UWB Radio: A Real Chance for Application of Chaotic Communications

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Abstract—For lack of empty radio bands, ultra-wideband (UWB) radio that allows the reuse of already occupied frequency bands is the only solution to accommodate new wireless data communication services. The recovery of the very short and extremely wideband wavelets used in UWB radio is not feasible. This is why noncoherent demodulation techniques have to be used. Introducing a general model for the noncoherent UWB modulation schemes the paper evaluates and compares the noise performances of the noncoherent pulse polarity modulation and the transmitted reference system. Closed-form expressions are given for the noise performance of both modulation schemes. Although the former requires a deterministic carrier, the TR system may use either deterministic or chaotic wavelets.

1. Introduction

Frequency band allocated to UWB radio extends from 3.1 GHz to 10.6 GHz. Since conventional narrowband systems have been operating in that frequency band, the power transmitted in a 1-MHz bandwidth is limited to -41.3 dBm. The bandwidth of transmitted UWB signal must exceed 500 MHz.

Since the recovery of UWB wavelets is not feasible, the following noncoherent UWB modulations schemes are considered here: (i) noncoherent pulse polarity modulation where a frequency-shifted bell-shaped Gaussian wavelet is transmitted, (ii) TR system with deterministic wavelets, and (iii) frequency-modulated chaos-shift keying (FM-DCSK) modulation scheme.

The noise performance of noncoherent chaotic communication schemes lags behind that of coherent conventional systems. Since coherent communications cannot be implemented in UWB application, the advantage of conventional systems over the chaotic ones is lost. Furthermore, in UWB application extremely wideband carriers are required and low cost transceivers featuring extremely low power consumption are needed. These requirements may be fulfilled with chaotic systems. This is why UWB radio offers a real chance for the application of chaotic communications.

2. Modulation schemes

The digital information to be transmitted is mapped to wideband wavelets of very short duration in UWB radio. The wavelets have a fixed waveform in impulse radio [1] and they are chaotic signals in chaotic UWB radio [2]. In the latter, the shape of transmitted wavelets is continuously varying even if the same information bit is transmitted repeatedly.

For the sake of simplicity, only binary systems are considered here. Two classes of modulations exist in UWB radio, namely, one information bit may be mapped to (i) one or (ii) two wavelets.

2.1. Structure of modulated UWB signals

Modulation schemes using one wavelet

The structure of UWB modulations using one wavelet is shown in Fig. 1, where $g(t)$ denotes the wavelet having an arbitrary waveform, T_{ch} is the wavelet duration and t_{pos} is the pulse positioning in a pulse bin T_{bin}. The pulse bin denotes the time elapsed between two consecutive wavelets, its duty is to prevent intersymbol interference in a multipath channel. Pulse positioning, amplitude and polarity of a wavelet may be varied in accordance with the modulation. Since the pulse polarity modulation offers the best noise performance, only the pulse polarity modulation is considered here.

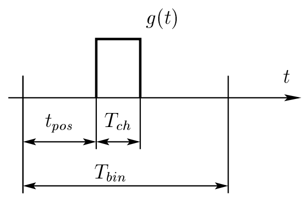

Figure 1: Structure of UWB modulation using one wavelet.

Modulation schemes using two wavelets

In this case two wavelets, called chips, are used to transmit one bit information. The first chip serves as a reference, while the second one carries the information.

The structure of modulated signal is shown in Fig. 2, where $g(t)$ denotes an arbitrary wavelet, T_{ch} is the chip duration and $\Delta T \geq T_{ch}$ gives the delay between the reference and the information bearing chips. The best noise performance is achieved by the antipodal modulation scheme, where the information bearing wavelet is equal to the delayed reference one for bit "1," and to the inverted and delayed reference wavelet for bit "0." This modulation scheme is frequently referred to as transmitted reference (TR) system.

The unique feature of a TR radio system is that the reference chip is not recovered at the receiver but it is transmitted via the same telecommunication channel as the information bearing chip. This solution makes the TR radio system very robust against the linear and nonlinear channel

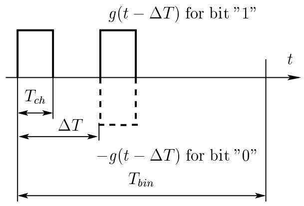

Figure 2: Structure of modulation using two wavelets.

distortions, but it has a serious drawback: both the reference and information bearing chips are corrupted by the channel noise. The noisy reference chip results in a noise performance degradation.

