A Blind Energy Detector for Impulse Radio UWB OOK Systems

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Abstract

Energy detector is one of the non-coherent receivers for impulse radio ultra-wideband (IR-UWB) systems using on-off keying (OOK) modulation. Energy detection for IR-UWB OOK systems gets accomplished based on a threshold value. In these systems, the threshold value depends on several parameters that should be determined in the receiver. In this paper, we propose a blind approach to estimate proper thresholds for the symbol decision. The performance of the proposed method turns out to be asymptotically comparable to that of the optimal threshold selection. The proposed algorithm was also improved using an optimum integration interval. By using a blind estimating of the channel time delay spread, the integration interval was adjusted. Simulation results show that this method improves the performance about 1.5 dB in BER of 10^{-4}.

Keywords — Ultra-wideband, OOK, Blind, Energy detector.

Nomenclature

w(t): UWB pulse
T_b: Symbol duration
b_i: binary information bits
n(t): White Gaussian noise
g(t): Channel response to UWB pulse
T_i: Integration interval
r(t): received signal
Z_{ED}: decision variable
Th_{opt}: Optimum threshold value
$p_0(x)$: Probability density functions of Hypotheses "0"
$p_1(x)$: Probability density functions of Hypotheses "1"
(m_0, σ_0^2): Mean and variance of Gaussian distribution for the hypotheses "0"
(m_1, σ_1^2): Mean and variance of Gaussian distribution for the hypotheses "1"
Th: Threshold value
M_0: Number of symbols for hypotheses "0"
M_1: Number of symbols for hypotheses "1"
T_{rms}: UWB channel rms delay spread
W: Bbandwidth
E_b / N_0: Ratio of Energy per Bit (Eb) to the Spectral NoiseDensity (No)

I. INTRODUCTION

Impulse radio Ultra-wideband (IR-UWB) systems work on the basis of the transmission of pulses with very short duration [1]. UWB communication systems are used as a way of high data rate transmission at very low power consumption. In UWB systems the bandwidth of the signal is very high. Therefore, the power of the signal spreads in a wide range of the bandwidth [2]. Because UWB systems are used for some special applications like body area networks, the detection process should be performed at a lower complexity.

The conventional coherent IR-UWB RAKE receiver exploits multipath diversity by capturing energy associated with the multipath components. Therefore, it is essential to have the exact information about the phase of the received signal. In coherent detection, it also needs to estimate the impulse response of the channel at the receiver. Furthermore in UWB systems, since the channel has a lot of multipath components, the channel estimation process has a high complexity. As the number of multipath components increases, more number of coherent IR-UWB RAKE correlators is required to extract the multipath energy, thereby leading to complexity problems. The problem faced by coherent IR-UWB RAKE receiver is mitigated using a non-coherent UWB receiver.

Energy detector (ED) is one of the conventional non-coherent detectors. In this detector, decision mechanism is made by the energy of the received signal. ED receiver is usually used for pulse position modulation (PPM) and on-off keying modulation (OOK). The decision mechanism in PPM is made by sign detector, and in OOK

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scheme, by comparing the output of the energy integrator with a threshold value [3]. The main advantages of using the ED-OOK system include: very low-complexity decision variable generation for symbol detection because of using sign detector, flexibility to avoid inter symbol interference (ISI) for a given symbol interval because in PPM the minimum distance between two pulse is the half of symbol interval, and bandwidth efficiency because the required bandwidth is B_{req} = Rb (a given rate) for OOK and B_{req}= 2Rb for PPM [8]. In comparison with multidimensional modulation methods, the generation of the decision variable with ED-OOK can be performed with a simple decision threshold form, which is ideal for slowly fading channels, as the thresholds needs to be updated only infrequently[4]. Furthermore, 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, it is inevitable to receive two separate predefined time intervals of which one is "empty". The main challenge issue faced by ED-OOK modulation is the estimation of the threshold at the receiver, because in this modulation, the threshold value depends on the amount of the signal to noise ratio (SNR) and the channel coefficients. The optimum threshold value at the receiver is achieved by using probability distribution functions of the "0" and "1" hypotheses and the maximum likelihood (ML) criterion. Many approaches for estimating the threshold value have been proposed in UWB systems with OOK modulation. The chi-square distribution for the hypotheses has been used and based on that, the threshold value has been estimated [5]. By using chi-square distribution for hypotheses, a closed form for threshold couldn't be achieved. In [6] & [7] Gaussian approximation for distribution function of hypotheses has been used and a closed form for threshold has been obtained. In [8], the threshold value has been estimated by using training sequences. In [9] performance of energy detector in time reversal UWB system based on PPM signaling was analyzed. To improve the performance of energy detector in OOK-UWB system, weighted energy detector (WED), which is a detector with multiple energy measurement, was proposed in [10]. In WED, some parallel integrators, whose integration intervals have no overlap, are utilized to decrease the noise effects. After that, the output of each integrator is multiplied by a factor and linearly combined with the others. Unfortunately this method needs either large number of integrators or high rate sampling and weight factor estimation [10, 11].

