Issues in the Performance and Covertness of UWB Communications Systems

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Abstract

UWB systems hold significant potential to serve as covert communications systems with a low probability of detection (LPD). In this paper, the performance and covertness of binary and M-ary pulse position modulation, bipolar as well as bipolar PPM modulation schemes are evaluated for UWB. The effect of channel coding on the covertness of UWB is also considered. Two radiometer-based detection systems are compared for use in the detection of impulse radio.

1. Introduction

Communications systems that are described as ultra-wideband (UWB) are often impulse radio systems that transmit information in very short duration pulses rather than the traditional method of using a sinusoidal carrier. The large bandwidth of a UWB system is dominated by the pulse shape and duration. This large system bandwidth relative to the information bandwidth allows UWB systems to operate with a low power spectral density. A low power spectral density would seem to indicate an inherent covertness of UWB, due to the fact that the UWB signal may be near or below the noise floor of a hostile detection device.

This paper evaluates some of the factors that affect the covertness of impulse radio UWB systems. Some of the communications system design choices such as modulation and channel coding are examined. The impact of the type of detector used on covertness is also considered.

2. UWB System

The UWB system considered here is an impulse radio based system that employs time hopping similar to that described in [1]. The received signal from a single user is given by:

$$s^{(k)}(t) = \sum_j A^{(k)}_{[j/N_s]} \, p\left(t - jT_f - c_j^{(k)} T_c - \delta d^{(k)}_{[j/N_s]}\right)$$

where the superscript (k) represents the kth user, $A_{[]}^{(k)}$ is the amplitude of the jth pulse based on the energy per pulse and the data sequence, N_s is the number of pulses used to represent one data symbol, $p()$ is the pulse shape with normalized energy, T_f is the frame repetition time, $c_j^{(k)}$ is a pseudorandom, repetitive time hopping sequence, T_c is the time hop delay, δ is the PPM time delay parameter, and $d_{[]}^{(k)}$ is a function of the data sequence (the [ ] notation represents the integer portion of the argument).

The choice of modulation is important to the performance and covertness of a UWB communications system. Possible modulation schemes that have been proposed are pulse amplitude modulation (PAM), on/off keying (OOK), bipolar signaling, pulse position modulation (PPM), and various combinations of these. An M-ary PPM scheme, bipolar signaling, and an M-ary combination of bipolar signaling and PPM (biorthogonal signaling) are considered in this paper. Some M-ary PPM UWB systems are considered in [2] and [3].

For the M-ary PPM, the data is contained in one of M possible time delays, so $d_{[]}^{(k)} = 0,1,..M-1$ and $A_{[]}^{(k)} = \sqrt{E_p}$. For bipolar signaling, the data is contained in the polarity of the transmitted pulses, so $d_{[]}^{(k)} = 0$ and $A_{[]}^{(k)} = \pm\sqrt{E_p}$. For biorthogonal signaling, the data is contained in the polarity of the pulse and one of $M/2$ possible time delays, such that $d_{[]}^{(k)} = 0,1,..M/2-1$ and $A_{[]}^{(k)} = \pm\sqrt{E_p}$.

The pulse shape assumed here is the Gaussian doublet given by:

$$p(t) = \sqrt{\frac{16}{3T_p}}\left(1 - 16\pi\left(\frac{t}{T_p}\right)^2\right)\exp\left(-8\pi\left(\frac{t}{T_p}\right)^2\right)$$

where T_p is assumed to be the pulse width (approximately 99.99% of the energy in p(t) is contained in the interval $-T_p/2$ to $T_p/2$).

The pulse repetition time is assumed a constant for this system. No specific time hopping sequences are assumed, so random sequences are used for simulation. The δ parameter is set to $2T_p$ to assure orthogonality between possible PPM time shifts.

