APPLICATION OF MULTI-USER DETECTION TECHNIQUES TO IMPULSE RADIO TIME HOPPING MULTIPLE ACCESS SYSTEMS

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ABSTRACT

Multiple Access Ultra Wideband (UWB) communications systems based on impulse radio have so far relied primarily on conventional matched filter techniques. This paper illustrates the nature of the multiple access interference and the application of multi-user detection to improve the performance of impulse radio system.

1. INTRODUCTION

The objective of this paper is to evaluate the application of multi-user detection to ultra-wideband (UWB) communication, commonly known as impulse radio. Time hopping multiple access system was proposed by Scholtz [1]. Impulse radio technology seems to be promising and it has some potential for application in indoor wireless especially with static terminals [2].

Most of the research in this area is based on conventional detectors where other users are assumed to have the Gaussian noise form [1],[3]-[5]. Capacity estimates and performance evaluation are based on this assumption. The research presented in this paper represent an effort to obtain more insight on multiple access interference and methods to mitigate them. Multiple-user detection is proposed to improve the performance and increase the capacity.

A motivation for multi-user detection is given through an experimental evaluation of multiple access interference. The system model used for simulation is given for proper assessment. Some multi-user detection techniques are then tested with impulse radio. Simulation results are analyzed and conclusions are drawn with an assessment of the validity of the Gaussian approximation. More importantly, the advantages of using multi-user detection techniques are illustrated through comparison with the conventional detection and the single user bound.

2. SYSTEM MODEL

The system model proposed by Scholtz [1] is used. The typical hopping format for impulse radio with pulse position modulation is given by

$$s^{(k)}(t) = \sum_{j=-\infty}^{\infty} w_{tr}(t - jT_f - c_j^{(k)}T_c - \delta d_{[j/N_s]}^{(k)}) \quad (1)$$

where $w_{tr}(t)$ is the transmitted monocycle. Subscript k indicates transmitter related quantity. T_f is the pulse repetition time. Each user is assigned a time hopping sequence shift pattern $c_j^{(k)}$. This hopping sequence provides an additional shift of $c_j^{(k)}T_c$. The transmission rate (R_s) determines the number N_s of monocycle to be modulated by a given binary symbol. Pulse position modulation is used with δ added delay if the modulated bit is one.

The channel model assumes that N_u users are active during transmission. The signal undergoes constant amplitude attenuation and waveform deformation. Pulse position modulation (PPM) is used with bits of 1 delayed by 0.156 nano-seconds. A typical received waveform is shown in Figure 1 and is given by

$$\begin{aligned} &w_{rec}(t + 0.35) = [1 - 4\pi(t/\tau_m)^2] \\ &with \quad \tau_m = 0.2877 \end{aligned} \quad (2)$$

When the number of users is N_u, the received signal is:

$$s(t) = \sum_{k=1}^{N_u} \sum_{j=-\infty}^{\infty} w_{rec}(t - \tau_k(u) - jT_f - c_j^{(k)}(u)T_c - \delta d_{[j/N_s]}^{(k)}(u)) + n(t,u) \quad (3)$$

A single bit of information is generally spread over multiple monocycles. The receiver sums the proper number of pulses to recover the transmitted information. The receiver is based on decorrelating the received impulse with the template signal shown in Figure 1. The template signal is the difference between the pulse the represent an information bit=1 and the pulse used for an information bit=0.

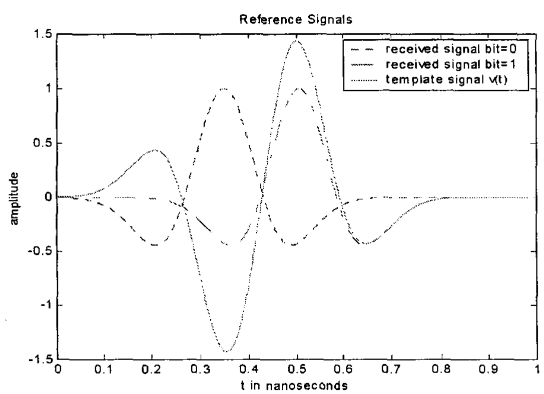


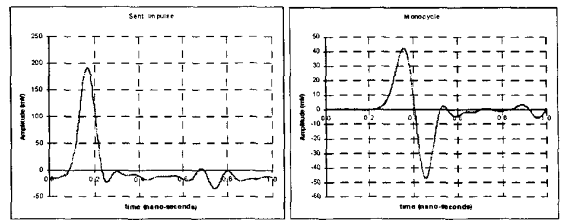
Figure 1: Typical Received Signal for bit=0, bit=1 and the typical waveform used by the receiver correlator

