Improving the Noise Performance of Energy Detector Based UWB Systems by Optimizing the Receiver Parameters

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***Abstract*—In an Ultra-WideBand (UWB) Low-Rate (LR) Wireless Personal Area Network (WPAN) application low-cost, low-power and low-complexity systems are expected to meet the requirements of the typical applications. These demands can only be satisfied by simple modulation schemes and easy to implement noncoherent receiver configurations. However performed field tests showed that the noise performance of such systems is quite poor. Therefore noise performance improvement is a must.**

This paper investigates and compares the Transmitted Reference (TR) modulation scheme with autocorrelation receiver, the On-Off Keying- (OOK) and the Pulse Position Modulation (PPM) schemes with energy detector for UWB impulse radio (IR) systems. The contribution provides an efficient method for the improvement of the noise performance of the UWB IR systems by matching the parameters of the receiver to the UWB pulse. Using this technique almost 8-dB noise performance improvement can be achieved. The Bit Error Rate (BER) of the three systems will be compared and an analytical expression will be provided for the estimation of the BER of each system.

I. Introduction

Due to their robustness and simple system configuration TR modulation scheme with autocorrelation receiver, OOK and PPM modulation schemes with energy detector are preferred candidates for the implementation of cheap noncoherent UWB IR LR-WPAN systems where the demodulation is performed without carrier recovery. Unfortunately, the noise performance of noncoherent receivers are relatively poor compared to their coherent counterparts. Investigating the UWB IR systems it can be found that the situation is even worse because of the extremely short pulses used to map the information to be transmitted.

In conventional communications the transmitted waveform fills up the entire symbol duration, consequently, the receiver is enabled continuously and the observation time period is equal to the symbol duration.

The situation is completely different in UWB impulse radio, where the digital information is mapped into extremely short pulses. Therefore, only a very small percentage of the symbol duration is exploited for communications, while only channel noise and interference is received in the remaining part of the symbol duration. Exploiting this feature the noise performance of the UWB receivers can be improved by matching the observation time period to the UWB pulse duration.

An exact analytical expression for the noise performance of UWB IR TR autocorrelation receivers has been published in [1]. For the noise performance of UWB IR OOK systems a very similar expression can be found in the literature in [2]. In this paper it will be shown that the analytical expression - introduced in [1] and repeated in Sec. III-A for convenience - is valid for each proposed UWB IR systems, i.e., for the UWB IR TR, OOK and PPM systems as well.

This expression shows that the TR autocorrelation receivers and energy detectors have a very unique noise performance, namely, their noise performance seriously depends on the product of the receiver noise bandwidth ($2B$) and observation time period τ. The higher the product, the worse the noise performance. To get the best receiver sensitivity, the product of $2B\tau$ has to be minimized.

This contribution shows that a 7.7-dB improvement in receiver sensitivity can be achieved by matching the observation time period and receiver noise bandwidth to the parameters of the UWB pulse. Addition to the improved sensitivity, the low duty cycle can be exploited to reduce the power consumption of the UWB receiver by switching off the UWB receiver outside the UWB pulse duration. Furthermore it is shown that in a low-cost, low-complexity UWB IR application the TR system offers the best solution in the CMOS implementation point of view.

II. Modulator Schemes and receiver configurations for UWB Impulse Radio Systems

Three noncoherent modulation schemes are proposed for the UWB impulse radio systems to transmit information via the wireless channel: (i) Transmitted Reference (TR) system, (ii) On-Off Keying- (OOK) and (iii) Pulse Position Modulated (PPM) system.

