Performance Improvement of Autocorrelation Detector Used in UWB Impulse radio

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***Abstract*— Transmitted reference (TR) modulation scheme and the autocorrelation receiver offer a simple and robust transceiver configuration for ultra-wideband (UWB) communications. Unfortunately, the TR UWB system has a poor noise performance. The paper shows that the noise performance of a TR autocorrelation system can be improved considerably by placing a noise filter before the autocorrelation detector. The optimum frequency response of required noise filter is derived.**

I. Introduction

Due to its robustness and simplicity, the transmitted reference modulation scheme and the TR autocorrelation receiver are frequently used to build UWB transceivers. Unfortunately, in a TR system both the reference and data pulses are corrupted by channel noise, consequently, the TR systems offers a relatively poor noise performance. The question is if the noise performance of TR autocorrelation receiver could be improved by a specially designed noise filter placed before the autocorrelation detector.

The paper proves that the noise filter improves the noise performance of a TR autocorrelation receiver considerably and assures the best noise performance that can be achieved by a noncoherent detector configuration. The optimum frequency response of noise filter is derived. Finally, the theoretical results are verified by computer simulation.

II. Structure of Modulated UWB TR Signal

In a TR system one bit information is transmitted by two UWB pulses. The first pulse serves as a reference, while the second one carries the information. The structure of modulated signal is shown in Fig. 1, where $g(t)$ denotes the UWB pulse, T_{ch} is the pulse duration and $\Delta T \geq T_{ch}$ gives the delay between the reference and data pulses. If the delay ΔT between the reference and data pulses is less than the coherence time of radio channel then both pulses undergo the same distortion in the channel and the effect of channel distortion is canceled. The data pulse is equal to the delayed reference one for bit "1," and to the inverted and delayed reference pulse for bit "0."

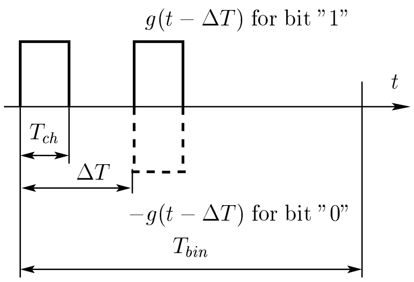

Fig. 1. Structure of modulated UWB signal.

The performance of TR modulation scheme does not depend on $g(t)$. Each pulse that satisfies the UWB emission mask may be used as $g(t)$. Because of their excellent spectral properties the following pulse shapes are considered: (i) Gaussian pulse [1], (ii) frequency-shifted bell-shaped Gaussian pulse [2], (iii) monocycle [1], and (iv) doublet pulse [1].

III. TR Autocorrelation Receiver

Due to its simple circuit configuration and robustness, the TR modulation scheme and the autocorrelation detector [3] are becoming more and more popular in UWB communications [4].

The autocorrelation detector is derived from the special structure of modulated TR signal. The information bits may be recovered from the sign of correlation measured between the reference and data pulses, as shown in Fig. 2. The received signal $r(t)$ is observed over the observation time period τ by the autocorrelation detector to get the observation variable z_m. Then an estimate $\hat{b}_m$ of transmitted bit is recovered by a decision circuit, i.e., by a level comparator. In a well designed receiver the observation time is equal to the pulse duration.

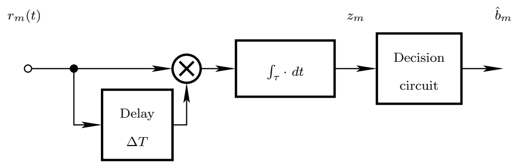

Fig. 2. Block diagram of UWB TR autocorrelation receiver.

The unique feature of a UWB 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 data pulse. This solution makes the UWB TR radio system very simple and robust against the channel distortions. For example, the UWB TR autocorrelation receiver can capture the energy from each multipath component of received signal or, it can be used even in a time varying channel provided that the channel characteristics remain constant over ΔT.

The reference pulse does not contribute to the information transmission. It is a test signal which measures the actual channel characteristics.

In summary, we conclude that the UWB TR autocorrelation receiver provides the simplest receiver configuration that is very robust against the channel distortion and where there is no need to recover the complex UWB pulse as in the coherent receivers.

Unfortunately, the TR modulation scheme suffers from a serious drawback, namely, both the reference and data pulses are corrupted by the channel noise. As shown in [5] the noisy reference pulse results in a relatively poor noise performance, consequently, any improvement in the noise performance of a TR autocorrelation receiver is essential.