Zhou et all present an adaptive synchronization and integration region optimization for energy detection IR-UWB receivers [12]. However, the complexity of this algorithm is relatively low but it has a moderate accuracy. In all of the methods for estimating the threshold in OOK modulation, power spectral density of the noise, energy of the received signal and some other parameters should have been known at the receiver, or the receiver need to utilize training sequences. Optimization of threshold is usually achieved with relatively long simulation time, or by using a fairly large number of pilot symbols [13].

In this paper we propose a method for estimation of the threshold value without training sequences and any other information. In the proposed method, the received data symbols is used to estimate the threshold. The distribution functions of the hypotheses are supposed to be Gaussian. As we know, Gaussian distribution has two parameters. To obtain the threshold value, it needs to estimate these two parameters. The proposed method does not need to transmit training symbols and the parameters of Gaussian distributions are extracted by using the received data symbols. Our simulation results show that the BER performance of the proposed system with optimum integration interval outperform the optimum threshold scenario. It is also observed that the BER performance of the proposed system is quite satisfactory when the time delay estimation error is below 10 % of time delay spread.

The rest of the paper is organized as follows. In section II, the system model of IR-UWB OOK and ED receiver is presented. The proposed method for estimating the threshold value is presented in section III. The performance evaluation and the simulation results are discussed in section IV. Finally, concluding remarks are presented in section V.

II. SYSTEM MODEL

We consider UWB OOK signaling in a single user scenario. The transmitted signal in OOK scheme can be expressed as follows:

$$s(t) = \sum_{i=-\infty}^{\infty} b_i \sqrt{E_w} w(t - iT_b), \quad (1)$$

where w(t) is the UWB pulse, E_w is the energy of w(t), T_b is the symbol duration and $b_i \in \{0,1\}$ is the binary information bits.

Signal s(t) propagates through a multipath channel according to IEEE802.15.4 channel model [14]. Then the received signal can be expressed as:

$$r(t) = \sqrt{E_w} \sum_{i=-\infty}^{\infty} b_i g(t - iT_b) + n(t), \quad (2)$$

where n(t) is the white Gaussian noise with the power spectral density $N_0/2$, and g(t) = w(t) * h(t) is the channel response to w(t).

The standard IEEE802.15.4a specifies IR-UWB for short range wireless communications to support low to medium data rates. It operates in the frequency band of 2 GHz to 10 GHz; also CM1 and CM2 are considered for LOS and NLOS conditions respectively [14]. The IEEE 802.15.4a models are completely specified in [14], and MATLAB programs for the implementation are given in its appendix for the convenience of the user.

A. Energy Detector

The energy detector can be used at the receiver for IR-UWB OOK systems. Block diagram of energy detector is shown in Fig. 1. The decision variable in ED is obtained as follows:

$$z_{ED} = \int_0^{T_i} r^2(t) dt, \quad (3)$$

where T_i is the integration interval and r(t) is the received signal passing through a band pass filter.

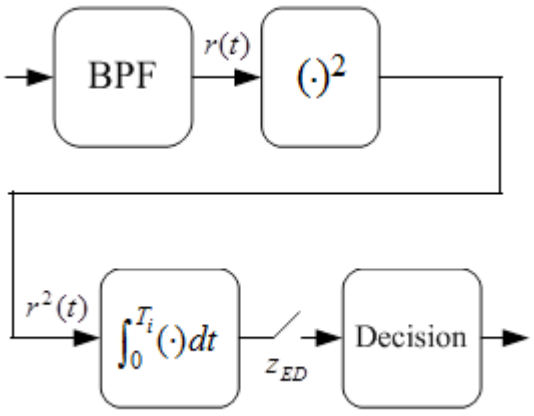

Fig.1. Block diagram of energy detector.

