On IEEE 802.15.6 UWB Symbol Length for Energy Detector Receivers’ Performance with OOK and PPM

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Abstract—**The IEEE 802.15.6 standard for short range communications in or around human body was published in February 2012. The wireless body area network (WBAN) standard characterizes both medium access control and physical layer (PHY) specifications. The medium access is disregarded here and the focus is on PHY definitions. There are three different PHY options defined in the standard. The interest in this article is in impulse radio ultra wideband (UWB) definitions. In it, the on-off keying (OOK) modulation is stated to be the one used with the mandatory mode. The simulation model has been implemented according to the standard’s UWB PHY definitions. The target in this study is to define (close to) an optimal integration interval for an energy detector receiver and an energy threshold required for the OOK detection. For the energy detector receivers, the optimal integration interval is channel dependent and playing an important role in the detection performance. As the data rate increases, the symbol duration is shortened in impulse radio UWB. Depending on the channel conditions, short symbols can be vulnerable for inter-symbol-interference. The used channel models in the simulations are the IEEE 802.15.6 channel model 3 (CM 3) and another one, measured in a real hospital environment at the Oulu University Hospital, Oulu, Finland. The study is continuing our earlier work related to the previously published impulse radio UWB standard, the IEEE 802.15.4-2011, earlier known as the IEEE 802.15.4a.**

Keywords—ultra wideband (UWB); IEEE 802.15.6; Energy Detector Receiver; Pulse Position Modulation; On-Off Keying;

I. INTRODUCTION

From wireless local area network (WLAN), through personal area network (WPAN) to body area network (WBAN), the geographic coverage area of networks can be seen decreasing over the years. Yet, the network size is rather increasing than decreasing, in terms of number of devices connected to it. At the same time, the physical size of wireless devices is getting as small as possible with a decent price. With a small physical size, particularly with portable devices, power consumption can be an issue through battery endurance. Obviously, the data rates should be high enough and in case of a new technology, the interference level for existing wireless technology should be kept low.

For short range communications, ultra wideband (UWB) technology, particularly impulse radio (IR), is one option for overcoming the power consumption issue with fairly high achievable data rates. Additionally, the interference to existing technologies is low which means also good security features. [1]

For IR-UWB, there are two released IEEE standards within the last six years. The IEEE 802.15.4a was the first published one in 2007 and it is currently, due to an updated version, known as the IEEE 802.15.4-2011 [2]. The latest standard including the IR-UWB definitions was published in February 2012 [3]. Considering the networks, the first one is targeted for WPANs and the latter one is for WBANs. Our earlier work [4]–[8] has been on the IEEE 802.15.4-2011 UWB communications and now we are extending it to include the UWB WBAN standard [3] as well.

Regarding modulation methods in UWB, there are many options. To mention few general ones particularly for IR-UWB, these can be pulse amplitude modulation (PAM), pulse position modulation (PPM), phase-shift keying (PSK), pulse shape modulation (PSM) and on-off keying (OOK). Binary PPM and PSK are utilized in the WPAN standard [2], OOK and differential PSK in WBAN standard [3]. PPM was defined to be used in the mandatory mode in the IEEE 802.15.4-2011 and OOK in the IEEE 802.15.6 mandatory mode.

In this study, we have implemented a Matlab® based simulator following the IEEE 802.15.6 UWB physical layer (PHY) definitions with OOK modulation. Additionally, due to the bit grouping applied in the OOK scheme, also referred as group-PPM, the system model includes an energy detector (ED) receiver with PPM. For the ED receivers, we analyzed by simulations, both optimal integration interval and for the OOK, optimal energy threshold in two different WBAN channels. The channel models include the IEEE 802.15.6 channel model 3 (CM 3) by the IEEE 802.15.6 channel modeling subcommittee [9] and a channel model, based on measurements carried out in a real hospital environment at the Oulu University Hospital, in Oulu, Finland [10]. Evaluating the integration interval of the ED receivers in two different channels and generally using two different WBAN channel models enables selection of a sufficient symbol length for each channel for avoiding inter-symbol-interference (ISI). As the data rate increase, the symbol duration is shortened which can lead to ISI due to the channel effects. The data rates, i.e., symbol durations, which are defined in the standard [3], were utilized in the simulation model. A reduced presentation of the data rates and symbol durations can be seen in Table 1.