3. Detection Methods

For narrowband and traditional direct sequence spread spectrum (DSSS) systems, the optimum signal detector is a radiometer, that measures the energy in a bandwidth, W, over a time interval, T. If the captured energy is greater than the detection threshold, the output of the radiometer indicates that a signal is present. [4] provides several different detectability models for wideband radiometers. For radiometers with a large time-bandwidth product, TW, many of these models are very closely approximated by Edell's model. The probability of detection, P_d, using this model is given by:

$$P_d = Q\left(Q^{-1}\left(P_{fa}\right) - \sqrt{\frac{T}{W}}\frac{S}{N_o}\right), \quad TW >> 1$$

where P_{fa} is the probability of false alarm in noise alone, S is the signal power at the radiometer, and N_o is the noise power spectral density. This single radiometer model is used by [5] to compare the covertness of a UWB system with more traditional wideband DSSS systems. To quantitatively evaluate covertness, [6] determines the probability of detection versus the relative distance between transmitter and interceptor. This assumes a scenario such as that depicted in Figure 3.1. The probability of detection can be found as a function of the ratio d/d_o, the ratio of the distance from the transmitter to interceptor (d) to the distance from the transmitter to the intended receiver (d_o). The interceptor in this situation is attempting to detect the presence of the transmitted signal, not demodulate it. This same metric will be used here to compare the covertness of UWB systems and also to compare different radiometer configurations.

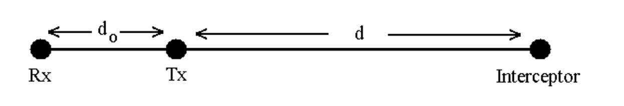

Figure 3.1. Illustration of transmitter and receiver pair with nearby hostile interceptor.

A time channelized multi-radiometer system is proposed in [7] to improve the detection of impulsive UWB signals over a single radiometer system. The configuration of such a multi-radiometer system is shown in Figure 3.2. This system consists of L radiometers which each detect energy over an interval of T_o. This gives an overall observation interval of $T = LT_o$. [7] considers the case where T of the radiometer system is equal to the frame time, T_f, of the UWB system, however this is not a necessary condition and actually creates some limitations to the performance of the detection system. If T is allowed to be greater than T_f these difficulties are alleviated as will be shown in Section 5.

The time interval for each channel of this system is on the same order as the pulse duration, T_p, which can yield T_oW approximately equal to 1. For these radiometers, Edell's model is no longer valid, but other models for a wide range of TW are given in [4]. Park [8] and Dillard's [9] models were chosen since they are derived from Barton's radar detector loss function [10] which is based on $TW = 1$. Probability of detection for each channel using Park's model can be expressed as:

$$P_{dl} = Q\left(Q^{-1}\left(P_{fao}\right) - \sqrt{2Y}\right)$$

and probability of detection for each channel using Dillard's model can similarly be expressed as:

$$P_{dl} = Q\left(\sqrt{-2\ln\left(P_{fao}\right)} - \sqrt{Y\left(1+\sqrt{1+9.2/Y}\right)}\right)$$

where:

$$Y = \frac{T_o S_l^2}{2.3WN_o^2 + S_l N_o}$$

where S_l is the average received power in the lth channel during one time interval, T_o.

The overall desired P_{fa} can be chosen by setting the probability of false alarm for each channel, P_{fao}, to meet the following relationship:

$$P_{fa} = 1 - \left(1 - P_{fao}\right)^L$$

The overall probability of detection of an impulsive UWB signal not known to be synchronized with the radiometer cannot be expressed simply, so simulation will be used to determine this relationship.