The fact that the reference chip is transmitted via the same telecommunication channel is generally considered as a disadvantage, since it is considered only as a loss in transmitted energy per bit. This statement is valid if an AWGN channel is considered. However, the real channels always have distortion, either linear or nonlinear. In case of channel distortion, the modulated carrier has to be correlated with a reference signal distorted in the same manner as the modulated carrier to get the best system performance. A correlation with the original distortion-free reference results in a performance degradation. Since in a TR system both the reference and information bearing chips undergo the same distortion, the TR system offers a better system performance when distortion is present in the channel, provided that the loss caused by the noisy reference chip is less than the gain arising due to the perfect correlation of the reference and information bearing chips. The reference chip should be considered as a test signal used to measure the actual channel characteristics. Consequently, the TR system may be used even in a time-varying channel for data communication.

2.2. Wavelets used in UWB radio

Wavelets with very short duration and ultra-wide bandwidth are used in UWB applications. The bandwidths are 500 MHz and 2 GHz in the narrowband and wideband, respectively, UWB radio systems. Except the maximum value of power spectral density and minimum bandwidth, the UWB radio regulation does not specify the type of UWB wavelets, either a fixed or a chaotic waveform may be used.

UWB radio with deterministic wavelet

Because of its excellent spectral properties, a frequency-shifted bell-shaped Gaussian pulse

$$g(t) = \sqrt{\frac{2E_b}{k\sqrt{\pi}\,u_B}}\exp\left(-\frac{t^2}{2u_B^2}\right)\cos(\omega_C t) \qquad (1)$$

is used as deterministic wavelet, where $k = 1$ and 2 when one or two wavelets, respectively, are used to transmit the information, $f_C = \omega_C/2\pi$ is the center frequency, E_b gives the energy per bit, and u_B is determined by the required bandwidth of UWB wavelet [1]. The shapes of deterministic wavelets are shown in the time domain for the bandwidths of 500 MHz and 2 GHz in Fig. 3. Although the duration of wavelets is infinite, their power decreases rapidly as a function of time, consequently, a finite wavelet duration may be defined.

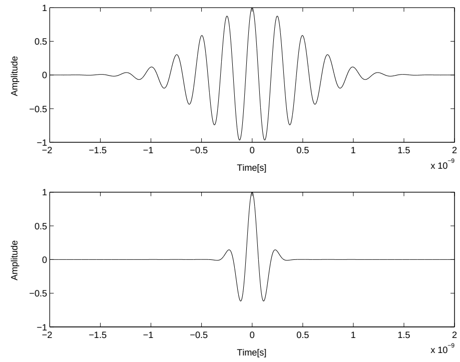

Figure 3: Bell-shaped Gaussian pulse with 500 MHz (upper trace) and 2 GHz (lower trace) RF bandwidths.

UWB radio with chaotic wavelet

In FM-DCSK, the wavelet $g(t)$ is a frequency modulated signal. This signal is generated in such a way that a chaotic signal is applied to the modulation input of an FM modulator. Although in the original version of FM-DCSK the chip duration T_{ch} and delay ΔT are identical [3], the reference and information bearing chips may be separated $\Delta T > T_{ch}$ to prevent intersymbol interference (ISI) in UWB application. The former assures the maximum data rate, while the latter prevents the intersymbol interference caused by the multipath channel.

3. UWB demodulator configurations

The wavelet recovery in UWB radio is not feasible because of the (i) very short pulse duration, (ii) complex wavelet waveform and (iii) channel distortion. This is why a noncoherent demodulation must be used. For the UWB modulation schemes using one and two waveforms, the detection with template signal and the autocorrelation detector, respectively, offer the best system performance. Both of them belong to the class of correlator-based receivers.

3.1. Detection of pulse polarity modulation

In pulse polarity modulation the information is carried by the sign of wavelet. Let $r_m(t) = g(t) + n(t)$ and $\tilde{r}_m(t) = \tilde{g}(t) + \tilde{n}(t)$ denote the received noisy signal before and after channel filtering, respectively. The channel noise described by its sample function $n(t)$ is modeled by a zero-mean stationary Gaussian process having a uniform two-sided power spectral density of $N_0/2$. The information $\hat{b}_m$ may be recovered if $\tilde{r}_m(t)$ is correlated by a template signal $p(t)$ as shown in Figs. 4 and 5. The template signal is a windowing and weighting pulse

$$p(t) = \begin{cases} 1/\sqrt{\tau}, & \text{if } |t| < \frac{\tau}{2} \\ 0, & \text{otherwise} \end{cases} \qquad (2)$$

where τ is the observation time period.