3. EXPERIMENTAL SETUP

An experimental setup was established in the Time Domain Laboratory at Virginia Tech to evaluate the performance of impulse radio. The setup consists of a pulse generator that sends impulses to the transmitting antenna through a balun (required to change from unbalanced to balanced signal). The received signal is observed using a digitizing oscilloscope. The receiver antenna is connected to the test set through a balun (required to connect the balanced signal from the antenna to unbalanced signal through the co-ax). The sampling oscilloscope is connected to a PC with data a acquisition unit.

Synchronization is achieved through an external circuit. The sampling oscilloscope requires a pre-trigger. The oscilloscope has to receive the pre-trigger 80 pico-seconds before the trigger signal to the transmitter. This is achieved by using a step generator driver that can supply the required trigger and pre trigger.

The transmitted impulse signal gets differentiated before it is demodulated. Which means that to receive the doublet signal, which is the second derivative of a Gaussian pulse, the transmitted signal should be a monocycle, which is the first derivative of the Gaussian pulse. The acquired signals in Figure 2 indicate an important source of interference, which is the reflection as a result of incomplete matching in the design of the transmitter. This non-ideality cannot be avoided. A completely time-limited signal cannot be generated especially at very high frequency. Reflections of the original pulse are a modified version of the original pulse.



(a) *(b)*

Figure 2: Acquired transmitted and received pulses

(a) Transmitted Gaussian pulse
(b) Received monocycle

To illustrate the effect of the fast switching, let's consider the following two cases. Case I: when two pulses in two consequent time slots have the same power as illustrated by Figure 3(a), the two pulses can easily be distinguished. Case II: when the two consequent pulses have different power as in the near-far effect, it can be seen from Figure 3(b) that the reflection from the first user is very comparable to the second pulse if the first user has an amplitude which is 6 times the first user. The effect is made clearer in the zoomed view of Figure 3(c)

For time hoping multiple access applications this could limit the capacity and the performance of the system. Knowledge of the interfering pulse could improve the performance. This motivates the application of multi-user detection techniques.

Both the non-orthogonal time sequence pseudo-random sequences and the high frequency switching reflections represent the major sources of multiple access interference.

4. Performance Evaluation

Most of the analysis conducted in the area of impulse radio is based on the assumption of Gaussian noise approximation to the multiple access interference. Gaussian approximation is given by:

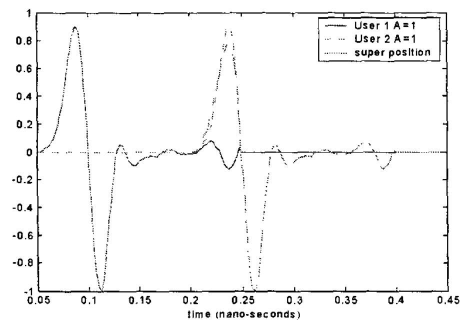
$$SNR_{out}(N_u) = \frac{(N_s A_1 m_p)^2}{\sigma_{rec}^2 + N_s \sigma_a^2 \sum_{k=2}^{N_u} A_k^2} \qquad (4)$$

where

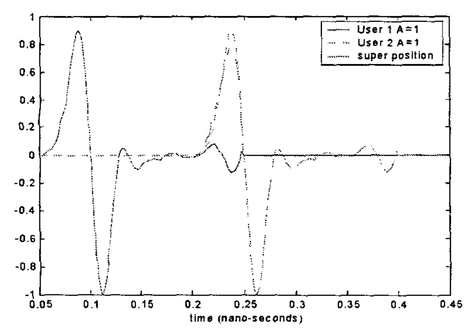
$$\sigma_a^2 = T_f^{-1}\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} w_{rec}(x-s)v(x)dx\right]^2 ds \qquad (5)$$

m_p: is the output when a single impulse is correlated with the template signal. The numerator of the SNR expression represents the useful power in the signal, which is related to the amplitude A, and the number of pulses per bit N_s. The second expression in the denominator is the approximation of the multiple access interference to Gaussian noise. The single user bound can be found by setting this expression to zero. $v(x)$ is the template signal used by the deocrrelator and shown in Figure 1. The error probability is then given by the formula for BPSK with coherent detection.