II. IEEE 802.15.6 UWB PHY DEFINITIONS

A. Symbol structure, symbol mapping and data rates

Fig. 1 presents the IEEE 802.15.6 IR-UWB symbol structure [3]. The symbol duration, T_{sym}, is alternating depending on the data rate. Presented in Table 1, the higher the data rate is, the shorter the symbol duration is. Due to the symbol mapping, i.e., bit grouping, the symbol is divided into two halves when the OOK modulation is being used. This leads to 16 possible burst hopping positions with the mandatory mode. With the optional mode, there are 32 possible hopping positions. The symbol mapping with OOK is implemented with a code word length of two, i.e., one data bit is expressed with a two-bit code word. The data bit 0 = [1 0] and the data bit 1 = [0 1]. This means that in the first half of the symbol when expressing bit ‘0’, there is an impulse transmission in one of the burst hopping positions and in the corresponding hopping position in the second half of the symbol, the impulse transmission is absent, according to OOK modulation, forming a code word [1 0]. [3]

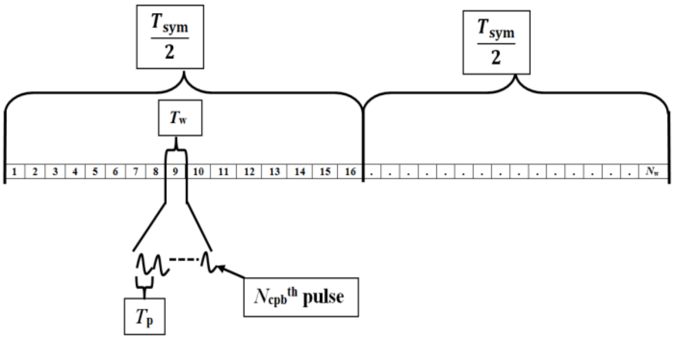

Figure 1. The IEEE 802.15.6 IR-UWB symbol.

In our implementations, the receiver receives the transmission in the both burst hopping positions separately, compares the energy level to a predefined threshold and makes a decision of the both received code word bit independently. When expressing bit ‘1’, the transmission of the code word is opposite to bit ‘0’, being [0 1], zero in the first half of the symbol and one in the second half. Note, that in this paper, we use the word ‘transmission’ also when nothing is actually transmitted, indicating a bit zero with OOK.

Table 1 presents the standard based parameters related to data rate, symbol length and number of pulses per burst [3]. However, the division to higher and lower data rates is purely our own division, mainly for comparison purposes.

Table 1. Data rate and symbol length parameters

	Lower data rates			**Higher data rates**		
Uncoded bit rate (Mbps)	0.487	0.975	1.950	3.90	7.80	15.60
Symbol duration (ns), T_{sym}	2051	1025	513	256	128	64
Pulses (T_p=2ns) per burst N_{cpb}	32	16	8	4	2	1

B. Time-hopping sequence description

The time-hopping sequence is based on an output of the linear feedback shift register described in the standard. Generally, the number of time-hopping positions is 32. Since one UWB symbol with the OOK modulation in the mandatory mode is divided into two halves due to the bit grouping, there are 16 possible time-hopping positions for a burst during one UWB symbol. The equations (94)-(98) in the standard, being rather complex, calculate the hopping sequence for each transmitted symbol. The equations basically try to prevent ISI by comparing the calculated time-hopping number of the m^{th} symbol to a predefined value for each data rate and calculating a new value for the next symbol, if necessary, i.e., if the predefined conditions are fulfilled. [3]

The nature of the equations can be seen as two-folded. With the lower data rates, i.e., fairly long symbol lengths, the meaning of the equation is to check and prevent that one or two last time-hopping positions in m^{th} symbol is not followed by the first or the second hopping position in the next symbol. If the predefined value is exceeded, it means that the time-hopping number of the m^{th} symbol is, for example with the mandatory mode, 15 or 16. Therefore the $(m+1)^{th}$ time hopping number is being recalculated and increased in order to prevent it being 1 or 2 for the $(m+1)^{th}$ symbol. This way, there exist a “guard interval”, as was specified in the symbol structure definitions in the IEEE 802.15.4-2011 [2].