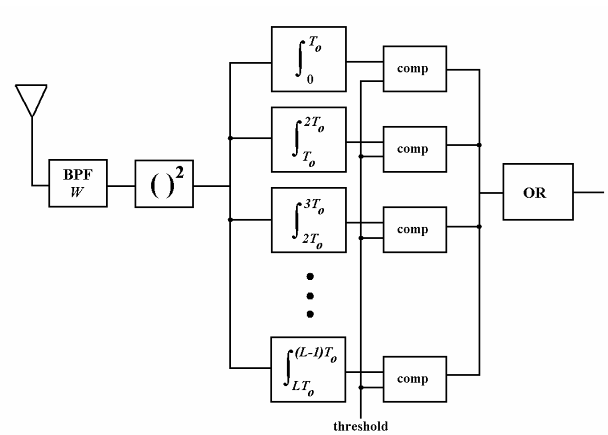

Figure 3.2. Time channelized radiometer detector for impulsive UWB signals.

4. Covertness of UWB

Simulation of UWB systems employing binary PPM, bipolar modulation, 4-ary PPM, 4-ary biorthogonal modulation, 16-ary PPM, and 16-ary biorthogonal modulation were carried out to evaluate BER performance in AWGN. Simulation of the binary PPM system using a rate 1/4, constraint length 9 convolutional code with Viterbi soft decoding was also performed.

Single Wideband Radiometer Detector

The parameters of the systems are described in Table 1. The bandwidth of the radiometer is assumed to be matched to the system that is to be detected and the observation interval is the same for both systems for a fair comparison. The noise power spectral density is also assumed to be the same for both systems.

Observation interval, T	100 µs
Probability of false alarm, P_{fa}	0.01
Path loss exponent	4
BER at friendly receiver	10^{-4}
IS-95 system	
Bandwidth, W	1.25 MHz
Data rate	9.6 kbps
UWB system	
Bandwidth, W	3.25 GHz
Pulse width, T_p	400 ps
Data rate, R_b	10 kbps
Pulse repetition rate	1MHz

Table 1. System parameters for covertness evaluation.

The covertness of the uncoded UWB systems, and a binary PPM system using a rate 1/4, constraint length 9 convolutional code with Viterbi soft decoding, with a single user detected by a single wideband radiometer (represented effectively by Edell's model) with an observation time of 100 µs is shown in Figure 4.1. This plot shows that higher order modulations and channel coding each can provide a covertness advantage.

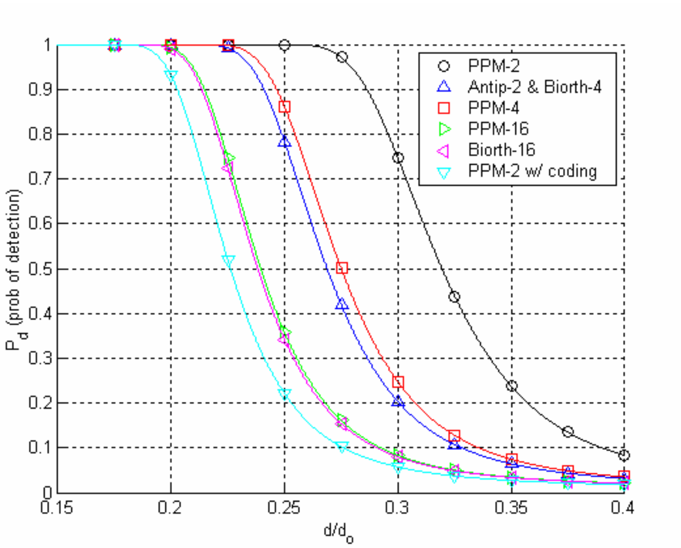

Figure 4.1. Covertness of UWB systems employing different modulation schemes. Also shown is the covertness of binary PPM using a rate 1/4, constraint length 9 convolutional code with Viterbi soft decoding. Detection is by a single wideband radiometer using an observation interval of 100 µs.

