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Research Articles

Evaluating the IEEE 802.15.6 2.4GHz WBAN Proposal on Medical Multi-Parameter Monitoring Under WiFi/Bluetooth Interference

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ABSTRACT

Wireless body area networks (WBAN) play a key role in the future of e-Health. In response, IEEE sets up working group 802.15.6 to standardize WBAN schemes. Of all existing standard proposals, the 2.4GHz proposal is the most mature and ready for mass production. However, as e-Health WBAN applications are often mission/life critical, people are concerned with the reliability (particularly, coexistence reliability) of this proposal. This study evaluates the 2.4GHz proposal under WiFi/Bluetooth interference in the context of medical multi-parameter monitoring. The authors conclude that WiFi poses a major threat to such application scenario, while Bluetooth does not.

Keywords: *Bluetooth, Coexistence, Multi-Parameter Monitor, Reliability, Robustness, WiFi, Wireless Body Area Networks (WBAN)*

1. INTRODUCTION

Healthcare has become a major concern for many countries across the globe. For example, the United States' healthcare expenditure surpassed US$2.3 trillion in 2008, which is 16.2% of the nation's GDP (National Health Care Expenditures Data, 2010); and China is facing the severe challenge of aging, as a consequence of long-lasting one-child policy (Kaneda, 2006).

To curb the healthcare crisis, medical devices and systems must be upgraded to expand capabilities, increase efficiency, improve safety, and enhance convenience. One enabling technology to these goals is *wireless body area networks* (WBAN).

A key application of WBAN is *multi-parameter monitoring* (i.e., monitoring multiple vital signs). For instance, during operation or

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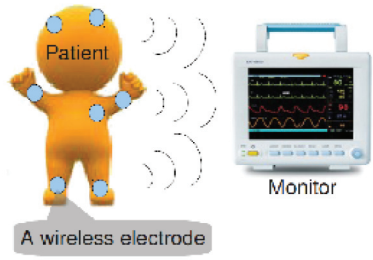
Figure 1. Multi-parameter monitoring through WBAN



intensive care, a patient must be attached with multiple electrodes to simultaneously monitor various vital signs: *electrocardiography* (ECG), *electroencephalography* (EEG), temperature, CO_2 level, oxygen level, blood pressure, etc.. In many cases, the patient must be plugged with these electrodes for hours, days, or even longer durations (e.g., 24×7 monitoring in *intensive care unit* (ICU)).

Goldman (2009) investigated the drawbacks of using wired electrodes instead of wireless electrodes in multi-parameter monitoring settings. According to his investigation, the wires of electrodes can literally tie a patient to the bed. Even worse, a small movement of the patient may stretch the wires, causing electrodes to fall off. This can be at least annoying to the patient and care givers, and sometimes can even cause lethal ramifications. In contrast, replacing wired electrodes with WBAN wireless electrodes will not only make the patient more comfortable, but also reduce the probability that electrodes fall off. This idea, which we call *WBAN multi-parameter monitoring*, is illustrated by Figure 1.

Same as wired monitoring, in Figure 1, the patient is attached with various types of electrodes, e.g., twelve ECG electrodes, one oxygen level electrode, one blood pressure electrode, one respiration electrode, etc. But unlike the wired case, all electrodes connect to the monitor through wireless. The monitor and all electrodes form a WBAN. The monitor plays the role of *base station*, while the electrodes play the role of *clients*. We call the wireless links from the base station to clients the *downlinks*, while the wireless links from clients to base station the *uplinks*.

Researchers and engineers have spent a lot of efforts to build WBANs. CodeBlue is a famous wireless sensor network solution for healthcare (Georgios, 2007). MobiHealth and UbiMon also contribute to regulate a ubiquitous wireless monitoring environment for wearable sensors (Halteren, 2004; Imperial College, 2011). Recently, IEEE 802.15.6 Task Group begins to define guidelines for wireless body area networks, focusing on low power, small size and light weight (Reichman, 2009).

A number of RF bands and wireless technologies can be the candidates for WBAN. The traditional *wireless medical telemetry service* (WMTS) bands include at least three exclusive bands: 608-614, 1395-1400, 1429-1432MHz (Baker, 2008). Exclusive medical bands like WMTS can effectively reduce interference threats, but such bands imply additional costs (e.g. for license) and are inadequate for today's many sophisticated applications. As a result, the free 2.4GHz *industrial scientific and medical* (ISM) band begins to attract the industry. Reichert (2009) studied how to deploy Bluetooth medical devices and customized Bluetooth standards/protocols (such as the *Bluetooth medical device profile*). Baker (2008) gave a solution on how to build IEEE 802.11 compatible networks for life-critical applications. *Bluetooth low energy* (BTLE) and Zigbee can also be good candidates for WBAN (Patel, 2010). The variety and the complex interdependencies of available candidate technologies forced the establishment of IEEE 802.15 Task Group 6 in

November 2007, to standardize WBAN *physical layer* (PHY) and *multiple access layer* (MAC).

