APPLICATION OF LAYERED SPACE-TIME PROCESSING TO ULTRA-WIDEBAND COMMUNICATION

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ABSTRACT

Ultra-wideband (UWB) signals use extremely short duration pulses (on the order of hundreds of picoseconds) for transferring information. This makes it the technology of choice for high-speed short-range communications in dense multipath channels [3]. In this paper we analyze the usefulness of using Layered Space-Time Processing [1] over a UWB system. VBLAST is one such approach proposed to increase spectral efficiency using multi-input multi-output channels [1]. We propose the exploitation of the large number of resolvable multipath components in a UWB environment to achieve similar spectral efficiency gains. In this paper we investigate the bit error rate versus spectral efficiency tradeoff by applying the VBLAST concept to a UWB system.

1. INTRODUCTION

Ultra-wideband (UWB) is seen to be a technology for delivering very high data rates at very low power spectral densities. The most common form of UWB is Impulse Radio, which communicates using very short pulses, typically on the order of hundreds of picoseconds. Due to the short pulse duration of the signal, it is believed that UWB signals are relatively immune to the fading effects that other narrowband signals suffer. Moreover, due to the extremely short duration of the pulses, ultra-wideband signals can be expected to have significantly more resolvable multipath as compared to narrowband signals. For high-speed communication, it is desirable to increase the spectral efficiency of the system with little or no degradation in energy efficiency. By using layered space-time processing we expect the spectral efficiency to increase by the amount of transmit antennas and intend to exploit the multipath in the channel to achieve the necessary de-correlation between the signals at the receiver.

VBLAST relies on rich scattering to achieve de-correlation between the signals from multiple transmit antennas at the receiver. In VBLAST, different signals are transmitted from different antennas. If the received signals are sufficiently uncorrelated at the receiver, then it is possible to recover each of the transmitted signals (provided that the number of receive antennas are equal to or greater than the number of transmit antennas).

In this paper we have applied the concepts of VBLAST to UWB with 1 receive antenna and several resolvable multipaths. The number of multipaths are analogous to additional receive antennas at the receiver. The paper outline is as follows. Section 2 gives an overview of the system model. Section 3 gives a detailed explanation of the concept of Layered Space-Time Processing, which has been applied to our system. Section 4 provides the simulation results while section 5 provides discussion and conclusions.

2. SYSTEM MODEL

A high-level system model is shown in Figure 1.

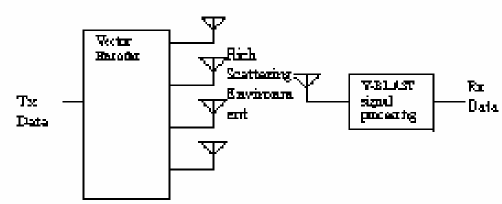

Figure 1. System Model diagram

The vector encoder de-multiplexes data into n_T independent Pulse Position Modulated (PPM) streams. PPM can be described by [3] as

$$s^{(k,i)}(t) = \sum_{j=-\infty}^{\infty} w(t - jT_f - c_j^{(k)}T_c - dd_{\lfloor j/N_s \rfloor}^{(k,i)}), \quad (1)$$

where T_f is the pulse repetition interval, $c_j^{(k)}$ is the time hoping code for user k, T_c is a time shift defined for the code, d is the time delay used for PPM modulation and $d_{\lfloor j/N_s \rfloor}^{(k,i)}$ is the data bit to be transmitted in frame $\lfloor j/N_s \rfloor$, $\lfloor \ \rfloor$ represents the integer portion and i corresponds to the i^{th} transmit antenna. N_s is the pulse repetition frequency. We have assumed binary PPM in which d is equal to a binary data bit b e {0,1}. $c_j^{(k)}$ is the time hopping code used by user k and is the same for all antennas. In addition to the PPM performed according to the data bit, this code is used to place the data randomly in a given frame. This is useful for multiple access and also helps reduce the spectral lines which may cause interference to systems occupying the same frequency band.

At the transmitter the data stream is split into independent paths according to the number of transmit antennas. At each antenna the data is modulated according to equation (1) and then transmitted from the antennas independently.

The channel is something of an unknown for UWB signals. While it is assumed that UWB is *immune* to fading, it has been found that UWB does experience some variation in the received signal. We have assumed what we call a Gaussian fading channel. This assumption may not be completely justified, but recognizes the lack good of a good model for UWB propagation. The assumed model reflects the fact that baseband transmission is assumed (i.e. channel is completely real) and that fading is not anticipated to be as severe as Rayleigh. The channel Υ_i is modeled as a real Gaussian Random Variable with mean = ½ and σ^2 = ½ (analogous to Ricean fading with *K=1*). The multipath delay profile is assumed to follow an exponentially decaying curve with an order of 0.25. In other words

$$P(t) = e^{-t/4T} \tag{2}$$

where $\tau = 0$ reflects the direct LOS component and T is the resolvability of the channel. The delay between each multipath is assumed to be the same and equal to T. The power delay profile of all the antennas has been assumed to be the same, although the channel realizations are independent for each antenna. At the receiver, a layered space-time processing algorithm is implemented as described below.