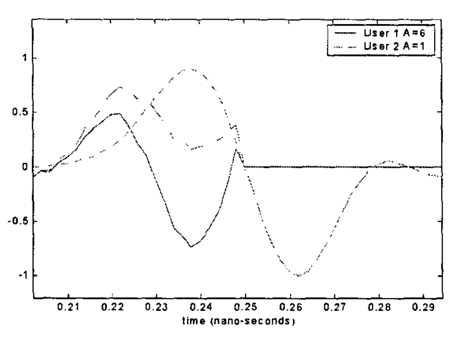
Both the Gaussian approximation and the single user bound will be used as reference evaluation measures in subsequent analysis.



(a) Case I: Equal power



(b) Case II: User 1 amplitude equal to 6 user 2 amplitude*



(c) Zoomed view for case II

Figure 3: Illustrative effect of multi-user interference as a result of high frequency switching

5. Simulated System and Parameters

In the following section we list the parameters used for the simulation. The signal used is as given in Figure 1. The pseudo-random hopping code is generated randomly without coordination between different users to account for the correlation between the users. The receiver is assumed to have access to these codes and some channel information as needed by some of the detection techniques. The MMSE detection algorithm is assumed to have knowledge of the value of Gaussian noise variance and the amplitudes of the signals from different users are also assumed to be known if needed by the detection technique.

Two simulation cases were considered one for synchronous and the other for asynchronous multiple access. The asynchronous case corresponds more to the practical use of impulse radio where pulses cannot be synchronized for mobile users since few centimeters corresponds to more than one chip time T_c. Different parameters were chosen due to the complexity associated with the designed detection code. Table 1 lists the different parameters for the two cases. In both cases coherent detection is assumed and the delay for all users can be estimated accurately.

To make sure that the selected parameters are within the system capacity and the system is not under used or saturated a simple capacity estimate was done based on the previous Gaussian approximation.

Parameters	Synchronous	Asynchronous
T_c	1	1
T_f	10	4
Nu	5	5
Ns	10	5
Rs	10Mbit/second	50Mbit/second

Table 1: Simulated Models (Coherence detection)

The huge number of users that can be accommodated by impulse radio is based on Gaussian approximation analysis. Before selecting the system to be simulated, we assess the capacity of the suggested system for simulation to assure that the system is not saturated.

With perfect power control, the number of users that can be supported for a given data rate (R_{Dmod}) can be calculated as a function of the required additional power using . The maximum number of user is the limit as the additional power is allowed to be infinite.

Using capacity analysis given in [3] , for the coherent case with a rate of 10Mbit/second, the maximum number of users that can be accommodated with BER $=10^{-3}$, 10^{-4} and 10^{-5} is estimated to be 53, 37 and 28 respectively. This gives us an idea of the expected system performance with 5 users. It will be shown later that the Gaussian approximation gives a very optimistic estimate.

6. Multi-User Detection Schemes

Different multi-users schemes are proposed. For the purpose of evaluating the performance of multi-user detection with impulse radio, the following algorithm were tested: decorrelator, MMSE, successive cancellation, 4 stage parallel cancellation, 4 stage parallel cancellation with decorrelator first stage, and the conventional detector. These techniques were evaluated against the single user bound and the Gaussian Approximation. The basic idea behind multi-user detection is to make a joint decision on the received signal. This is different than the case of conventional detector were the users are demodulated assuming other users are noise like interferers. Detailed description of these algorithms can be found in [6].

Single user is used as a an optimistic lower bound. The multi-user performance cannot be better than the case of a single user if the users are sending independent information. For the case of multi-stage cancellation (Parallel Cancellation) four stages were used to examine the need for more than multistage rather than just two.

7. Simulation Results

In the following section, simulation results for the two cases under consideration are discussed. First we start with the equal power case and then the unequal power.

When case I is simulated with equal power users the performance of different users is given in Figure 4. It is apparent that, though decorrelator based detectors have bad performance at low SNR, they improve sharply at higher SNR. When the performance of all users is average out successive cancellation perform the worst after the conventional detector. MMSE seems to perform very well at the cost of added channel information.

It worth to note that Gaussian approximation which supposed to estimate the performance of the conventional detector is very optimistic at least for the considered case.