In each investigated modulator scheme the same UWB pulse will be used, that is, the frequency-shifted Gaussian UWB pulse [3] as carrier

$$g(t) = \sqrt{\frac{Z_0 E_b}{\sqrt{\pi}\, k\, u_B}} \exp\left(-\frac{t^2}{2u_B^2}\right) \cos(2\pi f_C t) \qquad (1)$$

where Z_0 is the characteristic impedance over which E_b is measured, k denotes the number of pulses radiated for the transmission of one bit, f_C is the carrier frequency and the parameter u_B is determined by the required 10-dB RF bandwidth ($2f_B$) of the UWB pulse

$$u_B = \frac{1}{2\pi f_B \sqrt{\log_{10}(e)}}$$

The upper trace of Fig. 1 shows the frequency-shifted Gaussian UWB pulse, $g(t)$ in the time domain, while the frequency domain representation is depicted in the lower trace.

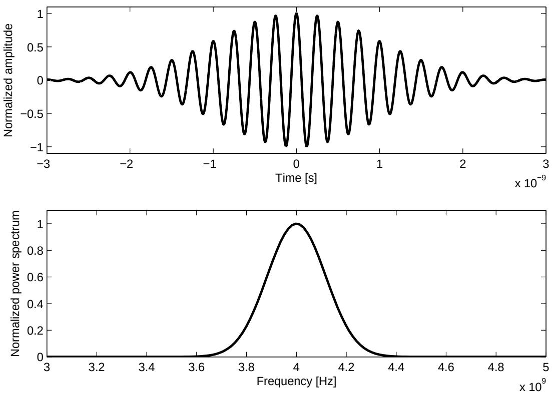

Fig. 1. Time function of frequency-shifted Gaussian pulse with 10-dB RF bandwidth of 500 MHz (upper trace) and that of the frequency domain representation (lower trace). The carrier frequency is 4 GHz.

Investigating Fig. 1 it can be found that $g(t)$ is limited neither in the time- nor in the frequency domain but it decays smoothly in both domains. However in practice a finite duration and bandwidth can be considered outside which the pulse energy is negligible.

To recover the information encoded by one of the proposed UWB modulation schemes, a proper detector configuration has to be chosen that is applicable for the demodulation. If an UWB IR TR modulator is used to encode the information then for the detection an autocorrelation receiver can be applied [1]. Those receivers whose operation principle based on energy detection can be used for the information recovery in case of OOK [4] or PPM modulations [5] .

The transmitted waveform fills up the entire bit or symbol duration in conventional communications, consequently, the observation time is not limited. However, in UWB impulse radio $T_{ch} << T_{bin}$, that is, for a considerable time slot the UWB receiver observes only channel noise and interference. To get the optimum noise performance the UWB receiver must be disabled for the time slot where only channel noise and interference can be observed. This is why the definition of *energy capture time*, denoted by τ, has been introduced in UWB impulse radio.

A. The UWB IR TR Modulator and Autocorrelation Receiver

As it is shown in Fig. 2, in the UWB IR TR system two pulses are used to transmit one bit information. The first pulse serves as a reference while the second one carries the information. Pulse $g(t)$ denotes the UWB carrier, formulated in (1), T_{ch} is the pulse duration and $\Delta T \geq T_{ch}$ gives the delay between the reference and the information bearing pulses. The time T_{bin} elapsed between two consecutive UWB TR signals determines the maximum attainable data rate. Note that $T_{slot1} = T_{slot2} = T_{bin}/2$ time slots are allocated for one UWB pulse but in a typical UWB IR system $T_{bin}/2 >> T_{ch}$.

It is formulated in (2) that the information bearing UWB pulse is equal to the delayed reference one for bit "1" and to the inverted and delayed reference UWB pulse for bit "0."

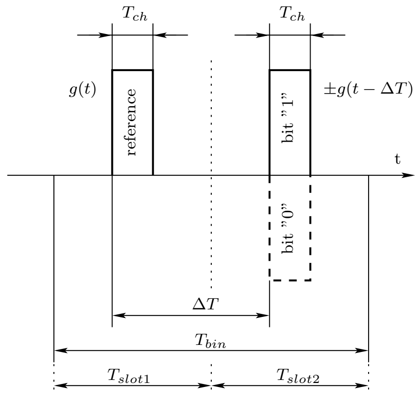

Fig. 2. Modulated UWB IR TR signal.

