Doufexi, A., Nix, A. R., & Beach, M. A. (2005). Combined spatial multiplexing and STBC to provide throughput enhancements to next generation WLANs. In IST Mobile & Wireless Communications Summit, Dresden, Germany.

Combined Spatial Multiplexing and STBC to Provide Throughput Enhancements to Next Generation WLANs

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***Abstract* — Recently, there has been an explosion of growth in research on MIMO (Multiple Input Multiple Output) systems. Current WLAN systems such as IEEE 802.11a and 802.11g Wireless Local Area Networks (WLANs) employ Coded Orthogonal Frequency Division Multiplexing (COFDM) and provide data rates of up to 54 Mbps in a 20MHz bandwidth. In this paper, space-time block coding (STBC) and spatial multiplexing MIMO techniques are considered as a means of enhancing the performance of COFDM WLANs. A hybrid 4x4 scheme is presented that combines spatial multiplexing and STBC to provide both increased throughput and diversity. Results showed that the proposed scheme can provide good performance even under correlated channels.**

I. INTRODUCTION

At present, Wireless Local Area Networks (WLANs) supporting broadband multimedia communications are being deployed around the world. Standards developed include IEEE 802.11a/g [1,2,12] based on orthogonal division multiple access (OFDM). These systems provide channel adaptive data rates up to 54 Mbps in a 20 MHz channel spacing. The IEEE is currently working towards a standard for next generation wireless LANs. This standard, known as 802.11n, will aim to offer a minimum of 100 Mb/s after the MAC layer.

In this paper a hybrid 4x4 scheme is investigated that combines spatial multiplexing and STBC to provide both increased throughput and diversity to future generation WLANs. STBC is a simple and attractive space time coding scheme that was proposed by Alamouti [5]. It requires only a small degree of additional complexity and is suitable for the slow fading environments in which WLANs are deployed. STBC can enhance performance by exploiting spatial diversity. This is particularly useful in the case where the delay spread of the environment is low (i.e. low frequency diversity). For these reasons, STBC techniques have been examined to enhance the PER performance of WLANs [6,7]. Spatial multiplexing [8] relies on transmitting independent data streams from each transmit antenna. These data streams can be multiplexed from the incoming source stream. If *N* transmit and receive antennas are present then data can be sent at *N*-times the rate of a standard terminal. Spatial multiplexing exploits the benefits of the MIMO channel to enhance the rate at which data is sent, rather than enhancing the reliability of its detection.

For this study, a WLAN physical layer simulator employing MIMO techniques [2,7] was developed to evaluate the PER and throughput of WLANs for the 2x2, 4x2 and 4x4 MIMO cases with and without the hybrid algorithm. PER and throughput results are produced for a number of channel scenarios.

II. WLAN PHYSICAL LAYER

The physical layers of 802.11a [1], 802.11g [12] and HIPERLAN/2 (H/2) [2] are based on the use of OFDM. OFDM is used to combat frequency selective fading and to randomize the burst errors caused by a wideband-fading channel. OFDM is implemented by means of an inverse FFT. 48 data symbols and 4 pilots are transmitted in parallel in the form of one OFDM symbol. In order to prevent ISI, a guard interval is implemented by means of a cyclic prefix (CP). When the guard interval is longer than the excess delay of the radio channel, ISI is eliminated. The physical layer provides several modes [1,2], each with a different coding and modulation configuration (Mode1: BPSK 1/2 rate, Mode2: BPSK ¾ rate, Mode3: QPSK ½ rate, Mode4: QPSK ¾ rate, Mode5: 16QAM 9/16 rate, Mode6: 16QAM 3/4 rate, Mode7: 64QAM 3/4 rate). These are selected by a link adaptation scheme. Physical layer details can be found in [1,2].