Currently, more than twenty manufacturers and organizations are participating the IEEE 802.15.6 standardization. These include Samsung, NICT, Philips, GE, Fujitsu, Olympus etc.. By April, 2010, at least three categories of PHY settings are proposed, including *impulse radio - ultra wide band* (IR-UWB), *frequency modulation – ultra wide band* (FM-UWB), and *narrow band* (Batra, 2010; Abedi, 2010). Among these proposals, the narrow band 2.4GHz PHY is the most mature. It is mostly based on well-known PHY components, which are already widely used in WiFi and Bluetooth; it is supported by the MedWiN alliance, which includes GE, Philips, TI, and Toumaz Technology (Davenport, 2009); and more importantly, it is well received in the IEEE 802.15.6 group meetings, and is almost certain to be included in the final standard. Therefore, it is meaningful to evaluate the IEEE 802.15.6 narrow band 2.4GHz proposal. *For simplicity, in the rest of the paper, unless otherwise denoted, we assume WBAN PHY uses the IEEE 802.15.6 narrow band 2.4GHz proposal, and the term "IEEE 802.15.6 2.4GHz" refers to "IEEE 802.15.6 narrow band 2.4GHz proposal".*

A (if not the) major challenge to IEEE 802.15.6 2.4GHz is the possible interferences from coexisting wireless schemes in the 2.4GHz ISM band. So far, the majority of commercially-off-the-shelf 2.4GHz ISM band wireless devices, including wireless medial devices, are using WiFi or Bluetooth. Therefore, we are particularly interested in evaluating the coexistence performance of IEEE 802.15.6 2.4GHz with WiFi and Bluetooth. We suspect both WiFi and Bluetooth threat IEEE 802.15.6 2.4GHz WBAN based on two observations: their transmission power, and their *clear channel assessment* (CCA) in MAC.

WiFi devices typically transmits at 30mW (Shin, 2007; Golmie, 2005); while IEEE 802.15.6 2.4GHz proposal typically transmits at 1mW (Abedi, 2010). Such transmission power asymmetry can be a strong cause for WiFi to jam IEEE 802.15.6 2.4GHz (Huang, 2010). Meanwhile, many WiFi devices deploy *carrier sense* (CS) based CCA for MAC (Gummadi, 2007). This implies they will only back off to IEEE 802.11 modulated signal, and will not back off to IEEE 802.15.6 2.4GHz signal even though the signal is heard.

Similarly, Bluetooth and IEEE 802.15.6 2.4GHz typically deploy the same transmission power (IEEE Standards Association, 2005; Abedi, 2010), and under many configuration profiles, Bluetooth does not carry out CCA based MAC to yield to IEEE 802.15.6 2.4GHz (IEEE Standards, 2005). All of these also qualify Bluetooth to jam IEEE 802.15.6 2.4GHz.

To effectively evaluate WiFi and Bluetooth's impacts on IEEE 802.15.6 2.4GHz, we choose medical multi-parameter monitoring as our evaluation application context. This is because medical multi-parameter monitoring is a typical medical application that requires high communications QoS.

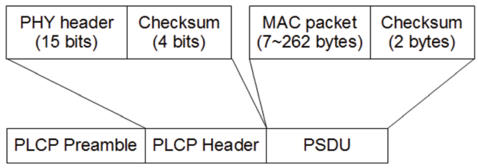
The rest of this paper is organized as follows. Section 2 introduces the IEEE 802.15.6 2.4GHz scheme. Section 3 analyses the *packet error rate* (PER) of IEEE 802.15.6 2.4GHz WBAN. Section 4 carries out a case study to compare the IEEE 802.15.6 2.4GHz WBAN multi-parameter monitoring performance under WiFi/Bluetooth interference. Section 5 discusses related work. Section 6 concludes this paper.

2. OVERVIEW OF IEEE 802.15.6 2.4GHZ PROPOSAL

The term "2.4 GHz" refers to the *radio frequency* (RF) spectrum of 2400~2483.5MHz. The IEEE 802.15.6 2.4GHz proposal divides this spectrum into 79 channels, and the carrier frequency for the n_cth ($n_c = 0,\ldots,78$) channel is $f_c = 2402.00 + 1.00 \times n_c$ (MHz).

Regardless of the carrier frequency, in baseband, a 2.4GHz PHY packet complies with the format shown in Figure 2.

Figure 2. Physical layer packet format



A PHY packet consists of three segments: preamble (a.k.a., PLCP preamble), header (a.k.a., PLCP header), and payload (a.k.a., PSDU). The preamble consists of 90 fixed well-known bits: the first 63 bits are for coarse-grain synchronization, and the next 27 bits are for fine-grain synchronization. The header consists of 19 bits of information, which are expanded into 31 bits by $19 / 31$ BCH coding (Proakis, 2002). These 31 bits are repeated four times, to create the 124-bit header. The payload encodes a MAC layer packet of 9~264 bytes with $51 / 63$ BCH coding, which expands every 51 bits of MAC layer packet into 63 bits.

