Abstract: - In this paper we introduce a technique of eigenbeamforming based on the channel correlation matrix and paired with orthogonal space-time code (O-STBC) at the transmitter side of the link. This structure combines the spatial signal paths decorrelation with the diversity gain provided by the space-time code, which results in performance improvement. The probability distributions for both bit-error-rate (BER) and symbol-error-rate (SER) are presented based on the received signal-to-noise ratio (SNR) for this system. The system has been simulated using four transmit antennas in both uncorrelated and correlated channels. Results showed that the proposed scheme provides a significant improvement in the error rate performance of spatially correlated channels.

Key-Words: - Adaptive beamforming, space-time channel, MIMO, transmit diversity, block coding

1 Introduction

It is often impossible to correctly detect the transmitted data at the receiver without some form of training signal or less-attenuated replica of the transmitted signal to provide redundancy in the spatial domain. This is due to signal fading introduced by the propagation channel, which degrades the performance of wireless communication systems. The classical approach is the use of receiver diversity where multiple antennas are employed at the receiving side for achieving spatial diversity to combat signal fading. By applying the same concept, spatial diversity can also be achieved by employing multiple antennas at the transmitter side, or both sides. In fact, it has been shown in [1]-[3] that the use of multiple antennas at both transmitter and receiver can greatly improve system capacity. However, in practice, it is more cost effective and feasible to employ multiple antennas at the base station (BS) only. Therefore, in the past decade considerable attention in transmission optimisation has turned to the BS transmit antenna array, so we will only consider transmit diversity.

Different transmit diversity schemes have been proposed in order to provide diversity gain. The technique described in [4] utilized feedback signalling to achieve its diversity gain. In [5], the technique of training information but no feedback is used. In 1998, Tarokh et al. proposed space-time trellis coding (STTC) in [6] by jointly designing forward error coding (FEC), modulation, transmit and receive diversity to provide high performance. The performance criteria for designing STTC were derived in [6] under the assumption that the channel is fading slowly and that the fading is frequency-nonselective. These advances were then also extended to fast fading channels. Despite the fact that STTC performs extremely well, it comes at the cost of relatively high encoding and decoding complexity. In addressing the issue of system complexity, Alamouti [7] discovered a remarkable space-time block code (STBC), which uses two transmit antennas and offers a significant low complexity system but at a cost of slight performance degradation. This invention motivates Tarokh et al. to go on to generalise STBC to an arbitrary number of transmitter antennas by orthogonal design in [8], called orthogonal space-time block coding (O-STBC). Its decoding algorithms and performance results are later presented in [9].

However, the primary requirement for diversity improvement of these space-time codes is based on the assumption that the channel is sufficiently uncorrelated. In practice, different signal paths arrived at the multiple antennas are often correlated to some degree. Hence, if the received signal has been severely attenuated by the propagation fading effect, it is highly likely that its replicas have also
experienced the same coherent deep fade. In [10], Siwamogsatham proposed a robust space-time code for data transmission over correlated Rayleigh fading channel. It is a concatenation of trellis coded modulation (TCM) and STBC as its outer encoder. It is proven to achieve a good performance in a broad range of correlated Rayleigh fading conditions but at a cost of high encoding and decoding complexity.

In this paper, we introduce a new transmit diversity scheme by jointly using transmit eigenbeamforming with orthogonal space-time block coding (O-STBC). This new scheme combines the capabilities of these two different transmission techniques in exploiting propagation channel characteristics to achieve a remarkable performance in wireless transmission in spatially correlated channel environment. There are other similar schemes proposed over the last few years [11]-[16], but they all require some sort of feedback signalling about the propagation channel or the use of training sequence to achieve their performance gain.

The underlying concept of our proposed scheme is the transmission of data symbols that is encoded by the O-STBC then transmitted in the direction of strongest signal path seen by the mobile station (MS). As for signal transmission in a multipath propagation environment described in [17], the paths used by both uplink and downlink can be assumed to be identical. Therefore, the number of paths, the path delays, and path angles are the same for both links. Based on this fact, the decorrelation of channel spatial covariance matrix can be performed at the BS by eigen-analysis of uplink path angles estimates. This eliminates the need for feedback signalling of the downlink channel estimates from the MS. Furthermore, it reduces the computation and the complexity of the system that is usually required in other schemes mentioned above.