IV. Noise Performance Improvement of UWB TR Autocorrelation Receiver

In general, the noise performance of noncoherent receivers can be improved by placing a bandpass filter before the detector as shown in Fig. 3. Our goal is to improve the noise performance of UWB TR autocorrelation receiver by applying a noise (suppression) filter with a frequency response that is matched to the characteristics of UWB TR waveform.

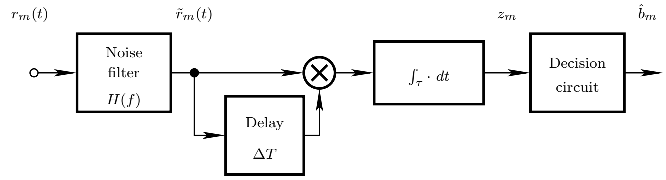

Fig. 3. Improving the noise performance of TR autocorrelation receiver by means of a noise filter.

To achieve the best noise performance with the UWB autocorrelation receiver, the following questions should be answered:

- Can the noise performance of a TR receiver be improved by means of a noise filter as shown in Fig. 3?
- Is there an optimum frequency response $H(f)$ for the noise filter that assures the best noise performance?
- If so then how should $H(f)$ be chosen to achieve the best noise performance?

A. Received signal space

The TR modulation scheme and autocorrelation receiver have been extensively studied in chaos-based communications [6], [5]. The main goal of those studies was to derive the detection algorithms from the properties of modulated signals and the channel conditions.

To get a mathematical framework for the derivation first a received signal space was constructed in which each signal, either deterministic or random, was fully represented. Then the characteristics of signals transmitting bits “1” and “0” were evaluated in the received signal space and the detection algorithm was derived. The Fourier analyzer concept was developed as a mathematical tool for the construction of the received signal space [7].

Figure 2 shows that the autocorrelation receiver observes the received signal $r(t)$ only over the observation time period τ. Consequently, a periodic signal with the period of τ can be constructed from the received signal

$$s_{\tau,m}(t) = \begin{cases} s_m(t), & \text{for } 0 \le t < \tau \\ s_m(t - C\tau), & \text{otherwise} \end{cases} \quad (1)$$

in order to get a discrete received signal space. In the above equation C is an arbitrary nonzero integer.

The received signal space is a Hilbert space spanned by the harmonically related sinusoidal functions

$$\cos\left(k\frac{2\pi}{\tau}t\right) \quad \text{and} \quad \sin\left(k\frac{2\pi}{\tau}t\right)$$

which are referred to as the Fourier base. The fundamental period of Fourier base is equal to the observation time τ.

If the Fourier analyzer concept is applied to the UWB TR modulation scheme then we conclude that the spectra of UWB waveforms carrying bits “1” and “0” are fully separated in the received signal space. Figures 4 and 5 show the power spectrum of modulated UWB TR waveform when a pure bit “1” and a pure bit “0,” respectively, sequences are transmitted. The two spectra look like the teeth of two combs that are pushed into one another.

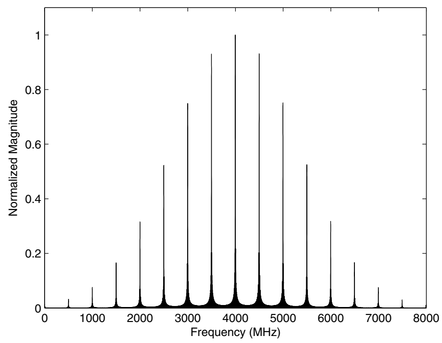

Fig. 4. Power spectrum of a UWB TR waveform in the received signal space when a pure bit “1” sequence is transmitted.

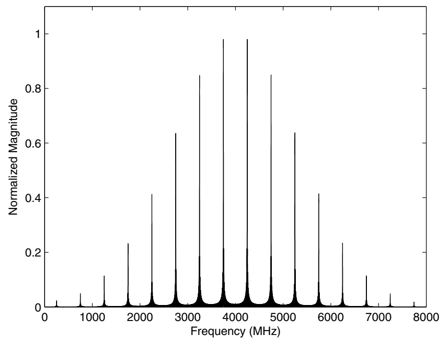

Fig. 5. Power spectrum of a UWB TR waveform in the received signal space when a pure bit “0” sequence is transmitted.

