Integration Interval and Threshold Evaluation for an Energy Detector Receiver with PPM and OOK Modulation

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ABSTRACT

In this paper, we are evaluating the performances of energy detector receiver with on-off-keying (OOK) and pulse position modulation (PPM) in ultra wideband (UWB) communications. Energy detector (ED) receivers are considered as a low-complexity and low-power consumption option for the more complex coherent receivers. Obviously, the tradeoff for low complexity is degraded detection performance. A challenge of the energy detector receiver is to define an optimized integration time and with OOK, defining the optimal energy threshold for the decision of the received bit. Here, we define these variables using two different channel models for comparison purposes: the IEEE 802.15.6 channel model 3 and a real, measured hospital channel model. Performance of the energy detector receiver with two different modulation methods, OOK and PPM, is compared using the two aforementioned channel models. The system model is based on the IEEE 802.15.4-2011 standard UWB physical layer signal structure and a modified version of it, suggested earlier.

Keywords

Ultra wideband, body area network, energy detector receiver, on-off-keying, pulse position modulation, hospital channel model.

1. INTRODUCTION

In impulse radio ultra wideband (IR-UWB) communications, there are a few options for modulating the transmitted signal. The most general ones are pulse amplitude modulation (PAM), pulse position modulation (PPM), on-off keying (OOK) and pulse shape modulation (PSM). Phase-shift keying (PSK) is often handled as another method but it is considered as a binary case of the pulse amplitude modulation. [1]

The aforementioned modulation methods of the IR-UWB signaling have been studied, for example, in [2]-[4]. Based on a comparative analysis in [2] and [3], PSK advantage is high power efficiency, smooth spectrum and with M-ary PAM it is possible to achieve higher data rates. If bandwidth is not an issue, M-ary PPM has low spectral lines and dimensionality. OOK on the other hand, provides the simplest transceiver structure but with more spectral lines and degraded detection performance.

Different combinations of modulation methods can also be performed, like in the IEEE 802.15.4-2011 with UWB PPM-PSK [5]. The drawback of this type of combination is that the position modulated bit needs to be detected first in a non-coherent manner and after this the demodulation of the coherent phase modulated bit is performed. If the position bit is miss-detected, the phase information is lost too with a 50% probability. This was one of the reasons why in [6] bypassing the position modulation was proposed.

Other reported combinations of modulation methods in UWB communications are in [4] and [7]. In the latter, the authors proposed a combination of PPM and PSM. They extend the model by a variation of energy levels, which enables single transmission containing a 3-bit symbol. Additional to PPM-PSM combinations, [4] also proposed a combination of OOK-PSM.

Our earlier work has been concentrating on different receiver structures capable of detecting the IEEE 802.15.4a UWB signal [8]-[11]. However in [6], we proposed to bypass the position modulation and use other modulations instead, or to hand out the freed time intervals for additional users. By utilizing the proposal, a UWB system based on the IEEE 802.15.4-2011 would have more flexibility to adapt for different demands. Different demands requiring adaptability can be, for example, need for improved performance, additional users or higher data rates. Even though having doubled number of pulses in a symbol, it would only have a minor influence on the processing gain of the system. Yet, it would retain backwards compatibility with the original model of the standard with the same symbol structure and channel coding methods.

In this paper, we study the detection performance of energy detection receivers with two different modulation methods, PPM and OOK, in two different channel models. The system model is based on the IEEE 802.15.4-2011 UWB physical layer definitions [5] which includes the PPM (and binary phase shift keying). The system model also includes a modified version of the IEEE 802.15.4-2011 UWB structure, suggested in [6], and therefore OOK is embedded in the system. As a result, the extended system model is comparable with the newly published wireless body area network (WBAN) standard IEEE 802.15.6 [12] and its IR-UWB scheme with OOK. The used channel models are the IEEE 802.15.6 channel model 3 (CM 3) [13] and a channel model measured in a real hospital environment [14].

The novelty of this paper is that it provides a performance evaluation of a standard defined modulation scheme and a modified version of the standard with another modulation scheme. The IEEE 802.15.4-2011 UWB physical layer signaling with PPM is now extended with OOK reaching to a comparable option for

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the IEEE 802.15.6 UWB scheme with OOK. Additionally, this is provided in two different body area channel models with channel specific optimized parameters. The detection performances are compared as methods but also the impact of different channel models is clearly visible.

