Performance Comparison of UWB Chirp IR TR and UWB FM-DCSK TR Systems Implemented with Autocorrelation Receiver

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Abstract— Transmitted reference modulation scheme with autocorrelation receiver offers a robust and simple transceiver configuration for ultra-wideband communications. However this configuration provides only a poor noise performance. The contribution shows how the noise performance can be considerably improved by introducing pulse compression technique. The paper compares the noise performance of the well known FM-DCSK system, as a reference, to the proposed UWB chirp impulse radio featuring pulse compression. It can be concluded, that assuming a real case scenario the improvement in the noise performance is 7.8 dB at $BER = 10^{-3}$

1. Introduction

The Transmitted Reference (TR) modulation scheme with autocorrelation receiver offers a robust and simple architecture to establish wireless communications systems. However the noise performance of the TR systems are relatively poor as both the reference and information bearing data pulses are corrupted by the channel noise and interference.

In indoor applications not the channel noise but mainly the multipath propagation degrades the performance of wireless communication systems. Multipath can cause frequency selective deep fading whose effect on the performance degradation may be eliminated by applying Ultra-WideBand (UWB) waveforms known from UWB Impulse Radio (IR) [1] or FM-DCSK signals known from chaos-based communications [2]. On the other side multipath makes the channel dispersive. As a consequence, the received pulses propagating along different propagation paths overlapping each other may not be separated at the receiver which is an other source of noise performance degradation. This problem can be handled by introducing pulse compression technique where an FM modulated UWB chirp IR signal is processed by a matched filter at the receiver.

The pulse compression approach has got at least two important features: (i) the FM modulated chirp signal generated at the transmitter is a constant-envelope signal that can be amplified by high-efficiency nonlinear power amplifiers and (ii) the pulse compression has a processing gain that improves the noise performance of the receiver.

The paper considers FM-DCSK system as a solid reference for BER perfromace comparison and shows how the pulse compression technique can be applied for UWB chirp IR systems by providing the necessary design equations. Finally the contribution highlights the efficiency of pulse compression and concludes that a 7.8-dB improvement can be achieved in the noise performance of the autocorrelation receiver at $BER = 10^{-3}$.

2. UWB FM-DCSK TR Signals

In UWB TR systems one bit information is transmitted by two UWB pulses at least. The first pulse serves as a reference while the second one carries the information. If a bit ”1” is transmitted then the information bearing pulse is a delayed copy of the reference one. If bit ”0” is transmitted then the second pulse is the inverted and delayed repetition of the reference one.

Each pulse that satisfies the UWB emission mask introduced by FCC [3] may be used for communications, so even an FM-DCSK signal can be applied as a UWB carrier.

Since the FM-DCSK, the TR modulation scheme and the autocorrelation reciver have been extensively studied in [4], [2] and [5], the application of FM-DCSK TR system for UWB applications is a good reference for performance comparison. The goal of this paper is to compare the noise performace of a UWB FM-DCSK TR system with that of a UWB chirp IR TR system.

Considering an UWB FM-DCSK TR system with RF bandwidth $2B$=1333.12 MHz [6] and center frequency f_c=5 GHz, the phenomena of spectrum separation, known from the literature [2], for pure zero bit and one bit sequences can be observed in the upper and lower, respectively, plots of Fig. 1.

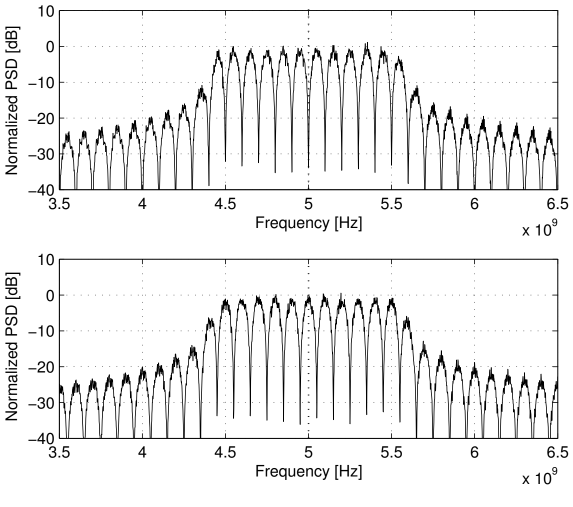

Figure 1: Spectrum of an UWB FM-DCSK TR signal for $2B$=1333.12 MHz when a pure bit ”0” sequence (upper figure) and a pure bit ”1” sequence (lower figure) is transmitted. Please note, the dotted line at f_c=5 GHz emphasizes the separation of the spectra.