B. Optimum noncoherent detection algorithm

In binary digital communications the bits to be transmitted are mapped into two waveforms, as depicted in Fig. 1. In the Fourier analyzer concept the two waveforms are represented in the received signal space by their Fourier coefficients. The *a priori* information, used later to construct the detection algorithm, is manifested by these Fourier coefficients.

The detector maps the received noisy signal $r(t)$ into the received signal space and returns its Fourier coefficients. Then the detector compares the Fourier coefficients of received signal with the *a priori* information to get the observation variable. Correlation is the mathematical tool of comparison. The decision is done in favor of bit whose UWB TR waveform is closer to the received one. The closeness of waveforms is expressed by the observation variable.

According to Figs. 4 and 5, the spectra of two UWB TR waveforms are fully separated in the received signal space. It means that the phase information in the *a priori* information may be neglected and the decision can be performed comparing only the magnitude of Fourier coefficients. These systems are referred to as noncoherent receivers [8]. The negligence of a part of *a priori* information results in noise performance degradation but gives a much simpler detector configuration.

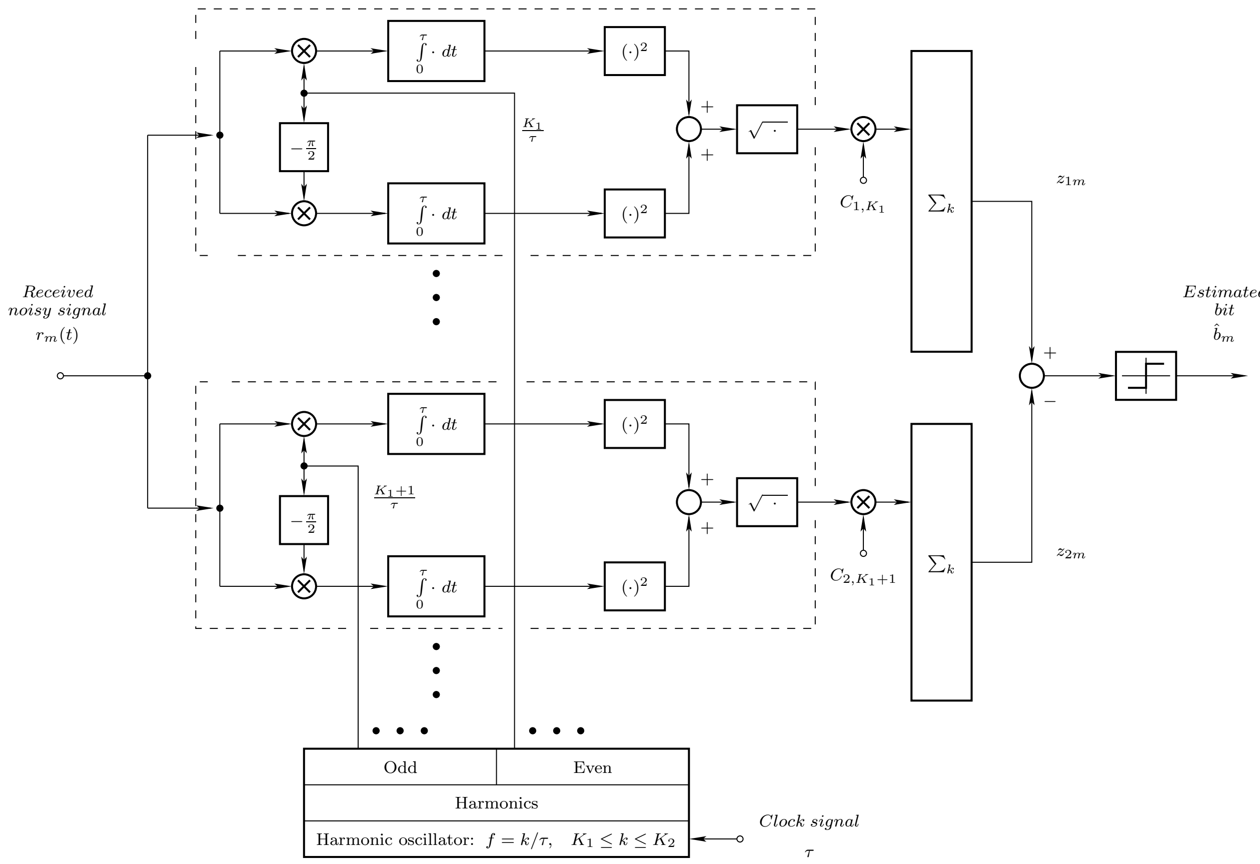

Fig. 6. Block diagram of optimum TR noncoherent detector.

