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Optimal Receiver for Space Time Spreading across a Time Hopping PPM over Ultra Wideband Saleh-Valenzuela MIMO Channel

Peter Vial
University of Wollongong, peterv@uow.edu.au

Beata J. Wysocki
University of Nebraska - Lincoln, bwysocki2@unl.edu

Tadeusz A. Wysocki
University of Nebraska-Lincoln, wysocki@uow.edu.au

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Peter Vial, Beata Wysocki & Tad Wysocki

University of Wollongong

Email: {Peter_Vial, Beata_Wysocki, Tad_Wysocki}@uow.edu.au

Abstract: This paper outlines a technique which can use multiple transmit antennas to send more than one binary bit using the same number of transmit antennas over a single transmission. It uses Ultra Wideband orthogonal pulse position modulation to achieve this, with the receiver employing a Rake receiver and a Maximum Ratio Combiner optimal detector. This is done over a Space Time Spreading Time Hopping Ultra Wideband Pulse Position Modulation system assuming a rich multipath Saleh-Valenzuela MIMO channel model. Simulation results indicate that a significant gain can be achieved compared with other proposed schemes utilising multiple transmit antennas for Ultra Wide Band Pulse Position communications. The gain is both in terms of transmission rate and the signal to noise ratio required for the simulator bit error rates.

Keywords: Space Time Spreading, MIMO, UWB, PPM, Saleh-Valenzuela, Rake, MRC, BER

1. Introduction

Ultra Wideband (UWB) systems are proposed as a wireless access system which are potentially able to provide broadband access speeds using large frequency spectrum bandwidths at low power over short distances (about 0-100 metres, also called pico cells in cellular systems). Over larger distances communication is possible but at lower access speeds. Even though the spectrum is wideband and will extend over frequencies which have been auctioned off to various commercial companies by governments, it is so low power that it appears as background radiation and forms part of the noise floor. The possible applications range from the radio used in the formation of Ad Hoc network low power devices in a Wireless Sensor Network (WSN) scenario (comprised of small radio devices termed motes) [1] to the access of the internet using wireless transceivers in a LAN (Local Area Network).

Two main classifications of UWB are referred to in the literature. One uses multiband orthogonal frequency division multiplexing (MOFDM) where spectra is sliced into relatively large widths of broadband frequency (as distinct from narrowband) and time hopping between frequency slices may be employed across the larger UWB spectrum available. The other technique is the use of Gaussian pulses whose bandwidth extends into many Gigahertz in terms of its spectrum. This is determined by the time duration of the pulses that are emitted by the UWB transmitter.

It is not clear how an Ultra Wideband system could use multiple antennas to transmit more than one binary bit in a single transmission period. Yang et. al.[2] have proposed techniques which use multiple antennas to transmit a single binary bit using two spreading sequences. This is inefficient in terms of the limited number of orthogonal spreading sequences and they also propose only one such scenario in their contribution which can be shown to use spreading sequences. This study, however, follows [2] where Pulse Position Modulation (PPM) is employed to generate a wireless communication data link. Hence this paper looks at systems employing PPM.

In [2] the authors employ an analog PPM modulation / demodulation technique using two transmit antennas and one receive antenna. They illustrate the use of PAM (Pulse Amplitude Modulation) and PPM, showing through theoretical analysis that the systems are very similar, one employing an amplitude modifier and the other employing a time shift. In [2] they perform their simulations without the use of Time Hopping.

Time Hopping allows multiple users to access the wireless medium without affecting each other provided they do not use the same time hopping pattern and their time hopping patterns are synchronised to some common time. In wireless MAC (Medium Access Control) schemes this is often done by the use of a beacon control packet/frame. In our study we use a Time Hopping Pattern which [2] does not. This smoothes the spectrum of the UWB system and thus allows the system to appear more like background noise to other wireless communication systems rather than the discrete spectra that would result without its use. For this reason it was decided that the simulated system must incorporate a time hopping pattern. For PPM the shift in pulse position also smoothes the spectra but its effect is less significant than the use of a time hopping pattern.

It is shown in this paper that the resultant BER is comparable to that obtained for a Yang Analog ST

coding type I scheme[2]. If the system is compared on a per antenna branch basis it is shown that a 3dB improvement is possible over the corresponding Yang ST coding type I scheme which can transmit only one binary bit compared to the two that Space Time Spreading (STS) sends per branch when two transmit antennas are employed. Thus it is shown how multiple antennas may be employed in a Space Time Spreading Time Hopping Ultra Wideband Pulse Position Modulation (STS-TH-UWB-PPM) system to achieve the transmission of multiple binary bits in one transmission period.