3. Adaptation of Pulse Compression Approach to UWB IR Receivers

The idea of pulse compression has been established in radar technology where the goal is to increase the peak power of the transmitted impulse by compression in time. Using pulse compression the high energy of a long pulse can be combined with the ultra-wide bandwidth of a narrow pulse. In this paper the pulse compression approach is adapted for UWB IR radio and its performance is compared to that of the UWB FM-DCSK TR system.

3.1. Basic Idea of Pulse Compression

The block diagram of pulse compression approach is shown in Fig. 2. Frequency modulation (FM) is applied to the carrier frequency at the transmitter in order to generate the radiated UWB carrier pulse $x_t(t)$. The received signal $x_r(t)$ is fed into a matched filter characterized by its impulse response $h(t)$. The compressed pulse $x_{comp}(t)$ is measured at the output of a matched filter [7].

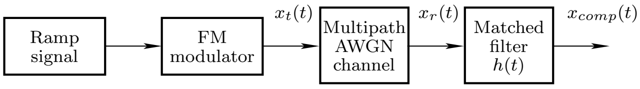

Figure 2: Signal processing in pulse compression.

In the linear chirp method, considered here, the instantaneous frequency of the carrier is varied linearly over the entire pulse duration

$$f(t) = f_0 + \mu t \tag{1}$$

where f_0 denotes the start frequency and μ is the chirp rate. Note, the generated chirp signal is a constant envelope signal. The relation between the RF bandwidth $2B$ of generated pulse and the duration T_c of UWB chirp pulse is established by the chirp rate

$$\mu = \frac{2B}{T_c} \tag{2}$$

The impulse response of matched filter is derived from the parameters of the radiated chirp signal

$$h(t) = \exp\left\{j2\pi\left[f_0(T_c - t) + \frac{\mu}{2}(T_c - t)^2\right]\right\} \tag{3}$$

3.2. Waveforms in the UWB Chirp IR System

Consider a UWB IR system where $2B = 1333.12$ MHz [6]. Let $T_c = 100$ ns in order to get a reasonable high E_b compared to conventional UWB IR systems where $T_c \approx (2B)^{-1} \approx 0.75\ ns$. As shown in Fig. 3 the power spectrum of radiated UWB chirps, denoted by $x_t(t)$ in Fig. 2, is smooth and free from spikes. This chirp waveform meets the FCC Regulations.

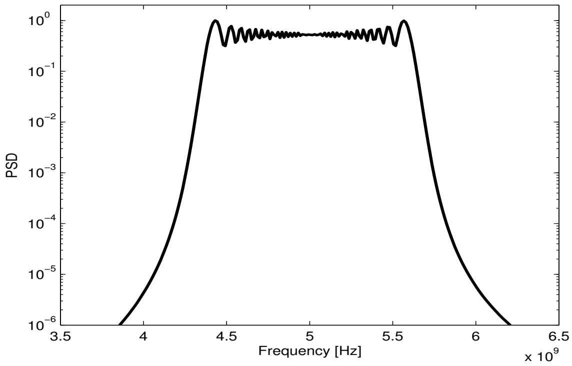

Figure 3: Spectrum of the UWB chirp pulse.

The output $x_{comp}(t)$ of matched filter performing the pulse compression in Fig. 2 is depicted in Fig. 4.

4. Pulse Compression in Noisy IEEE 802.15.4a Multipath Channel

The IEEE 802.15.4a Channel Modeling Subcommittee has developed channel models for various UWB propagation environments in order to evaluate and compare the performance of different UWB IR systems. A Matlab code has been developed for 9 different application areas [8], the use of these channel models (CM) is mandatory.

To demonstrate the effectiveness of pulse compression, the received noisy UWB signals before and after pulse compression are plotted. To get a figure that is easy to evaluate, CM9 developed for snow-covered open air propagation condition has been chosen. The Matlab program has shown that one realization of CM9 has 4 propagation paths.