Let $s_m(t), m = 1, 2$ denote the modulated UWB TR signal for bits "1" and "0," respectively. These waveforms constitute the signal set. The *a priori* information, i.e., the Fourier coefficients of UWB TR signals are obtained in the received signal space as

$$\alpha_{mk} = \frac{2}{\tau}\int_0^\tau s_m(t)\cos\left(k\frac{2\pi}{\tau}t\right)dt$$
$$\beta_{mk} = \frac{2}{\tau}\int_0^\tau s_m(t)\sin\left(k\frac{2\pi}{\tau}t\right)dt$$

To get a noncoherent detector the phase information is neglected and only the magnitudes of Fourier coefficients are used as the exploited *a priori* information

$$C_{mk} = \sqrt{(\alpha_{mk})^2 + (\beta_{nk})^2} \tag{2}$$

The transmitted signal $s_m(t)$ is corrupted by channel noise $n(t)$. The detector observes the noisy received signal $r_m(t) = s_m(t)+n(t)$ and returns its Fourier coefficients

$$\begin{aligned} a_{mk} &= \frac{2}{\tau}\int_0^\tau r_m(t)\cos(k\frac{2\pi}{\tau}t)dt \\ b_{mk} &= \frac{2}{\tau}\int_0^\tau r_m(t)\sin(k\frac{2\pi}{\tau}t)dt \end{aligned} \tag{3}$$

from which the magnitudes of Fourier coefficients are obtained as

$$R_{mk} = \sqrt{(a_{mk})^2 + (b_{mk})^2} \tag{4}$$

The closeness of received signal to both elements of signal set is characterized by observation signal that is determined as the cross-correlation of (2) and (4)

$$z_{mn} = \frac{\tau}{2}\left(R_{mK_1}\cdots R_{mK_2}\right)\left(C_{mK_1}\cdots C_{mk}\right)^T \tag{5}$$

where superscript T denotes the transpose of the vector.

Substituting (3) into (4), then substituting (2) and (4) into (5), the observation variable is obtained as

$$\begin{aligned} z_{mn} = \sum_{k=K_1}^{K_2} C_{mk} \Bigg(&\left[\int_0^\tau r_m(t)\cos\left(k\frac{2\pi}{\tau}t\right)dt\right]^2 \\ + &\left[\int_0^\tau r_m(t)\sin\left(k\frac{2\pi}{\tau}t\right)dt\right]^2\Bigg)^{\frac{1}{2}} \end{aligned} \tag{6}$$

where the constants K_1 and K_2 are determined by the bandwidth of UWB pulse $g(t)$ [7].

The decision is done in favor of bit "1" if

$$z_{m1} > z_{m2} \quad \text{or} \quad z_{m1} - z_{m2} > 0 \tag{7}$$

The optimum noncoherent detection algorithm is given by (6) and (7). The detector configuration constructed from the detection algorithm is shown in Fig. 6.

C. Derivation of noise filter parameters

This contribution is going to show that the noise performance of a TR autocorrelation receiver can be improved considerably by placing a noise filter in front of the detector as shown in Fig. 3. Next the block diagram of optimum noncoherent detector given in Fig. 6 has to be transformed into the detector configuration of Fig. 3.

In Figure 6, the circuits in the dashed boxes are the quadrature receiver equivalents of noncoherent matched filters [8], each one matched to one harmonic component