Channelized Wideband Radiometer Detector

For the channelized radiometer system, the performance of the detector is affected by the parameters chosen. [7] chooses the total interval time for detection decisions to be equal to the frame time of the UWB signal. If the detector's frame is synchronized with the received UWB signal's frame, then when a signal is present, each detector frame will have a channel that overlaps with the UWB pulse transmitted during that frame. But if the detector's frame is not synchronized (exactly half a frame time off for example) there will be some detector frames that contain no UWB pulses (assuming the pulse in a given frame is randomly distributed due to the time hopping code). These frames that do not overlap with a pulse will have a very low probability ($=P_{fa}$) of indicating that a signal is present. This also has a 'ceiling' effect on the maximum achievable average probability of detection when the detector is not synchronized. The probability of detection as a function of distance for the uncoded binary PPM signal is plotted in Figure 4.2 for the cases where the detector is perfectly synchronized with the receiver (worst case covertness), the detector is exactly half a frame and half a pulse width off from synchronization (best case covertness), and the detector is assumed to have a uniformly random time offset from synchronization (average covertness). For this comparison the overall observation interval was set equal to the UWB frame duration ($T = T_f$), the observation interval of each channel was set equal to the pulse duration ($T_o = T_p$), and the overall probability of false alarm was set to 0.01. All plots giving the results of the channelized radiometer detector are from simulations using Park's model for each radiometer channel. The results from the simulations using Dillard's model are nearly identical and thus are not shown.

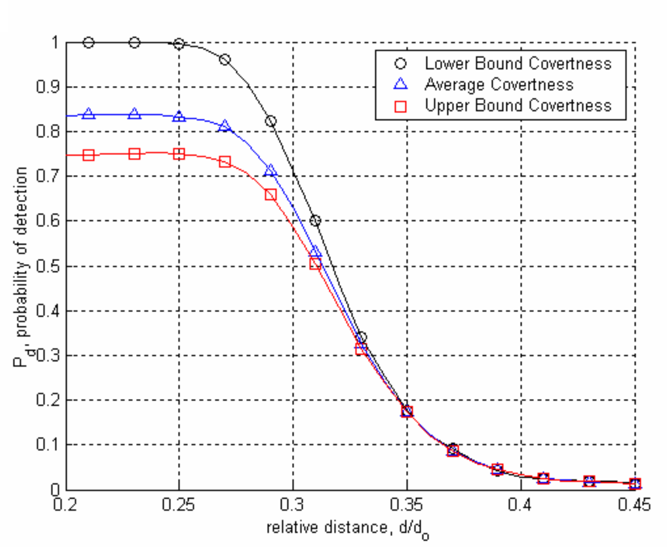

Figure 4.2. Upper bound, lower bound, and average covertness for channelized radiometer detector using Park's model with $T = T_f$ and $T_o = T_p$.

The probability of detection for the channelized radiometer can be improved by increasing the overall observation interval. A similar effect is seen in the single wideband radiometer when the observation interval is increased [5]. By increasing the overall observation time to multiple frames, the 'ceiling' effect seen in Figure 4.2 disappears and the difference between best and worst case covertness due to frame synchronization is greatly minimized. The performance of the channelized detector for the uncoded binary PPM UWB signal (the least covert of the UWB systems considered) is compared to the performance of a single radiometer detector for the same UWB signal and for an IS-95 signal in Figure 4.3 radiometer (similar to the comparison in [5]). The overall observation interval of the channelized system and the observation interval of the single radiometer are set equal (100 µs) to allow for a fair comparison.

As can be seen in Figure 4.3, the channelized radiometer is able to detect the UWB signal from a greater distance than the single radiometer (except for very small probability of detection values). It is interesting to note that the channelized radiometer detection curve has a steeper slope than the single radiometer curve. This implies that the distance between almost certain detection and almost certain failure of detection is smaller for the channelized radiometer. Even in the presence of the improved channelized detector, the UWB signal is significantly more covert than the IS-95 DSSS signal.