2. ENERGY DETECTOR RECEIVER

Simple and low-power consumption receivers are targeted especially for sensor networks. Energy detector receiver is one suitable candidate due to its low complexity features. As pointed out, for example, in [2] and [3], the cost for achieving low complexity feature is generally a weaker detection performance. An advantage of the ED receiver, if compared to coherent receivers, is its tolerance against synchronization errors [15].

When utilizing two different modulation methods on an ED receiver, it is good to remember the benefits and drawbacks of both of the used modulation schemes, PPM and OOK. With both modulations, the ED receiver is still exposed to variations of the optimal integration interval. With different channel conditions, the length of the optimal integration time changes, as will be shown later in the paper and which has also pointed out in [16]-[18].

The benefit of the PPM is that there is no need for any estimation of an energy threshold in the decision of the received bit. The receiver simply makes a comparison of the energy levels captured in two separate, predefined, time intervals. Another advantage of the PPM is that it has improved power efficiency if compared to OOK. Simplicity is the benefit of the OOK, but with higher error probability. One of the challenges of OOK is the threshold estimation in order to make a decision of the received bit. On the other hand, the advantage of the OOK modulation is that the receiver is capturing the energy only in the dedicated time intervals when it is expecting information of the transmitted bit. In PPM case, it is inevitable to receive two separate predefined time intervals of which one is “empty”. [2] [3]

Different approaches have been reported when evaluating the optimization of the ED receiver. The study in [17] has similarities to the research of this paper. Generally in both papers, the evaluation of optimized integration interval and energy threshold for OOK is performed by simulations. In [17], the search of BER minimizing parameters is done by transmitting 100000 bits of pilot symbols in each channel model. Here, we use remarkable amount of bits, 1.5x10^6, per each inspected parameter for achieving statistically reliable simulation results.

However, there exist noticeable differences between the researches one being the used channel models. In [17], the authors use the IEE 802.15.4-2011 UWB CM 1-4 while we are using the IEEE 802.15.6 CM 3 [13] and a WBAN model based on our own measurements in a real hospital environment [14]. Another difference is that the system in this paper is based on the IEEE 802.15.4-2011 UWB physical layer signaling model with two different modulation methods for ED receivers, PPM and OOK. In [17], the system model is a general impulse radio UWB ED receiver with OOK only. The results in the two papers are also focusing on slightly different aspects. Here, we represent the differences in the detection performance caused by the diverse channel models and also the variations caused by different demodulation. The results presented in [17] are mainly focusing on the advances achieved due to the optimization process in the different standard defined channel models.

As a general rule concerning the optimized parameters, i.e., the integration interval and energy threshold for OOK, is that better detection performance is achieved with optimized than with un-optimized parameters. Optimization is usually achieved with relatively long simulation time, or as in [17], by using a fairly large number of pilot symbols. Achieving optimized results for a certain scenario is justified for research purposes, despite of fairly long lasting simulations.

However, if creating a real implementation, when the energy consumption and time for estimation needs to be minimized, some different and more practical approach is probably more suitable. For example, in [19],the authors suggest a very simple but non-optimal method for OOK energy threshold by choosing an average value of the integrated energy of symbols ‘0’ and ‘1’ over N symbols. Another way is reported in [16] where the authors estimate the energy threshold based on Gaussian approximation of the Chi-Square statistics which is usable only with large bandwidths and long integration intervals as pointed out by the authors in [20]. The authors of [20] propose a look-up table based on predefined values, a similar to the approach in [16] but with smaller processing requirements.

As a conclusion, the main parameters to optimize in ED receiver are the integration interval and additionally in OOK case, the energy threshold. In this paper, we are concentrating on evaluation of these two parameters in two different channel models. Therefore we assume perfect synchronization of the single transmitter-receiver pair. No other types of interference are assumed, only noise and fading channels. The integration interval and energy threshold parameter estimation is performed by simulating 1.5x10^6 bits per each inspected parameter variable in both of the used channel models. From the simulations, the inspected parameter values which are minimizing bit error rate (BER) are chosen when performing the overall performance simulations. The BER minimizing values are averaged results over 100 channel realizations of each channel model.