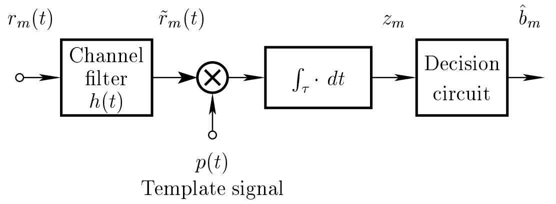

Figure 4: Detection of pulse polarity modulation with a template signal $p(t)$.

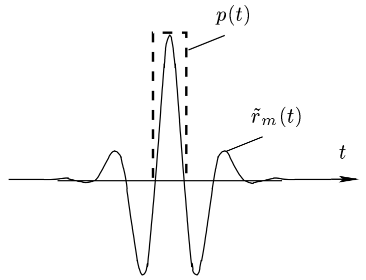

Figure 5: Noiseless received and template signals.

Noise performance
To get the noise performance, the probability distribution of observation variable

$$z_m = \int_{T_{bin}} \tilde{r}_m(t)p(t)dt = \pm \int_\tau \tilde{g}(t)p(t)dt + \int_\tau \tilde{n}(t)p(t)dt \qquad (3)$$

has to be found, where $p(t)$ is given by (2). In a well designed system the channel filter does not distort the received signal, i.e., $\tilde{g}(t) = g(t)$.

The observation variables of correlation-based receivers have been investigated in [4]. The second term in (3) is a time-invariant linear transformation. Since the channel noise is modeled as a stationary zero-mean Gaussian process, the second term has a Gaussian distribution with zero mean and variance $N_0/2$ [4].

In (3), the mean of observation variable is given by the first term

$$E[z_m] = \int_\tau \tilde{g}(t)p(t)dt \qquad (4)$$

For $p(t) = g(t)$, $E[z_m] = \sqrt{E_b}$. However, as shown in Fig. 5, there is always a mismatch error between $p(t)$ and $g(t)$. The sources of mismatch are threefold: (i) to get a simple configuration, $g(t)$ is a simple windowing pulse, (ii) there is a alignment error between $p(t)$ and $g(t)$, and (iii) the width of windowing template function may also deviate from its ideal value. These errors corrupt the noise performance. Figure 3 shows that the wavelet duration is less than 3 ns, consequently, even a small timing error results in a large performance degradation.

Assume that the received and template signals are aligned perfectly as shown in Fig. 5. Then the non-optimum width of template signal is the only source of loss in $E[z_m]$. Let this loss be expressed by a parameter α

$$E[z_m] = \sqrt{\alpha E_b}\,. \qquad (5)$$

The *template matching efficiency*

$$e_{tm} = \sqrt{\alpha} = \sqrt{\frac{E[z_m]}{E_b}}$$

is plotted in Fig. 6 against the width of windowing template function, i.e., energy capture time τ, for two different RF bandwidths and for a 4-GHz center frequency.

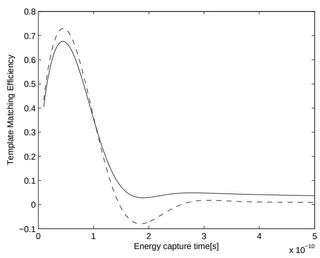

Figure 6: Template matching efficiency as a function of the width of template signal. The RF bandwidths of bell-shaped Gaussian impulses are 2 GHz (dashed curve) and 2.5 GHz (solid curve).

Figure 6 shows that the demodulator is very sensitive to the timing error, any timing error reduces the separation of message points in the observation space and, consequently, results in a considerable performance degradation. The template matching efficiency also depends on the RF bandwidth, for 2-GHz bandwidth even the sign of $E[z_m]$ is inverted in a certain range of energy capture time. Note, this means that the demodulator inverts the received bits.

Figure 6 shows that in optimum case the template detector has about a 3-dB theoretical implementation loss.

