximum likelihood estimates of this model's parameters are given in Table 3. P_0 depends on the average losses occurring close to the transmitter and will depend on the kind of antenna. The parameter m_0 represents the average exponential decay rate in dB/cm of the creeping wave component diffracting around the body. The parameter P_1 can be interpreted as the average attenuation of components radiating away from the body and then reflected back at the receiving antenna. Finally, σ_p is the log-normal variance (expressed in dB) around the average trend representing the average path loss variations measured at different body and room locations. Figure 3 shows the path loss results calculated using the hospital LOS (CHM1, CHM2a/b) and NLOS (CHM5) models. In addition, the path loss results for the body area network model are also shown. CHM1 was used for computing the propagation loss between a WBAN BLE and another BLE in the room whereas CHM5 (with $L_{MW} = 0$) was used for the interference caused by in-rooms BLEs not communicating with the WBAN's BLEs.

Table 3. Parameters for body path loss model.

Parameter	2.45 GHz
P_0, dB	-25.8
m_0, dB/cm	2.0
P_1, dB	-71.3
σ_p, dB	3.6

C. BLE Path Loss Measurements

Since the emphasis in this study is on the performance on BLE devices in a patient's room, a set of measurement experiments were conducted using the recently released Nordic Semiconductor's nRF52840 development kit [8] that features the support BLE (v 5.0) PHYs. The measurements were conducted for a system operating using the traditional 1 Mbit/s PHY and the newly-introduced coded PHY. Of interest to study was the indoor behavior of the long-range mode that this version supports. The long-range capability is achieved by a combination of a forward error correction code and higher transmit power. Possible applications of the long-range option include building environmental monitoring. If this application is implemented in hospitals, it has the potential of becoming another source of interference on the BLE based WBANs. The measurements were conducted in a 4-floor building at the University of Oulu, Finland. The layout of the 4th floor and the location of the BLE devices used is shown in Fig. 4.

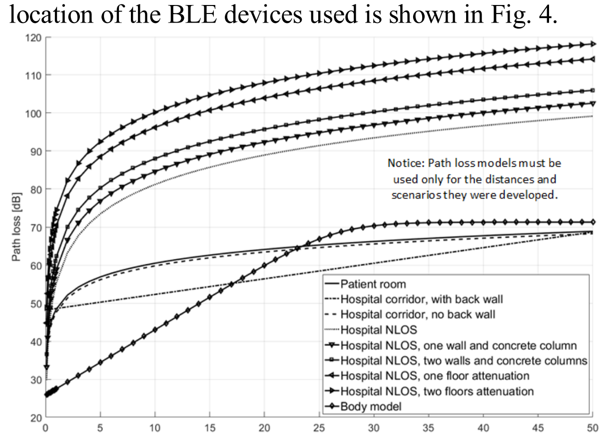

Figure 3. Path loss values as a function of distance.

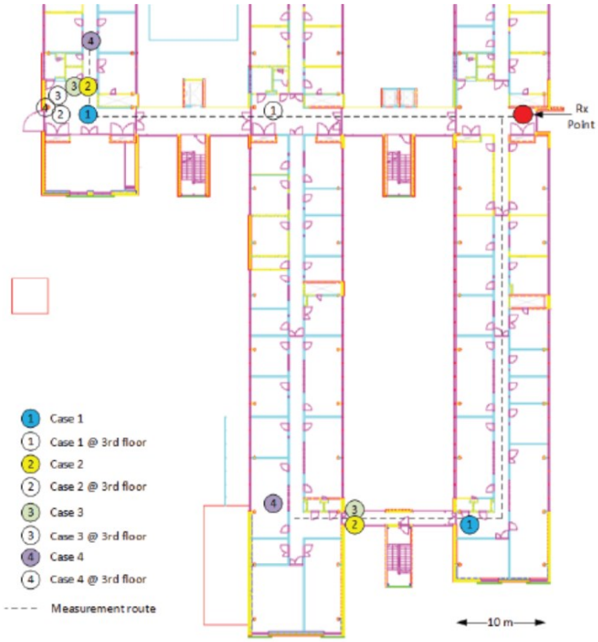

Figure 4. Measurement results on the floor map.

The received signal strength indicator (RSSI) values measured on the 3rd and 1st floors were taken right under the Rx position (red circle) in the 4th floor.