$$k\frac{2\pi}{\tau}, \quad K_1 \le k \le K_2$$

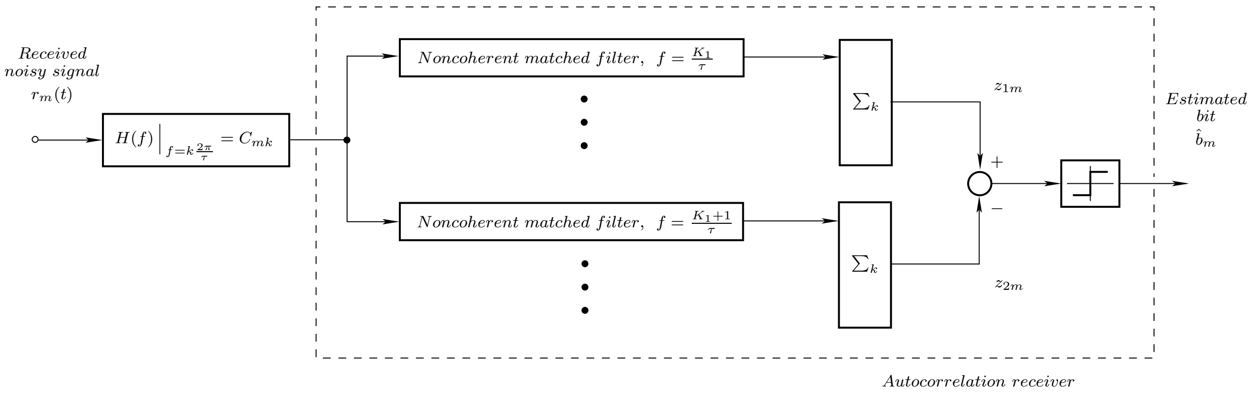

Fig. 7. Block diagram of modified optimum TR noncoherent detector.

of the Fourier base. The output of each noncoherent matched filter is weighted by C_{mk}.

The order of noncoherent matched filter and multiplication by the weight C_{mk} can be exchanged in Fig. 6. Then the effect of weights appearing before each noncoherent matched filters can be lumped into the frequency response of a single filter, referred to as noise filter in Fig. 3. The frequency response of noise filter is obtained as

$$H(f)\Big|_{f=k\frac{2\pi}{\tau}} = C_{mk}, \quad K_1 \le k \le K_2 \tag{8}$$

Applying these transformations to Fig. 6, the block diagram shown in Fig. 7 is obtained that is a modified block diagram of optimum noncoherent detector.

It has been shown in [9] that the circuits included in the dashed box of Fig. 7 implement the TR autocorrelation receiver shown in Fig. 2. Substituting the block diagram of TR autocorrelation receiver into the dashed box we get the block diagram shown in Fig. 3 which is the detector configuration of an optimum noncoherent TR autocorrelation receiver. The frequency response of noise filter has to be matched to the modulated UWB signal as defined by (8). Constants C_{mk} in (8) are scalar numbers, consequently, the phase response of noise filter is irrelevant. The frequency response is defined only at discrete frequencies, this freedom may be used to design the simplest noise filter.

V. Conclusions and Verification of Theoretical Results

Optimum TR noncoherent detector offers a better noise performance than the TR autocorrelation detector. It has been shown that the block diagram of an optimum TR noncoherent detector can be transformed into a cascade connection of a noise filter and a TR autocorrelation detector. The mathematical derivation of the new receiver configuration has shown that the amplitude response of noise filter has to be matched to the spectrum of modulated UWB signal to get the optimum receiver configuration. The equation defining the optimum frequency response of noise filter has been derived and given by (8).

To verify the theoretical results, the noise performances of TR autocorrelation detector and that of the improved version have been determined by computer simulation. The results are compared in Fig. 8 where the solid and dotted curves give the noise performances of original UWB TR autocorrelation detector and improved autocorrelation detector, respectively. The figure shows that a 1.4-dB improvement at the BER=10^{-3} can be achieved with the application of the noise filter.

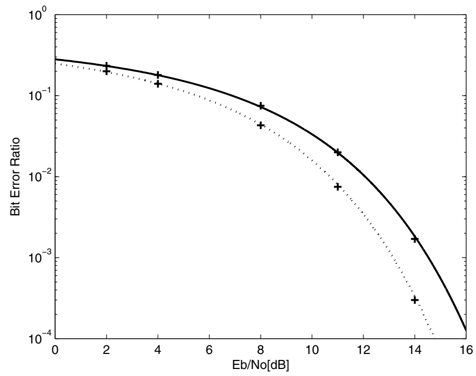

Fig. 8. Noise performances of original UWB TR autocorrelation detector (solid curve) and that of modified autocorrelation detector (dotted curve).

Acknowledgments

This work has been financed by the Hungarian-Chinese Intergovernmental S&T Cooperation Programme. T. Krébesz's participation was supported in part by the Mecenatura Fund, National Office for Research and Technology (NKTH), Hungary and by the Hungarian Scientific Research Fund (OTKA) under grant number TS-73496.

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