2.1 Transmitted waveform

The transmitted UWB waveform during the k^{th} symbol interval is expressed as [5]

$$x^{(k)}(t) = \left[1 - 2g_1^{(k)}\right] \sum_{n=1}^{N_{\mathrm{cpb}}} \left[1 - 2s_{n+kN_{\mathrm{cpb}}}\right] \times p\left(t - g_0^{(k)}T_{\mathrm{BPM}} - h^{(k)}T_{\mathrm{burst}} - nT_{\mathrm{c}}\right) \quad (1)$$

where $g_0^{(k)}$ is the position modulated bit and $g_1^{(k)}$ is the phase modulated bit. Sequence $s_{n+kN_{\mathrm{cpb}}} \in \{0,1\}$, $n = 0, 1, \ldots, N_{\mathrm{cpb}} - 1$ is the scrambling code used in the k^{th} interval and $h^{(k)}$ is the k^{th} burst hopping position defined also by the scrambler. $p(t)$ is the transmitted pulse waveform at the antenna input, T_{BPM} is the half length of a symbol defining the position of the burst in the symbol, T_{burst} is the length of a burst and T_{c} is the length of a pulse. [5]

Note that the energy of each transmitted burst, whether containing 2 or 16 consecutive pulses as used in the simulation presented later, is always normalized to one. The burst containing 16 pulses is the mandatory mode of the IEEE 802.15.4-2011 UWB standard. The burst with 2 pulses is an optional mode providing higher data rates than the mandatory mode. With the mandatory mode the guard interval for preventing inter-symbol-interference is 256 ns. With the optional mode used, the guard interval is 128 ns. Maximum multipath delay in either of the used channel models is less than 100 ns.

Since we assume perfect synchronization, there are no media access control features implemented in the system model. 1.5x10^6

randomly generated bits are simply channel coded with Reed-Solomon (63,55) and modulated based on the standard definitions as presented in (1) which is followed by a transmission through a channel. At the receiver side, after the detection of the signal, the decoding is decrypted and the number of correctly received bits is calculated.

2.2 Body Area Network Channel Models

Two different channel models are used in this study. Both of them are WBAN channel models modeling hospital environment. The first one is published by the IEEE 802.15.6 channel modeling subcommittee [13] and the second one is based on a measurement campaign by Centre for Wireless Communications (CWC) in a real hospital environment in Oulu University Hospital [14] and it is therefore referred as CWC channel model.

In Table 1, a summarized comparison of some key parameters of the channel models is provided. Detailed channel model information can be found from the original documents of the channel models, [13] and [14]. In [21], 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 [10], but with different receiver structures, such as rake receiver.

Table 1. Comparison of some key parameters of the two channel models

	IEEE 802.15.6 CM 3	**CWC's hospital channel model**
Average number of arrival paths:	38	over 500
Number of arrival path distribution:	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

Figure 1 presents normalized impulse responses of the two used channel models, CM 3 and CWC. As can be seen, there are relatively big differences in the channel models, especially in the energy distributions of the multipath propagated signal components. In the red taps of the CM 3, the average 38 multi paths 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 energies of the taps in both channels are always normalized to one.

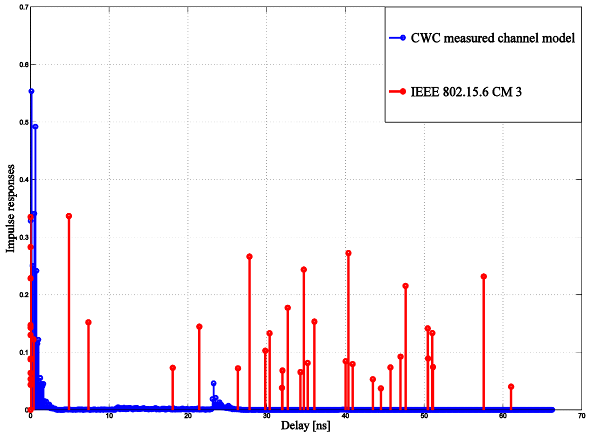

Figure 1. Impulse responses of the two used channel models.

2.3 ED receiver with PPM and OOK

The k^{th} received symbol can be written as

$$r^{(k)}(t) = x^{(k)}(t) * h(t) + n(t), \tag{2}$$

where $x^{(k)}(t)$ is the transmitted signal as in (1), $h(t)$ is the channel impulse response, '*' states convolution and $n(t)$ is a zero mean white Gaussian noise with variance of 1.

In the simulated receiver structures, two different demodulations are utilized by the ED receiver, PPM and OOK. Other than the demodulation, the receiver structure is the same with extended integration intervals in the two WBAN channels. The difference is that with PPM, the detection of a single bit is a comparison between the energy levels of the two predefined and separately received time slots as with OOK, the detection of a received bit is made by comparing the integrated energy to a certain predefined energy threshold.