3. LAYERED SPACE-TIME PROCESSING CONCEPT IMPLEMENTATION

The analysis here is similar to that shown in [2]. The received signal at the output of n_R matched filters (one for each resolvable multipath component) in vector form is,

$$\mathbf{y} = \sum_{i=1}^{n_T} \mathbf{h}^{(i)} x^{(i)} + \mathbf{n} \tag{3}$$

where $x^{(i)}$ is the transmitted signal and $\mathbf{h}^{(i)}$ is the channel vector from the i^{th} antenna, and $\mathbf{n}$ is the Additive White Gaussian Noise. The total power of the channel taps is equal to unity.
In matrix notation

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{4}$$

where

$$H = \begin{bmatrix} h^{(11)} & . & . & . & h^{(n_T 1)} \\ . & & & & . \\ . & & & & . \\ . & & & & . \\ h^{(1 n_M)} & . & . & . & h^{(n_T n_M)} \end{bmatrix} \tag{5}$$

$$\mathbf{y} = \begin{bmatrix} y^{(1)} \\ . \\ . \\ . \\ y^{(n_R)} \end{bmatrix}, \mathbf{x} = \begin{bmatrix} x^{(1)} \\ . \\ . \\ . \\ x^{(n_T)} \end{bmatrix}, \; n = \begin{bmatrix} n^{(1)} \\ . \\ . \\ . \\ n^{(n_R)} \end{bmatrix} \tag{6}$$

We have applied the same concept as that used by V-BLAST [1] with one modification in the algorithm. We assume only one receive antenna and conceptually the number of receive antennas is replaced by the number of resolvable multipath components. The implemented algorithm is a successive interference cancellation type of algorithm and is described below.

We initially correlate the received signal with the correlation envelope at each delay being tracked to n_R matched filter outputs. This vector of outputs is then processed using a nulling/cancellation algorithm to recover the n_T independent data streams. The nulling/cancellation is repeated for each transmit antenna. We have assumed in this work perfect channel estimation at the receiver. In the algorithm we find a nulling vector, which is used to project the received signal vector away from all but the signal of interest. Either zero forcing (ZF) or minimum mean squared error (MMSE) type of nulling criterion can be used. The ZF solution is an easier solution but not optimum as it enhances the noise. Instead we have used the MMSE method, which gives us better performance.

In the first iteration, we set $H_i = H$ and $y_i = \mathbf{y}$. We calculate the pseudo inverse of H_i as

$$G_i = H_i^{+} = (H_i^H H_i + I / SNR)^{-1} H_i^H , \tag{7}$$

where H_i^H is the complex conjugate transpose of H. I is an identity matrix. All the rows of G_i are the nulling vectors for the i^{th} transmit antenna. We can choose any row of G_i to null the signal from the i^{th} transmit antenna. However, it was shown in [1] that it is best to start with the signal that has the greatest signal to noise ratio (SNR). The post detection SNR is given by,

$$SNR = \left| x_{z_i} \right|^2 \Big/ \left\| z_i \right\|^2 \tag{8}$$

where z_i is calculated in equation (9). To increase the SNR we need to find that row of G_i that has the minimum norm. The norm is calculated as

$$z_i = \min_{j=\{1,2,..n_T\}} \left\| (G_i)_j \right\|^2 , \tag{9}$$

We now define the nulling vector to be the z_ith column of $\mathbf{G}_i$

$$w_k^{(z_i)} = (G_i)_{z_i}^T \tag{10}$$

We remove the effect of the signal transmitted from the z^{th} antenna by multiplying the received vector by the nulling vector.

$$x_k^{(z_i)} = w_{z_i}^T y_i \tag{11}$$

As we are using binary PPM, the correlation template is the transmitted pulse for a transmitted 0 and the inverse of the transmitted signal for a transmitted 1. This narrows our decision making process to determining the sign of $x_k^{(z_i)}$. After we make the decision for the signal sent from the z_{th} transmit antenna, we remove the detected signal from the received signal to obtain a better estimate of the remaining pulses. The received vector becomes,

$$y_{i+1} = y_i - x_k^{(z_i)} (H_i)^{z_i}, \qquad (12)$$

The channel matrix is also changed as we do not require the $(z_i)^{th}$ column of the matrix. It is thus eliminated.

