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On IEEE 802.15.6 IR-UWB Receivers – Simulations for DBPSK Modulation*

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***Abstract*—In 2002, Federal Communications Commission (FCC) was the first in defining regulations for ultra wideband (UWB) communications followed by Europe and Japan some years later. Focusing on impulse radio (IR) UWB, in 2007 was the time for the first published standard targeting in personal area networks, released by the IEEE. The second IEEE released standard including UWB definitions is targeted for wireless body area networks (WBAN) and was published in 2012. As the wireless communications has been and will be passing through almost any levels in society, the natural step with WBAN is using it in different medical, healthcare and wellbeing applications. The arguments for these are related to the modern lifestyle, in which people have increasingly more free time and are more interested in taking care of their health and wellbeing. Another challenge is the population composition, i.e., aging in developed countries which call for new solutions and procedures, particularly from cost wise. In this paper, we are evaluating UWB receivers based on the IEEE 802.15.6 physical layer definitions and capable of detecting differentially encoded modulation. The evaluation is performed using two different WBAN channel models.**

I. Introduction

In the late 19^{th} century, in the dawn of the wireless communication using radio waves, both Heinrich Hertz and Guglielmo Marconi, among many others, were using spark gap emitters for creating electromagnetic radiation. The transmitters produced short impulses radiating to the surroundings. During the following decades, the technology developed and transmitting only impulses was given away from using more sophisticated methods, such as, transmitting frequency modulated carrier signals. The use of impulse transmissions started to interest again in the 1960s, but mainly for radars. As the technology developed onwards and the demands for using wireless radio communication for different purposes were varying, it gave a rise for the interest of using impulse radio (IR) for communication purposes too. In the late 1980s, Defense Advanced Research Projects Agency (DARPA) was the first to define the term Ultra Wideband (UWB). In the 1990s, UWB started to attract both scientific and industrial research. The potential advantages of IR-UWB technology are, for example, low-complexity with fairly high achievable data rates, low power consumption and low interference level to existing wireless technologies. [1-3]

In the new millennium, the IEEE has released two standards including IR-UWB definitions, after the FCC published the first national regulations concerning UWB in 2002. The first published standard including IR-UWB was in 2007, the IEEE 802.15.4a, currently known as the IEEE 802.15.4-2011 [4] and it is targeted for wireless personal area networks. The second one, the IEEE 802.15.6 was published in 2012 [5] and it is designed for wireless body area network (WBAN) purposes.

In this paper, we introduce the latest results concerning a transceiver model following the IEEE 802.15.6 physical layer (PHY) definitions. More precise, we have implemented in Matlab® an IR-UWB transceiver system according to the PHY definitions of the high quality of service (QoS) mode. The modulation method embedded into the system is differentially encoded binary phase-shift keying (DBPSK). According to the standard, it is defined as mandatory modulation method in the high quality of service mode which shall be used for high priority medical applications. [5]

We are presenting simulation results of three different receiver structures, two of them capable of detecting the DBPSK modulated signal. The performance of the receivers is evaluated in two different wireless body area network channels. The channel models are the IEEE 802.15.6 channel model 3 (CM 3) [6] and another channel model, based on measurements carried out in a real hospital environment in Oulu, University Hospital, Oulu Finland [7]. This work is continuing and extending our earlier works [8-11], which are dealing mostly with the IEEE 802.15.4-2011 system model and different receiver performance evaluations.

II. System Model

In the IEEE 802.15.6, there are two modes of operations defined for UWB communications. These are default mode and high quality of service mode. In the previous one, IR-UWB is defined to be the mandatory PHY with on-off-keying (OOK) modulation. In the latter one, IR-UWB is also defined as mandatory PHY, but with differential encoded PSK modulation. This includes both differential binary and differential quadrature PSK modulations. [5] In this paper, we are focusing only on the DBPSK and the quadrature PSK is left for future work.

The simulation model built in Matlab® is following the IEEE 802.15.6 UWB QoS mode definitions. The model includes a transmitter and a receiver pair communicating according to the standard IR-UWB PHY procedures. However, the model is simplified. For example, we are not considering any medium access control features or multiuser interference. In the model, the overall scenario consists of a transmitter transmitting bursts of pulses and a receiver -

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knowing the exact transmission instants - receiving the propagated signals. Therefore, the only things affecting the performance of the studied receivers are the receiver structure itself and the used channel model and additional white Gaussian noise (AWGN). The wireless surroundings are the two aforementioned hospital environments.