The PHY packet preamble and header are modulated with $\pi / 2$-DBPSK with a symbol rate of $600\,\mathrm{K}$ (symbol/s). The PHY packet payload can be modulated with either $\pi / 2$-DBPSK or $\pi / 4$-DQPSK, both at a symbol rate of $600\,\mathrm{K}$ (symbol/s). The $\pi / 2$-DBPSK mode is mandatory. Therefore, unless explicitly denoted, we assume the PHY always uses $\pi / 2$-DBPSK.

The proposal also regulates that PHY shall provide the capability to perform CCA (Clear Channel Assessment). The following three CCA methods are suggested: *CCA Mode 1*: Energy above threshold (CCA shall report "busy channel" upon detection of signal energy exceeding a threshold); *CCA Mode 2*: Carrier Sense Only (CCA shall report "busy channel" upon detection of IEEE 802.15.6 compliant signal); *CCA Mode 3*: Carrier Sense with Energy above Threshold (combination of CCA Mode 1 and CCA Mode 2).

3. ANALYSIS OF 2.4GHZ WBAN

3.1. Bit Error Rate of 2.4GHz WBAN

In *additive white Gaussian noise* (AWGN) channel, the *bit error rate* (BER) P_{ber} of DBPSK is:

$$P_{ber} = \frac{1}{2}\exp(-\frac{E_b}{N_0}), \tag{1}$$

where N_0 is the AWGN power spectrum density; E_b is the per bit energy. E_b is further decided by:

$$E_b = P_{rx} T_b,$$
$$P_{rx} = P_{tx} / (10^{\alpha/10}),$$

where P_{tx} is the transmitter power and α (dB) is the path loss coefficient. α (dB) is a function of transmitter-receiver distance d. $\alpha(d)$ follows the well-known log-distance model:

$$\alpha(d) = \alpha_0 + 10n\log d / d_0, \tag{2}$$

where $d_0 = 0.1\,(\mathrm{m})$, and α_0 and n are derived from the raw experiment data (Miniutti, 2008).

3.2. WiFi/Bluetooth Interference Model

We will show WiFi can easily jam WBAN. To show this, it suffices to show one scheme of WiFi can easily jam WBAN. Without loss of generality, we focus on IEEE 802.11b, the most basic and widely supported WiFi scheme. IEEE 802.11b PHY deploys *direct sequence spread spectrum* (DSSS) modulation and occupies a much wider spectrum (22 MHz) than WBAN PHY (1.2 MHz). Therefore, IEEE 802.11b can be regarded as additive white Gaussian noise (AWGN) for WBAN PHY. We can use standard AWGN analysis to derive N_0 in Equation (1).

Modeling Bluetooth interference is more challenging.

Bluetooth carries out *Gaussian frequency shift keying* (GFSK) modulation at 1 MHz symbol rate. Let T_1 $(= 1\mu$ s) denote the Bluetooth per symbol duration. Suppose a Bluetooth symbol starts at time 0, then its pass band complex equivalent signal is:

$$s(t) = \begin{cases} A_1 e^{j\varphi(t)} e^{j2\pi f_c t}, & when\ t \in [0, T_1] \\ 0, & otherwise \end{cases}, \quad (3)$$

where phase $\varphi(t)$ is given by

$$\varphi(t) = \int_0^t 2\pi k_f b m(\tau) d\tau. \quad (4)$$

In Equation (4), k_f is a scaling constant, b is the bipolar information bit (± 1) the Bluetooth symbol represents, and $m(\tau)$ is the normalized Gaussian pulse.

Suppose a WBAN receiver receives both WBAN and interfering Bluetooth signals. As Bluetooth bandwidth and WBAN bandwidth are similar, we cannot simply model Bluetooth interference as AWGN. Rather, a finer granularity modeling is described in the following.

As Bluetooth and WBAN share identical carrier frequency specifications and similar bandwidth (the symbol duration of Bluetooth and WBAN are 1μ s and 1.67μ s respectively) (Abedi, 2010; IEEE Standards, 2005), the adjacent band interference from Bluetooth to WBAN is not a major concern. Hence we focus on the case where both Bluetooth and WBAN use the same carrier frequency.

We can start from analyzing the interference from *one* Bluetooth symbol to *one* WBAN symbol.

Figure 3 depicts the temporal relationship between an interfering Bluetooth symbol $Symb_1$ and a victim WBAN symbol $Symb_2$. Let T_1 $(= 1\mu$ s) and T_2 $(= 1.67\mu$ s) denote the duration of $Symb_1$ and $Symb_2$ respectively. Without loss of generality, suppose the $Symb_2$ spans $[0, T_2]$; and the $Symb_1$ spans $[t_1, t_1 + T_1]$. Since both Bluetooth and WBAN transmit at low rate (slower than 1M symbol/second), we can assume the channel is flat fading. That is, we do not need to consider multipath effects. Therefore, only when $-T_1 < t_1 < T_2$ can $Symb_1$ interfere $Symb_2$ (Figure 3).