Let the bit energy radiated for the transmission of one bit be denoted by E_b. In the case of TR modulation the energy carried by one waveform is $E_b/2$ because two UWB pulses are used for the radiation of one bit.

$$\begin{cases} g(t) + g(t-\Delta T) & \text{for bit "1";} \\ g(t) - g(t-\Delta T) & \text{for bit "0".} \end{cases} \qquad (2)$$

Due to the special structure of the TR signal, the information bits may be recovered from the sign of correlation measured between the reference and information bearing UWB pulses as shown in Fig. 3, where $r_m(t) = g(t) + n(t)$ and $\tilde{r}_m(t) = \tilde{g}(t) + \tilde{n}(t)$ are the received AWGN noisy signals before and after, respectively, the channel filter, z_m denotes the observation signal formulated in (3), and $\hat{b}_m$ is the estimated bit sequence.

$$\begin{aligned} z_m &= \pm \int_\tau \left[\tilde{g}(t)\tilde{g}(t-\Delta T) + \tilde{g}(t)\tilde{n}(t-\Delta T) + \right. \\ &\qquad \left. + \tilde{g}(t-\Delta t)\tilde{n}(t) + \tilde{n}(t)\tilde{n}(t-\Delta T)\right] \mathrm{d}t \end{aligned} \qquad (3)$$

The channel filter characterized by its impulse response $h(t)$ is a bandpass filter that determines the receiver noise bandwidth $2B$. The integrator, an integrate-and-dump circuit, determines the energy capture τ which is referred to as observation time in conventional telecommunications.

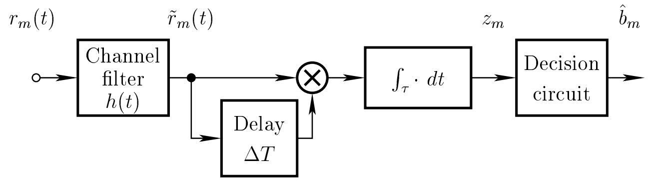

Fig. 3. Block diagram of TR autocorrelation receiver.

The unique feature of a TR radio system is that the reference pulse is not recovered at the receiver but it is transmitted via the same telecommunication channel as the information bearing pulse. This solution makes the TR radio system very robust against the linear and nonlinear channel distortions, but it has a drawback: both the reference and information bearing pulses are corrupted by the channel noise.

The fact that a reference pulse is transmitted is generally considered only as a loss in the transmitted energy per bit. However, the real channels always have distortion and they may suffer from multipath propagation. In these cases the modulated carrier should be correlated with a reference signal distorted in the same manner as the modulated carrier in a coherent receiver. A correlation with the original distortion-free reference results in a performance degradation.

Since in a TR system both the reference and information bearing pulses undergo the same distortion, the TR system offers a relatively good system performance among the non-coherent receivers when distortion is present in the channel, provided that the loss caused by the noisy reference pulse is less than the gain arising due to the perfect correlation of the reference and information bearing pulses. The reference pulse serves as a test signal used to measure the actual channel characteristics. This feature is especially important if the channel is time varying, or if, as in UWB communication, the frequency dependence of channel attenuation cannot be neglected. The TR autocorrelation receiver also offers a simple alternative solution to the rake receiver since it also collects all bit energy arriving along the different propagation paths in a multipath channel.

B. The UWB IR OOK Modulator and Energy Detector

If on-off keying is used to map the information to be transmitted into the UWB carrier the presence or the lack of the UWB signal determines whether bit "1" or bit "0," respectively, have been radiated. Therefore the radiate pulse is $g(t)$ for bit "1" and zero for bit "0."