This paper is organized in the following format: in Section 2, signal model for the transmit beamforming transmission in a multiple input multiple output (MIMO) channel configuration is presented. Its description and mathematical models will be given as well as the signal model for the forward link. The encoding and decoding algorithms of a $\frac{1}{2}$ rate O-STBC using four transmit antennas are presented in Section 3. In Section 4, a description of the space-time channel model with hyperbolically distributed scatterers is provided. Error probability analysis for the proposed system is described in Section 5. In Section 6, we present simulation results of the new transmission scheme and compare their performance in two different channel conditions. Finally, Section 7 presents our conclusions and remarks.

2 Signal Model

A general structure of a transmission system comprising transmit beamforming and space-time coding transceiver is shown in Fig 1. Consider wireless transmission in a multiple input multiple output (MIMO) wireless channel configuration comprising $N_t$ transmit antennas at the base station (BS) and $N_r$ receive antennas at the mobile station (MS). We assume that a uniform linear array (ULA) is used at the BS with a spacing of $d$ meters between the antenna elements. In the uplink transmission over a multipath channel environment, let the $n$th path signal impinging on an ULA have an angle-of-arrival (AoA) of $\theta_n$. The array propagation vector can be found as follows:

$$a(\theta_n) = [1 \ e^{j\beta} \ e^{j(2\beta)} \ \ldots \ e^{j(x\lambda-1)\beta}]$$

where $\beta = \frac{2\pi}{\lambda} \cdot d \cdot \sin(\theta_n)$ and $\lambda$ being the carrier frequency wavelength. According to [18], the spatial covariance matrix that specifies the spatial correlation between antenna elements is given by:

$$R = \frac{1}{L} \sum_{\beta=0}^{L-1} a(\theta_n) a^H(\theta_n)$$

where $L$ denotes the number of dominant resolvable signal paths. Let $h_j$ denotes the channel vector between the $j$th mobile receive antenna the BS transmit antennas. It has a form of $h_j = \sqrt{R} U_j$ with $U_j = [u_{1,j} \ u_{2,j} \ \ldots \ u_{N_t,j}]^T$, where $(.)^T$ denotes vector transpose operation. $u_{i,j}$ is the channel fading coefficient between the $i$th transmitting antenna (at the BS) and the $j$th receiving antenna (at the MS) and is modelled as a zero-mean complex-valued Gaussian process with Jakes power spectrum density.

To maximize the transmitted signal power along the dominant multi-paths, eigen-decomposition of the spatial covariance matrix (2) should be performed, then apply the resulting antenna weights.
given by the eigenvector that corresponds to the largest eigenvalue. The eigen-decomposition has the following form:

\[ R = VDV^H \]  

where \( D = \text{diag}(\mu_1, \mu_2, \cdots, \mu_{N_t}) \) is a diagonal matrix with ordered eigenvalues on the main diagonal and unitary matrix \( V \) is composed with corresponding eigenvectors. Hence, the transmit weight vector \( \mathbf{w} = [w_1 \ w_2 \ \cdots \ w_{N_t}]^T \) can be found is the first column of \( V \).

If the transmit weight vector is applied prior to the signal transmission, the transmitted signal \( \mathbf{x} \) has a form of:

\[ \mathbf{x} = [w_1^* x \ w_2^* x \ w_3^* x \ w_4^* x]^T. \]  

(4)

The received signal at the \( j \)th MS antenna can be expressed as:

\[ y_j = \mathbf{x}h_j + \eta_j \]  

(5)

where \( \eta \) is the additive white Gaussian Noise with one-sided sample variance of \( N_0/2 \).

### 3 Orthogonal Space-Time Block Code

In comparison between different space-time codes described in [4], [5], [6], [7], and [10], the orthogonal space-time block code (O-STBC) in [8] is considered in this paper due to its simplicity in encoding and decoding algorithms and its appealing performance over Rayleigh fading channel using multiple transmit antennas.

The construction of this STBC was based on a classical mathematical framework of orthogonal design. The original data symbols of size of \( k \) are first fed to the space-time encoder. At the output of the encoder there is a transmission matrix with a dimension of \( p \times N_t \), where \( N_t \) is the number of transmit antennas and \( p \) represents the number of time slots used to transmit \( k \) input symbols. This matrix is a linear combination of input data signal and the signal replicas artificially created at the encoder.