This paper starts by describing briefly a Yang Analog ST coding type I scheme from [2] in Section 2 and shows how it is in fact using orthogonal Walsh-Hadamard codes on each antenna. Section 3 describes STS and how it is applied to a TH-UWB-PPM system. Section 4 describes how the simulator in Simulink for Section 3 was modified to provide a Yang Analog ST coding type I scheme and shows the simulation using the Simulink model developed for Yang's ST coding I scheme versus the relevant data from [2]. Section 5 then compares Yang's ST coding I scheme in terms of measured E_b/N_o (dB) to the proposed STS-TH-UWB-PPM scheme for Partial and Selective Rake systems for the number of used multipath values (L) of 1 and 4. Section 6 is then the conclusion and future work.

2. Yang's Analog ST coding I scheme

In [2], one of the proposed techniques to be employed to provide space diversity using two transmit antennas is termed Analog ST coding scheme I. The authors of [2] profer that at the transmitter a Space Time (ST) encoder is used on each transmitting antenna to form the transmitted signal. The ST encoding occurs over many frames of transmitting Gaussian shaped pulses within short time periods of length T_f. In their simulations and our simulations T_f had a value of 100 ns (nano-seconds). They also deployed the SV (Saleh-Valenzuela) channel described in [3], which is a non-line of sight model of the multipath channel. The number of such frames in a symbol is denoted N_f. They indicate that N_f is usually even (as it is for our spreading code in Section 3 which uses an $N_f=32$).

Proceeding, Yang et. al. form two signals that are transmitted at the same time from the 0th antenna and the 1st antenna. From the 0th antenna they transmit the waveform (reproduced from [2] equation 10):

$$s_o(t) = s\left(\sqrt{\frac{\varepsilon}{2N_o}}\right)\sum_{n_f=0}^{N_f-1}(-1)^{n_f}\,w(t-n_fT_f) \qquad (1)$$

And from the 1st antenna they transmit the waveform (reproduced from [2] equation 11):

$$s_1(t) = s\left(\sqrt{\frac{\varepsilon}{2N_o}}\right)\sum_{n_f=0}^{N_f-1}w(t-n_fT_f) \qquad (2)$$

The factor of 2 in the denominator is used to normalise the power to that used in a SISO system (as we also do in Section 3). They do not incorporate a time hopping pattern as we do in Section 3 and 4. The signal w(t) is the Gaussian pulse waveform used or pulse shaper (which is normalised so that the integral over a time period T_f of its squared value is equal to unity, or in other words has unit energy [2]). The term 's' is the coded value of the bit transmitted. The value of s is either -1 representing a '0' or +1 representing a '1'. N_f is the number of frames in a symbol and does not incorporate the time hopping pattern used (the actual period when time hopping is incorporated for one symbol would then be N_f times T_f times the number of slots in the Time Hopping pattern in total, see Section 3).

The signal described by equation (1) and (2) are then demodulated over a symbol by multiplication by a template which considers all of the channel multipath gains and appropriately time shifted values of the pulse shaper. This is then combined in an L-finger Rake receiver and then an MRC detector. The procedure is fully described in [2].

These signals described by equation (1) and (2) should be examined closely. In [2] they do not include discussion of spreading codes being used as we will do in our STS-TH-UWB-PPM proposed system. However, they are, in fact, using a simple form of Walsh-Hadamard codes to form the difference equation which allows them to demodulate the single bit or symbol transmitted by the ST encoder. The orthogonal Walsh-Hadamard codes used in [2] are the first two:

spreading code 0:   +1 -1 +1 -1 +1 -1 +1 -1
spreading code 1:   +1 +1 +1 +1 +1 +1 +1 +1

For this reason it is logical that the Analog ST coding I scheme deployed in [2] can be compared to the STS-TH-UWB-PPM system described next in Section 3. The STS-TH-UWB-PPM Simulink simulator will be validated and compared against the results found in [2] using the same SV channel parameters in Section 4.