It is shown in Fig. 4, that signal energy can only be expected in T_{slot1}. If an infinitely long random bit stream is considered to be transmitted then the energy corresponding to one UWB pulse is $2E_b$. Note, no pulse energy is radiated if bit "0" is transmitted.

The UWB pulse is expected to arrive only in T_{slot1}. The received signal $r_m(t)$ if filtered by the channel filter and then

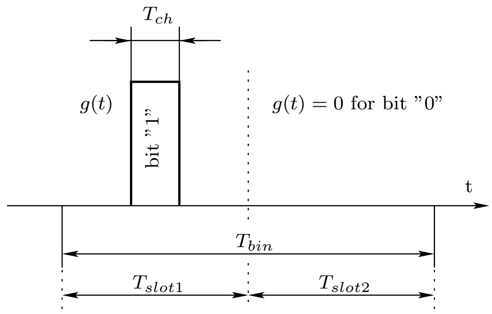

Fig. 4. Modulated UWB IR OOK signal.

it is fed into a square-law device whose output is integrated over τ, i.e., the receiver measures the UWB pulse energy that arrives in T_{slot1}.

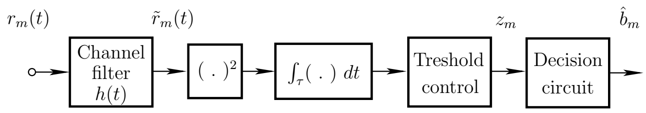

Fig. 5. Block diagram of energy detector for UWB IR OOK pulses.

In this case the observation variable, z_m can be formulated as follows:

$$z_m = \begin{cases} \int_\tau \left[\tilde{g}^2(t) + 2\tilde{g}(t)\tilde{n}(t) + \tilde{n}^2(t)\right]\mathrm{dt} & \text{for bit "1";} \\ \int_\tau \tilde{n}^2(t-\Delta T)\mathrm{dt} & \text{for bit "0";} \end{cases} \tag{4}$$

At the receiver the decision threshold level depends on the bit energy-to-noise density ratio (E_b/N_0). Therefore the application of adaptive threshold level is necessary. Decision is done in favor of bit "1" if the detected energy exceeds, and bit "0" if it is below, respectively, the threshold level.

The main advantage of the energy detector is the simple architecture, however adaptive threshold level control is needed to be implemented.

C. The UWB IR PPM Modulator and Energy Detector

In the pulse position UWB IR system the information is encoded into the position of the transmitted waveform in T_{bin} as it is formulated in (5).

$$\begin{cases} g(t) & \text{for bit "1";} \\ g(t-\Delta T) & \text{for bit "0".} \end{cases} \tag{5}$$

It is shown in Fig. 6, that the UWB pulse can arrive in one of the two adjacent time slots, i.e., in T_{slot1} for bit "1" or in T_{slot2} for bit "0." To transmit one bit information the UWB pulse energy is $1E_b$ in the case of PPM modulation because one UWB pulse corresponds to one bit information.

Table I summarizes the energy that can be carried by the radiated pulse in each proposed modulation scheme. It has an important message for the CMOS circuit designers who have to design circuits under strong voltage level constraints. The lowest energy is carried by the pulse of the UWB IR TR system, therefore the voltage level can be considerably reduced for the radiated UWB pulse if TR modulation scheme is applied. In the implementation point of view the worst choice is the OOK system where the highest the energy carried by the UWB pulse, i.e., the highest the voltage level.

TABLE I
PULSE ENERGIES OF DIFFERENT UWB SYSTEMS FOR THE RADIATION OF ONE BIT

UWB IR	TR	OOK	PPM
Pulse Energy	$E_b/2$	$2E_b$	E_b
# of pulses (k)	2	1/2 (avg.)	1

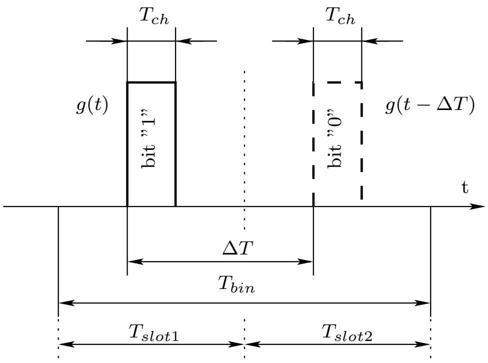

Fig. 6. Modulated UWB IR PPM signal.