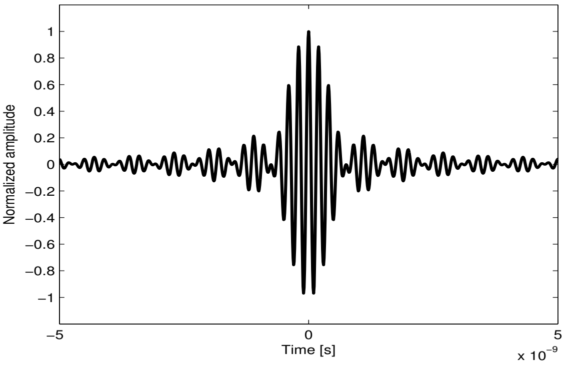

Figure 4: The compressed UWB chirp pulse at the output of matched filter.

The low number of propagation paths allows us to identify each received pulse in a separated manner and to evaluate the efficiency of pulse compression by observation.

Figure 5 shows the received signal $x_r(t)$ in the time-domain before pulse compression. Addition to the multipath propagation the received signal is corrupted by Gaussian white noise, the signal-to-noise ratio, SNR, is −3 dB. Note, the channel conditions are so bad that the received UWB signal cannot be even recognized in the time-domain.

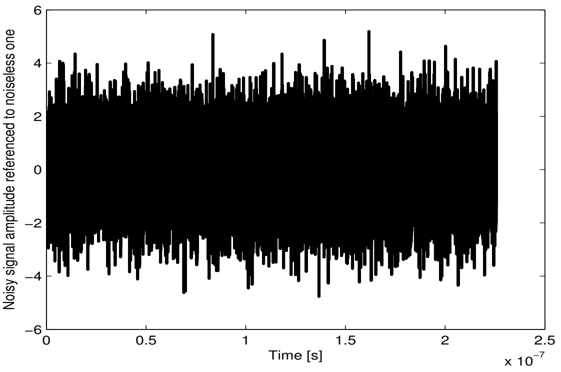

Figure 5: Received signal $x_r(t)$ in a noisy IEEE 802.15.4a compliant channel. CM9 has 4 propagation paths in the studied case.

An important advantage of pulse compression is that it improves the SNR at the output of the matched filter. The processing gain is proportional to the ratio of pulse duration measured before and after pulse compression

$$R = 2\,\frac{T_c}{T_{comp}} = 2BT_c \qquad (4)$$

where T_{comp} gives the duration of compressed chirp pulse.

The output $x_{comp}(t)$ of the matched filter performing the pulse compression is shown in Fig. 6. The matched filter compresses the UWB pulse in time and due to its processing gain it improves the SNR considerably. Note, four received UWB pulses that are hidden in the received signal plotted in Fig. 5 become clearly distinguishable in Fig. 6.

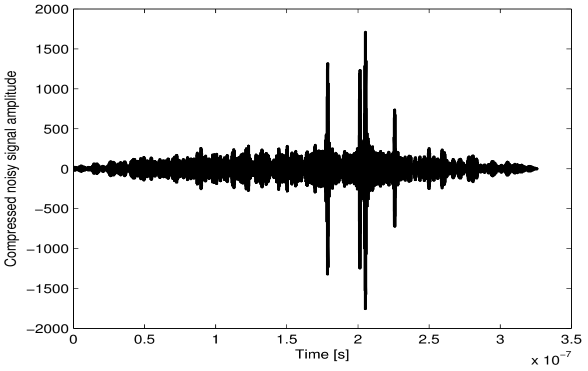

Figure 6: Compressed UWB chirp signal $x_{comp}(t)$ in a noisy IEEE 802.15.4a compliant channel. CM9 has 4 propagation path in the studied case.

5. Improvement in the Receiver's BER Performance

It is a widely accepted fact today that only noncoherent detectors are feasible in UWB communications [1].

The TR modulation can be demodulated by an autocorrelation receiver, the most robust noncoherent receiver configuration. In a TR signal each bit b_m to be transmitted is mapped into two UWB IR pulses, where the first pulse serves as a reference while the second one carries the information. The autocorrelation receiver determines the correlation between the reference and information bearing pulses and the sign of correlation is used to perform the detection. The time delay between the reference and information bearing pulses has to be large enough to prevent the interference caused by the multipath channel.