III. SPACE TIME BLOCK CODING

In [5] Alamouti proposed a simple transmit diversity scheme which was generalized by Tarokh [9] to form the class of Space Time Block Codes. These codes achieve the same diversity advantage as maximal ratio receive combining. The transmit diversity scheme can be easily applied to OFDM in order to achieve a diversity gain over frequency selective fading channels [6,7]. In Alamouti's encoding scheme 2 signals are transmitted simultaneously from the 2 transmit antennas. The transmission matrix is given by [5]:

$$G^h{}_2 = \begin{bmatrix} X_1 & X_2 \\ -X_2^* & X_1^* \end{bmatrix} \tag{1}$$

where, in the case of OFDM, X_1, X_2 are the transmitted signals at a given subcarrier *k* (from two consecutive OFDM symbols) before being input to the IDFT and after the serial to parallel conversion (S/P) of the QAM modulated data.

In [9], Tarokh proposed and evaluated the performance of STBC for the case of 3 and 4 transmit and receive antennas. For two antennas STBC provides full spatial diversity and represents a rate one code. For complex constellations and for the specific cases of three and four transmit antennas, diversity schemes were proposed in [9] that provide ¾ of the maximum possible transmission rate. In [13], these codes (G^h_3 and G^h_4 [9]) were applied for an OFDM based WLAN system. In [13], we observed that due to the throughput reduction (¾ rate code) these codes provided enhanced throughput only at very low SNR values, where extra diversity was required. This result together with the observations for the 4x4 spatial multiplexing (see next section) lead to the conclusion that not all of the antennas should be used only for diversity or only for spatial multiplexing and that a hybrid approach should be considered.

IV. SPATIAL MULTIPLEXING

Spatial multiplexing, also known as Bell Laboratories Layered Space Time Architecture (BLAST), represents a direct exploitation of the available space-time resources. The first BLAST proposed in the literature is Diagonal BLAST (D-BLAST [8] which has a diagonal layering space-time coding process with sequential nulling and interference cancellation decoding. One of the disadvantages of this type of structure is that with diagonal layering some space-time is wasted at the start and end of a burst. Also, it is constructed using 1-N_T constituent codes (where N_T represents the number of transmitting antennas), generally block codes, in order to decode each diagonal layer. This is therefore an impractical system for enhancement of 802.11a. Vertical BLAST[10] overcomes this problem by using a horizontal layering space-time structure that does not waste space-time resources, and does not require N_T constituent codes. However, the major drawback of V-BLAST is that it does not utilize transmit diversity. This is solved in this study by introducing a convolutional code with a space interleaver before the data is demultiplexed, as well as exploiting the frequency diversity of OFDM.

Maximum likelihood detection (ML) is the optimal method for minimising the bit error rate in spatial multiplexing schemes. However the main drawback of such a detection technique is the complexity it brings to the system as it has to perform M^{N_T} vector searches per subcarrier, where M is the number of symbols in the constellation and N_T is the number of transmit antennas. To reduce the complexity of such a detector, suboptimal techniques that range in performance can be used. These techniques range from linear processing techniques such as zero forcing (ZF) and minimum mean squared (MMSE) methods to nonlinear techniques such as ordered successive interference cancellation (OSIC), this technique was the initial decoding algorithm proposed by Foschini. In this study, ZF detection algorithms were used.

The transmit vector **x** can be expressed as:

$$\mathbf{x} = [X_1, X_2, ...X_{N_T}]^T \qquad (2)$$

where N_T represents the number of transmitting antennas and the operation $(.)^T$ represents the transpose. In the case of OFDM, on a subcarrier by subcarrier basis, a multicarrier system can be considered analogous to a narrowband architecture and hence the transmit vector **x** applies per subcarrier. Assuming there are N_R receiving antennas, the received vector can be expressed as:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \qquad (3)$$

where **H** represents the channel matrix of size N_T x N_R and ***n*** represents AWGN noise.