3. STS-TH-UWB-PPM system

A simulator was designed and is described in [4]. The parameters used to model the SV channel were the same as described in [2] Section V. These followed the SV channel descriptor, with rays arriving in clusters given by Poisson process cluster arrival rate, Λ, such that $\frac{1}{\Lambda} = 2$ ns. The rays within each cluster arrived in a Poisson Process with arrival rate λ, such that $\frac{1}{\lambda} = 0.5$ ns. The amplitudes of each of the arriving rays is found from a Rayleigh distributed random variable having exponentially decaying mean squared value with variables Γ and γ such that $\Gamma = 33$ ns and $\gamma = 5$ ns [2]. The pulse width of the Gaussian pulse (which is the second derivative) was also chosen to be 0.7 ns in accordance with [2].

Further, the real part of the multipath signal was taken, and then a search and marking of useful rays were chosen such that they were one nanosecond or more away from the next nearest multipath ray. This then became the channel model. Many such simulations were run and a database of channel instances was compiled for direct use in the Simulink simulator. These values were not, however, modified for using 0, 1 and 2 ns pulse position modulation. This could have been done to improve the performance of the STS-TH-UWB-PPM by avoiding the possibility of a 2 ns shift corresponding to a pulse position in the alternate PPM shift cases that the MRC needs to calculate when detecting / deciding whether a 0 ns, 1ns or 2ns offset in the chip position was sent in any particular chip (a chip being one bit of a spreading sequence).

It should be noted that the decisions in [4] were based on the chip level data and de-spreading occurred on the hard decision made at the chip level. In these STS simulations, in accordance with the description in [2], an MRC detector is used after all of the symbols pulses are collected. This is done by accumulating the data at the chip level in accumulators according to a calculated receiver matrix which considers the signals that could possibly be transmitted on the two antennas for the given spreading sequence used in the STS encoder. This needs to be calculated on a spreading sequence basis and will change with a different spreading sequence. It, however, only needs to be done during initialisation and a spreadsheet was employed to check the calculations.

The STS encoder produces spread signals on both antennas in a similar way to the Yang's ST Analog coding I system. The difference, however, is that instead of being based on a spreading sequence per antenna, it is based on the sum and difference of spreading sequences according to the equations [4]:

$$b_1 c_1[j] + b_2 c_2[j] = \begin{Bmatrix} 2 \\ 0 \\ -2 \end{Bmatrix} \quad for \quad j = 1,...,32 \qquad (3)$$

While for the difference stream we have:

$$b_2 c_1[j] - b_1 c_2[j] = \begin{Bmatrix} 2 \\ 0 \\ -2 \end{Bmatrix} \quad for \quad j = 1,...,32 \qquad (4)$$

Where the individual chips of the spreading sequences are represented by $c_1[j]$ and $c_2[j]$. These are the two Walsh-Hadamard spreading sequences used in Space Time Spreading and j is the counter for the individual chips within that sequence which here is a integer in the range $\{1,2,..,32\}$. The symbols b_1 and b_2 in Equation 3 and 4 represent the two binary bits in $\{-1,+1\}$ coding to be transmitted across the UWB channel [4]. The chip level data on each antenna is then '-2', '0', or '2'. These can be represented by 0ns, 1ns and 2ns shifts respectively in a PPM UWB system. Also equations (1) and (2) show that the two binary bits to be sent are coded into both the 0th and 1st antenna stream which provides the two fold diversity of STS when using two transmit antennas [5].

The STS-TH-UWB-PPM simulation assumes that each antennas channel or branch is uncorrelated. To model this a different set of channel multipath gains were generated for each antenna and embedded in the simulator. This also means that one channel's multipath could interfere with another, however the decision vector formed at the MRC models all possible combinations of the two channels without the addition of noise making the decision based on an Optimal dectector [6][7] when Gaussian noise was added.

A fixed Time Hopping pattern of :

$$[6 \quad 0 \quad 5 \quad 3 \quad 6 \quad 4 \quad 5 \quad 3]$$

was used throughout all simulations. Each slot was made up of eight one hundred nano second frames and when the time hopping pattern was completed, it was restarted again. Statistics were only calculated when an active slot was encountered. At all other times the channel was silent as described in [4].