Suppose at the WBAN receiver, the WBAN signal carrier phase is 0, while the Bluetooth carrier phase is θ. Then the received in-phase and quadra-phase components from the Bluetooth symbol at time t are respectively:

$$s^I(t) = M(t)\sqrt{\frac{2}{T_1}} A_1 \cos[\varphi(t - t_1)] \cos(2\pi f_c t + \theta),$$

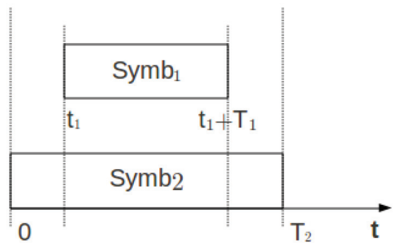
$$s^Q(t) = -M(t)\sqrt{\frac{2}{T_1}} A_1 \sin[\varphi(t - t_1)] \sin(2\pi k_c t + \theta),$$

where:

$$M(t) = \begin{cases} 1, & if\ t \in [t_1, t_1 + T_1] \\ 0, & otherwise \end{cases}.$$

Let n^{II} and n^{IQ} be the in-phase and quadra-phase noise that $s^I(t)$ creates for the demodulation of $Symb_2$ respectively; and n^{QI}

Figure 3. Temporal view of an interfering bluetooth symbol and a victim WBAN symbol



and n^{QQ} be the in-phase and quadra-phase noise that $s^{Q}(t)$ creates for the demodulation of $Symb_2$ respectively. Then:

$$n^{II} = \frac{2A_1}{\sqrt{T_1T_2}} \int_a^b \cos[\varphi(t - t_1)]$$
$$\cos(2\pi f_c t + \theta)\cos(2\pi f_c t)dt$$
$$= \frac{A_1}{\sqrt{T_1T_2}} \int_a^b \cos[\varphi(t - t_1)]$$
$$[\cos(4\pi f_c t + \theta) + \cos\theta]dt$$
$$= \frac{A_1}{\sqrt{T_1T_2}} \cos\theta \int_a^b \cos[\varphi(t - t_1)]dt$$

where:

$$a = \begin{cases} \max\{0, t_1\}, & when\ -T_1 < t_1 < T_2 \\ 0, & otherwise \end{cases}, \quad (5)$$

$$b = \begin{cases} \min\{T_2, t_1 + T_1\}, & when\ -T_1 < t_1 < T_2 \\ 0, & otherwise \end{cases}. \quad (6)$$

Similarly, we have:

$$n^{IQ} = \frac{A_1}{\sqrt{T_1T_2}} \sin\theta \int_a^b \cos[\varphi(t - t_1)]dt,$$
$$n^{QI} = -\frac{A_1}{\sqrt{T_1T_2}} \sin\theta \int_a^b \sin[\varphi(t - t_1)]dt,$$
$$n^{QQ} = \frac{A_1}{\sqrt{T_1T_2}} \cos\theta \int_a^b \sin[\varphi(t - t_1)]dt.$$

where a and b are defined by Equation (5) and (6).

Thus, the final Bluetooth interferences received at in-phase and quadra-phase branches for demodulating $Symb_2$ are:

$$n^{I} = n^{II} + n^{QI},$$
$$n^{Q} = n^{IQ} + n^{QQ}.$$

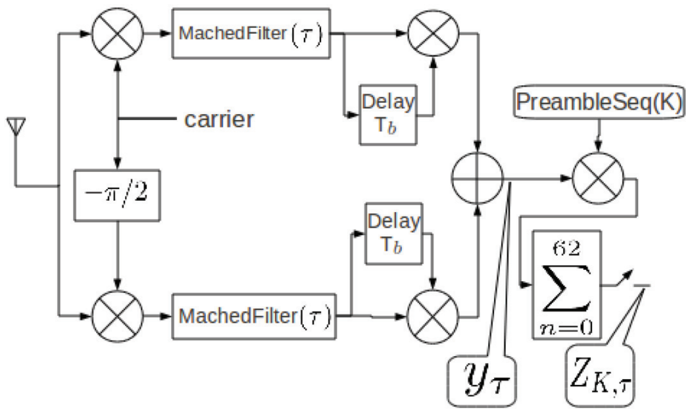
The above single symbol jamming analysis can be easily extended to the symbol sequence case, which we are not going to elaborate due to page limit.

With the above methods to quantify Bluetooth interference noise, we can use simulations to derive the bit error rate P_{ber} for a WBAN communication link. Note, since Bluetooth interference cannot be modeled as AWGN, we cannot use Equation (1) to derive P_{ber}.

3.3. Synchronization Error Rate Analysis

The first step for a WBAN receiver to receive a packet is to synchronize with the transmitter. This is done by testing multiple phase hypotheses on packet preamble in parallel (Viterbi, 1995). Without loss of generality, we assume a mainstream preamble hypothesis testing circuit as shown in Figure 4.