With the higher data rates and therefore shorter symbol lengths, the time-hopping number is practically forced to only few higher numbers. The exception is the highest data rate, in which the only time-hopping position is #16, the last one. Using only a few last hopping positions provides a guard interval close to a half symbol length. The half symbol length is 32 ns with the shortest symbol length and 64 ns with the second shortest. The standard defined a parameter, maximum expected delay spread, τ_{max}=90 ns. Therefore having a half symbol guard interval of 32 ns or 64 ns, may not be enough in all channels.

Fig. 2 presents time-hopping sequences for three different data rates for the first 200 bits.

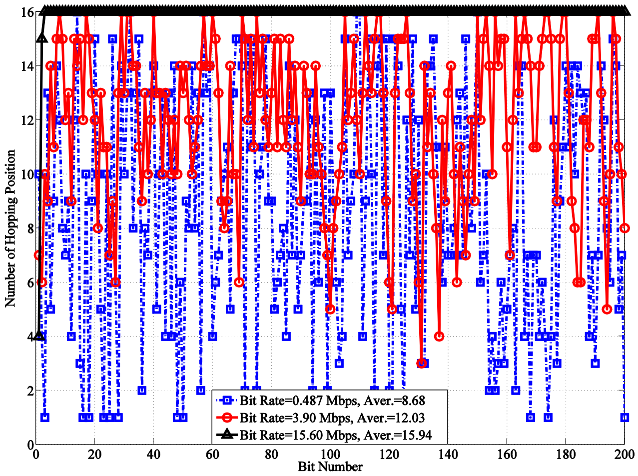

Figure 2. Time-hopping sequences for three different data rates.

Visible in the Fig. 2 with the blue squared line describing the mandatory mode’s time-hopping sequence, there is a variety of all 16 possible time-hopping positions, the average being above 8. As the data rate increases, the hopping sequence gets higher values. With the highest data rate with the black line of triangular marker, the #16 is practically the only one used.

III. SYSTEM MODEL

A. Transmitted waveform

Based on the standard [3], the transmitted waveform $x^{m}(t)$ during the m^{th} symbol in the burst pulse option is

$$x^{(m)}(t) = \sum_{n=0}^{2K-1} d_n^m \times w_{2Km+n}\big(t - n(T_{\text{sym}}/2) - mKT_{\text{sym}} - h^{(2Km+n)}T_w\big), \qquad (1)$$

where d_n^m is the n^{th} code word component over the m^{th} symbol, T_{sym} is the symbol duration, $h^{(2Km+n)}$ is the time-hopping sequence, T_{w} is the length of a burst and $w_n(t)$ corresponds to a scrambled burst of N_{cpb} pulses. In OOK, the variable K is set to 1, i.e., one information bit is expressed with a two-bit code word per one symbol. For a bit zero, code word bits [1 0] are transmitted per one symbol and for a bit one, [0 1]. [3] Note that the energy of each transmitted burst, independent of the number of pulses per burst, is always normalized to one. The reason for normalizing the energy of a burst is that there is one burst always transmitted during one symbol (the receiver detects two burst intervals corresponding to a code word length of two, but there is only one information bit transmitted leading to a ratio of one burst per one bit).

B. WBAN channel models

There are two different WBAN channel models used in this study, both modeling a hospital environment. The first one was published by the IEEE 802.15.6 channel modeling subcommittee [9] 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 [10]. It is therefore referred as CWC channel model. IEEE 802.15.6 channel modeling subcommittee published also other channel models, but the CM 3 is the only one for hospital environment as is the case with the CWC channel model. Table 2 summarizes some key parameters of the channel models. [9] [10]

Table 2. 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

Detailed channel model information can be found from the original documents, [9] and [10]. In [11], a comparison of the IEEE 802.15.6 CM 3 and the measured channel model was presented with analysis. A similar receiver performance comparison in the two aforementioned channel models, as in this paper, is offered in [6] and in [8]. In the first one it was performed with different receiver structures such as rake receiver and in the latter one with a system model based on the IEEE 802.15.4-2011.