Figure 7 shows the detector configuration proposed for the detection of pulse position modulated UWB IR pulses. The energy detector applied for demodulation has to be modified compared to the one that has been proposed in II-B. To evaluate the received bit, the receiver has to measure and compare the energy received in two adjacent time periods, namely, in T_{slot1} and in T_{slot2}. Therefore the output of the channel filter, $\tilde{r}_m(t)$ is fed into a square-law device and integrated over τ of T_{slot1} and then that of T_{slot2}. The results of integration, i.e., the energies received in the two adjacent time slots are stored by a sample-and-hold capacitor network for bit slicing. A relative compare is then performed on the voltages of the two capacitors for the input of the decision circuit to evaluate the received bit [5].

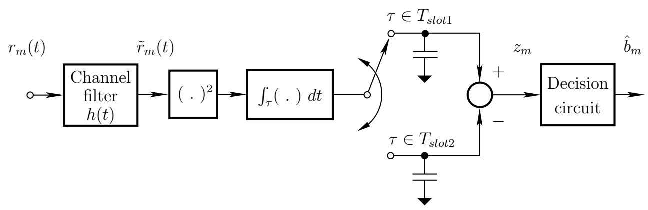

Fig. 7. Block diagram of energy detector for UWB IR PPM pulses.

The observation variable, z_m is formulated in (6).

$$z_m = \begin{cases} \int_\tau \Big[\tilde{g}^2(t) + 2\tilde{g}(t)\tilde{n}(t) + \\ \quad +\tilde{n}^2(t) - \tilde{n}^2(t-\Delta T)\Big]\,\mathrm{dt} & \text{for bit "1"} \\ -\int_\tau \Big[\tilde{g}^2(t-\Delta T) + 2\tilde{g}(t-\Delta t)\tilde{n}(t-\Delta T) + \\ \quad +\tilde{n}^2(t-\Delta T) - \tilde{n}^2(t)\Big]\,\mathrm{dt} & \text{for bit "0".} \end{cases} \tag{6}$$

A big advantage of the receiver configuration depicted in Fig. 7 is that there is no need an adaptive threshold level control. The relative compare for bit slicing assures that the decision threshold level is always zero.

III. NOISE PERFORMANCE OF THE UWB IR SYSTEMS

Because in UWB IR systems $T_{ch} << T_{bin}$ the integration time, τ should be matched to the UWB pulse duration that contains considerable pulse energy. This special property of UWB IR systems has a serious effect on the noise performance, namely, it strongly depends on the product of $2B\tau$.

A. Theoretical noise performance of the UWB IR Systems

The expression for the Bit Error Rate (BER) of a UWB TR autocorrelation receiver has been published in [1]. The theoretical value of BER can be predicted by

$$P_e = \frac{1}{2^{2B\tau}} \exp\left(-\frac{E_b}{2N_0}\right) \sum_{i=0}^{2B\tau-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \times \sum_{j=i}^{2B\tau-1} \frac{1}{2^j} \begin{pmatrix} j + 2B\tau - 1 \\ j - i \end{pmatrix} \tag{7}$$

where E_b is the energy of the two UWB pulses used to transmit 1 bit information, $N_0/2$ denotes the psd of channel noise, $2B$ is the receiver noise bandwidth determined by the channel filter and τ denotes the energy capture time of the autocorrelation receiver. Equation (7) is valid

- for any kind of UWB pulses $g(t)$ provided that the energy per bit, E_b, is kept constant.
- if an ideal bandpass channel is used as channel filter;
- for integer values of the $2B\tau$. That is a theoretical limit which comes from the mathematical model used during the derivation of (7).