Figure 4. Synchronization circuit for testing one preamble phase hypothesis



In Figure 4, $MatchedFilter(\tau)$ means the matched filter samples at time $iT_b + \tau\ (i \in \mathbb{Z})$, where T_b is the preamble bit duration, and $\tau \in [0, T_b)$ is a fine-grain phase hypothesis. In practice, we try $\tau = 0$, $\frac{1}{4}T_b$, $\frac{2}{4}T_b$, and $\frac{3}{4}T_b$; $PreambleSeq(K)$ is the well-known first 63 bits of WBAN preamble, shifted cyclically by K bits. The circuit of Figure 4 tests if the preamble phase is $KT_b + \tau$. If so, the output of $Z_{K,\tau}$ is maximized.

The circuit to produce y_τ in Figure 4 depends on the PHY symbol modulation scheme. In our WBAN, it is $\pi/2$-DBPSK. Therefore, our interference analysis in Section 3.2 "WiFi/Bluetooth Interference Model" applies. Through MATLAB simulation, we can derive the synchronization error rate P_{pream} under WiFi/Bluetooth interference.

3.4. Channel Coding Analysis

After successful synchronization, the receiver needs to process the WBAN packet header and payload, which are encoded with 19/31 and 51/63 BCH code respectively.

Both 19/31 and 51/63 BCH codes are light-weight *forward error correction* (FEC) codes for correcting at the most two error bits. The error rate $P_{word}(L)$ of a code word of L bits is:

$$P_{word}(L) = 1 - (1 - P_{ber})^L - C_L^1 P_{ber}(1 - P_{ber})^{L-1} - C_L^2 P_{ber}^2 (1 - P_{ber})^{L-2},$$

where P_{ber} is the *bit error rate* (BER). Assume a segment, no matter header or payload, consists of N_w code words, the segment error rate P_{seg} is given by:

$$P_{seg}(N_w, L) = 1 - (1 - P_{word}(L))^{N_w}.$$

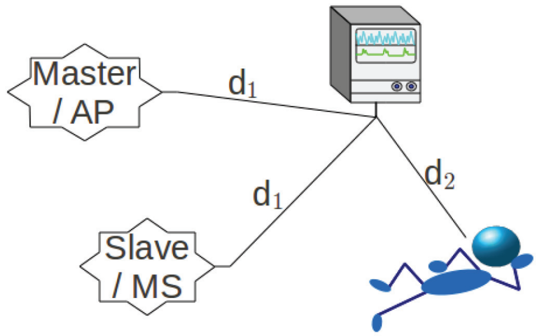
3.5. Packet Error Rate Calculation

Packet error rate (PER) P_{per} is obtained from the error rate of each segment: preamble, header and payload.

The preamble error rate P_{pream} is derived through simulation (see Section 3.3).

The packet header has a length of 31 bits repeated four times (i.e., 124 bits in total), so the header error rate P_{header} is:

Figure 5. Layout of simulation



$$P_{header} = [P_{seg}(1,31)]^4.$$

We assume the payload uses the mandatory $\pi / 2$ -DBPSK without repetition, and the packet length is 63×3 bits (i.e., coded from 51×3 information bits with 51/63 BCH coding), which is sufficient for most WBAN data packets in medical monitoring. The payload error rate $P_{payload}$ is then:

$$P_{payload} = P_{seg}(3,63).$$

Thus, the packet error rate P_{per} is:

$$P_{per} = 1-(1-P_{pream})(1-P_{header})(1-P_{payload})$$

4. CASE STUDY

4.1. Simulation Scenario

In this section, we carry out a case study on multi-parameter monitoring using IEEE 802.15.6 2.4GHz WBAN under WiFi/Bluetooth interference. Figure 5 illustrates the case study scenario. In the scenario, a centralized monitor periodically polls a patient's ECG electrodes through IEEE 802.15.6 2.4GHz WBAN. The distance between the monitor and the electrodes is d_2 (here we assume all electrodes have the same distance from the monitor). Meanwhile, the WBAN is interfered by two jamming sources. Both are d_1 away from the WBAN monitor. We study two cases: that the jamming sources are WiFi; and that the jamming sources are Bluetooth.

For studying WiFi to WBAN interference, we assume one jamming source is an *access point* (AP), and the other is a *mobile station* (MS), as shown in Figure 5.

We assume the WiFi nodes transmit at 30 mW, a typical value adopted in practice (Shin, 2007; Golmie, 2005). We assume WBAN electrodes transmit at 1 mW. We are not particularly interested in knowing the WBAN monitor's transmit power due to the following reason. Our hypothesis is that WiFi *can* effectively interfere WBAN. To test this hypothesis, we need to make our evaluation *optimistic* on the WBAN side. Specifically, we assume WBAN downlink communications (i.e., from the monitor to electrodes) always succeed.

We assume both the WBAN and WiFi comply with the path loss model of Equation (2). For WBAN, we choose $\alpha_0 = 35.6901$ and $n = 1.81199$, which are derived from real-world measurements (Miniutti, 2008). For WiFi, we choose $\alpha_0 = 20.0542$ and $n = 2$ when $d_1 < 8$ m; and $\alpha_0 = -4.5020$ and $n = 3.3$ when $d_1 \geq 8$ m. This is a common model for WiFi evaluation (Golmie, 2001).