In Fig. 3, normalized impulse responses of the two used channel models are presented. Clearly visible, there are significant differences in the channel models, especially in the energy distributions of the multipath components. In the red taps of the CM 3, the average 38 multipaths are almost evenly distributed within the ~60 ns delay. However, in the blue taps of the CWC channel model, the first arriving signal cluster within 3-4 ns contains the majority of the arriving signal energy. Due to the different energy distributions of the channels, especially the optimal integration interval will differ as will be shown later in the paper. The combined energies of the taps in each channel are always normalized to one.

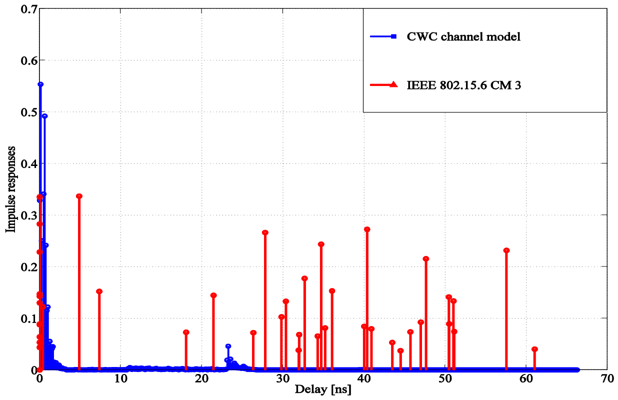

Figure 3. CWC and IEEE 802.15.6 CM 3 impulse responses.

C. ED receivers with OOK and PPM

There are two modulation methods simulated with the ED receiver structure, OOK and PPM. The first one is according to the mandatory mode of the IEEE 802.15.6 standard, being effectively the same with the utilized symbol mapping as PPM, or group-PPM as stated in the standard [3]. However, the ED receiver structures are similar with burst detection and optimal integration intervals. The difference is that with OOK, the decision of the received bit is a comparison to a predefined threshold as with PPM, the decision is based on a comparison of the energy levels of the two received burst intervals during one symbol.

After propagating through the channel, the received burst is passed through an ideal band-pass filter for noise reduction. The decision variable of the first stage of the ED receiver is expressed as

$$w_n^{(\text{m})} = \int_q^{q+T_{\text{w}}+T_{\text{ext}}} r(t)^2 \, dt, \qquad (2)$$

where T_{w} corresponds the minimum integration time used by the energy detector. T_{ext} is defined as the optimized extension of integration interval caused by multipath characteristics of the channel. The extensions of integration intervals are optimized for each channel and for different burst lengths, as presented in Fig. 4 with fixed signal-to-noise ratio E_{b}/N_0=16 dB. In the simulations, the optimization of the integration interval is performed first, before proceeding to the OOK energy threshold evaluation. Therefore, the OOK energy threshold is optimized with the optimized extensions in the integration intervals.

With the OOK demodulation, the integrated energy from (2) is compared to a predefined energy threshold ξ as

$$w_n^{(m)} \overset{\text{"0"}}{\underset{\text{"1"}}{\stackrel{\le}{>}}} \xi. \qquad (3)$$

If the squared and integrated energy is higher than the predefined threshold, the received bit is one, otherwise it is zero. Due to the symbol mapping, i.e., the 2-bit code word for a data bit, there is a possibility for miss-detection by detecting either [0 0] or [1 1] within one symbol interval. If the detection result is one of the previous code words, the decision is made according to the latter bit. In other words, if the 2-bit code word is controversial, the decision is returned to a basic OOK modulation; no transmission indicates data bit ‘0’ and a transmission indicates data bit ‘1’.

The decision on the m^{th} received bit in the PPM demodulation is based on the comparison between the decision variables from (2) and it is expressed as

$$w_0^{(m)} \overset{\text{"0"}}{\underset{\text{"1"}}{\stackrel{>}{\le}}} w_1^{(m)}. \qquad (4)$$

If the amount of integrated energy in the first received time slot is higher than in the delayed received time slot, the received bit is zero, otherwise it is one.

