Gated Threshold Compensated Noncoherent PPM Receiver for UWB Impulse Radio

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***Abstract*—Since the coherent receivers are not feasible to implement low-cost ultra-wideband (UWB) impulse radio (IR) devices featuring extremely low power consumption, energy detector-based (ED-based) noncoherent receivers are more and more frequently chosen. The Pulse Polarity Modulation (PPM) scheme with a threshold compensated receiver is a promising candidate for the implementation of cheap and robust UWB IR devices.**

Unfortunately, the field tests and computer simulations have shown the well known fact that the noise performance of noncoherent demodulators is much behind that of their coherent counterparts. The poor noise performance results in a such a bad receiver sensitivity that prevents the use of noncoherent receivers in the majority of real applications.

This contribution shows how the noise performance of noncoherent threshold compensated PPM receiver can be improved considerably by disabling the receiver outside of the UWB pulse where only channel noise and interference is observed. The novel receiver configuration, referred to as gated threshold compensated noncoherent PPM receiver offers an 8-dB improvement in receiver sensitivity.

I. Introduction

A widely accepted conclusion has been reached recently: the coherent receivers known from the theory of conventional communication systems are not feasible to implement low-cost and robust UWB IR receivers especially if they have to offer an extremely low power consumption. Instead, ED-based noncoherent receivers have to be used [1]. Unfortunately, the noise performance of the ED-based receivers is relatively poor compared to that of the coherent receivers. The pure noise performance results in a low receiver sensitivity.

A project financed by the European Commission was launched to develop physical layers for UWB IR devices [2]. In the framework of the project, many ED-based UWB IR receivers had been developed and built. Based on the results of computer simulations a receiver sensitivity of -70 dBm was expected. Unfortunately, the sensitivity of the built receiver was worse by 10 dB. A UWB IR receiver with such a poor sensitivity cannot be used to establish communications in the WLAN/WPAN applications. A performance improvement in noise performance is a must.

In conventional digital communications the entire bit duration is exploited for the transmission of information. The transmitted waveform fills up the entire bit/symbol duration, consequently, the receiver is enabled continuously. The observation time period is equal to the bit 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 bit duration is exploited for communications, while only channel noise and interference is received in the remaining part of bit duration. The noise performance of each noncoherent UWB receivers can be improved considerably by disabling the receiver outside the UWB pulse.

This recognition is exploited here to improve the noise performance of an ultra low power UWB IR chipset developed by the Massachusetts Institute of Technology (MIT) [3]. The pulse position modulation scheme and a threshold compensated noncoherent receiver is used in the MIT CMOS chipset. This contribution gives an exact analytical expression for the noise performance of noncoherent PPM demodulator and shows that the noise performance of noncoherent PPM demodulator strongly depends on the product of the receiver noise bandwidth $2B$ and observation time period τ. The higher the product, the worse the noise performance. The worse noise performance results in a worse receiver sensitivity.

Disabling the receiver outside the UWB pulse results in a 7.7-dB improvement in the receiver sensitivity. The low receiver duty cycle offers another important advantage, namely, it reduces the receiver power consumption considerably.

II. The Noncoherent UWB IR PPM Transceiver

In the UWB impulse radio extremely short pulses are used to carry the digital modulation. Due to their excellent spectral properties, frequency shifted gaussian pulses are most frequently used as carrier

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

where Z_0 is the characteristic impedance over which the energy per bit E_b is measured, f_C denotes the center frequency of UWB pulse and the parameter u_B is determined by the required 10-dB RF bandwidth $2f_B$ of UWB pulse

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

A. Pulse Position Modulation

Let T_{bin} denote the time slot that is used to transmit one bit information. In PPM, the information is encoded into the position, t_{pos1} or t_{pos2}, of the transmitted UWB pulse

$$s_m(t) = \begin{cases} g(t - t_{pos1}) & \text{for bit "1"} \\ g(t - t_{pos2}) & \text{for bit "0"} \end{cases}$$

An important feature of PPM modulation is: it can be demodulated by both coherent and noncoherent receiver.

As shown in Fig. 1, the bit duration T_{bin} contains two identical time slots denoted by T_{int1} and T_{int2} in the PPM modulation scheme. The position of the frequency shifted gaussian pulse $g(t)$ is varied according to the bit to be transmitted, the duration of one UWB pulse is T_{ch}.