We assume the WiFi AP and MS carry out continuous FTP under IEEE 802.11b 1 Mbps, the most widely supported WiFi mode. The FTP data packet size is 1500 bytes (i.e., 12 ms under IEEE 802.11b 1 Mbps); and the WiFi RF band completely includes the WBAN RF band (here we assume the WBAN does not carry out frequency hopping; in case WBAN carries out frequency hopping, our scenario shall include three pairs of WiFi AP/MSs, which jam the whole 2.4 GHz ISM band).

For studying Bluetooth to WBAN interference, we assume one jamming source is a Bluetooth Master, and the other is a Bluetooth Slave, as shown in Figure 5.

We assume both the Bluetooth nodes and WBAN electrodes transmit at 1 mW; while the monitor transmits at 100~1000mW, as it is plugged to power cable, which provides sufficient power supply. Such huge asymmetry in transmission power allows us to assume that the WBAN downlink communications (i.e. from the monitor to electrodes) always succeed. Therefore, we can focus only on the WBAN uplink communications (i.e., from the electrodes to monitor).

We assume both the WBAN and Bluetooth comply with the path loss model of Equation (2) with $\alpha_0 = 35.6901$ and $n = 1.81199$, which are derived from real-world measurements (Miniutti, 2008).

Our hypothesis is that Bluetooth *cannot* effectively interfere WBAN. To test this hypothesis, we need to make our evaluation *pessimistic* on the WBAN side. Specifically, we assume the Bluetooth Master is continuously transmitting to the Slave, and the Bluetooth frequency hopping is always coinciding with the WBAN RF band. Note this is an extremely pessimistic assumption. In reality, a Bluetooth Master/Slave link carries out TDMA with time slot duration of 625μ s: 259μ s of each 625μ s time slot is idle; every time slot has only $\frac{1}{79}$ chance of coinciding with WBAN RF band due to Bluetooth frequency hopping; moreover, in most cases, Bluetooth Master and Slave run on alternate slots (IEEE Standards Association, 2005).

4.2. WBAN MAC Schedule

It is widely agreed that centralized polling is the proper MAC for medical multi-parameter monitoring (Abedi, 2010). Specifically, a polling period is called a *super frame*. A super frame starts with a downlink beacon, followed by fixed TDMA time slots for (typically uplink) data packets.

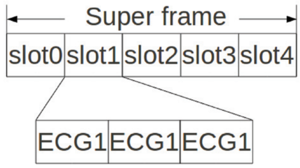
In our case study, the WBAN consists of a monitor and four ECG electrodes sampling at 100 Hz, a typical setting in ECG multi-parameter monitoring (PhysioNet, 2010). Each ECG electrode sample typically has 12 info bits (PhysioNet, 2010), hence can be encapsulated into an uplink packet with PHY layer payload of 164 symbols. Under the $\pi / 2$ -DBPSK 600 K symbol/s mode, such a packet takes 0.631 ms to send (see Section 2).

The details of our case study WBAN MAC schedule is depicted by Figure 6. In the figure, a super frame consists of five slots of 2 ms each. The 0 th slot is for (downlink) beacon, the next four slots (Slot1~4) are assigned to the four (uplink) ECG electrodes respectively. In each slot, an ECG packet (encapsulating one ECG sample) is repeated three times (see the zoom-in of Figure 6). As such super frame lasts 10 ms, we can upload 100 ECG samples per second for each ECG electrode (i.e., 100 Hz sampling rate, a typical setting on ECG monitoring in medicine (Mark, 1998)). Chipara (2010) found that over sampling could be an easy way to improve performance of WBAN. In our design, every ECG sample is repeated three times, which is equivalent to over sampling.

4.3. Mean Time to Failure Definition

For our case study of ECG multi-parameter monitoring, the *mean time to failure* (MTTF) of WBAN depends on vital sign (in our case, ECG) sampling rate f_s and WBAN failure rate P_f^{BAN}. P_f^{BAN} depends on the number of electrodes n, and the failure rate of an individual

Figure 6. Schedule of a super frame



electrode P_f, which, in turn, depends on packet error rate P_{per} and packet repetition times N_r. Thus, we have:

$$MTTF = \frac{1}{f_s \times P_f^{BAN}},$$
$$P_f^{BAN} = 1 - (1 - P_f)^n,$$
$$P_f(i) = (P_{per})^{N_r}.$$

The packet error rate analysis are given before (see Section 3). The picking of f_s depends on medical domain specific knowledge. When an ECG electrode works under monitoring mode, a reasonable sampling rate is $f_s = 100$ Hz (Mark, 1998).

4.4. Simulation Results on WiFi Interference

Figure 7 (a) shows the WBAN PER (P_{per}) under WiFi interference when d_2 (distance from WBAN monitor to electrodes) equals 0.5 m, 1 m, 1.5 m, and 2 m respectively.