The channel matrix is given by:

$$\mathbf{H} = \begin{bmatrix} H_{1,1} & H_{1,2} & \cdots & H_{1,N_T} \\ H_{2,1} & H_{2,2} & \cdots & H_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ H_{N_R,1} & H_{N_R,2} & \cdots & H_{N_R,N_T} \end{bmatrix} \qquad (4)$$

where $H_{i,j}$ are frequency responses in the case of OFDM. The ZF solution is given by:

$$\hat{\mathbf{x}} = \left(\mathbf{H}'\mathbf{H}\right)^{-1}\mathbf{H}'\mathbf{r} \qquad (5)$$

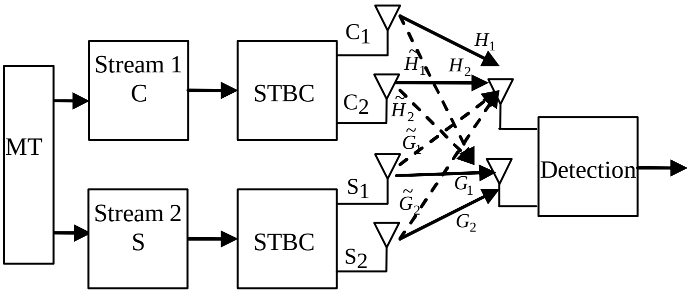

Figure 1. Block Diagram of the hybrid approach

V. THE HYBRID ALGORITHM

This section presents a hybrid algorithm [11] that combines spatial multiplexing and space time block coding techniques to achieve both enhanced throughput and packet error rate performance. Both a 4x2 and a 4x4 configuration will be examined. Figure 1 shows a block diagram of the proposed architecture for the 4x2 configuration. As described in the previous sections, results showed that not all of the antennas should be used for only spatial multiplexing or only diversity. In [11], the authors proposed interference suppression with STBC that can be used to increase system capacity. They presented a system with K synchronous co-channel users where each user is equipped with N transmit antennas. K antennas were required to suppress the interference from K-1 synchronous co-channel users, while maintaining the diversity order of N provided by the STBC. The same concept is applied here in order to increase the throughput of future OFDM based WLANs. Instead of suppressing the interference from other users we will use the ZF interference suppression technique that exploit the structure of the STBC [11] to suppress the interference from the two parallel streams we are transmitting. We will apply this method for an OFDM based WLAN system, and the transmitted streams will be interleaved for additional diversity as described in Section IV. For example, if we assume the 4x2 configuration in Figure 1, there are K= 2 streams, and each stream goes to a STBC scheme and is transmitted over N=2 antennas. Hence the terminal has

KxN=4 transmit antennas and a minimum of K= 2 receive antennas are required to detect the streams employing ZF techniques. The above configuration provides double the throughput (similar to 2x2 spatial multiplexing) and a diversity order of 2.

If we apply the STBC as described in section III, from Figure 1, the received signal R_y^x at receive antenna x and at time y, after the DFT and the CP removal, is given by:

$$\begin{aligned} R_1^1 &= H_1C_1 + H_2C_2 + \tilde{G}_1S_1 + \tilde{G}_2S_2 + N_1 \\ R_1^2 &= G_1S_1 + G_2S_2 + \tilde{H}_1C_1 + \tilde{H}_2C_2 + N_2 \\ R_2^{1^*} &= -H_1^*C_2 + H_2^*C_1 - \tilde{G}_1^*S_2 + \tilde{G}_2^*S_1 + N_3 \\ R_2^{2^*} &= -G_1^*S_2 + G_2^*S_1 - \tilde{H}_1^*C_2 + \tilde{H}_2^*C_1 + N_4 \end{aligned} \tag{6}$$

where N_1, N_2, N_3, N_4 represent AWGN and H, G, $\tilde{H}$, $\tilde{G}$ are frequency responses, at a given subcarrier k, as depicted in Figure 1. Equation (6) can also be written as:

$$\begin{bmatrix} R_1^1 \\ R_2^{1^*} \end{bmatrix} = \begin{bmatrix} H_1 & H_2 \\ H_2^* & -H_1^* \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} + \begin{bmatrix} \tilde{G}_1 & \tilde{G}_2 \\ \tilde{G}_2^* & -\tilde{G}_1^* \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} + \begin{bmatrix} N_1 \\ N_3 \end{bmatrix}$$