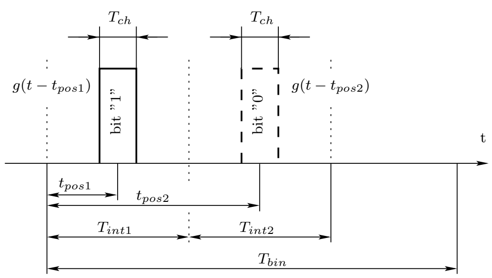

Fig. 1. Stucture of pulse position modulated UWB IR signal.

B. Threshold Compensated Noncoherent PPM Receiver

The block diagram of threshold compensated noncoherent receiver built by MIT using 90-nm CMOS technology is shown in Figure 2. To recover the transmitted bit, the receiver measures and compares the energy received in the two adjacent time slots denoted by T_{int1} and T_{int2} in Fig. 1.

The channel noise $n(t)$ corrupting the received signal $r_m(t) = g(t) + n(t)$ is suppressed by the channel filter $h(t)$ and the filter output $\tilde{r}_m(t)$ is fed into a square-law device, then its output is integrated. The results of two integrations, that is, the energies received in the two adjacent time slots are stored in a sample-and-hold capacitor for bit slicing. The stored voltages are compared and the decision is done in favor of the larger received signal energy [3]. In the MIT transceiver $T_{int1} = T_{int2} = T_{bin}/2$.

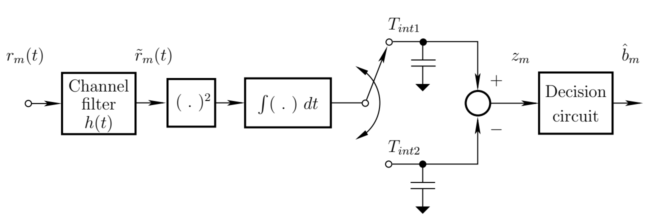

Fig. 2. Block diagram of the noncoherent threshold compensated UWB IR PPM receiver.

Compared to ED-based On-Off Keying (OOK) demodulator [1] the block diagram shown in Fig.2 may seem to be a bit complicated. However, this configuration has a huge advantage, the optimum decision threshold is constant and does not depend on the SNR measured at the input of demodulator. Recall, in the ED-based OOK demodulators the optimum decision threshold depends on the SNR and it has to varied adaptively according to the channel conditions.

C. Idea of Sensitivity Improvement

The field tests performed with the implemented UWB IR devices have shown that these devices have a too short radio coverage. Since both the radiated *peak power* and the radiated *average power* are limited by the FCC Regulations [4], the area covered by UWB radio communications can be increased (i) by using more than one UWB pulse to transmit one bit information or (ii) by improving the receiver sensitivity. The latter approach is used in this contribution.

Since the attainable noise figure and implementation loss are limited by the CMOS technology, the only way to improve the receiver sensitivity is to improve the noise performance of the noncoherent PPM demodulator.

The observation variable z_m of the threshold compensated noncoherent UWB IR demodulator is obtained from Fig. 2 as

$$\begin{aligned} z_m = &\int_0^{T_{int1}} \left[\tilde{g}^2(t - t_{pos1}) + 2\tilde{g}(t - t_{pos1})\tilde{n}(t) + \tilde{n}^2(t)\right] dt \\ &- \int_{T_{int1}}^{T_{int2}} \left[\tilde{g}^2(t - t_{pos2}) + 2\tilde{g}(t - t_{pos2})\tilde{n}(t) + \tilde{n}^2(t)\right] dt \end{aligned} \quad (1)$$

where $b_i \in (0, 1)$ denotes the transmitted bit. Unfortunately, two noise-square terms appear in z_m. The noise-square terms cannot be found in the observation signal of coherent demodulators, they appear only in the ED-type detectors. These terms are responsible for the relatively poor noise performance of ED-type detectors [5].

A detailed analysis of the noise-square terms shows that both their mean and variance depends on the product of $2B\tau$ [1]. Note, these parameters are the most important parameters of each receiver that are chosen by the circuit designer. Parameter $2B$ defines the receiver noise bandwidth, while τ gives the observation time period. We will match these parameters to the characteristics of UWB pulse $g(t)$ in such a way that the product $2B\tau$ will be kept minimum in order to achieve the best noise performance and get the best receiver sensitivity. The receiver bandwidth and observation time may be reduced until a loss in captured E_b occurs, see terms one and four in (1).

III. Noise Performance Improvement

A. Theoretical Noise Performance of ED-Type Demodulators

Consider the threshold compensated PPM demodulator shown in Fig. 2. An analytical expression for the theoretical Bit Error Rate (BER) has been derived in [5] for the ED-type demodulators

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

where $N_0/2$ denotes the power spectral density (psd) of channel noise. Although (2) had been developed for the Transmitted Reference (TR) transceiver in chaotic communications, later it was shown that (2) is valid for any kind of carriers including UWB pulses [6], conventional sinusoidal and chaotic carriers [5] provided that E_b is kept constant. Later, using a different approach, [1] also confirmed that the BER of a TR system and a PPM system with energy detector are identical.

