# UWB IMPULSE RADIO WITH GATED TRESHOLD COMPENSATED PPM RECEIVER

**Tamás KRÉBESZ**
**Advisors: Géza KOLUMBÁN, Tamás DABÓCZI**

## I. Introduction

General agreement has been reached recently, that the coherent optimum receivers known from the theory of conventional communication systems are not feasible to implement low-cost and robust Ultra-WideBand (UWB) Impulse Radio (IR) receivers, especially if they have to offer an extremely low power consumption. Instead, Energy Detector (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, resulting in a low receiver sensitivity.

This contribution shows that a 7.7 dB improvement in receiver sensitivity can be achieved by disabling the receiver outside the UWB pulse duration. The low duty cycle offers an important extra advantage, namely, it reduces the receiver power consumption.

## II. The Noncoherent UWB IR PPM (Pulse Position Modulation) Transceiver

In the UWB impulse radio short impulses are used to carry the digital information. Due to their excellent spectral properties, frequency shifted Gaussian pulses are most frequently used as carriers

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

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 which is $2f_B$ of UWB pulse

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

In the latter equation $e$ denotes the base of natural logarithm.

### 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

$$s_m(t) = \begin{cases} g(t - t_{pos1}) & \text{for bit "1"} \\ g(t - t_{pos2}) & \text{for bit "0"} \end{cases}. \tag{3}$$

A great advantage is that the PPM signal can be demodulated by both coherent and noncoherent receiver.

As shown in Fig. 1, the bit duration $T_{bin}$ is divided into two identical time slots denoted by $T_{int1}$ and $T_{int2}$ in the UWB IR transceiver proposed in [2]. 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 $T_{ch}$.

### B. Threshold Compensated Noncoherent PPM Receiver

The block diagram of threshold compensated noncoherent receiver [2] built by MIT (USA) 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 $\tilde{r}_m$ 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.

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 be varied adaptively according to the channel conditions.

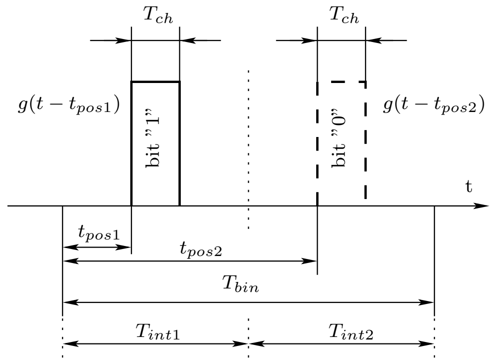


Figure 1: Modulated UWB IR PPM signal.

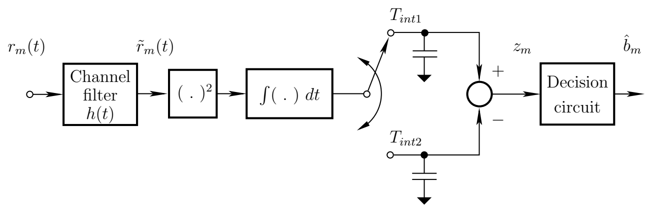


Figure 2: Block diagram of the threshold compensated noncoherent UWB IR PPM receiver.

## 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

$$P_e = \frac{1}{2^{2B\tau}} \exp\left(-\frac{E_b}{2N_0}\right) \times \sum_{i=0}^{2B\tau-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \sum_{j=i}^{2B\tau-1} \frac{1}{2^j} \binom{j + 2B\tau - 1}{j - i} \qquad (4)$$

where the power spectral density of channel noise equals $N_0/2$, $2B$ and $\tau$ denotes the receiver bandwidth and the energy capture time, respectively. Although (4) had been developed for the Transmitted Reference (TR) transceiver in chaotic communications, later it was shown that (4) is valid for any kind of carriers $g(t)$ including UWB pulses [6], conventional sinusoidal carriers, and chaotic carriers [5] provided that $E_b$ is kept constant.

It was confirmed in [1] that the BER of a TR system and a PPM system with energy detector are identical. Consequently, (4) is valid to describe the noise performance of the noncoherent UWB IR PPM transceiver.

I determined the noise performance of threshold compensated noncoherent UWB IR PPM receiver as 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 (4), while marks '+' give the results of simulations. As expected, the product of $2B\tau$ has a very serious influence on the noise performance, to get the best receiver sensitivity $2B$ and $\tau$ have to be matched to the bandwidth, $\sim 2f_B$, and duration, $\sim T_{ch}$, of the UWB pulse $g(t)$, respectively.

### B. *Gated Threshold Compensated UWB IR PPM Receiver*

The block diagram of the gated threshold compensated noncoherent UWB IR PPM receiver is shown in Fig. 4 where the channel filter matches the receiver noise bandwidth to the bandwidth of UWB carrier pulse and the two gates disable the receiver outside the duration of UWB carrier pulse.

## IV. Optimal Fitting of 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 and data rate of 1 Mbit/s. Assuming that one waveform is transmitted for one bit then $T_{bin} = 1000$ ns.