The block diagram of UWB autocorrelation receiver used to evaluate the BER performance is shown in Fig. 7. The received UWB chirp signal $x_r(t)$, fed to input (1), is processed by the matched filter and then the compressed signal $x_{comp}(t)$ is processed by the correlator. The energy capture time is set by the bandwidth of low-pass filter, and the observation signal z_m is fed into the decision circuit. The decision circuit is a level comparator, its output gives the estimated bit $\hat{b}_m$.

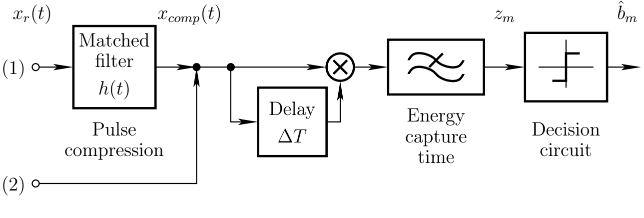

Figure 7: Block diagram of autocorrelation receiver used in BER performance evaluation and comparison.

To get a fair comparison, in the case of the reception of UWB FM-DCSK TR signal the same autocorrelation receiver is used which means that the received UWB FM-DCSK signal is fed into point (2) in Fig. 7.

Using the receiver models depicted in Fig. 7 and each Matlab UWB channel models [8] elaborated by IEEE 802.15.4a Channel Modeling Subcommittee, a huge number of simulations have been done to compare the BER performance of the UWB chirp IR and FM-DCSK systems.

The results of simulations are shown in Fig. 8. The solid curve depicts the theoretical noise performance [9] of the UWB FM-DCSK system with TR modulation. The '+' marks denote the simulated points that are in a close agreement with the theoretical BER curve. The dotted and dashed curves are plotted based on simulations exploiting the pulse compression technique for CM9 ignoring and including, respectively, the frequency dependent nature of the channel. The effect of frequency dependency will be discussed in Sec. 5.1.

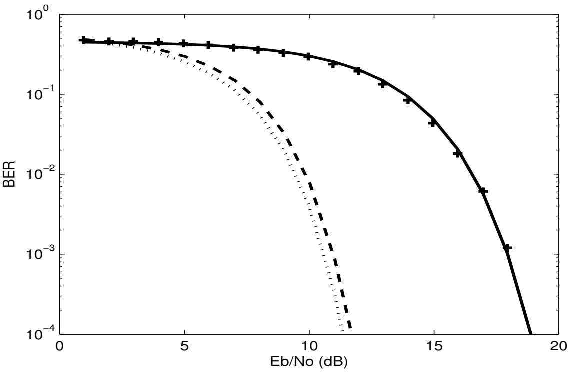

Figure 8: Noise performance of the UWB FM-DCSK TR system (solid curve) with the simulated points ('+' marks) and that of the UWB chirp IR system featuring pulse compression, considering (dashed curve) and ignoring (dotted curve) the frequency dependence of the channel.

In a noncoherent radio system $BER = 10^{-3}$ is a good reference for noise performance comparison. The results of simulations have shown that a 7.8-dB improvement can be achieved, on average, in favour of the UWB chirp IR system exploiting pulse compression.

5.1. Frequency Dependence of the Radio Channel

The frequency dependent term in path gain can be formulated [8] as $10\,(-2\kappa - 2)\,\log_{10}(f/f_0)$ where the reference frequency f_0 is set 5 GHz, f gives the signal frequency and κ denotes the frequency dependence factor. Depending on the propagation environment the value of κ goes from -1.427 to 1.53. In Figure 8 the dashed curve illustrate the effect of the frequency dependent nature of the channel for $\kappa = 0.53$. A marginal, about 0.5 dB, noise performance degradation can be observed.

6. Conclusions

The contribution introduced a new technique for UWB IR applications, namely the application of pulse compression in UWB chirp IR systems. The UWB chirp is constant envelope signal, so it can be amplified by even a nonlinear power amplifier.

The main advantage of pulse compression is that it provides a processing gain at the receiver that considerably improves the noise performance of the autocorrelation receiver. Our simulations showed that the noise performance improvement can be as high as 7.8 dB at $BER = 10^{-3}$ compared to the noise performance of the UWB FM-DCSK TR systems. Further advantage of the pulse compression is that it makes the overlapped pulses caused by channel dispersion separated at the receiver providing better resolution.

Acknowledgment

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