As shown by (7), the noise performance of a UWB autocorrelation receiver heavily depends on the product of the channel bandwidth and the energy capture time.

B. Simulated Noise Performance of UWB IR Receivers

A tested Matlab computer simulator, developed to simulate wireless communications systems, has been used for performing simulations for the different UWB IR systems and to validate (7).

If (3), (4) and (6) are compared it can be found by inspection that each expression contains very similar signal multiplied by signal, noise multiplied by noise and mixed terms, therefore it can be expected that the noise performances of the compared three UWB IR systems should be close to each other.

The simulated results of the noise performances of the three systems are plotted in Fig. 8 where $2B\tau$ is chosen as the parameter. The product of $2B\tau$ is set to 2 (solid curve), 25 (dashed curve) and 250 (dotted curve). Curves show the theoretical BER calculated from (7), while marks '+', '∇' and '$\diamond$' give the results of simulations of the UWB IR TR, OOK and PPM systems, respectively.

As expected, the product of $2B\tau$ has a very serious influence on the noise performance. The smaller the product the better the noise performance.

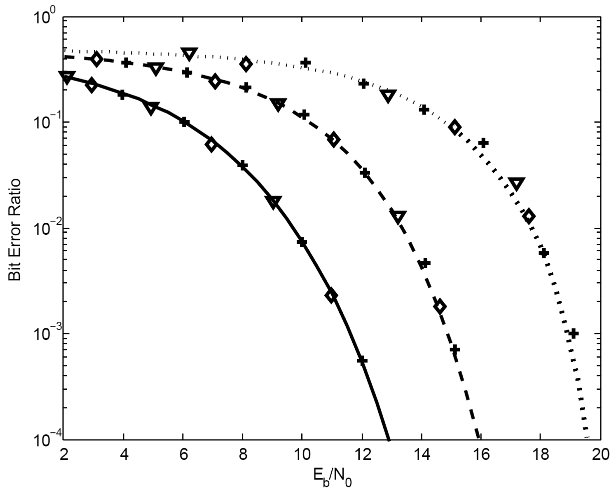

Fig. 8. Noise performance of UWB IR systems when $2B\tau$ is set to 2 (solid curve), 25 (dashed curve) and 250 (dotted curve). Curves show the theoretical results calculated from (7), while marks '+', '∇' and '$\diamond$' give the result of simulations of the UWB IR TR, OOK and PPM systems, respectively.

The values of E_b have been kept constant. The simulated results of the UWB IR PPM and OOK systems show very strong coincidence with the theoretical curves of Fig. 8. Therefore it can be concluded that (7) is valid for not only the prediction of the BER of UWB IR TR systems, but it is also valid for that of the UWB IR PPM and UWB IR OOK systems as well provided that E_b is kept constant.

An equation for the BER of UWB OOK system that is very similar to (7) has already been published in [2] however it says nothing about the importance of the matching of energy capture time to the UWB pulse duration. Furthermore, this contribution extends the validity of (7) for the pulse position UWB IR systems with energy detector.

IV. Noise Performance Improvement by Matching The Receiver Parameters to the Transmitted UWB Pulse

A. *Parameters of UWB IR TR System to be Implemented*

To illustrate the efficiency of performance improvement technique proposed here let us consider an IEEE Std 802.15.4a-compliant UWB IR TR system [6] with UWB bandwidth of 499.2 MHz and data rate of 1 Mbit/s. To get the 1-Mbit/s raw data rate, $T_{bin} = 1000$ ns and $\Delta T = T_{bin}/2 =$ 500 ns have been chosen. The transmitter uses a frequency-shifted Gaussian UWB pulse formulated in (1).