At first in the receiver, the received signal is passed through a band-pass filter for noise reduction. Assuming that the filter does not cause distortion to the received signal, the decision variable is written as

$$w_i^{(k)} = \int_q^{q+T_{\text{burst}}+T_{\text{ext}}} r(t)^2\, dt,\ i = 0, 1. \tag{3}$$

T_{burst} is 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 Figure 2 with fixed 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 optimized extensions in the integration intervals were utilized when the optimized thresholds were simulated.

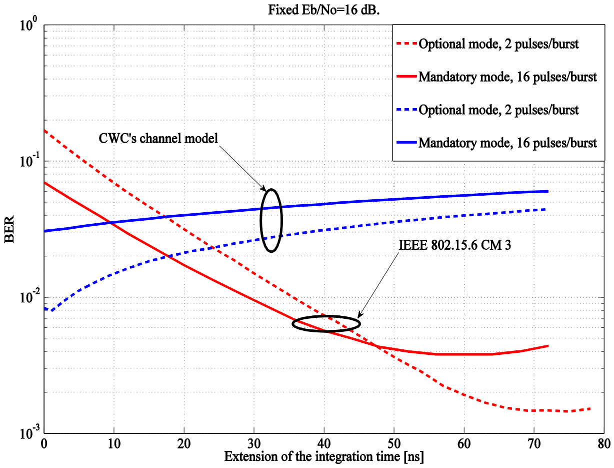

Figure 2. Extension of the integration interval.

As can be seen from Figure 2, the length of the optimized extension of the integration interval is quite different for the two channel models. The solid lines express the extension of the mandatory mode and the dashed lines with the optional mode of 2 pulses. The red curves are with IEEE 802.15.6 CM 3 and the blue ones with CWC's channel model. In CM3, additionally to the length of the burst, the optimized extension is approximately 60 ns with the mandatory mode of the signal and with the optional mode consisting 2 pulses per burst, the optimized extension is almost 70 ns. In CWC's channel model, the extension is only 1 ns with the optional mode and with the mandatory mode, the optimized integration interval is the same as the burst length. This behavior is due to the differences in the channel model, presented in Figure 1. The energy of the arriving signal components is almost evenly distributed in the CM 3, as in CWC channel model, the first arriving signal cluster contains the majority of the signal energy. Therefore in CM 3, it is beneficial to extend integration interval up to ~70 ns in order to minimize BER. With the mandatory mode in CWC channel model, increasing the integration interval from the length of the burst will increase the effect of noise causing increased BER rates. In the optional mode, the extension is 1 ns leading only to minor improvement in BER.

The decision on the received bit in the PPM demodulation is based on the comparison between the decision variables from (3) and it is expressed as

$$w_0^{(k)} \underset{\text{"1"}}{\overset{\text{"0"}}{\gtreqless}} w_1^{(k)} \,. \tag{4}$$

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.

In the case of the OOK demodulation, the integrated energy from (3) is compared to a predefined energy threshold

$$\xi \underset{\text{"1"}}{\overset{\text{"0"}}{\gtrless}} w^{(k)} \tag{5}$$

If the squared and integrated energy is higher than the predefined threshold, the received bit is one, otherwise it is zero.

The simulation resolution in the integration time evaluation is 1 ns, i.e., the extension is increased in steps of 1 ns. With higher resolution, the accuracy is increased but with significant increase in the simulation time. In the integration time optimization, the 1 ns resolution gives accurate results, as can be seen from Figure 2. There are only negligible differences in the BER curve with consecutive x-axis values, i.e., integration interval extension. Especially with the values which are minimizing the BER. Therefore the 1 ns resolution in the optimum integration interval simulations is sufficient.

In OOK threshold simulations, the initial resolution of 0.1 turned out to cause some inaccuracies in the BER results with consecutive E_b/N_0 values and therefore the resolution was improved to 0.025 with threshold values smaller than 0.1. Figure 3 presents threshold evaluation results of the OOK with a few E_b/N_0 values in CWC channel. As can be seen, the threshold value is decreasing as the E_b/N_0 increases. Also the effect of the resolution with chosen discrete steps can be seen from the curve presenting the results with E_b/N_0=18dB. There are two possible threshold values which are providing the minimized BER when E_b/N_0=18dB. With the other E_b/N_0 values, especially in the high end, there is a single value that clearly provides the minimized BER.