A more important metric is the multi-parameter monitoring application's MTTF. In wired multi-parameter monitoring, a main cause for failure is that the patient's movement stretches the wires, causing electrodes to fall-off (Chipara, 2010). By eliminating the wires, WBAN multi-parameter monitoring is expected to greatly improve the MTTF. Through talking to nursing experts, we find that an MTTF of beyond 3 hours is attractive enough to trigger a major shift from the current wired multi-parameter monitoring practice to WBAN based multi-parameter monitoring in healthcare. Therefore, we are concerned on achieving an MTTF of beyond 3 hours.

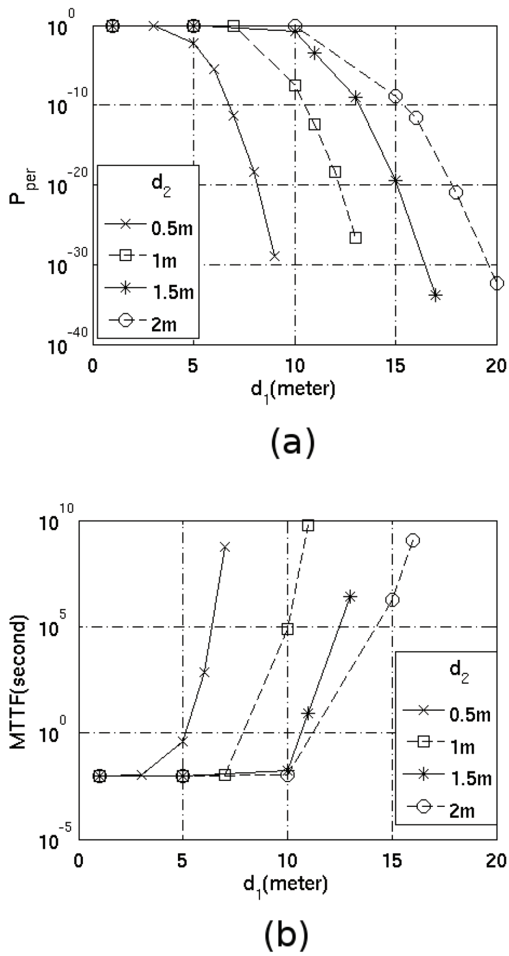
In our WBAN case study, Figure 7 (b) plots the WBAN ECG multi-parameter monitoring MTTF under WiFi interference. According to the figure, even when $d_2 = 0.5$ m (i.e., the received WBAN signal is very strong), the WiFi jamming source must be more than 6 m away from WBAN receiver to guarantee an MTTF above 3 hours. When $d_2 = 2$ m (i.e., the received WBAN signal is very weak), the WiFi jamming source must be even farther away (more than 14 m) from WBAN receiver. *Such results show that WiFi can effectively interfere IEEE 802.15.6 2.4GHz WBAN.*

4.5. Simulation Results on Bluetooth Interference

Figure 8 (a) shows the WBAN PER (P_{per}) under Bluetooth interference when $d_2 = 0.5$ m, 1 m, 1.5 m, and 2 m respectively. The figure shows even when $d_2 = 2$ m (i.e., the received WBAN signal is very weak), PER goes below 10^{-5} as long as $d_1 > 3$ m.

Figure 8 (b) plots the WBAN ECG multi-parameter monitoring MTTF under Bluetooth interference. According to the figure, even when $d_2 = 2$ m (i.e., the received WBAN signal is very weak), the MTTF goes beyond 3 hours as long as the Bluetooth jamming source is more than 3.1 m away from the WBAN receiver. When $d_2 = 0.5$ m (i.e., the received WBAN signal is very strong), the Bluetooth jamming source only needs to be more than 0.7 m away to achieve an MTTF more than 3

Figure 7. (a) ECG PER P_{per} under WiFi interference. (b) WBAN MTTF under WiFi interference. d_1 is the distance between WiFi jamming source and WBAN receiver; d_2 is the distance between WBAN transmitter and WBAN receiver (Figure 5).



hours. Assuming the downlink communication is always successful (see Section 4.1), *these results show Bluetooth is NOT a major threat to IEEE 802.15.6 2.4GHz WBAN.*

5. RELATED WORK

A huge volume of work exists in the literature on 2.4GHz ISM band wireless coexistence.

Some works study the coexistence issues from the MAC layer perspective, using packet collision time as the main metric. These works usually assume carrier sense CCA. In other words, different wireless schemes are blind to each other. For example, if WiFi uses carrier sense CCA, it will only back off to IEEE 802.11 compatible signals. Under such assumptions, Golmie et al. (2001) model WiFi interference as Poisson events. The interval of WiFi traffic sessions follows exponential distribution. Lansford et al. (2001) show that a longer Ethernet packet from AP would cause more significant Bluetooth packet losses. El-Hoiydi et al. (2001) analyze the time collision between Bluetooth piconets. Shin et al. (2005) analyze Zigbee and WiFi collision time.