In OOK scheme, the demodulation stage has two hypotheses:

$$\begin{cases} H_0 : z_{ED} = \int_0^{T_i} n^2(t) dt & (bit\,0) \\ H_1 : z_{ED} = \int_0^{T_i} (g(t) + n(t))^2 dt & (bit\,1) \end{cases}, \quad (4)$$

Where g(t) and n(t) are the received desired signal and noise respectively. The symbol decision in receiver is made by comparing z_{ED} with a threshold value. If the energy of the received signal is lower than the threshold value, the detector decides that the transmitted bit is "0". If the energy of the received signal is larger than the threshold value, the detector decides that the transmitted bit is "1". Therefore:

$$\begin{cases} if \quad z_{ED} < Th_{opt} \quad : \quad H_0 \\ if \quad z_{ED} \geq Th_{opt} \quad : \quad H_1 \end{cases}. \quad (5)$$

The optimal threshold for an energy detector will vary for different channel realizations, therefore a receiver design that optimizes the performance for a particular channel realization is needed. The optimum threshold value (Th_{opt}) is obtained using the ML criterion. ML criterion is based on the probability density functions of the hypotheses. Hypotheses "0" and "1" have the probability density functions (PDF) $p_0(x)$ and $p_1(x)$, respectively. Gaussian approximation methods have been used to solve the error probability analysis of the system using OOK-ED signals. Based on the central limit theorem, the PDFs of $p_0(x)$ and $p_1(x)$ are approximated by Gaussian distribution [6, 7].

However, when the number of degrees of freedom (DOF), which is determined by the product of the signal bandwidth and symbol integration time, is low, then Gaussian approximation methods become inaccurate and more accurate threshold selection and analysis techniques are required. On the other hand, one may want to adjust adaptively the integration time, and the instantaneous integration time may be occasionally rather short, indicating that the receiver should support a low number of DOFs also from this perspective [15]. Therefore, the approximation of the threshold value (Th) can be calculated by solving the following equation:

$$\frac{1}{\sqrt{2\pi\sigma_0^2}} \exp\left(-\frac{(Th - m_0)^2}{2\sigma_0^2}\right) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp\left(-\frac{(m_1 - Th)^2}{2\sigma_1^2}\right), \quad (6)$$

where (m_0, σ_0^2) and (m_1, σ_1^2) are the mean and variance of Gaussian distribution for the hypotheses "0" and "1" respectively. By taking the natural logarithm of both sides of (6), the following quadratic equation can be achieved:

$$C_1 Th^2 + C_2 Th + C_3 = 0, \quad (7)$$

where the coefficients are given by:

$$\begin{cases} C_1 = \sigma_1^2 - \sigma_0^2 \\ C_2 = -2(m_0\sigma_1^2 - m_1\sigma_0^2) \\ C_3 = \sigma_1^2 m_0^2 - \sigma_0^2 m_1^2 - 2\sigma_0^2\sigma_1^2 \ln(\sigma_1/\sigma_0) \end{cases}. \quad (8)$$

For calculating these coefficients, it needs to determine the power spectral density of the noise and the energy of the received signal at the receiver [6, 7]. In the other word, optimization is usually achieved with relatively long simulation time, or by using a fairly large number of pilot symbols. The optimum parameters for BER minimizing are obtained by using searching method and transmitting 100000 and 1.5x106 bits of pilot symbols in each channel model in [13] and [16] respectively.

III. PROPOSED METHOD FOR ESTIMATING THE THRESHOLD VALUE

The aim of this section is to find the threshold value by using Gaussian approximation and without transmitting the training sequences. Suppose that transmitted symbols are "0" and "1" and they are equiprobable. At the receiver, first the energy of some symbols (N first received data symbols) are calculated and based on this calculation the threshold value will be estimated. After estimating the threshold, decision on the transmitted symbols will be made.

When the training symbols are used for estimating the threshold, the receiver knows that the received training symbol is "0" or "1". In proposed method the first N data symbols are used for estimating the threshold but we don't know that the received data symbol is "0" or "1". To separate N data symbols to hypotheses "0" and "1" the initial threshold value is obtained in step 2 and then the final value of the threshold is obtained in step 3.