With higher E_b/N_0 values, i.e. 24 or above, the resolution of the threshold can cause significant differences on the detection performance. For example with E_b/N_0=30 dB, if the threshold is 0.025, the BER is approximately $6 \cdot 10^{-3}$. But if the threshold would have set to 0.05, the BER would increase to $7 \cdot 10^{-2}$. Therefore the energy threshold evaluation with accurate enough resolution for each E_b/N_0 is an important factor for the performance of the OOK-ED receiver.

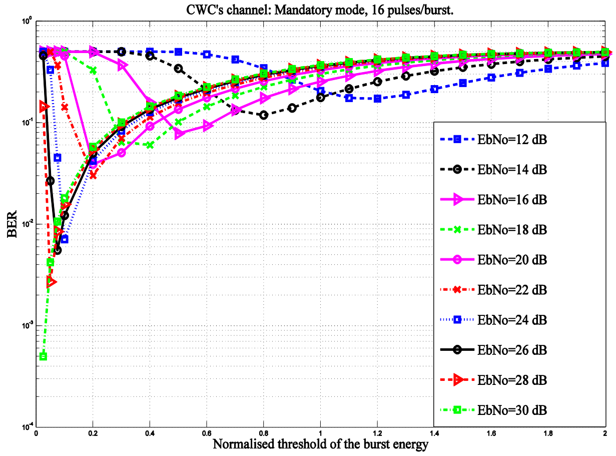

Figure 3. OOK energy thresholds with some E_b/N_0 values.

The optimized, or very close to optimal due to simulation resolution, values for each channel model and for different burst lengths were utilized in the performance simulations, presented in the next chapter. However, due to the discrete steps in OOK threshold evaluations, there will be some deviations in the BER curves of the ED receiver using OOK.

3. RESULTS

Figure 4 and 5 present BER curves of 3 different demodulation methods. Both PPM and OOK are presented in the two hospital environment WBAN channels. Additionally, a coherent 15 finger p-rake (partial-rake) receiver with binary phase-shift-keying (BPSK) is also presented for comparison purposes to see the difference of the ED receivers when compared to a more complex coherent receiver. In the p-rake case, only the phase of the burst is detected as presented in [6]. The blue curves in both figures present the performance of a receiver in CWC channel model and the red curves in CM 3. OOK is presented with square markers, PPM with circle markers and p-rake receiver without any marker. Figure 4 presents the results with the mandatory mode of the IEEE 802.15.4-2011 UWB standard containing 16 pulses per burst and Figure 5 with an optional mode of 2 pulses per burst.

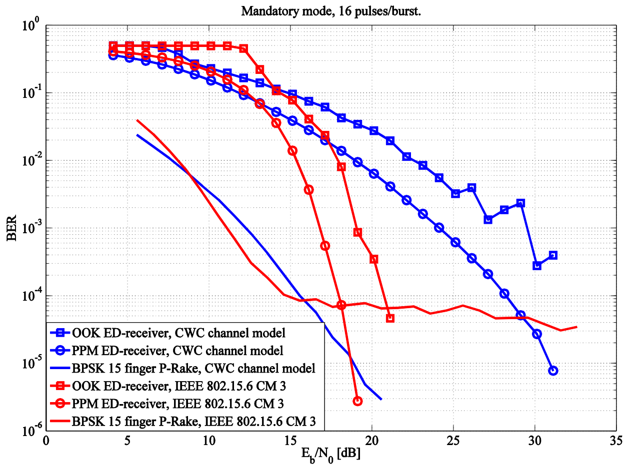

Figure 4. BER with the mandatory mode, 16 pulses/burst.

As expected, ED receiver with PPM has better performance in BER than with OOK. The difference remains the same, approximately between 2-4 dB in both of channels used. Also the p-rake receiver, in general, performs better than the ED receivers. However, in Figure 4 with the mandatory mode in CM 3, the BER performance saturates after 15 dB. Other than this, with p-rake receiver the same BER is achieved with smaller E_b/N_0 than with ED receiver. For example BER level 10^{-4} in CM 3 is achieved with p-rake 15 finger receiver when E_b/N_0=15 dB, with PPM-ED when E_b/N_0=18 dB and with OOK-ED when E_b/N_0=21 dB.