Due to the specifics of the Nordic SW solution used (based on nRF5 SDK v13.0.0) the experimental procedure was as follows. The two devices (further referred to as Tx and Rx nodes) are initially located at the Rx position and used advertising channels and 1 Mbit/s PHY to establish a connection. Then the devices were switched to the target PHY mode (1 Mbit/s or coded) and the test was started. The data for transmission was generated by the Tx node continuously, whilst the Rx node was acknowledging the data from the Tx node. After this, the Tx node was slowly moved along the route shown in the map until the connection was broken due to the packet losses. The locations where the connection was broken are shown in Fig. 4 with numbered small circles. Table 4 shows the parameters and results of the measurements as well as the RSSI of the last correctly received packet (RSSI stop) and the minimum RSSI received for individual packets (RSSI min).

Table 4. BLE measurement results.

Case	Tx power [dBm]	PHY setting	RSSI stop [dBm]	RSSI min [dBm]	RSSI at 3rd floor [dBm]	RSSI at 1st floor [dBm]
1	0	(1)	-80	-83	-71	-82
2	9	(1)	-85	-90	-60	-77
3	0	(2)	-91	-95	-70	-83
4	9	(2)	-94	-99	-59	-76

(1) 1 Mbps
(2) 1 Mbps, Long range mode, Coded S=8 (information rate: 125 Kbps).

Based on the results of these measurements, and similar findings described in [9], Equation 3 was amended when considering the interference from *m* rooms above and/or below the target room

$$PL(d) = PL_c + 10nlog_{10}\left(\frac{d}{d_{h0}}\right) + L_{MW} + 15 + 4(m-1). \quad (5)$$

D. Symbol Error Rate

For the geometry shown in Fig. 2, the signal to interference ratio (SIR), γ, at the affected node can be computed using an extension of the formula proposed in [10] to take into account additional interferers

$$\gamma[dB] = (P_s - PL(L) - \sum_{i=1}^{N}\left(W_{D,I}P_i - PL(d_i)\right). \quad (6)$$

where the desired signal power is P_S and P_i is the power of the *i*:th interferer (in dB). The distance between the two nodes in the affected wireless network is L and d_i is the distance from the *i*:th interferer to the origin in Fig. 2. $W_{D,I}$ is a coefficient that limits the interfering power to the bandwidth occupied by the technology being interfered with. It is defined as [4],

$$W_{D,I} = \begin{cases} 1, & \text{if } B_I \leq B_{DS} \\ B_{DS}/B_I, & \text{if } B_I > B_{DS} \end{cases}. \quad (7)$$

B_I is the bandwidth of the interferer signal and B_{DS} is the bandwidth of the target node receiver filter. For this study the BLE is assumed to use GFSK modulation with bandwidth 1 MHz, bit rate R_b = 1 Mbit/s, BT = 0.5 and modulation index h = 0.5. For non-coherent demodulation, the symbol error rate (SER) given in [10] and [4] is

$$SER = \frac{1}{2}e^{-E_s/2N_0} = \frac{1}{2}e^{-\gamma/2}, \quad (8)$$

where E_s is the energy per symbol and N_0 is the noise power spectral density per Hz.

E. Temporal Model

A temporal packet collision model is proposed in [2] and has been used in [4] for the case of one interferer. In this paper we also modify this approach to account for multiple interferers. A temporal model for a worst-case scenario is illustrated in Fig. 5 for an interval of 20 ms. Assuming an ideal TDMA coordination among the nodes, there is always just one ZigBee node transmitting. Also the Wi-Fi transmission from the base station in the corridor is constant during that interval. In the scenario of Fig. 5 there is always interference to an AWN BLE packet caused by a Wi-Fi and a ZigBee transmission. Interference from a BLE 5 node is also considered. BLE 5 Long Range Extension with strong coding uses long packets (17 ms) and full collision is assumed to occur with the BLE packet. Thus, the capture effect is not accounted for. Following the procedure outlined in [2] and [4], the PER for the affected BLE node is then

$$PER = 1 - (1 - p)^K, \tag{9}$$

where K is the length of the packet of the desired signal and p is the SER that can be calculated using Eqs. 8 and 6.

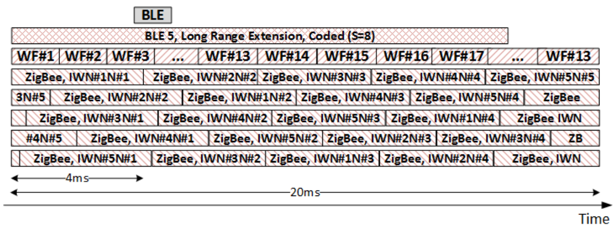

Figure 5. Temporal model.

IV. Results

The mathematical model presented in the previous section and the parameters shown in Table 5 were used to compute the PER for the cases when the target node link is on-body and when the target link is between an on-body node and an off-body BLE device within the same room. The traffic load values are the same as the ones used in [4]. The numerical results are shown in Figs. 6 and 7.