The new channel matrix becomes [1],

$$H_{i+1} = H_i^{-z_i} \qquad (13)$$

We repeat steps (6) through (13) until all the signals are detected. We should note that as we reduce the number of signals present in the received vector in each subsequent detection, the diversity level will increase for each subsequently detected layer.

In algorithm form, the process is described as below

Initialization:

$$i = 1 \qquad (14)$$

Each iteration:

$$G_i = H_i^+ \qquad (15)$$

$$z_i = \min_{j=\{1,2,\ldots n_T\}} \left\| (G_i)_j \right\|^2 \qquad (16)$$

$$w_k^{(z_i)} = (G)_{z_i}^T \qquad (17)$$

$$x_k^{(z_i)} = w_{z_i}^T y_i \qquad (18)$$

$$\text{if } (x_k^{(z_i)} > 0)\ \hat{a}_{k_i} = 0 \text{ else } \hat{a}_{k_i} = 1 \qquad (19)$$

$$y_{i+1} = y_i - x_k^{(z_i)} (H_i)^{z_i} \qquad (20)$$

$$H_{i+1} = H_i^{-z_i} \qquad (21)$$

$$i = i + 1 \qquad (22)$$

4. RESULTS

Figure 2 shows the implementation of VBLAST over UWB for the case of 2 multipaths. The multipaths are assumed to follow an exponential distribution. We observe that since there are only 2 dimensions in the received signal vector, the system quickly becomes interference limited as the number of transmit antennas increases. Specifically, performance degrades significantly for more than 2 transmit antennas. We conclude that the number of multipaths should be at least equal to the number of transmit antennas so that the system is not interference limited.

We extended the analysis to a system with 5 resolvable multipath components (Figure 3). We observe that due to the increased dimensionality of the system we see better performance. For the 1 Tx – 1 Rx case also we observe better BER performance due to the increased diversity achieved by combining 5 multipaths. Further, due to the extra dimensionality of the received signal, this system is less interference limited. Similarly we achieve even better performance when 10 multipath components exist (Figure 4).

For the case of 10 multipath components and a target bit error rate of 1%, we are able to improve the spectral efficiency 4 fold by sacrificing 1 dB of degradation in performance and without increasing the order of the modulation scheme which would limit multiple access capabilities.

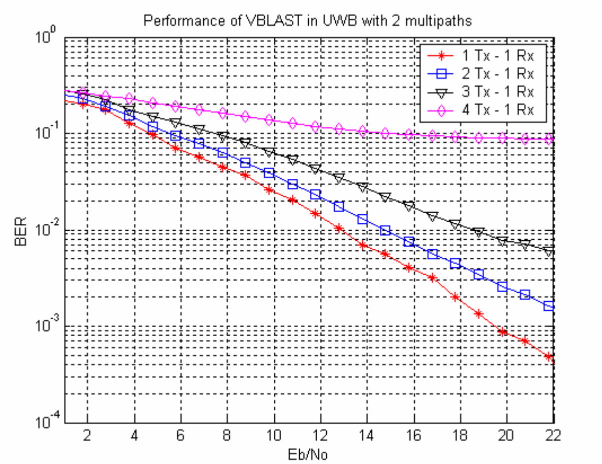

Figure 2. Performance of VBLAST over UWB with 2 multipaths and 1, 2, 3 and 4 transmit antennas. (Exponential decay of multipaths)

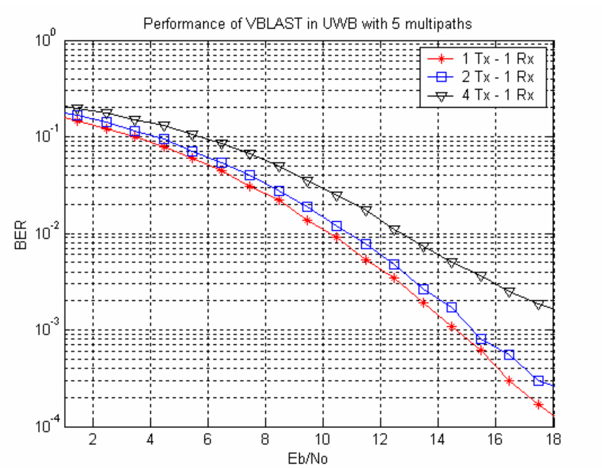

Figure 3. Performance of VBLAST over UWB with 5 multipaths and 1, 2 and 4 transmit antennas. (Exponential decay of multipaths)

Note that all the curves have been normalized such that the total combined power always remains the same (*i.e.*, E_b/N_o is constant). This provides a fair comparison.