$$\begin{bmatrix} R_1^2 \\ R_2^{2^*} \end{bmatrix} = \begin{bmatrix} \tilde{H}_1 & \tilde{H}_2 \\ \tilde{H}_2^* & -\tilde{H}_1^* \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} + \begin{bmatrix} G_1 & G_2 \\ G_2^* & -G_1^* \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} + \begin{bmatrix} N_2 \\ N_4 \end{bmatrix}$$

$$\begin{aligned} \mathbf{R^1} &= \mathbf{H_1C} + \mathbf{G_1S} + \mathbf{N_1} \\ \mathbf{R^2} &= \mathbf{H_2C} + \mathbf{G_2S} + \mathbf{N_2} \end{aligned} \tag{7}$$

where $\mathbf{R^1}$ and $\mathbf{R^2}$ represent the received vectors at antennas 1 and 2 respectively, $\mathbf{C}$ and $\mathbf{S}$ are the vectors of code symbols from streams 1 and 2 respectively. The matrices $\mathbf{H_1}$ and $\mathbf{H_2}$ are the channel matrices from the first STBC to receive antennas 1 and 2 respectively and the matrices $\mathbf{G_1}$ and $\mathbf{G_2}$ are the channel matrices from the second STBC to receive antennas 1 and 2 respectively. $\mathbf{G_1S}$ can be seen as an interfering stream to antenna 1 and $\mathbf{H_2C}$ as an interfering stream to antenna 2 (see also Figure 1). Equation (7) can be rewritten as:

$$\begin{aligned} \mathbf{r} &= \begin{bmatrix} \mathbf{R^1} \\ \mathbf{R^2} \end{bmatrix} = \mathbf{H} \cdot \tilde{\mathbf{C}} + \mathbf{N} \\ &= \begin{bmatrix} \mathbf{H_1} & \mathbf{G_1} \\ \mathbf{H_2} & \mathbf{G_2} \end{bmatrix} \begin{bmatrix} \mathbf{C} \\ \mathbf{S} \end{bmatrix} + \begin{bmatrix} \mathbf{N_1} \\ \mathbf{N_2} \end{bmatrix} \end{aligned} \tag{8}$$

We can detect the desired signal vectors, $\mathbf{C}$ and $\mathbf{S}$ from equation (8), using either a ZF or MMSE solution and hence remove the interference between the two transmitted streams and subsequently implemented the STBC decoding. The hybrid algorithm can be extended to a 4x4 configuration where the extra two receiving antennas will offer a diversity advantage. The 4x4 configuration will provide double the throughput (similar to 2x2 spatial multiplexing) and a diversity order of 4.

VI. CHANNEL SCENARIOS

In [4], we defined a number of MIMO statistical channel scenarios with different parameters. Table I presents the channel scenarios that were used in this paper. The angular width (uniform distribution) determines the correlation between the antennas. Note this is not the rms angular spread. The rms angular spread can be calculated from the angular width.

TABLE I. CHANNEL SCENARIOS

Channel Scenario	rms delay spread	K factor	Angular width
H_50_0_60	50 ns	Rayleigh	60°
H_50_0_90	50 ns	Rayleigh	90°
H_50_0_360	50 ns	Rayleigh	360°

VII. PERFORMANCE RESULTS

A. Performance of Spatial Multiplexing

Firstly the performance of spatial multiplexing is presented. All the results in this work are for ideal channel estimation. More on channel estimation for MIMO WLAN systems can be found in [6]. The results in Figures 2 to 8 are presented for channel scenario H_50_0_360 (uncorrelated channels). Figure 2, shows the spatial multiplexing PER performance for all transmission modes for a 2x2 configuration for ZF. These transmission modes can now offer now double the throughput compared to the ones in the 802.11a physical layer (up to 108 Mbps). This can be seen in Figure 3 where the link throughput over SNR is presented for ZF. The link throughput when retransmission is employed is given by: Throughput = R (1-PER), where R and PER are the bit rate and packet error rate for a specific mode respectively. A link adaptation scheme has been assumed in which the mode with the highest throughput is chosen for each instantaneous SNR value. Figure 4 shows the PER performance for the 4x4 case for uncorrelated channels. The 4x4 configuration will quadruple the throughput (in specific channel conditions).