The frequency-shifted Gaussian UWB pulse is limited neither in the time- nor in the frequency-domains. The receiver has a fixed noise bandwidth and observes the received signal for a finite time period, consequently, a slight loss in the reception of UWB signal energy per bit E_b is inevitable. The optimization of UWB IR TR autocorrelation receiver is performed in two steps:

1) during the coarse fitting of receiver parameters $2B$ and τ are optimized using (7) which is valid only for integer values of $2B\tau$. That makes possible only a coarse tuning of receiver parameters.
2) during fine fitting the computer simulation is used to find the optimal values of $2B$ and τ.

B. *Coarse Fitting of Receiver Parameters*

The noise bandwidth of autocorrelation receiver has to be wide enough to pass the received UWB signal without a considerable distortion. Since the bandwidth of IEEE Std 802.15.4a-compliant modulated UWB signal is 499.2 MHz, let $2B = 500$ MHz chosen.

If the data rate is 1 Mbit/s and the *energy capture time is not minimized* then $\tau = \Delta T = 0.5$ μs and $2B\tau = 250$. As shown by the dotted curve in Fig. 8 if a bit error ratio of 10^{-3} has to be achieved by these receiver parameters then $E_b/N_0 = 19$ dB has to be assured at the input of autocorrelation detector.

Due to the short duration of transmitted UWB pulses, the energy capture time may be reduced considerably without loosing a noticeable part of E_b. Our investigations have shown that the energy capture time can be reduced to 4 ns. Recall, Fig. 1 shows the time domain representation of the investigated pulse, that confirms the proposed value for τ.

Let the receiver noise bandwidth kept unchanged, that is, $2B = 500$ MHz, but let the *energy capture time be reduced* to $\tau = 4$ ns. Then the receiver parameter $2B\tau$ becomes 2 and as shown by the solid curve in Fig. 8 the required E_b/N_0 is reduced to 11.6 dB. Note, a considerable, 7.4-dB improvement has been achieved in the noise performance by reducing the energy capture time.

C. *Fine Fitting of Receiver Parameters*

The frequency shifted Gaussian pulse is decaying smoothly both in the frequency and time domains. Equation (7) is valid only for integer values of $2B\tau$, it cannot take into account the smooth decay of UWB pulse. For example, if the receiver bandwidth $2B$ is further reduced than a part of E_b is lost but simultaneously a part of channel noise is also suppressed. The optimum value of $2B$ is a trade-off between the two effects. An extra improvement in noise performance can be achieved if the optimum values of $2B$ and τ are determined by computer simulation.

A raw BER of 10^{-3} has to be achieved in LR-WPAN applications. According to Fig. 8, this BER requires an $E_b/N_0 \approx 12$ dB at the input of the autocorrelation receiver. To check the effect of fine tuning of τ and $2B$ on the noise performance, E_b/N_0 is set to 12 dB. Recall, the coarse fitting resulted in the following receiver parameters: $\tau = 4$ ns and $2B = 500$ MHz.

Figure 9 shows the effect of energy capture time on the BER where the receiver noise bandwidth was set to 500 MHz. Observe, the energy capture time has to be reduced to 3 ns to get the best receiver noise performance.

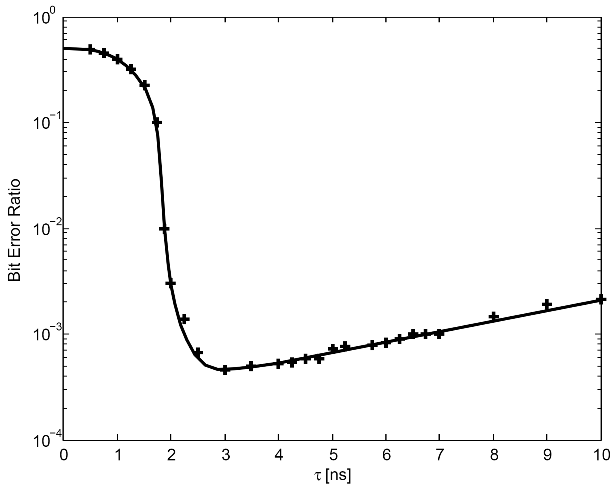

Fig. 9. Effect of energy capture time on the noise performance of UWB IR TR autocorrelation receiver where $2B = 500$ MHz and $E_b/N_0 = 12$ dB. Results of computer simulation are marked by '+'.