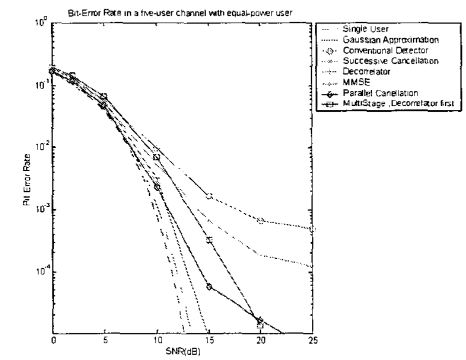


Figure 4: Performance of multi-user detection for equal power users

It is important to note that, though successive cancellation performed the worst when performance of all users is average out, it can result in a promising performance for some specific users cancelled at later stages. This means unequal performance for equal power users. This is recommended when the receiver is not interested in all users as might be the case for impulse radio receivers. Figure 5 illustrates the pronounceable different in the performance of the five detected users.

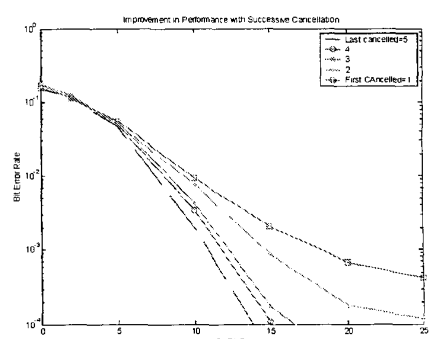


Figure 5: Unequal performance for equal power user with successive cancellation

The effect of multi-stages on both the parallel cancellation with conventional first stage and with decorrelator first was also studied. The results indicate that more than two stages do not add much to the performance especially with hard decisions made at the previous stages.

The more practical asynchronous case was considered next. For this case only parallel cancellation and successive cancellation were tested. Parallel cancellation outperforms the successive canceller as shown in Figure 6.

An effort was made to evaluate the performance with the use of the decorrelator however the singularity of the solution made the detector more difficult to simulate. It is important to note that whenever decorrelator is used one has to switch to conventional detector when the correlation matrix cannot be inverted or the inversion is close to singular. The determinant of the correlation matrix can be compared to a specific value and decision on singularity should be made as a result. This value is critical to the performance of the decorrelator detectors and has to be optimized for better performance

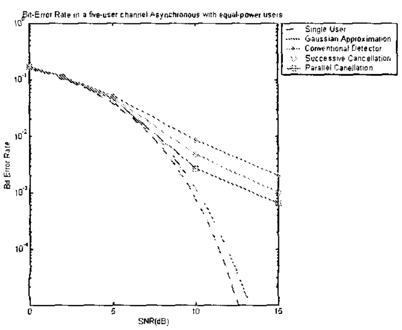


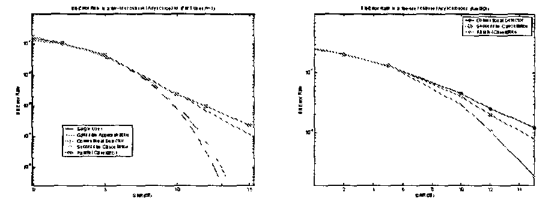
Figure 6: Multi-user detection performance for equal-power asynchronous

Unequal power was also consider with the interferers having power levels as -3dB, -4dB, -5dB and –6dB relative to the first users. The performance of the asynchronous case is shown in figure 7 (a) and (b). The first plot is to show the performance for the first user and the second plot is for the average performance. An important fact is revealed by comparing the two plots that multi-user detection might not be recommended when the strongest user is the desired user only as in the studied example.

8. Summary and Conclusive Remarks

Multi-user detection was shown to have a potential for application with impulse radio multiple access technology. In fact the argument extends to different applications with high frequency switching that utilize TDMA.

The output of the simulation work results in emphasizing the selection of the proper multi-user detection technique based on the operation region in terms of SNR and BER. Moreover, for applications



(a) Performance for the strongest users *(b) Averaged performance*

Figure 7: Performance of Multi-user detection when unequal power is considered

where all users have equal importance the parallel cancellation technique is a good candidate. Successive cancellation works well when only single user is of interest and the delay and complexity factors could be tolerated. Decorrelator detectors, though perform badly at low SNR, exhibits a very sharp water fall like performance curve as the SNR is increased.

Then Gaussian approximation was shown to be over optimistic for impulse radio, which utilizes very large bandwidth. The simple analysis performed here suggests that the characteristics of multi-user detection that have been observed in CDMA systems, are also applicable to UWB radio systems. Although capacity may not currently be an issue for UWB, near-far effects are a concern. The work here lays the groundwork for more detailed investigations of multi-user detection for impulse radio.

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