At any time instant, \( i \), the elements in the \( i \)th row of the transmission matrix is transmitted simultaneously from \( N_t \) transmit antennas. Hence, the transmission code rate can be easily calculated by:

\[ r = \frac{k}{p}. \]  

(6)

An example of O-STBC encoding scheme using four transmit antennas for a code rate of \( \frac{1}{2} \) is given by [8]:

\[
G_4 = \begin{pmatrix}
    s_1 & s_2 & s_3 & s_4 \\
    -s_2 & s_1 & -s_4 & s_3 \\
    -s_3 & s_4 & s_1 & -s_2 \\
    -s_4 & -s_3 & s_2 & s_1 \\
    \end{pmatrix}
\]

(7)

The decoding algorithm at the receiver is the maximum likelihood detection that minimizes the decision metric over all possible values of codeword. The decision metric for decoding \( x_1 \) is given by:

\[
\begin{aligned}
&\frac{1}{2} \sum_{j=1}^{N_t} \left[ (y_{1,j}h_{1,i} + y_{2,j}h_{2,i} + y_{3,j}h_{3,i} + y_{4,j}h_{4,i} + (y_{5,j})^* h_{1,j} - x_{1})^2 \\
&+ 1 + 2 \sum_{i=1}^{N_t} \sum_{j=1}^{N_t} (y_{i,j}^* h_{i,j} + (y_{i,j}^*)^* h_{i,j} + (y_{i,j})^* h_{i,j}) \right] x_{1}^2
\end{aligned}
\]

(8)

The decision metric for decoding \( x_2 \) is given by:

\[
\begin{aligned}
&\frac{1}{2} \sum_{j=1}^{N_t} \left[ (y_{1,j}h_{1,i} - y_{2,j}h_{2,i} - y_{3,j}h_{3,i} + y_{4,j}h_{4,i} + (y_{5,j})^* h_{2,j} - x_{2})^2 \\
&+ 1 + 2 \sum_{i=1}^{N_t} \sum_{j=1}^{N_t} (y_{i,j}^* h_{i,j} - (y_{i,j}^*)^* h_{i,j} + (y_{i,j})^* h_{i,j}) \right] x_{2}^2
\end{aligned}
\]

(9)

The decision metric for decoding \( x_3 \) is given by:

\[
\begin{aligned}
&\frac{1}{2} \sum_{j=1}^{N_t} \left[ (y_{1,j}h_{1,i}^* + y_{2,j}h_{2,i}^* - y_{3,j}h_{3,i}^* - y_{4,j}h_{4,i}^* + (y_{5,j})^* h_{3,j} - x_{3})^2 \\
&+ 1 + 2 \sum_{i=1}^{N_t} \sum_{j=1}^{N_t} (y_{i,j}^* h_{i,j}^* - (y_{i,j}^*)^* h_{i,j} + (y_{i,j})^* h_{i,j}) \right] x_{3}^2
\end{aligned}
\]

(10)

The decision metric for decoding \( x_4 \) is given by:
where $D$ is the distance between the BS and the MS.

5 Error Probability Analysis

To evaluate the performance of the proposed system, we have developed computer simulation to calculate the bit-error-rate (BER) and symbol-error-rate (SER). Following the same notation in the previous sections and that used in [20], a general form of calculating BER and SER for a system employing 4-ary PSK baseband modulation can be given by:

$$P(e) = Q \left( \sqrt{2\gamma_b} \right)$$

and:

$$P(e) = 2Q \left( \sqrt{2\gamma_b} \right) \left[ 1 - 0.5Q \left( \sqrt{2\gamma_b} \right) \right],$$

respectively, where $\gamma_b$ is the average received signal-to-noise ratio (SNR) at the output of maximum ratio combiner (MRC). Detailed derivation is given in [20]. $Q(.)$ is the Q-function given by:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-t^2/2} dt$$

The received SNR ($\gamma_b$) should be found from the following formula:

$$\gamma_b = \frac{E[\|Y\|_F^2]}{pN_r \sigma_n^2}$$

where $Y$ is the received signal matrix, which has the form $Y = CWH$, where $C$ is the O-STBC matrix, with a dimension of $p \times N_r$, $W = \text{diag}(w_1, w_2, \ldots, w_{N_r})$, $H = [h_1, h_2, \ldots, h_{N_r}]$ is the channel matrix, and $\sigma_n^2$ is the noise variance.