The proposed algorithm is as follows:

Step1:

According to Eq.(3), the energy of N data symbols are calculated.

Step2:

Although the probability of the hypothesis "0" and hypothesis "1" of the data symbols are the same but the number of the hypothesis "0" and hypothesis "1" in N first data symbols is unknown. In this step, a few number of the N data symbols are selected to estimate the threshold value. Therefore, 2P symbols of that N data symbols (2P<N) are selected to estimate the threshold. Since in general, the energy of the received signal in hypothesis "1" is greater than that in hypothesis "0", P symbols which have the greatest energy among N data symbols are supposed to be hypothesis "1" and P symbols which have the least energy among them are supposed to be hypothesis "0". Based on these selected symbols, mean and variance of the distribution functions of hypotheses will be calculated as follow:

$$\begin{cases} \hat{m}_0 = \frac{1}{P}\sum_{i=1}^{P} z_{ED0,i} \\ \hat{\sigma}_0 = \frac{1}{P}\sum_{i=1}^{P} (z_{ED0,i} - \hat{m}_0)^2 \end{cases}, \quad (9)$$

$$\begin{cases} \hat{m}_1 = \frac{1}{P}\sum_{i=1}^{P} z_{ED1,i} \\ \hat{\sigma}_1 = \frac{1}{P}\sum_{i=1}^{P} (z_{ED1,i} - \hat{m}_1)^2 \end{cases}, \quad (10)$$

where $(\hat{m}_0, \hat{\sigma}_0^2)$ and $(\hat{m}_1, \hat{\sigma}_1^2)$ are the approximation of mean and variance of the Gaussian distribution for the hypotheses "0" and "1" respectively [8]. $\{z_{ED0,i}, i = 1, 2, ..., P\}$ and $\{z_{ED1,i}, i = 1, 2, ..., P\}$ are the selected energy values for hypotheses "0" and "1" respectively.

According to Eqs.(7) and (8) and parameters which have been achieved from Eqs .(9) and (10), the initial value is calculated for threshold estimation. Because of using some special symbols for estimating the threshold value in this step, it won't a precise approximation, therefore in order to increase the accuracy of threshold estimation, all of the N data symbols are used for estimation of the threshold in the next step.

Step3:

In this step, the final value of the threshold for detection will be calculated by using the initial value of the threshold which has been achieved from the step 2 and all of the N data symbols. By using the initial value of threshold, these N symbols, based on their energies are separated to hypotheses "0" and "1". If the energy of the symbol is lower than the initial value of the threshold, it supposes as hypothesis "0", and if the energy of the symbol is greater than the initial value of the threshold, it supposes as hypothesis "1". Based on the energy of the separated symbols, according to following equations, the mean and variance of decision variable of the hypotheses "0" and "1" ($(\hat{m}_0, \hat{\sigma}_0^2)$ and $(\hat{m}_1, \hat{\sigma}_1^2)$) will be updated for all of the N separated symbols as follow and the threshold value will be estimated:

$$\begin{cases} \hat{m}_0 = \dfrac{1}{M_0}\sum_{i=1}^{M_0} z_{ED0,i} \\ \hat{\sigma}_0 = \dfrac{1}{M_0}\sum_{i=1}^{M_0} (z_{ED0,i} - \hat{m}_0)^2 \end{cases}, \qquad (11)$$

$$\begin{cases} \hat{m}_1 = \dfrac{1}{M_1}\sum_{i=1}^{M_1} z_{ED1,i} \\ \hat{\sigma}_1 = \dfrac{1}{M_1}\sum_{i=1}^{M_1} (z_{ED1,i} - \hat{m}_1)^2 \end{cases}, \qquad (12)$$

where M_0 and M_1 are the number of symbols for hypotheses "0" and "1" respectively, $\{z_{ED0,i}, i = 1, 2, ..., M_0\}$ and $\{z_{ED1,i}, i = 1, 2, ..., M_1\}$ are the separated energy values for hypotheses "0" and "1" respectively, and $M_0+M_1=N$. Because in this step all of N data symbols are used to estimate the threshold value, this value has a high accuracy.

END

The threshold value which has been estimated in the step 3 will be used for detecting the first N symbols and the other transmitted symbols. It is better to use a data scrambling/descrambling method in transmitter to overcome the non-uniform distribution of transmitted symbols of "0" and "1".