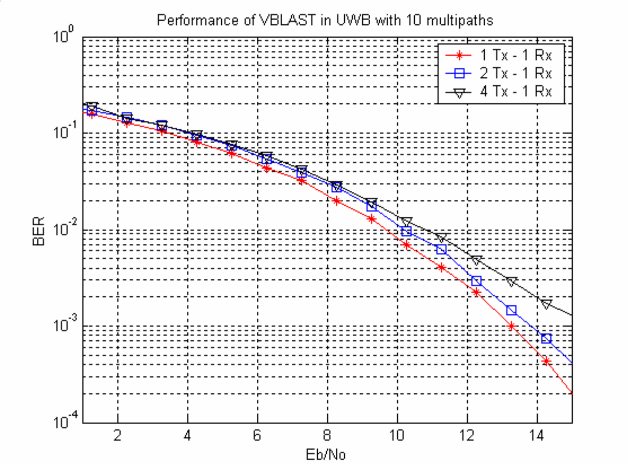

Figure 4. Performance of VBLAST over UWB with 10 multipaths and 1, 2 and 4 transmit antennas. (Exponential decay of multipaths)

We also ran simulations for the case in which all the multipath components have equal energy. The results for a 5 multipath case and 10 multipath case are shown in Figures 5 and 6 respectively. We observe that with equal power in all the multipaths, the performance of the system is improved as compared to the case in which the multipaths have an exponentially decaying distribution as we achieve more diversity in the system. We also observe little or no degradation in performance in the system when comparing the 1 transmit antenna case with the 2 and 4 antenna case, as the signals are more easily detected due to the decreased correlation between received channel vectors.

5. SUMMARY AND CONCLUSION

In this paper we have studied the application of layered space-time coding/decoding to UWB systems. The studied cases include 1,2 and 4 transmit antennas, 2, 5, and 10 multipath components. The initial results assumed perfect channel knowledge are very encouraging since we see a 4-fold increase in the performance of the system with little degradation in BER performance. Similar improvements could be obtained through higher order modulation. However, this will limit multiple access capabilities and is thus undesirable. Although the assumption of Gaussian fading is not necessarily valid, we expect to see similar gains in performance for other types of fading channels. More severe fading will improve orthogonality between signals, while more benign fading will degrade this orthogonality. This assumption will be examined as better channel models become available for UWB. Additionally, the independence between transmit antennas needs to be examined.

Finally, this work is based on the assumption of perfect channel estimation at the receiver. With 10 resolvable multipath components, channel estimation will not be a trivial task. As an extension to our analysis in future work, we will examine the effects of channel estimation error on the gains that we have observed.

6. REFERENCES

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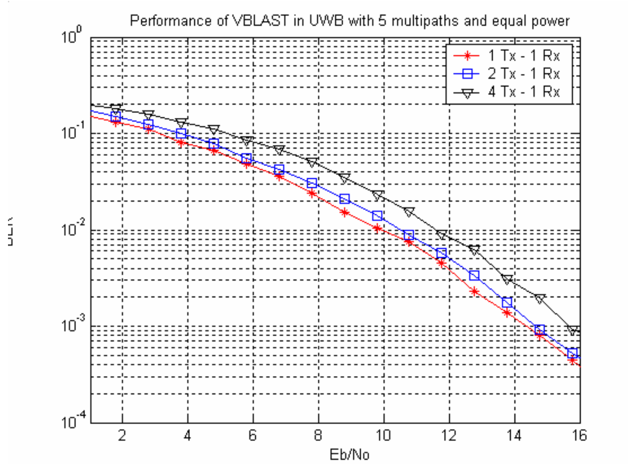

Figure 5. Performance of VBLAST over UWB with 5 multipaths and 1, 2 and 4 transmit antennas. (Equal power multipath)

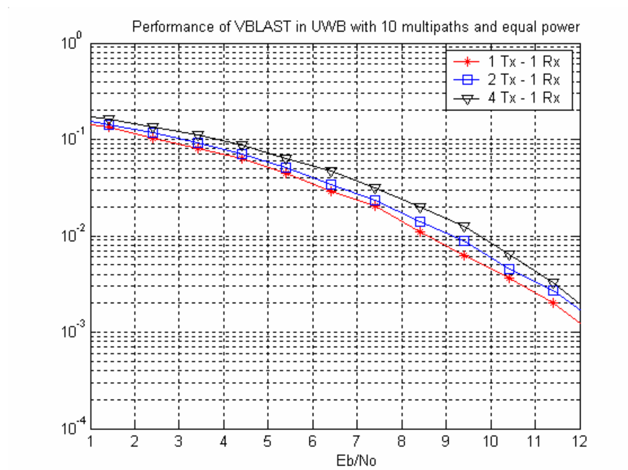

Figure 6. Performance of VBLAST over UWB with 10 multipaths and 1, 2 and 4 transmit antennas. (Equal power multipath components)