The noise performance of noncoherent threshold compensated UWB IR PPM receiver is plotted in Fig. 3 where $2B\tau$ is chosen as parameter. $2B\tau$ is set to 2 (solid curve), 25 (dashed curve) and 250 (dotted curve). Curves show the theoretical BER calculated from (2), while marks '+' give the results of simulations. As expected, the product of $2B\tau$ has a very serious influence on the noise performance, the lower the product of $2B\tau$ the better the noise performance. To get the best receiver sensitivity $2B$ and τ have to be matched to the bandwidth, $2f_B$, and duration, T_{ch}, of the UWB pulse $g(t)$, respectively.

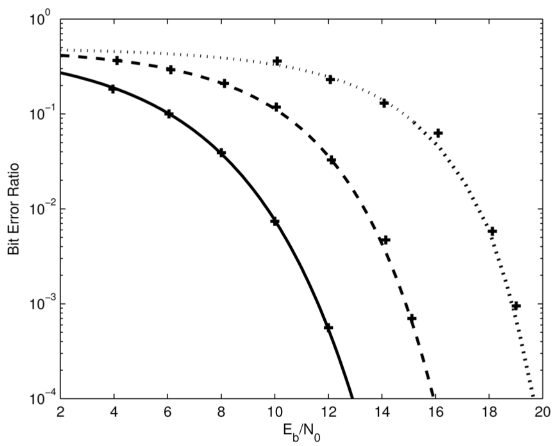

Fig. 3. Noise performance of noncoherent threshold compensated UWB IR PPM receiver when $2B\tau$ is set to 2 (solid curve), 25 (dashed curve) and 250 (dotted curve). Curves show the theoretical results calculated from (2), while marks '+' give the result of simulations.

B. Gated Threshold Compensated UWB IR PPM Receiver

To get the best receiver sensitivity, the receiver bandwidth is limited by a bandpass channel filter and the observation time period is restricted by a gating circuit. The block diagram of gated threshold compensated UWB IR PPM receiver proposed here is shown in Fig. 4 where the the receiver noise bandwidth is matched to the bandwidth of UWB carrier pulse and the two gates disable the receiver outside the duration of UWB carrier pulses.

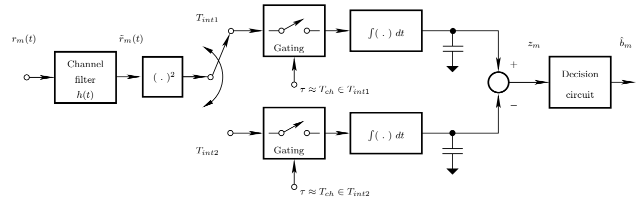

Fig. 4. Block diagram of the noncoherent gated threshold compensated UWB IR PPM receiver.

IV. Optimum Fitting The Receiver Parameters

To illustrate the efficiency of performance improvement technique proposed here let us consider an IEEE Std 802.15.4a-compliant UWB IR PPM system with UWB bandwidth of 499.2 MHz [7] and data rate of 1 Mbit/s. Assume that one UWB pulse is used to carry one bit information.

The frequency-shifted Gaussian UWB pulse is limited neither in the time- nor in the frequency-domains. However, the receiver has a fixed noise bandwidth and observes the received signal for a finite time period. A slight loss in the reception of UWB signal energy per bit is inevitable.

The optimization of receiver parameters is performed in two steps:

1) during *coarse fitting*, $2B$ and τ are optimized using (2). Since the analytical expression is valid only for integer values of $2B\tau$, only a coarse fitting of receiver parameters can be performed in Step 1.
2) during *fine fitting*, a computer simulation is used to find the optimal values of $2B$ and τ.

A. Coarse Fitting of Receiver Parameters

The receiver noise bandwidth has to be wide enough to pass the received UWB signal without a considerable loss in E_b. Since the bandwidth of IEEE Std 802.15.4a-compliant UWB signal is 499.2 MHz [7], let $2B = 500$ MHz be chosen.

If the data rate is 1 Mbps and the *energy capture time is not fitted* then $\tau = T_{int1} = T_{int2} = T_{bin}/2 = T_{slot_i} = 0.5$ 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 the threshold compensated PPM demodulator.