In CWC's channel model the differences are generally bigger. 15-finger p-rake receiver achieves the BER level 10^{-4} approximately with the same E_b/N_0 as in CM 3, but the ED receivers in CWC's channel require much higher E_b/N_0 than in CM 3. For PPM-ED, the BER level 10^{-4} is achieved with 28 dB and with OOK-ED it requires at least 32 dB.

The reason for the better performance of the ED receivers in CM 3 than in CWC's measured channel is due to the differently distributed energy of the propagated signal. Presented in Table 1 and in Figure 3, there is a huge difference in the number of multipath components, and therefore in the energy distribution of the propagated signal, between the two used channel models. In CM 3, the transmitted signal energy spreads on average over 38 multipath signal components as in CWC's channel model the same signal energy is spread over 500 multipath components.

In Figure 5 with the optional mode containing 2 pulses per burst, the performances are similar than with the mandatory mode in Figure 4. The biggest change is with the ED receivers in CWC's channel model, where the BER rates are better and therefore closer to the BER curves of the ED receivers in CM 3. With the CM 3, the optimized extension of the integration interval is around 60-70 ns being much longer than the burst duration. In CWC's channel the optimized extension is 1 ns with the optional mode and 0 ns with the mandatory mode. Therefore in CWC's channel model with very strong first arriving signal cluster it is beneficial to use shorter bursts than longer ones when the energy of burst is normalized to one, whether containing 16 or 2 pulses. This way the effect of noise can be reduced at the receiver.

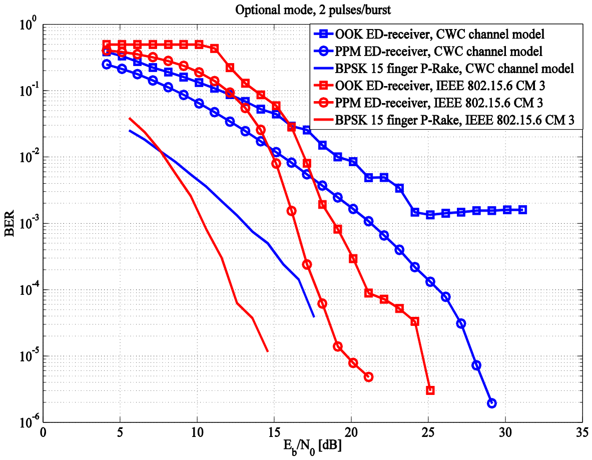

Figure 5. BER with an optional mode, 2 pulses/burst.

There is also a saturation level for the OOK-ED receiver in CWC's channel. The level is achieved with E_b/N_0=25 dB with BER level saturating close to 10^{-3}. With higher E_b/N_0 it would have required more accurate OOK threshold resolution than 0.025, but due to the highly increased simulation time it was decided to accept this imperfection in the results.

4. CONCLUSIONS

In this paper, we have presented simulated results of UWB energy detector receiver with two different modulation methods, PPM and OOK, both capable of detecting the IEEE 802.15.4a signal. The results consists the use of two different channel models, IEEE 802.15.6 CM 3 and a real measured channel model. Due to the channel effects, it was necessary to find optimized integration interval and in the case of OOK, optimized energy threshold for the decision of the received bit. The optimization of these parameters was performed before the actual system performance simulations. As was already pointed out by other researchers, these parameters are considered ones of the main parameters influencing the performance of the ED receiver. The results confirm the outcome of the other studies. Additionally, this study presents the optimized parameters for ED receivers capable of detecting the IEEE 802.15.4a UWB signal model in two different body area network channels and shows the significant variations in the performance when the parameter values are changed. Also a comparison of the ED receiver performance with two different modulations is provided.

The difference in E_b/N_0 between the two modulation methods of the ED receiver is 2-4 dB on BER level of 10^{-4} in both of the human body area channels used. PPM is, in general, providing better performance metrics but with OOK the ED receiver would be simpler in a real implementation. The difference between the PPM and the OOK is not major, but requires optimization of the integration interval and in the case of OOK, optimization of the energy threshold. Also a noteworthy is that OOK is not according to the IEEE 802.15.4a standard definition, but it is in the WBAN standard of the IEEE 802.15.6. Therefore it can provide an option for UWB communications when the simplicity of a receiver is a key feature. Another thing concerning the two IEEE UWB standards is that it would probably be beneficial to somehow combine these standards or at least high level of compatibility would be useful. An impulse radio transmission is very similar whether the standard is personal or body area network and therefore it would be justified to combine these two standards or at least have backward compatibility option.

5. ACKNOWLEDGMENTS

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