IV. RESULTS

Fig. 4 presents the integration interval optimization for three different symbol lengths in both of the used channel models. Green lines express the mandatory mode in the both channels, blue lines with bit rate 7.8 Mbps and red lines with the highest data rate 15.60 Mbps. In the CWC channel, the extension on top of the burst length is maximum 1 ns as in CM 3, the extension is up to 60 ns, depending on the burst length. The exception is the highest data rate in CM 3, i.e., the shortest symbol length. Due to ISI, the extension will only have a minor improvement for the BER performance.

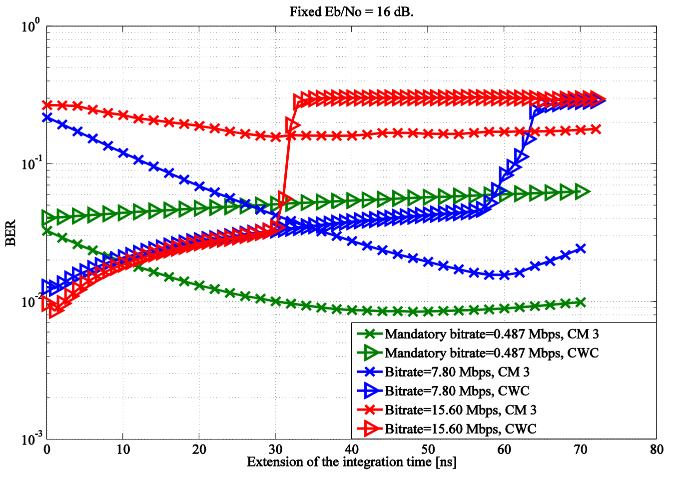

Figure 4. Integration interval optimization in the used channel models.

Fig. 5 presents OOK energy threshold evaluation results for some E_b/N_0 values in CM 3 with the mandatory mode. The most important conclusion based on the threshold simulations is that the resolution needs to be high enough in order to find the optimized value. It might have a big influence on the BER performance if the threshold value is not accurate enough. For example with E_b/N_0=26 dB the threshold change from 0.2 to 0.1 will change the BER from 10^{-5} to 10^{-2}. Additionally, the resolution we utilized due to the simulation time restrictions seems to provide minor inaccuracies to the results. With E_b/N_0=28 dB the BER minimizing threshold is between the simulated values 0.1 and 0.2, resulting on a “flat” spot in the curve, instead of a sharp peak.

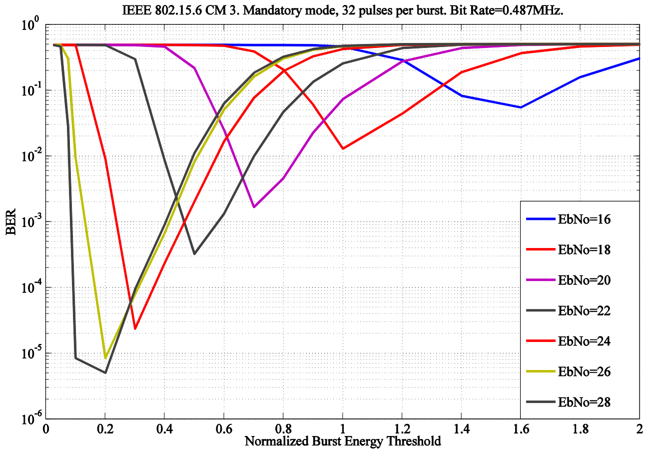

Figure 5. OOK energy threshold evaluation with some E_b/N_0 values.

Fig. 6 and Fig. 7 present the overall ED receiver performances in both of the used channel models, the IEEE 802.15.6 CM 3 and CWC, respectively. The simulations are applied with the optimized parameters from the previous figures, presented also in (2) and (3). The green curves in both figures present the mandatory mode of the standard with 32 pulses per burst, the blue lines with the bit rate 7.80 Mbps and the red lines with the highest data rate 15.60 Mbps. The curves with a circle marker present the BER performance of ED receiver with OOK modulation and the square marker with PPM modulation.