Due to the short duration of transmitted UWB pulses, the energy capture time may be reduced considerably. Our investigations have shown that the energy capture time can be reduced to 4 ns without loosing a noticeable part of E_b.

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 $2B\tau$ becomes 2 and, as shown by the solid curve in Fig. 3, the required E_b/N_0 becomes 11.6 dB. Note, a 7.4-dB improvement is achieved in the receiver sensitivity by fitting the receiver parameters to the UWB carrier pulse.

B. Fine Fitting of Receiver Parameters

The frequency shifted Gaussian pulse is decaying smoothly both in the frequency and time domains. Equation (2) is valid only for integer values of $2B\tau$, it cannot take into account the smooth decay. For example, if the receiver bandwidth $2B$ is further reduced than a part of E_b is lost but, on the other hand, 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 optimization.

A raw BER of 10^{-3} has to be achieved in the majority of WPAN applications. According to Fig. 3, this BER requires an $E_b/N_0 \approx 12$ dB at the input of the noncoherent gated threshold compensated PPM demodulator. To check the effect of fine tuning of τ on the noise performance, E_b/N_0 is fixed at 12 dB.

Figure 5 shows the effect of fine tuning of τ on the BER when the receiver noise bandwidth is set to 500 MHz. Observe, the energy capture time has to be reduced to 3 ns to get the best receiver noise performance.

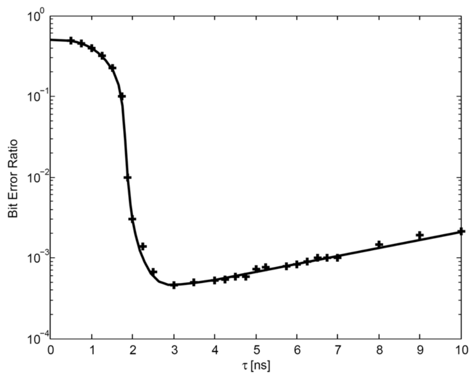

Fig. 5. Effect of energy capture time on the noise performance for $2B =$ 500 MHz and $E_b/N_0 = 12$ dB. Results of simulation are marked by '+'.

The effect of fine tuning of $2B$ on the BER is plotted in Fig. 6 where the energy capture time is set to 4 ns. Note, to get the best noise performance the receiver noise bandwidth has to be slightly increased, its optimum value is about 600 MHz.

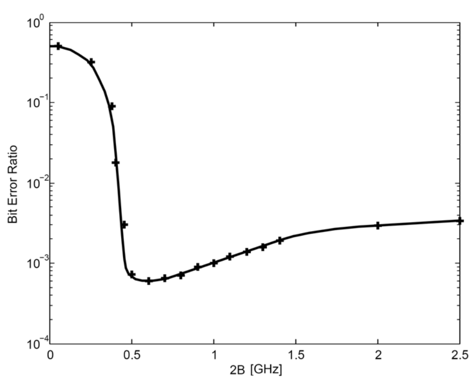

Fig. 6. Effect of receiver noise bandwidth on the noise performance for $\tau = 4$ ns and $E_b/N_0 = 12$ dB. Results of simulation are marked by '+'.

Applying fine fitting a further 0.3-dB improvement in noise performance can be achieved. Summing up the result of both coarse and fine fittings we conclude that a 7.7-dB improvement in receiver sensitivity can be achieved if the receiver parameters are matched the UWB carrier pulse.

Figures 5 and 6 show that the noncoherent gated threshold compensated PPM UWB IR receiver proposed here is very robust against the variation in $2B$ and τ provided that they exceed certain thresholds that are $\tau = 2.5$ ns and $2B =$ 500 MHz in the investigated UWB system. Below these limits a considerable loss in captured E_b appears that strongly limits the receiver sensitivity.

V. Conclusion

The threshold compensated noncoherent PPM receiver proposed by MIT offers a simple and robust CMOS solution to the cheap low-rate WPAN UWB IR transceivers featuring a very low power consumption. Unfortunately, the sensitivity of the built MIT receiver is relatively poor that limits the attainable radio coverage of this UWB IR device.

This contribution has shown that the noise performance of noncoherent threshold compensated PPM demodulator strongly depends on the product of receiver bandwidth $2B$ and energy capture time τ. The lower the product, the better the noise performance and the better the receiver sensitivity.

By fitting the energy capture time and noise bandwidth of the noncoherent PPM receiver to the parameters of UWB carrier pulse, a 7.7-dB improvement has been achieved in receiver sensitivity. That improvement enables the application of cheap CMOS gated threshold compensated UWB IR receiver in many new LR-WPAN applications.

Acknowledgment

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