In the simulation setup, 1.6×10^6 randomly generated bits are expressed as a burst of pulses and modulated accordingly. Modulation is followed by the signal propagation through the WBAN channels and at the receiver, inverse to the transmitter is performed. The results are calculated by comparing the received bits to the original ones and then presented in bit error rate (BER) curves as a function of signal-to-noise ratio, E_b/N_0, E_b being energy over one burst, i.e., energy of one bit, and N_0 zero mean Gaussian noise.

A. Transmitted waveform

The m^{th} transmitted signal according to the standard is [5]

$$x(t) = \sum_{m=0}^{N} c_m \times w\left(t - mT_{\text{sym}} - h^{(m)}T_w\right), \quad (1)$$

where

$$c_m = c_{m-1}e^{(j\,\varphi_m)} \quad (2)$$

represents the m^{th} differentially encoded BPSK (or QPSK) symbol, $m = 0, 1, 2, \ldots, N$ and $c_{-1}=1$. The phase φ_m is 0 for bit 0, and π for bit 1 in binary case. T_{sym} is duration of one symbol, $h^{(m)}$ is a pseudo-random time-hopping sequence, T_w is the length of one burst and $w(t)$ is the transmitted burst with static scrambled pulses. Fig. 1 presents the UWB symbol structure consisting of 32 possible burst hopping positions [5]. In other words, one burst is inserted in one of the burst hopping positions during one symbol interval and the 31 remaining are left empty for multiuser interference avoidance.

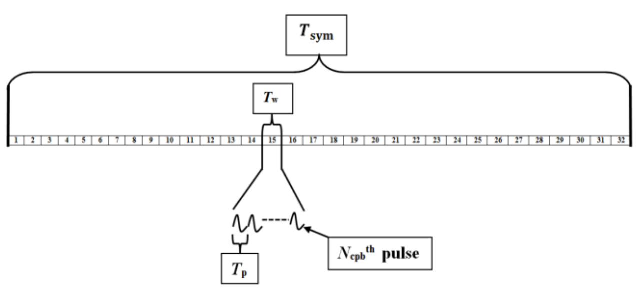

Figure 1. UWB symbol structure.

Note that the energy of each transmitted burst, independent of the number of pulses, is always normalized to one. The reason for normalizing the energy of a burst is that a single burst always corresponds to one symbol, i.e., one bit.

B. WBAN channel models

Besides the AWGN only, the receiver performances are compared also in two different WBAN channel models, both modeling hospital environment. The first one was published by the IEEE 802.15.6 channel modeling subcommittee [6] and the second one is based on a measurement campaign by the Centre for Wireless Communications (CWC) in a real hospital environment in Oulu University Hospital [7]. It is therefore referred as CWC channel model. IEEE 802.15.6 channel modeling subcommittee published also other channel models, but the CM 3, measured also in a hospital environment, is a corresponding channel model when compared to the CWC WBAN channel model. Table 1 summarizes some key parameters of the channel models. For the simulations, the channel taps of each channel model have been normalized to one. [6] [7]

Detailed channel model information can be found from the original documents, [6] and [7]. In [12], a comparison of the IEEE 802.15.6 CM 3 and the measured channel model was presented with analysis. Our earlier work has also been comparing different receiver structures in the two aforementioned channels. In [11], we were considering energy detector receivers and in [10], the different receiver structures were capable of detecting the symbol structure defined in the IEEE 802.15.4-2011.

TABLE I. Some key parameters of the used channel models

	IEEE 802.15.6 CM 3	**CWC channel model**
Average number of arrival paths	38	over 500
Distribution of number of arrival path	Poisson	Poisson
Mean time difference between consecutive arriving paths	1.85 ns	0.125 ns
Path amplitude distribution	Log-normal	Log-normal
Cluster model	single cluster model	double cluster model

C. DBPSK receiver structures

After passing through the channel, the m^{th} received signal is presented as

$$r(t) = x(t) * h(t) + n(t), \quad (3)$$

where $x(t)$ is the m^{th} transmitted signal as in (1), $h(t)$ is the channel impulse response and $n(t)$ is white Gaussian noise. '*' states for convolution.

We have implemented three different receiver structures. The first type is a conventional receiver performing BPSK demodulation without differential decoding for comparison purposes. Two others have implemented to decode the differential encoding defined in the standard.

The coherent detection for these receivers is expressed as

$$v = \int_{l}^{l+T_{uw}} r(t)u(t)d\tau, \quad (4)$$

where

$$u(t) = \left(\sum_{i=0}^{N_{cpb}-1}(1-2s_i) \times p(t - iT_p)\right) * h(t), \quad (5)$$

is a locally generated reference, T_{uw} is the length of the locally generated reference burst, T_p is the length of one pulse, N_{cpb} is the number of pulses per burst and s_i is the static scrambling sequence consisting of zeros and ones. In (4), the starting instant for the integration is defined as $l = mT_{\text{sym}}+hT_w$. Generating $u(t)$ this way performs an all-rake (a-rake) receiver collecting all multipath propagated signal components for the decision. Naturally, it is not realistic considerations but provides us knowledge of the best possible performance. Therefore, in practice, simpler and more realistic selective-rake or partial-rake receivers have to be used. In this paper, we are presenting only a-rake receiver results, p- and s-rake receivers are left for future work.