Some other works study the coexistence issues from a PHY-MAC cross-layer perspective. Lansford et al. (2001) treat in-band noise; out-band noise and colored noise differently. Shin et al. (2005) model the WiFi interference to Zigbee as white noise. El-Hoiydi et al. (2001) include channel coding in the analysis of Bluetooth coexistence performance. In our paper, we model WiFi interference to WBAN as additive white Gaussian noise; and model Bluetooth interference to WBAN at an even finer granularity. We consider the effect of channel coding to header and payload individually. We also take into consideration of PHY layer synchronization and data segment repetition in our analysis.

Zigbee is another good candidate for WBAN. It also works in the 2.4GHz ISM band. For whatever reason, the current IEEE 802.15.6 2.4GHz proposal is similar to Zigbee, but not the same. Therefore, it is necessary to study the coexistence performance of the current IEEE 802.15.6 2.4GHz proposal instead of directly reuse the Zigbee coexistence study results. Besides, as the majority of nowadays commercially-off-the-shelf 2.4GHz ISM band wireless devices (including medical wireless devices) are still WiFi or Bluetooth, we focus on studying the coexistence with WiFi and Bluetooth in this paper.

There are works based on experiments in real hospital environments. Paksuniemi et al. (2006) analyze the problems when applying Bluetooth, Zigbee and UWB to vital sign monitoring in intensive care units (ICU) and operating rooms. Chipara et al. (2010) deploy Zigbee based patient monitoring in a general hospital unit. Ko et al. (2010) focus on the patient monitoring in emergency room. However, few of these works are on coexistence issues of different wireless schemes. For example, Chipara et al. (2010) choose Zigbee channel 26 (the center frequency is 2480MHz) to their network deployment. This avoids most WiFi devices, as they typically run on WiFi channel 1, 6 or 11, which are all far away from Zigbee channel 26.

6. CONCLUSION AND FUTURE WORK

In this paper, we evaluate the IEEE 802.15.6 2.4GHz WBAN under WiFi/Bluetooth interference in the context of medical multi-parameter monitoring. Our evaluation metrics are mainly PER and MTTF. To get an accurate evaluation of PER, we inspect each segment of a typical IEEE 802.15.6 2.4GHz WBAN packet, taking into consideration of BER, BCH coding rate, repetition times etc. The BER under WiFi interference is obtained through closed form analysis, while the BER under Bluetooth interference is obtained through combined close form analysis and simulation. Once have the accurate PER values, we apply them to the multi-parameter monitoring scenario, a representative medical WBAN application that requires high communications/networking QoS, to produce the MTTF curves. The MTTF curves show us that WiFi is a major threat to IEEE 802.15.6 2.4GHz WBAN, while Bluetooth is not.

As our future work, we plan to carry out more comprehensive studies on the coexistence issues of IEEE 802.15.6 WBAN with other wireless schemes along more dimensions. Based on the results of such study, we will further develop an effective scheme for policing wireless technologies in the medical contexts.

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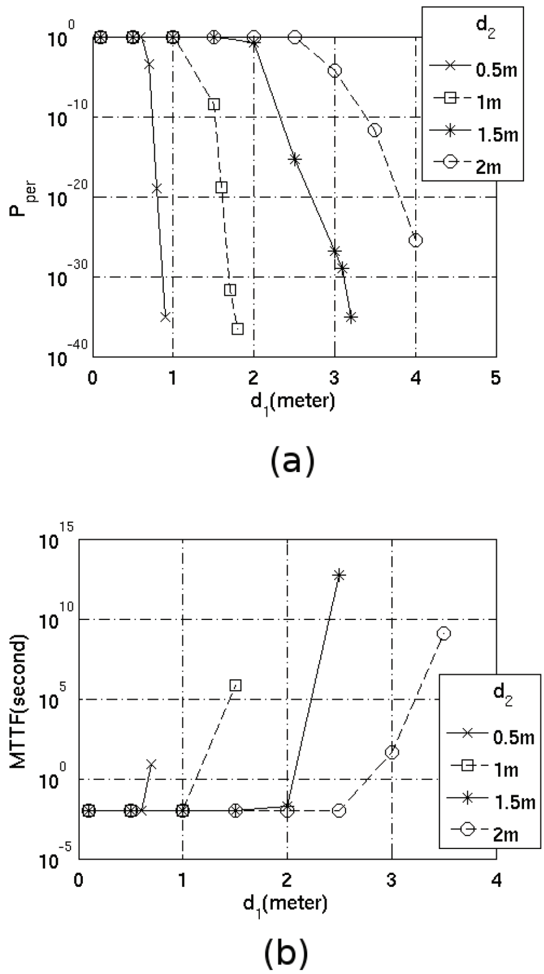
Figure 8. (a) ECG PER P_{per} under Bluetooth interference. (b) WBAN MTTF under Bluetooth interference. d_1 is the distance between Bluetooth jamming source and WBAN receiver; d_2 is the distance between WBAN transmitter and WBAN receiver (Figure 5).



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