The performance of proposed method can be improved by selecting an optimum integration interval. Optimum integration interval changes substantially for different channel models. In order to optimize the receiver performance of proposed method according to different multi-path environment, variable integration interval is required. If the integration interval is determined a significant gain can be obtained in energy detector. Unfortunately, there is not a close form for optimum integration interval. The optimum integration interval for each E_b / N_0 is calculated by simulations. By using a method similar to [17], the optimum integration time for UWB OOK system could be approximated as:

$$T_{opt} = T_{rms} \times \ln\left(\frac{2.39}{(WT_{rms})} \times \frac{E_b}{N_0} + 4.753\right) \qquad (13)$$

where T_{rms} is UWB channel rms delay spread.

This illustrates that the optimal integration interval is proportional to the channel's RMS delay spread, with a proportionality. Our simulation results show that it is appropriate to set the integration interval of ED-OOK UWB system to about $2T_{rms}$ in long channel impulse response and/or large bandwidth. To apply the proposed algorithm for optimum integration interval, a blind rms delay spread estimation method, estimation of channel rms delay spread is not the subject of this paper, applied in step 1 and then set $T_i=2T_{rms}$. The other steps of algorithm do not change for optimum integration interval.

In the proposed method, we assumed there are bits "0" and "1" in the first N symbols. When the energy of the first N symbols are near to each other it shows all of the symbols are "0" or "1". To prevent this problem in practical data, scrambling technique can be used. Data scramblers randomize the data patterns. This would prevent the continuous transmission of repetitive data.

At beginning of the data detection at receiver, the proposed system has some delay because it takes decision after receiving N data symbols. Based on our simulation results, we can set N=1000 which is not a large value in practical UWB systems.

IV. SIMULATION RESULTS

Simulations are done in IEEE 802.15.4a CM1 and CM2 channel models [14] with the maximum delay spread (T_{mds}) truncated to

200nsec. The second derivative of the Gaussian pulse is used with pulse duration T_p=1.5nsec, and the symbol duration is T_b=200nsec. The energy of the channel impulse response is normalized to have the unit power gain, i.e. $\sum \alpha_j^2 = 1$.

Fig. 2 shows the bit error rate (BER) performance of the proposed ED receiver as a function of the number of the received data symbols (N) which estimates the threshold value. In this figure, 20 percent of the N data symbols (2P symbols) are used to estimate the initial value of the threshold. It is clear that the BER performance improves by increasing N. In high amounts of N the BER performance of CM1 and CM2 channel models is almost constant. The computational complexity increases with N, and in high values of N the BER is constant, therefore the number of the required received symbols to converge to the threshold estimates is near one thousand (N=1000) for practical operating scenarios. In Fig. 3, BER performance is shown for different number of the data symbols (2P) in order to estimate the initial value of the threshold. In this figure, the number of the data symbols for estimating the threshold value is fixed at N=1000. The BER performance improves as the number of the data symbols for estimating the initial value of the threshold increases. As it is seen, the BER is almost constant after 2P=150 therefore 150 data symbols are sufficient to achieve statistically reliable simulation results.

Fig. 4 shows the BER performance of OOK modulation with the optimum threshold and the proposed algorithm for estimating the threshold for N=1000 and P=100. For low E_b / N_0 values, the proposed algorithm has a high accuracy. Also for high E_b / N_0 values in CM1 and CM2 channel, the performance of proposed scheme is almost the same as the one with the optimum threshold value. Performance comparison of proposed scheme and optimal threshold at BER of 10^{-3} show that the ED receiver with the optimum threshold value is only 0.15dB and 0.05dB better than the proposed ED receiver in CM1 and CM2 channel model, respectively. But regardless of optimal threshold ED receiver, in the proposed method we don't use the training sequence and any other information at the receiver. Therefore, the performance of proposed method is satisfying.

Fig. 5 shows the optimum integration interval versus E_b / N_0 in CM1 and CM2 channel model. The optimum integration interval was modeled by curve fitting tool (cftool) in Matlab R2012a software with 95% confidence bounds and the custom equation of cftool is as in [17]. It is seen a goodness of fit is observed especially at high E_b / N_0. As mentioned in previous section, simulation results show that it is appropriate to set the integration interval of ED-OOK UWB system to about $2T_{rms}$ in long channel impulse response and/or large bandwidth.