After the correlator, the decision variable is compared to zero in order to make a decision of the received bit

$$v^{(m)} \underset{"0"}{\overset{"1"}{\gtrless}} 0. \quad (6)$$

If the correlator output is greater than zero, the bit is detected as '1', otherwise it is '0'. The first studied receiver type is used for reference of the best detection performance. The BER calculations are performed for data based on the decision from (6) forming a binary antipodal demodulation.

The second type of the studied receivers performs (4), (5) and (6) as explained, but the standard defined differential encoding with the studied receivers is decoded by multiplying consecutive decision variables v^{m-1} and v^{m} as

$$v^{(m-1)} \times v^{(m)} \underset{"1"}{\overset{"0"}{\gtrless}} 0. \quad (7)$$

If the multiplication of the consecutive decision variables is positive, the m^{th} received bit is '0', otherwise it is '1'. In another word, if there is a phase change between the consecutive symbols, a bit '0' has been received and if the phase remains the same, a bit '1' is received.

A third studied receiver type performs similar procedure as in (4), but instead of using locally generated reference, it uses previous received burst as $u(t)$. A similar approach has been reported for example in [13]. Therefore there is no need for any channel estimation in the receiver and implementation is simple. The drawback of this method is that the sample multiplication of the received burst and the previous received burst contains more noise than in (4), therefore causing deterioration to the detection performance. The decision variable for the third type is presented as

$$v^{(m)} = \int_{l}^{l+T_{uw}} r_m(t) r_{m-1}(t) d\tau \underset{"1"}{\overset{"0"}{\gtrless}} 0. \quad (8)$$

If bigger than zero, the bit is detected as '0', otherwise as '1'.

III. RESULTS

In Fig. 2, all the studied receiver structure performances are presented in AWGN. Additionally, the theoretical BPSK and DBPSK BER curves are presented. There are also several BER curves of the third receiver type with various burst lengths as this is the only studied receiver type which gets affected by the increased noise due to increased burst length. The red curves in both of the figures present the first receiver type performing BPSK, purple curves the second type and black curves of DBPSK, in which the previous received burst is used in the decision.

As can be seen from the Fig. 2, the red curve of the BPSK receiver follows the blue BER curve of the theoretical BSPK verifying the correctness of the simulation model of the receiver. The purple curve on the other hand, falls in between the theoretical BPSK and DBPSK curves. The reason for this is that in this receiver type, there is a differential decoding performed with coherent binary PSK receiver, therefore having exactly twice as many error bits detected than in BPSK. The theoretical DBPSK curve is for a receiver in which the phase change between consecutive symbols is being compared, not the actual phase. The receiver performing correlation with the consecutive received signals has the worst performance. The highest data rate is presented in the solid black line and has approximately 3 dB worse performance than the theoretical DBPSK curve. The reason for this is that there is more noise included for the decision variable if the previous received bursts are used for performing (4). The next black curves present the same receiver, but for every curve, the data rate is halved compared to the previous which means that the burst length is doubled. This causes 1 dB weakening for performance every time. This is due to the effect of noise, which is increasing as the burst length is increasing.

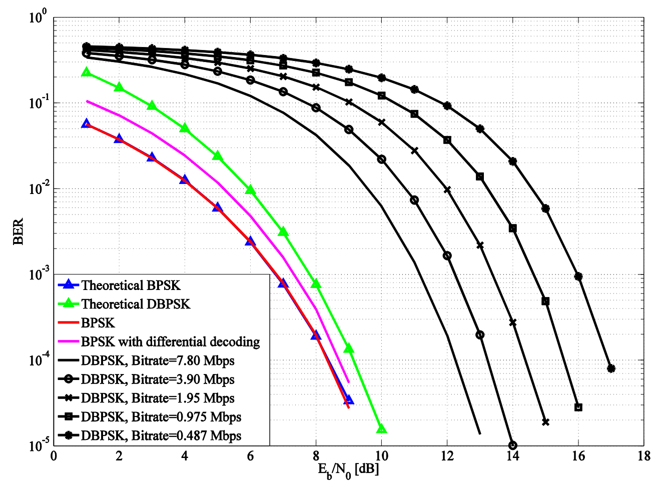

Figure 2. Theoretical and simulated results in AWGN.