The choice of the observation interval for each channel is also important to the performance of the detector. This choice may be influenced by the hardware difficulties for detecting energy over such short intervals or due to lack of information about the pulse width of the signal to be detected. Figure 4.4 compares the performance of the channelized detector for different channel observation intervals. As the channel observation interval grows larger than the pulse duration, more noise is captured relative to the energy of the pulse and the performance of the detector decreases. The performance of the channelized system to detect the binary PPM UWB signal with $T_o = 25T_p$ (shown in Figure 4.4) yields roughly equivalent performance to the single wideband radiometer (shown in Figure 4.3). The energy distribution over time of the pulse used determines the optimal value for the channel observation interval for the detector. Simulation revealed this optimum value is slightly less than T_p for detecting the UWB system described in this paper.

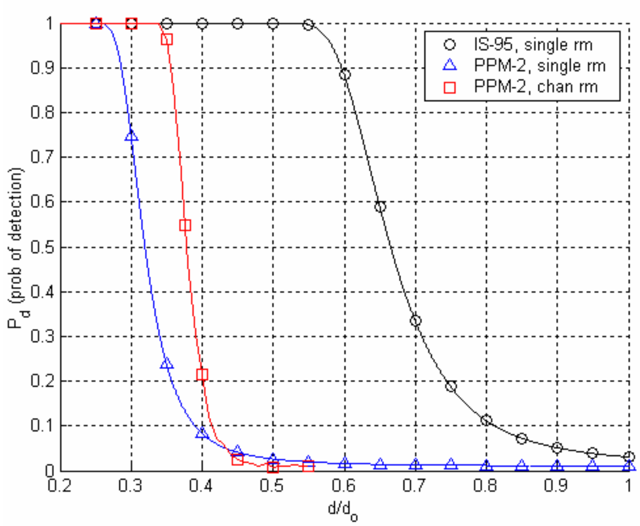

Figure 4.3. Covertness of UWB signal detected by a single radiometer (T = 100 µs), UWB signal detected by a channelized radiometer, Park's model (T = 100 µs, $T_o = T_p$), and IS-95 signal detected by a single radiometer (T = 100 µs).

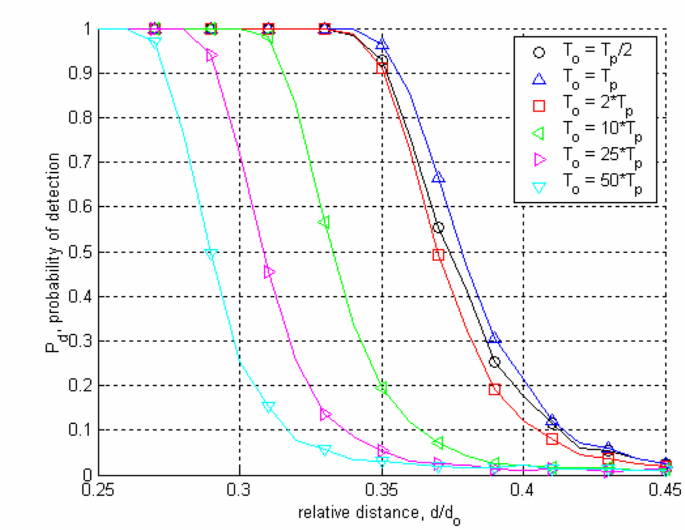

Figure 4.4. Performance of channelized detector for different channel observation intervals (T = 100 µs).

5. Conclusions

The performance of two different *M*-ary modulation schemes for an impulse radio based UWB communications system has been evaluated. For uncoded systems, the energy efficiency (and thus covertness) increases as *M* increases as expected for *M*-ary orthogonal and biorthogonal modulation schemes. However, the bandwidth is not affected since the bandwidth is dominated by the pulse duration, but the choice of *M*-ary modulation will have an effect on other system considerations such as multiple access performance which have not been evaluated here.

The performance of a channelized radiometer detector was evaluated for use in detecting impulse radio signals and compared to the single wideband radiometer detector. The parameters that impact the performance of such a channelized detector were evaluated and it was shown that it is possible to construct a channelized radiometer detector that improves detectability of impulse radio signals over a single radiometer if sufficient information about the UWB system is known.

6. References

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