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, consequently, a slight loss in the reception of UWB signal energy per bit is inevitable. The optimization of receiver parameters is performed in two steps: (i) during the coarse fitting, $2B$ and $\tau$ are optimized using (4). Since the analytical expression is valid only for integer values of $2B\tau$ it makes possible only a coarse fitting of receiver parameters. (ii) During fine fitting, a computer simulation is used to find the optimal values of $2B$ and $\tau$.

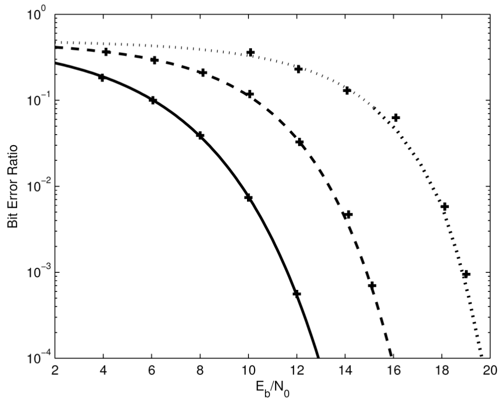


Figure 3: Noise performance of threshold compensated noncoherent UWB IR PPM receiver when $2B\tau$ is set to 2 (solid curve), 25 (dashed curve) and 250 (dotted curve). Curves show the theoretical results calculated from (4), while marks '+' give the result of simulations.

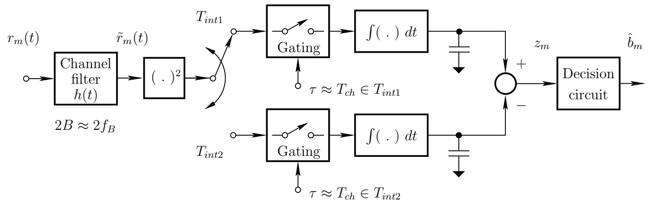


Figure 4: Block diagram of the gated threshold compensated noncoherent UWB IR PPM receiver.

### 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, let $2B = 500$ MHz be chosen. If the data rate is 1 Mbit/s and the *energy capture time is not fitted* then $\tau = T_{bin}/2 = 0.5$ $\mu$s 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 proposed PPM demodulator.

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 $2B\tau$ 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 has been achieved in the demodulator noise performance and in the receiver sensitivity by fitting the energy capture time to the duration of 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 (4) 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 then 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 $\tau$ 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 $\tau$ on the performance, $E_b/N_0$ is set to 12 dB.

Figure 5 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.

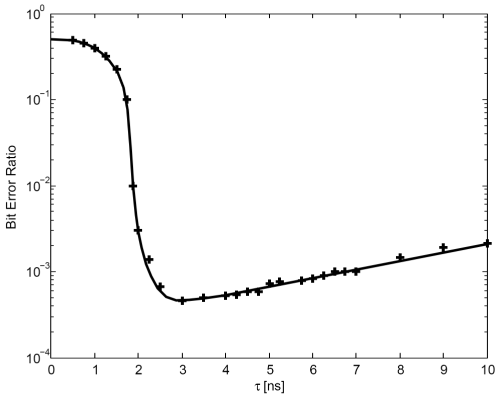


Figure 5: Effect of energy capture time on the noise performance for $2B = 500$ MHz and $E_b/N_0 =$ 12 dB. Results of simulation are marked by '+'.

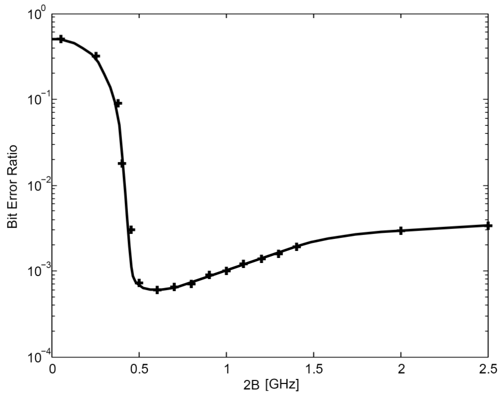


Figure 6: Effect of receiver noise bandwidth on the noise performance for $\tau = 4$ ns and $E_b/N_0 =$ 12 dB. Results of simulation are marked by '+'.

The effect of receiver noise bandwidth on the BER are plotted in Fig. 6 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 about 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 coarse and fine fitting we conclude that a 7.7 dB improvement in receiver sensitivity has been achieved.

## V. Conclusion

The low-rate UWB impulse radio operates with an extremely low duty cycle. The paper has shown how this low duty cycle can be exploited to improve the receiver noise performance and its sensitivity. By fitting the energy capture time and noise bandwidth of the noncoherent demodulator to the parameters of UWB carrier pulse, a 7.7 dB improvement has been achieved in the receiver sensitivity. That improvement enables the application of cheap CMOS gated threshold compensated UWB IR receiver in many new LR-WPAN applications.

## References


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