The effect of receiver noise bandwidth on the BER are plotted in Fig. 10 where the energy capture time was set to 4 ns. Note, to get the best noise performance the receiver noise bandwidth has to be slightly increased, its optimum value is 600 MHz.

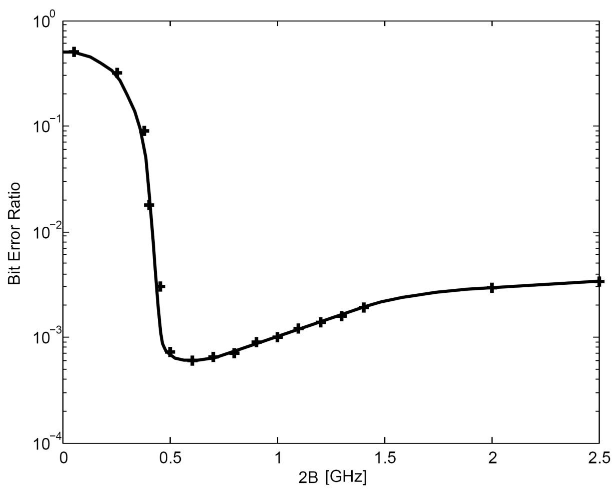

Fig. 10. Effect of receiver noise bandwidth on the noise performance of UWB IR TR autocorrelation receiver where $\tau = 4$ ns and $E_b/N_0 = 12$ dB. Results of computer simulation are marked by '+'.

Applying the fine fitting of the receiver parameters further 0.3-dB noise performance improvement can be achieved. Summing up the result of both coarse and fine fitting we conclude that a 7.7-dB improvement in receiver sensitivity has been achieved.

Figures 9 and 10 show that the UWB IR TR autocorrelation receiver is robust against the receiver noise bandwidth and energy capture time provided that they exceed certain thresholds that are $\tau = 2.5$ ns and $2B = 500$ MHz in the investigated UWB system.

V. Conclusions

The UWB IR TR modulation with an autocorrelation receiver and UWB IR PPM and OOK modulation with energy detector offer simple and robust solutions to build cheap, low-complexity UWB systems with a very low power consumption. Unfortunately, the noise performance of the built UWB IR receivers is relatively poor, an improvement is a must.

The UWB impulse radio operates with an extremely low duty cycle. We propose to exploit this unique property to improve the noise performance of UWB receivers.

The noise performance of UWB autocorrelation receiver and energy detector strongly depends on the product of receiver bandwidth $2B$ and energy capture time τ; the lower the product, the better the noise performance provided that the reduction in $2B$ and τ causes only a negligible loss in received UWB pulse energy and E_b is kept constant.

The paper has shown how the noise performance of UWB IR TR autocorrelation receiver and energy detector can be improved by matching the energy capture time and receiver noise bandwidth to the parameters of UWB carrier pulse. The coarse and fine parameter fitting techniques improved the noise performance of the proposed UWB IR receivers by 7.7 dB.

Using the results of simulations to compare the different systems, this contribution concluded that the same analytical expression is valid for the noise performance of the UWB IR TR system with autocorrelation receiver and that of the UWB IR OOK and UWB IR PPM systems with energy detector as well.

In the CMOS implementation point of view the application of the UWB IR TR system is proposed because it requires the lowest voltage level compared to the OOK and PPM systems to assure the same systems performance.

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