Note that $\|\cdot\|_F$ denotes the Forbenius norm defined as $\|A\|_F = \sqrt{\sum_{i,j}|a_{ij}|^2}$. The result of this numerical analysis will be presented in the next section.

6 Simulation Results and Discussion

In this simulation we consider a MIMO channel configuration as shown in Fig. 1 with $N_r = 4$ uniform linear array (ULA) having element spacing of $0.5\lambda$ at the BS, and $N_r = 2$ at the MS. We assumed that the number of dominant resolvable paths is $L = 4$ for the estimation of spatial covariance matrix. Since a single path propagation model has always been used for the performance
evaluation of space-time codes, we also adopt this method for our forward link simulations.

In general, quasi-static fading channel is modelled with the amplitude coefficients of \(u_{i,j}\) being Rayleigh distributed having \(E[|u_{i,j}|^2] = 1\), while the phase is uniformly distributed over the interval \([0, 2\pi]\). The channel fading coefficient is kept constant for the duration of space-time encoded block length but independently generated for different antenna paths and blocks. The receiver is assumed to have perfect knowledge of these coefficients for maximum likelihood decoding.

For the performance evaluation of the proposed transmit diversity scheme, we simulated the system with O-STBC in two different channel environments. In the spatially correlated macrocell environment with geometrical based hyperbolically distributed scatterers (GBHDS) channel model proposed in [19], we set \(a_1 = 0.2\), \(a_2 = 0.007\), and \(D = 1000\) meters. With these parameter values applied in equation (6) and (8) of [19], dominant and local scatterers are hyperbolically distributed at a maximum of 700 meters and 50 meters respectively from the MS. These parameter values set the GBHDS channel model to a typical macrocell scenario.

In the case of no channel correlation, the spatial covariance matrices have the following form:

\[
R = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (21)

Note that eigen-analysis of this channel environment provides no spatial decorrelation and only sets the amplitude equally to all antenna elements of a value of 0.5.

We simulated the new transmit diversity system in two different channel environments with one being spatially correlated and the other being uncorrelated. The O-STBC encoding scheme used for \(N_t = 4\) is \(G_4\) as specified in (7) and the decoding algorithm is provided in (8)-(11). Different numbers of receiving antennas are used for the new scheme; also considered in both channel environments. QPSK for the baseband modulation of information bits is employed at the transmitter and both symbol error rate (SER) and bit error rate (BER) are being calculated at the receiver.

Fig. 2 shows both SER and BER performance curves of the new transmit diversity scheme in a channel that has no spatial correlation between...
antenna paths. The diversity improvement in having an additional receive antenna is at an average of 4.5 dB over a single receive antenna for both SER and BER. It is very consistent with the simulation results in [9].

A very similar performance curve is shown in Fig. 3, but with lower system error probability when the forward link channel is modelled as macrocell environment with hyperbolically distributed scatterers. This proves that the decorrelation process (eigen-decomposition) gives better performance in an environment with a higher degree of spatial channel correlation. The diversity improvement of using two receive antennas over a single antenna is at an average of 5.5dB in the GBHDS channel model.

More importantly, if we compare the error rate performance over these two figures, a significant gain in SNR of about 4dB at an error rate of $10^{-4}$ for $N_r = 2$ and 4.3dB at an error rate of $10^{-2}$ for $N_r = 1$ in both SER and BER is obtained.

In addition to the above simulation results, we have also provided error probability results based on theoretical analysis for the uncorrelated channel model. Results of this analysis results are shown in Fig. 4; they are very similar to the results of the numerical simulation shown in Fig. 2. Comparing these two figures, a slight variation in the performance could be noticed; this is due to the fact that the random realizations of channel coefficients in the numerical simulation were not always equal to the statistical averaged value used in the theoretical analysis. Nevertheless, it provides comparable system performance curves.

7 Conclusion

A high performance transmit diversity scheme is proposed. The idea involves combining transmit eigenbeamforming with orthogonal space-time block coding. The system has been simulated and tested in two channel models with different spatial correlations. Simulation results have shown that the proposed technique preserves the same diversity gain in uncorrelated channel environments as in the case of using only orthogonal space-time block coding, however, it provides a remarkable improvement in the diversity gain in spatially correlated channel environments.

References:


