Performance Improvement of UWB Autocorrelation Receivers by Minimizing the Energy Capture Time

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***Abstract*— Due to their robustness and simple system configurations the Transmitted Reference (TR) modulation scheme and autocorrelation receiver are preferred candidates for the implementation of cheap Ultra WideBand (UWB) Impulse Radio (IR) systems. Unfortunately, the results of simulations and field tests performed on built UWB IR TR systems have shown a relatively poor noise performance. This noise performance results in such a bad receiver sensitivity that prevents the application of TR modulation and autocorrelation receivers in real applications.**

This contribution shows that the noise performance of UWB IR TR autocorrelation receiver can be improved considerably by reducing the energy capture time of the receiver. By matching the receiver parameters to that of the transmitted UWB pulse, an almost 8-dB improvement in receiver sensitivity has been achieved.

I. Introduction

The TR autocorrelation receiver offers a simple and robust configuration for the UWB IR receivers where the demodulation is performed without carrier recovery. Unfortunately, the noise performance of TR autocorrelation receivers is relatively poor compared to that of the coherent receivers, resulting in a low receiver sensitivity.

A research project financed by the European Commission was launched to develop physical (PHY) layers for UWB impulse radio systems [1]. In the framework of the EU Project, a UWB IR TR autocorrelation receiver was developed and built, the results of computer simulation suggested that a receiver sensitivity of -70 dBm would be achieved. Unfortunately, the sensitivity of the built receiver was 10 dB worse, that is, only -60 dBm. A UWB receiver having such a poor sensitivity cannot be used to establish communications in a Wireless Personal Area Network (WPAN), a performance improvement in the UWB IR TR autocorrelation receiver is a must.

An exact analytical expression for the noise performance of UWB TR autocorrelation receivers has been published in [2]. That expression, repeated later in Sec. IV-A for convenience, shows that the TR autocorrelation receivers have a very unique noise performance, namely, its noise performance 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. The receiver noise bandwidth $2B$ has to be matched to the bandwidth of transmitted UWB signal, otherwise, a part of the useful UWB signal energy is lost.

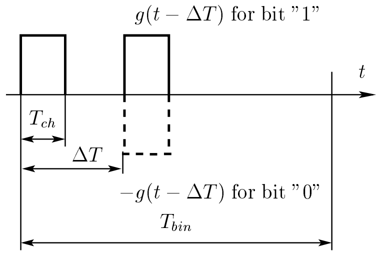

Fig. 1. Modulated UWB IR TR signal.

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 symbol duration is exploited for communications, while only channel noise and interference is received in the remaining part of symbol duration. The sensitivity of UWB receiver can be improved by matching the observation time period to the UWB pulse duration.

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.

II. Transmitted Reference UWB Impulse Radio System

A. The UWB IR TR Modulator

In UWB IR TR systems two pulses are used to transmit one bit information. As shown in Fig. 1, the first pulse serves as a reference while the second one carries the information. Pulse $g(t)$ denotes an arbitrary UWB carrier, 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. 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."

The IEEE 802.15.4a Standard [3] defines the parameters of Low-Rate (LR) WPAN radio. In Band Group 1 where CMOS transceivers can be built, the bandwidth of UWB pulses is 499.2 MHz and the duration of reference pulse is 2 ns. Considering a raw data rate of 1 Mbit/s, it gives a duty cycle of 0.4%. The lower the data rate, the lower the duty cycle.

B. Autocorrelation Receiver for UWB IR TR signal

Due to the special structure of 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. 2, where $r_m(t)$ and $\tilde{r}_m(t)$ are the received signals before and after, respectively, channel filtering, z_m denotes the observation signal and $\hat{b}_m$ is the estimated bit. 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 observation time period τ. To emphasize the pulsed operation, the observation time period is referred to as *energy capture time* in UWB impulse radio.

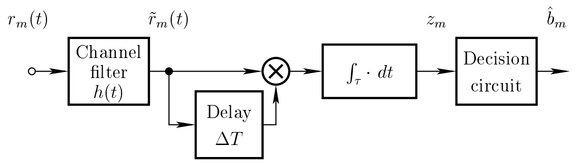

Fig. 2. Block diagram of the UWB IR TR autocorrelation receiver.

In conventional communications the signaling time period is equal to the entire symbol duration. Therefore, to get the best noise performance the observation time has to be equaled to the symbol duration.

However, in UWB impulse radio $T_{ch} << T_{bin}$, consequently, the received signal is nothing else than channel noise and interference for a considerable period of T_{bin}. To get the best noise performance the energy capture time τ has to be reduced to T_{ch}.

The pulsed operation of UWB IR systems can be also exploited to minimize the power consumption of the receiver by switching it off outside the UWB pulse duration T_{ch}.

C. Features of Autocorrelation Receivers

The TR system suffers from two disadvantages: (i) two UWB pulses are used to transmit one bit information and (ii) the reference UWB pulse also suffers from channel noise and interference.

On the other hand the TR autocorrelation receiver offers a very simple and robust receiver configuration. Since both the reference and information bearing pulses are transmitted via the same channel and undergo the same distortion, the TR system provides the best system performance 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 can be considered 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 communications, the frequency dependence of channel attenuation cannot be neglected. A further advantage is that in a multipath environment a TR receiver collects all the energy traveling along the different propagation paths, the application of a complex rake receiver can be avoided.

III. Required Sensitivity of a UWB Receiver

Since the Power Spectral Density (psd) of transmitted UWB signals is limited by the FCC Regulations [4] and the UWB bandwidth is fixed by the IEEE 802.15.4a Standard [3], the area covered by UWB communications can be increased only by improving the receiver sensitivity.

A. Required Receiver Sensitivity

Assume that the distance between the transmitting and receiving antennas is beyond the far-field distance. Then the channel attenuation may be estimated by

$$a_{CH}^{[\mathrm{dB}]} = 32.5 + 20\log_{10} f_C^{[\mathrm{GHz}]} + 10\,n\log_{10} d^{[\mathrm{m}]} + \mathrm{X}_\sigma^{[\mathrm{dB}]} \qquad (1)$$

where f_C is the center frequency of the transmitted UWB signal, d denotes the distance between the transmitting and receiving antennas, path-loss exponent n depends on the application environment and X_σ is a zero mean Gaussian random variable with variance of σ^2. The values of n and σ are determined from measured data [5].

The required receiver sensitivity can be determined from

$$P_{rec,sens}^{[\mathrm{dBm}]} = P_{EIRP}^{[\mathrm{dBm}]} + G_R^{[\mathrm{dB}]} - a_{CH}^{[\mathrm{dB}]} \qquad (2)$$

where G_R denotes the receiver antenna gain.

Consider Band Group 1 defined in IEEE Std 802.15.4a [3] where $2B = 499.2$ MHz and $f_C = 3993.9$ MHz. Using (1) and (2) the required receiver sensitivities (i) in an office building and (ii) in case of Line-of-Sight (LoS) propagation can be calculated as a function of radio coverage. Table I shows that if a UWB physical (PHY) layer is intended to be used in WPAN system then the receiver sensitivity has to be better than -70 dBm.

TABLE I

Required receiver sensitivity.

Propagation	d	n	$P_{rec,sens}$
LoS	5 m	2	-69.6 dBm
Office	3 m	2.6	-68.0 dBm

B. Sensitivity of Built UWB Autocorrelation Receiver

A European project entitled Pervasive Ultrawideband Low Spectral Energy Radio Systems (PULSERS) [1] was launched to explore the potential features of the UWB approach and to introduce new services, applications and devices based on the UWB IR technology. In the framework of the project, a UWB TR impulse radio with autocorrelation receiver was built and tested. The measured sensitivity of PULSERS UWB autocorrelation receiver was as poor as -60 dBm at BER=10^{-3}. Table I shows that sensitivity prevents the application of PULSERS autocorrelation receiver in WPAN/WLAN applications. The sensitivity of UWB autocorrelation receiver must be improved.

Figure 2 shows that an autocorrelation receiver can be characterized by two basic parameters: (i) the energy capture time τ and (ii) receiver noise bandwidth $2B$. This contribution evaluates the influence of $2B\tau$ on the noise performance first then τ and $2B$ will be matched to the parameters of UWB carrier pulse $g(t)$ in order to achieve the best sensitivity with UWB IR autocorrelation receiver.

IV. Noise Performance of UWB Autocorrelation Receiver

The received signal is correlated with a noise-free reference one in the correlation receivers to get the observation variable. In TR modulation both the reference and information bearing signals are sent via the same radio channel, consequently, the reference signal is also corrupted in the channel. This property makes the noise performance of every TR autocorrelation receiver very unique, namely, the noise performance depends on the product of $2B\tau$.

A. Theoretical Noise Performance

Consider the autocorrelation receiver shown in Fig. 2. An analytical expression for the theoretical value of bit error rate (BER) has been derived in [6]

$$P_e = \frac{1}{2^{2B\tau}} \exp\left(-\frac{E_b}{2N_0}\right) \times \sum_{i=0}^{2B\tau-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \sum_{j=i}^{2B\tau-1} \frac{1}{2^j} \begin{pmatrix} j+2B\tau-1 \\ j-i \end{pmatrix} \quad (3)$$

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. It has been shown that (3) is valid for any kind of carriers $g(t)$ from UWB pulses [2] to chaos-based communications [6] provided that E_b is kept constant.

B. Noise Performance of UWB Autocorrelation Receivers

The noise performance of a UWB TR autocorrelation receiver is plotted in Fig. 3 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 (3), while marks '+' give the results of simulations. As expected, the product of $2B\tau$ has a very serious influence on the noise performance.

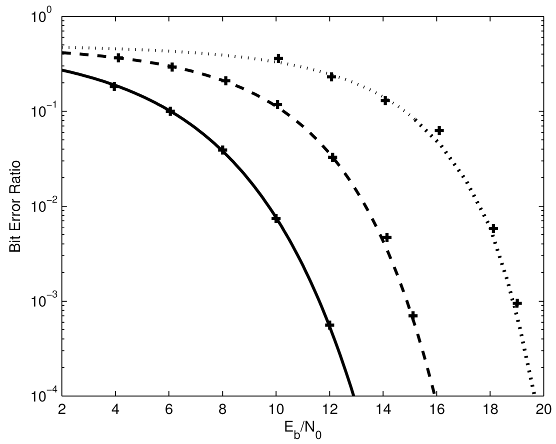

Fig. 3. Noise performance of UWB autocorrelation receiver when $2B\tau$ is set to 2 (solid curve), 25 (dashed curve) and 250 (dotted curve). Curves show the theoretical results calculated from (3), while marks '+' give the result of simulations.

V. 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 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 [7] as UWB carrier

$$g(t) = \sqrt{\frac{Z_0 E_b}{\sqrt{\pi}\, u_B}} \exp\left(-\frac{t^2}{2u_B^2}\right) \cos(\omega_C t) \quad (4)$$

where Z_0 is the characteristic impedance over which E_b is measured and the parameter u_B is determined by the required 10-dB RF bandwidth ($2f_B$) of UWB pulse

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

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 course fitting of receiver parameters $2B$ and τ are optimized using (3) which is valid only for integer values of $2B\tau$. That makes possible only a course tuning of receiver parameters.
2) during fine fitting a computer simulation is used to find the optimal values of $2B$ and τ.

B. Course 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. 3 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.

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. 3 the required E_b/N_0 is reduced to 11.6 dB. Note, a considerable improvement has been achieved by reducing the energy capture time. The 7.4-dB improvement in noise performance and receiver sensitivity makes the use of TR autocorrelation receiver possible in UWB IR application.

C. Fine Fitting of Receiver Parameters

The frequency shifted Gaussian pulse is decaying smoothly both in the frequency and time domains. Equation (3) 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. 3, this BER requires an $E_b/N_0 \approx 12$ dB at the input of autocorrelation receiver. To check the effect of fine tuning of τ and E_b on the noise performance, E_b/N_0 is set to 12 dB. Recall, the course fitting resulted in the following receiver parameters: $\tau = 4$ ns and $2B = 500$ MHz.

Figure 4 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.

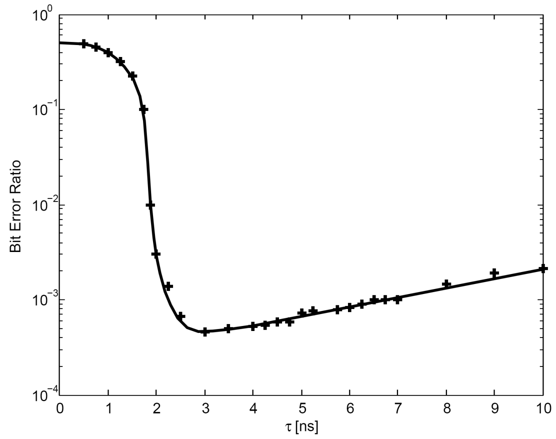

Fig. 4. Effect of energy capture time on the noise performance of UWB IR TR autocorrelation receiver where $2B = 500$ MHz and $E_b/N_0 = 12$ dB. Results of computer simulation are marked by '+'.

The effect of receiver noise bandwidth on the BER are plotted in Fig. 5 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.

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

Figures 4 and 5 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.

VI. Conclusion

The UWB IR TR modulation with an autocorrelation receiver offers a simple and robust solution to build cheap LR-WPAN UWB systems with a very low power consumption. Unfortunately, the sensitivity of the built UWB IR autocorrelation receivers is relatively poor, an improvement in the noise performance is a must.

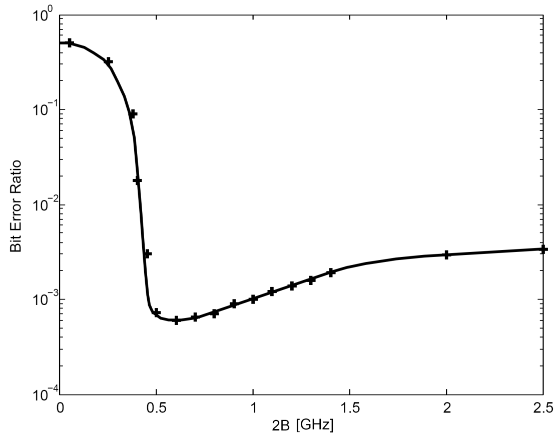

Fig. 5. Effect of receiver noise bandwidth on the noise performance of UWB IR TR autocorrelation receiver where $\tau = 4$ ns and $E_b/N_0 = 12$ dB. Results of computer simulation are marked by '+'.

The noise performance of UWB autocorrelation receiver 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.

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 paper has shown how the noise performance of UWB IR TR autocorrelation receiver can be improved by matching the energy capture time and receiver noise bandwidth to the parameters of UWB carrier pulse. The course and fine parameter fittings proposed here improved the noise performance and sensitivity of UWB IR TR autocorrelation receiver by 7.7 dB. That improvement enables the application of cheap UWB IR TR autocorrelation receivers in LR-WPAN applications.

References

[1] *Pervasive Ultrawideband Low Spectral Energy Radio Systems (PULSERS)*, IST Programme (FP6) of the 6th EU Framework Programme, Online: <http://www.pulsers.eu/pulsers/index.php?home>, 2005.

[2] G. Kolumbán and T. Krébesz, "UWB radio: A real chance for application of chaotic communications," in *Proc. NOLTA'06*, Bologna, Italy, September 11–14 2006, pp. 475–478.

[3] *IEEE Std 802.15.4a-2007 (Amendment to IEEE Std 802.15.4TM-2006), Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), Amendment 1: Add Alternate PHYs*, IEEE, August 31 2007.

[4] F. C. Commission, *Part 15 of the Commissions Rules Regarding Ultra-Wideband Transmission Systems-Subpart F*, FCC, Online: <http://sujan.hallikainen.org/FCC/FccRules/2009/15/>.

[5] S. Rao, "Estimating the ZigBee transmission-range ISM band," *EDN*, pp. 67–72, May 24, 2007.

[6] G. Kolumbán, "Theoretical noise performance of correlator-based chaotic communications schemes," *IEEE Trans. Circuits and Systems—Part I: Fundamental Theory and Application*, vol. 47, no. 12, pp. 1692–1701, December 2000.

[7] K. Siwiak and D. McKeown, *Ultra-Wideband Radio Technology*. Chichester, UK: Wiley, 2004.