4. Simulation of Yang's Analog ST coding I

The STS-TH-UWB-PPM system described in Section 3 was modified by changing the STS encoder to an encoder formed from equation (1) and (2). The STS encoder provides pulse positions for -2, 0, and 2. The modification involved changing the STS coder section to a ST coder that provided only pulse positions -2 and 0, which then represented -1 and +1 for the values of 's' in Equation (1) and (2). The MRC detector array was also modified so that only the terms which contributed to the decision were included in the detector module. Thus, apart from modifications in the ST encoder and MRC detector modules the implementation of Yang's Analog ST coding scheme I used the STS-TH-UWB-PPM simulator described in Section 3.

The other difference in this simulation is that Yang et. al. did not include a time hopping pattern, whereas this is already built into the STS-TH-UWB-PPM simulator so it was also included in the implementation of Yang's Analog ST coding I scheme. This should not have a significant impact on the results as the fixed time hopping pattern is only used in deciding when to measure the statistical data in the simulator and allow for experiments with more than one user into future research as well as smoothing the spectra.

The Simulation of Yang's Analog ST coding I system in Simulink was run for different expected SNR (Signal to Noise Ratio) using three different seed values. An estimate of the corresponding data set (from Figure 7 and Figure 8 of [2]) was plotted versus the data with 95% confidence intervals included. The data from our study was normalised for comparison purposes. Figure 1 shows the results for L=1 and L=4 for a Partial Rake system. This uses the first L useful rays to form the template in the MRC detector.

Figure 1 shows similar results for low expected SNR, with our Simulink simulations BER results for the Yang Analog ST coding I schema. For higher expected SNR our simulation produced lower BER results. The actual simulator data used in [2] for the channel model was unavailable to us so we could only use the statistical parameters provided in [2] to generate our own channel model data set. One possible explanation is that for the study in [2] their multipath was richer than that used in our simulation as we limited the maximum number of multipath for any single channel instance to 200 multipath gains (truncating if more were produced).
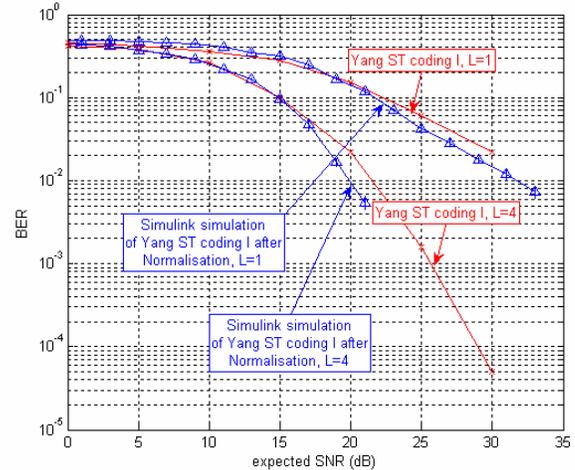

Figure 1: Yang et. al. results from [2] compared to Simulink implementation of [2]'s Analog ST coding I schema with Simulink simulation normalised

5. Comparison with STS system

The Yang et. al Analog ST coding type I system (incorporating Time Hopping) was then simulated and the BER versus Eb/No (dB) was measured using the Simulink Simulator. This was then compared to the STS-TH-UWB-PPM proposed system. This was done for L=1,4 and for Partial and Selective Rake detection schemes. Partial rake used the first L useful rays in the template and Selective Rake used the L highest energy useful rays in the template. Figure 2 shows the results for the Partial Rake comparison and Figure 3 shows the results for Selective Rake comparison. It should be noted that the results reported in [2] were only using Partial Rake from our discussion in Section 4.

Examining Figures 2 and 3 it can be seen that the performance of STS-TH-UWB-PPM was comparable to that found for the Simulink simulation of Yang's Analog ST coding I system. However, it should be noted that the STS system transmits two binary bits within a symbol period whereas Yang's ST coding I system only transmits one binary bit.