The bit error rate of noncoherent pulse polarity modulation built with template detection is obtained from (3) [5]

$$P_e = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\alpha E_b}{N_0}}\right)$$

The noise performance of pulse polarity modulation built with template detection is shown in Fig. 7 for different RF bandwidths (BW) and template matching efficiencies. Note that the energy capture time has a strong influence on the noise performance, even worse, Figs. 6 shows that if the energy capture time is about $1/f_C$ then the demodulation becomes practically impossible.

3.2. Autocorrelation TR receiver

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 chips

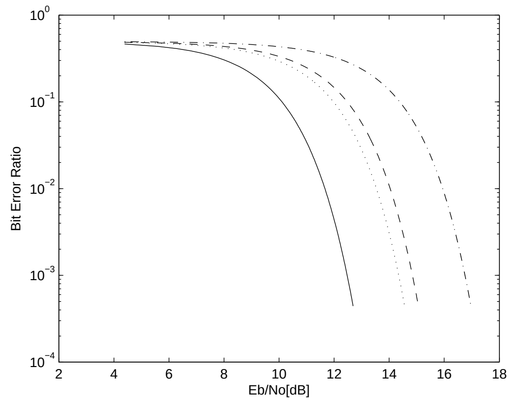

Figure 7: Noise performance of pulse polarity modulation built with template detection. Solid curve: BW=2 GHz and $e_{tm} = 0.69$; dotted curve: BW=2 GHz and $e_{tm} = 0.40$; dashed curve: BW=500 MHz and $e_{tm} = 0.35$ and dash-dotted curve: BW=500 MHz and $e_{tm} = 0.20$.

as shown in Fig. 8. The channel filter is a bandpass filter that determines the noise bandwidth of receiver. The integrator is an integrate-and-dump circuit.

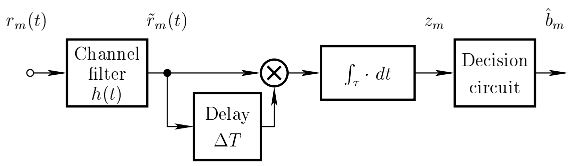

Figure 8: Block diagram of TR autocorrelation receiver.

Both noncoherent UWB impulse radio and FM-DCSK systems belong to the TR systems, but in the former a fixed waveform while in the latter a chaotic carrier is used as $g(t)$. The advantages of these TR systems are: (i) the optimum decision threshold is always zero, consequently, there is no need for an adaptive threshold control and training sequence, (ii) the reference chip measures the actual channel characteristics, (iii) a simple autocorrelation receiver may be used. The TR systems also have a few disadvantages: (i) transmission of a reference chip results in a loss in the energy per bit E_b (however, this loss may be reduced if more than one information bearing chips are transmitted after one reference chip), (ii) the reference chip is also corrupted by the channel noise.

Noise performance

The equation developed in [4] for the noise performance of FM-DCSK may be generalized to any kind of TR systems implemented with an autocorrelation receiver. The bit error rate (BER) is obtained as

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

where τ denotes the energy capture time of autocorrelation receiver. This equation is valid for both fixed and chaotic wavelets provided that the energy per bit E_b is kept constant if chaotic wavelets are used.

Note that the noise performance of a TR system depends on the product of $2B\tau$, but the delay $\Delta T - \tau \geq 0$ between the reference and information bearing chips has no influence on the noise performance. The dependence on $2B\tau$ reflects the fact that both the reference and information bearing chips are corrupted by the channel noise.

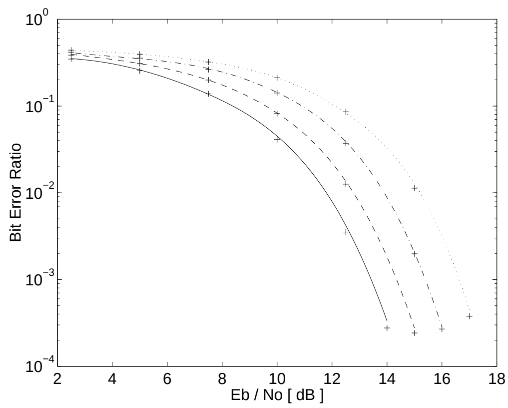

Figure 9: Noise performance of a TR system built with an autocorrelation receiver. From left to right $2B\tau$ is 8.5, 17, 34 and 68.

4. Conclusions

The noise performances of UWB impulse radio and chaotic FM-DCSK system have been compared. Figures 7 and 9 show that these systems offer a very similar noise performance.

Acknowledgments

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