In Fig. 3, different receiver structures using the mandatory bit rate of the high QoS with 32 pulses per burst are compared in the two different hospital WBAN channel, explained in Section II b. The solid lines in Fig. 3 represent the performance curves in CM 3 and the dotted lines in CWC channel model. It can be seen that the receiver structure performance order is the same as in Fig. 2 with AWGN. The difference is that the performance of DBPSK receiver compared to BPSK with differential decoding is now around 10 dB in CM 3 and almost 12 dB in CWC channel, as in AWGN the difference is slightly over 8 dB with mandatory bit rate of 0.487 Mbps.

Table 1 presents some key parameters of the channel models. Based on comparison in it, there are quite big differences between the two channel models. For example, the number of multipath components is very different even though the average maximum delays are close to same, around 60-70 ns. In CM 3, it is on average 38 and in CWC channel model over 500. The big differences in performances are visible in Fig. 3 as well. On a BER level of 10^{-3}, the detection performance of same receivers, depending on the channel model, has approximately 5 dB difference. In CM 3, the performance of the receivers is better than in CWC channel model.

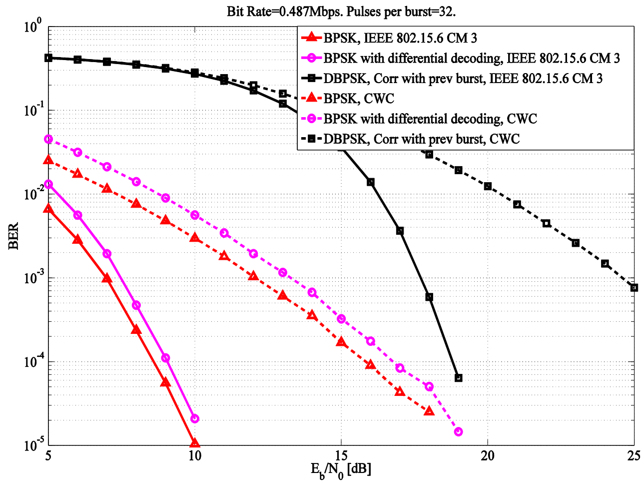

Figure 3. Mandatory bit rate simulation in two WBAN channels.

The results are in line with our earlier work with the same channel models but with different signal model. For example in [10], we were using a transceiver system based on the earlier published standard, the IEEE 802.15.4-2011 and in [11], energy detector receivers. The channel model is one of the main factors for the performance. Another big influence is the receiver structure. In Fig. 3, the difference of the black curves is approximately 10 dB worse than the purple and red ones. Using previous received signal which is corrupted by noise and fading, for the decision, will affect the detection performance much more than using noiseless signal templates.

We also made comparisons of different burst lengths on the receiver performance in WBAN channels. In Fig. 2 with AWGN, the difference is nearly 5 dB between the shortest and the longest burst lengths. In CWC channel, difference is decreasing to 3 dB and in CM 3, to 1 dB.

IV. Conclusion and Discussion

In this paper, we have presented simulation results using a transceiver system following the IEEE 802.15.6 IR-UWB PHY definition for the high QoS mode for high-priority medical applications. The receivers capable of detecting the standard defined signal structure are being compared in AWGN and in two different UWB WBAN hospital channel models. The results indicate that the channel model can be very important factor for the detection performance, together with the receiver structure. The effect of the channel for the receiver structure performance is around 5 dB between the used channel models. Between the receiver structures, there is approximately 9 dB difference between the best and the worst performing receiver structure in AWGN. However, the differences between the receiver structures are being magnified by the WBAN channel. In CM 3, the difference between the best and the worst one is 10 dB, in CWC 12 dB.

For discussion is an idea, we have presented earlier too, for example in [9] and in [11]. After continuing the work with IEEE 802.15.6 IR-UWB definitions, the idea is still well-founded. If evaluating the symbol structure presented in Fig. 1 and the transmitted signal in (1), the impulse radio transmission in UWB is very similar, despite the modulation method used. Therefore, extending number of possible usable modulation methods in the standard could be useful in many cases. It would increase the adaptability for different demands. For example, with the given symbol structure in Fig. 1, there is a possibility to use other modulation methods than DBPSK, for example BPSK, which we used in this study, or OOK. By this way, to mention few benefits, a user could maximize the detection performance or simplicity of a receiver structure, according to its application specific needs. A backward compatibility to the original standard could still be maintained.

Our future work includes developing the receivers further. Partial- and selective-rake receivers will be implemented into the system. Another topic is to compare the receivers capable of detecting differential encoding to the default mode receivers using OOK modulation. On top of these, the influence of interference, both narrowband and multiuser, is on the list. Another interesting topic would be using channel models with mobility aspects.

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