If one considers the individual transmitting antenna branches of the STS and Yang Analog ST coding I system, the STS system has encoded the two bits to be transmitted (this is the case in both antenna branches) whereas Yang's equivalent technique only has one. If this is considered then the results in Figure 4 and 5 are applicable where a significant improvement per antenna can be seen.
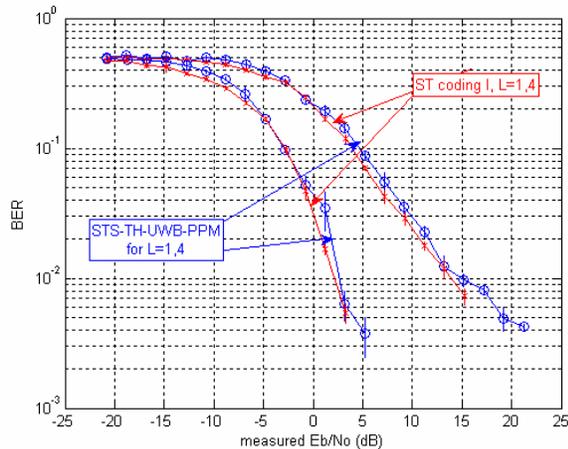
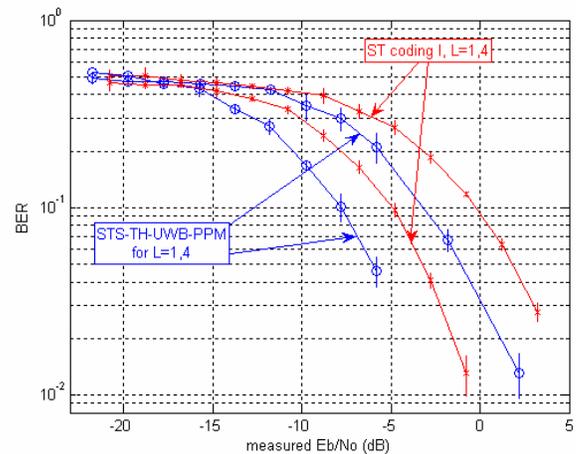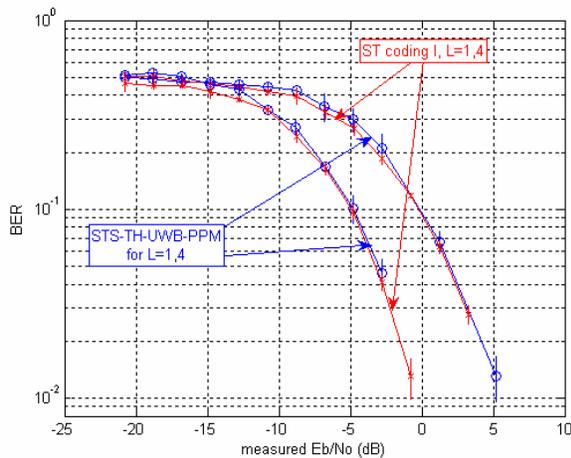Figure 2: Simulation of Analog ST coding I and STS-TH-UWB-PPM proposed system for Partial Rake L=1,4

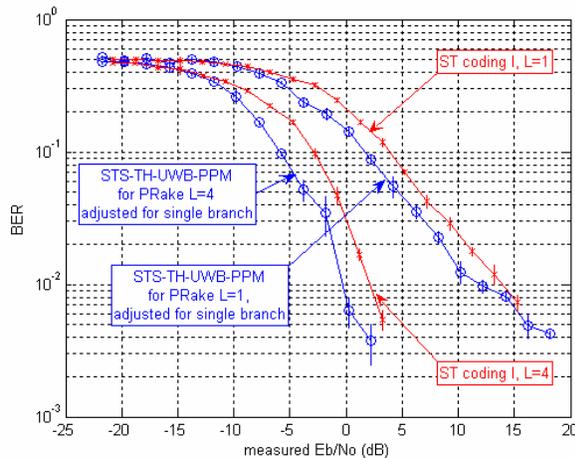Figure 3: Simulation of Analog ST coding I and STS-TH-UWB-PPM proposed system for Selective Rake L=1,4

Figure 4: Simulation of Analog ST coding I and STS-TH-UWB-PPM per antenna branch proposed system for Partial Rake L=1,4

Figure 5: Simulation of Analog ST coding I and STS-TH-UWB-PPM per antenna branch proposed system for Selective Rake L=1,4

6. Conclusion

We propose a novel technique to allow transmission of two binary bits using two transmit antennas called STS-TH-UWB-PPM. It has the advantage that the binary bits are available on both antenna signals and requires two spreading sequences to transmit two binary bits. This compares to Yang's Analog ST coding I schema which uses two spreading codes (and only one set allowed) to transmit one binary bit. This proposed system has comparable or significantly better performance to the Analog ST coding I schema described in [2].

Future work will include investigating the effect of MAI (Multiple Access Interference) for one to four interferers and possible mitigation techniques which could be employed, such as spreading codes with low cross correlation sidelobes.

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