The BER performance of the proposed system with optimum integration interval (T_i) is shown in Fig.6. Comparison of Figs 4 and 6 show that in BER of 10^{-4} an improvement of 1.5 dB is observed in proposed method with optimum threshold scenario. Fig. 7 showed the effect of delay spread estimation error on the performance of the proposed algorithm with optimum integration time. It is observed that an estimation error of about 10 % in time delay spread degrades the performance only about 0.1 dB in BER of 10^{-4}, therefore the proposed algorithm has a gain of 1.4 dB in this scenario. Hence if the receiver can estimate the time delay spread with estimation error smaller than 10%, the proposed system can work in with a negligible degradation in performance.

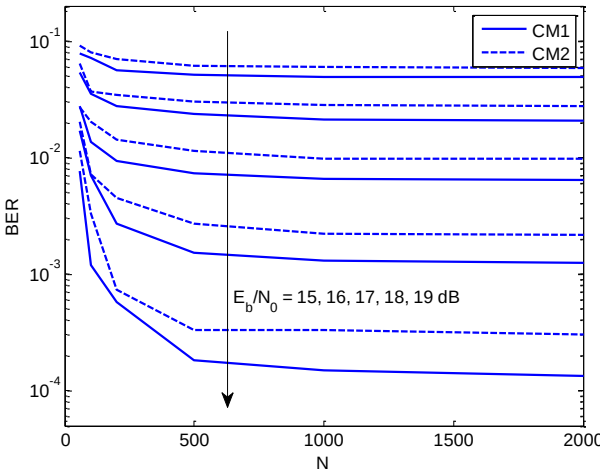

Fig. 2. BER performance at the receiver versus N with 2P=20% of N.

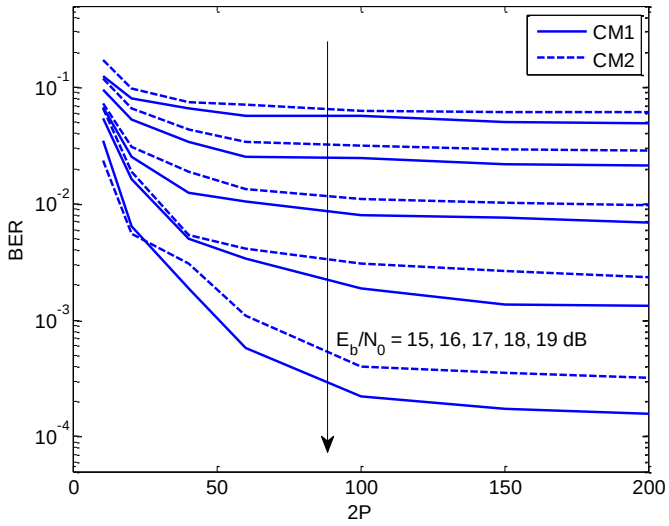

Fig. 3. BER performance at the receiver versus 2P with N=1000.

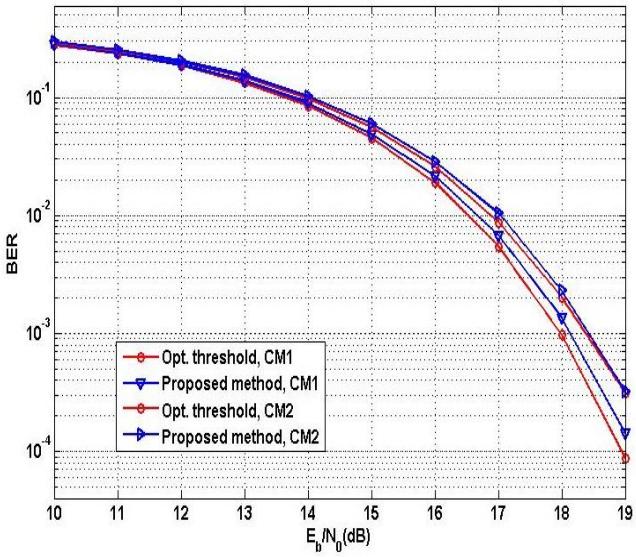

Fig. 4: BER performance of proposed method with N=1000 and 2P=200 and without optimum integration interval