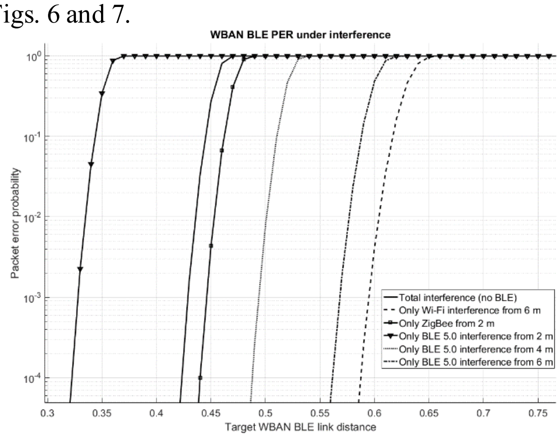

Figure 6. PER results for a WBAN on-body BLE link.

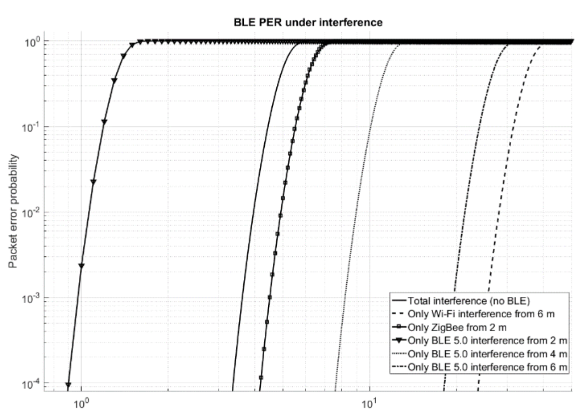

Figure 7. PER results for link on-body BLE to off-body BLE.

Table 5. Parameters for BLE performance evaluation.

Parameter	Value
Distance to IWNs	$IWN_1 = 2$m; $IWN_2 = 4$m; $IWN_3 = 6$m; $IWN_4 = 8$m; $IWN_5 = 10$m
Distance to BLE 5 node	$BLE5_1 = 2$m; $BLE5_2 = 4$m; $BLE5_3 = 6$m
Target BLE link length	0.1 – 2 m (WBAN); 0.1 – 50 m (room)
Frequency	2.412 GHz
Transmit power, ZigBee	0 dBm
Transmit power, Wi-Fi BS	20 dBm
Transmit power, BLE 5	8 dBm
Length of packet, ZigBee	128 octets
Length of packet, Wi-Fi	1024 octets
Length of packet, BLE	40 octets
Packet rate BLE node	One packet every 20 ms
Packet rate ZigBee node	One packet every 40 ms
Packet rate Wi-Fi BS	Continuous transmission
Traffic load (BLE)	16 kbps
Traffic load (ZigBee)	25.6 kbps
Traffic load (Wi-Fi)	11 Mbps

V. Discussion

For the interference on the WBAN link it is obvious that the presence of the coded BLE transmission severly limits the length of this link to less than 35 cm before the PER becomes too large (greater than 1%). For all the cases shown in Figs. 6 and 7 the presence and location of the long-range BLE 5 interferer is dominant when compared with the other technologies (Wi-Fi and ZigBee). The location of the ZigBee nodes inside the target room also need to be properly managed if the range of the affected BLE links needs to be longer. Traffic load estimates generated by the WBAN sensors, as given in [11], call for a BLE packet within a 20 ms. The duration of the long-range BLE packet is about 17 ms and thus there is a high probability for it to interfere with a transmision from a WBAN BLE transmission. It is expected that the transmission rate of the BLE long-range mode is much lower than the rates of the BLE nodes in the AWNs. Thus the results presented here are for a worst case when a full packet collisions are assumed to occur as introduced above using our temporal model.

VI. Conclusion

A mathematical model that considers multi-floor propagation has been proposed and used to evaluate the interference of wireless technologies on BLE enabled devices in a hospital environment. An indoors measurement campaign was conducted to assess the impact of the long-range mode of BLE v 5.0. This mode exhibits only a moderate range increase indoors when compared to BLE v 4. Based on our analysis the recommendation is that the BLE long-range node location should be 6 m or more from an affected BLE based AWN within the patient's room. The location of the Wi-Fi and ZigBee nodes also need to be properly managed to increase the range of the BLE enabled WBAN. In future work we intend to conduct real-life measurement to verify the analytical interference evaluation results.

ACKNOWLEDGMENT

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