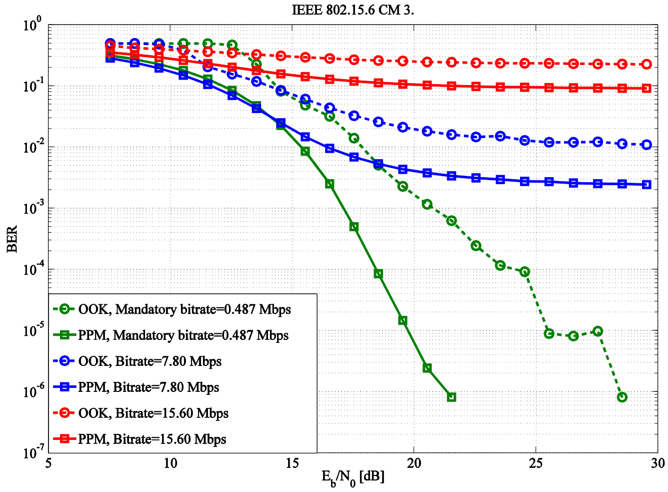

Figure 6. BER with PPM and OOK with different burst lengths.

The difference in E_b/N_0 between the modulation methods is almost the same, independent of the channel model. PPM as a method gives approximately 2-4 dB better BER performance than OOK. The difference is the same as in the results of [8] with the IEEE 802.15.4-2011 system model.

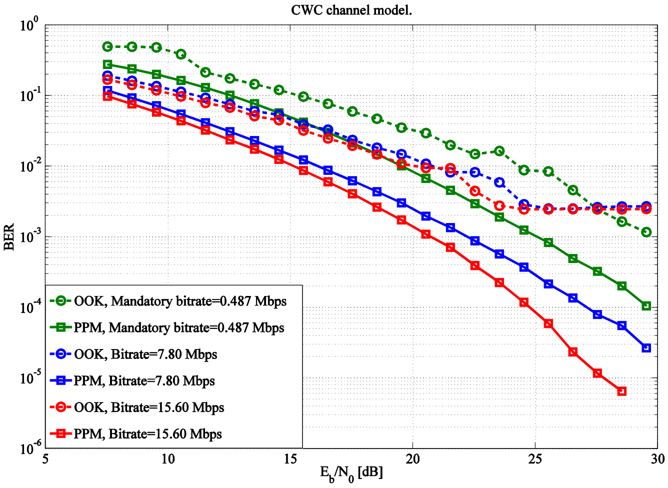

Figure 7. BER with PPM and OOK with different burst lengths.

The biggest differences are due to the channel model and the burst length. For example in the CWC channel with strong first arriving signal cluster, it is beneficial to use rather short burst lengths than long ones. If compared to Fig. 6 with the CM 3, using short bursts when trying to achieve high data rate, the BER performance is very weak. Having longer multipath delays than the symbol length causes very strong ISI basically damaging part of the data transmission. This was shown also with the IEEE 802.15.4-2011 system model in [7].

The effect of the resolution shortage with the energy threshold evaluation is visible in the BER curves. Some of the OOK performance curves have minor deviation and in Fig. 7, the red and blue BER curves with OOK are saturating due to the small resolution in the evaluation process.

V. CONCLUSIONS

This paper presented a simulations implemented according to the IEEE 802.15.6 UWB PHY definitions in two different WBAN channels. Based on the results, few general conclusions were noticed, for example the importance of channel specific integration interval of an ED receiver and the predefined energy threshold of an ED receiver with OOK.

More explicit information regarding the standard defined UWB system was observed also. This includes the tradeoff between data rate and performance in BER. In certain channel conditions, such as the IEEE 802.15.6 CM 3, it is not beneficial to use the highest admissible data rates since due to ISI the BER performance is fairly weak.

In addition, a general conclusion based also on our earlier studies on the IEEE 802.15.4-2011 [5] [8] can be expanded to the IEEE 802.15.6 UWB PHY, too. Why limit possible adaptation ability of receiver structures by allowing the use of only one or two modulation methods? An impulse radio UWB transmission is very similar despite of modulation method and therefore it would be justified to allow using different modulations, depending on data rate requirements, multi-user scenario, channel conditions etc. in order to increase adaptability for different demands.

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