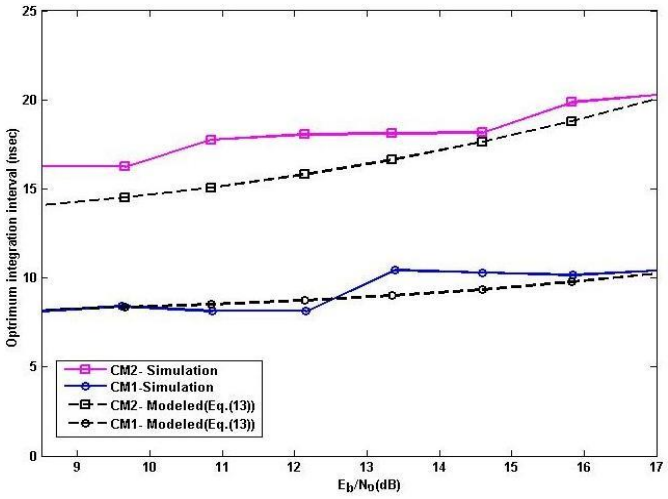

Fig. 5. Optimum integration interval in CM1 and CM2 channel model.

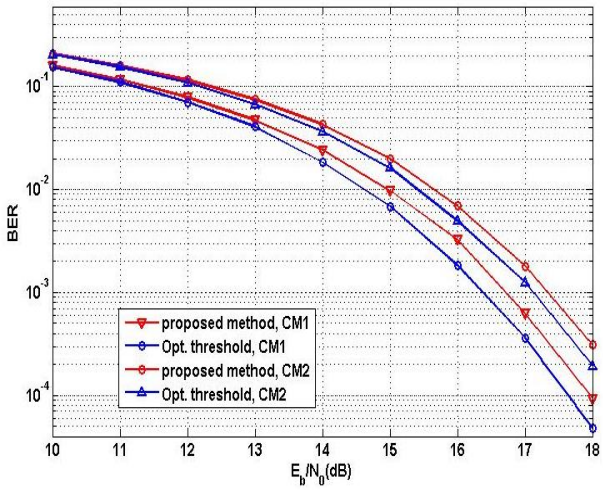

Fig. 6. Performance of the proposed system for optimum integration interval

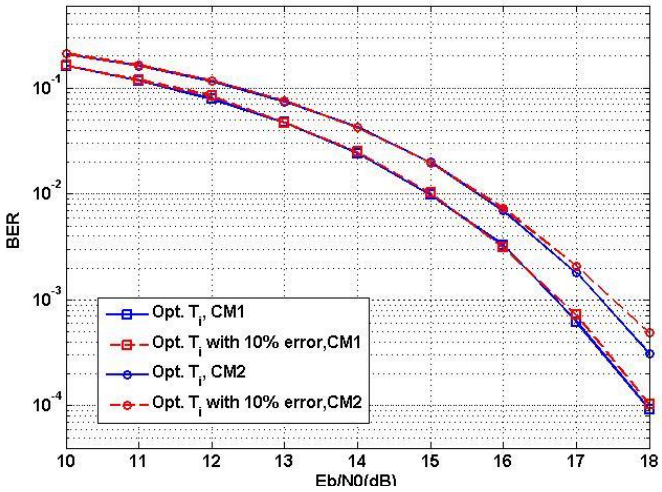

Fig. 7. Performance of the proposed algorithm with optimum integration interval in estimated delay spread estimation error of 10 %

V. CONCLUSION

In this paper, we proposed a blind method for estimating the threshold value of the IR-UWB OOK systems. In the proposed method, there is no need to transmit the training sequences and it works only based on received data symbols in order to estimate the threshold. Simulation results show that as the numbers of the data symbols are increased for estimating the threshold value, the performance of system gets better. Moreover, in small values of E_b/N_0, the proposed algorithm is more accurate. Also for large E_b/N_0, the difference between the performance of the proposed system and the optimum threshold value is negligible. The number of required received symbols to converge to the threshold estimates was shown to be near one thousand for practical operating scenarios. Furthermore, we enhanced the system

performance by selection of optimum integration interval. It is observed that by blind estimating the time delay spread of channel and adjusting integration interval, the performance of proposed method could enhance about 1.5 dB in BER of 10^{-4}. Finally, the simulation result shows that the error of about 10 % in time delay spread estimation degrades the performance only about 0.1 dB in BER of 10^{-4}.

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