In [3] we examined the performance of spatial multiplexing under different channel scenarios. It was observed that increasing the K-factor introduces more correlation between the channel paths and reduces the capacity of the channel, which results in a degradation in performance. In addition, the performance is reduced in channels with low angular spread again due to increased correlation between the antennas. In [3] we also observed that as far as the difference in performance between the 2x2 and 4x4 cases is concerned, especially for low angular spread cases the 4x4 SM systems perform worse than the 2x2 systems. This is due to the fact that SM systems employing two transmit antennas and two receive antennas cope with high channel correlation better than systems with more antennas. In [3,4] it was observed that the 4x4 spatial multiplexing system performs well only under certain channel conditions and in most cases it cannot achieve four times the throughput of a SISO (Single Input Single

Output) system. Hence, it was clear that it would be better to use some of the antennas for diversity.

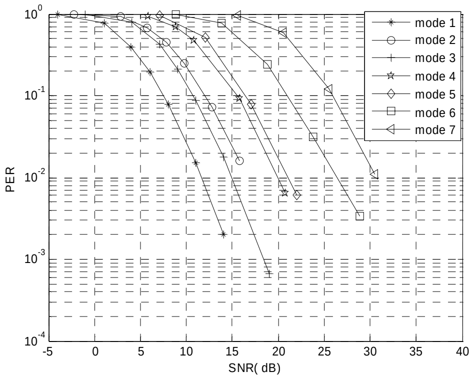

Figure 2. PER performance for 2x2 Spatial Multiplexing, ZF

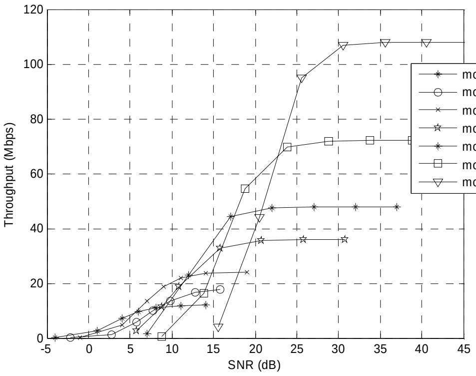

Figure 3. Link Throughput for 2x2 Spatial Multiplexing, ZF

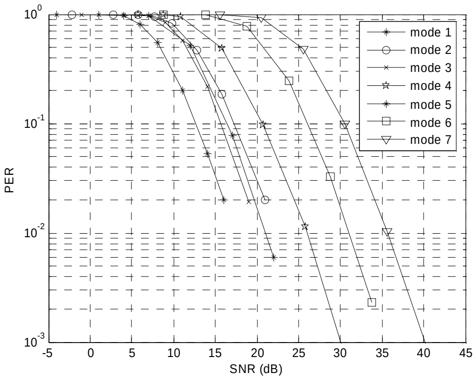

Figure 4. PER performance for 4x4 Spatial Multiplexing, ZF, ZF

B. *Performance of the Hybrid Algorith*

The performance of the hybrid system, which makes use of the antennas for increasing both throughput and diversity, can be seen in Figure 5 for the 4x2 configuration. Figure 5 shows the enhanced performance that can be achieved relative to a standard spatial multiplexing system. The increased performance is due to a diversity order of 2. The 4x4 hybrid system can enhance performance further since it can provide a diversity order of 4. Figure 6 compares the performance of the 4x4 hybrid system with that of the 4x2 hybrid system and the standard spatial multiplexing case for mode 6 (16 QAM ¾ rate). Gains up to 11dB can be observed relative to the standard spatial multiplexing case at a PER of 10^{-2}. PER performance results for all modes can be seen in Figure 7 for ZF. If we compare the results of Figure 7 with Figure 2 (standard spatial multiplexing, ZF), it can be seen that the PER performances for all modes have been considerably enhanced. This enhanced PER performance results in increased throughput as can be seen in Figure 8. Table II shows the gain in throughput that can be achieved with the hybrid approach. It is interesting to observe that for SNR values up to 20dB, we can double the throughput of standard spatial multiplexing system even if we are using some of the antennas for diversity.

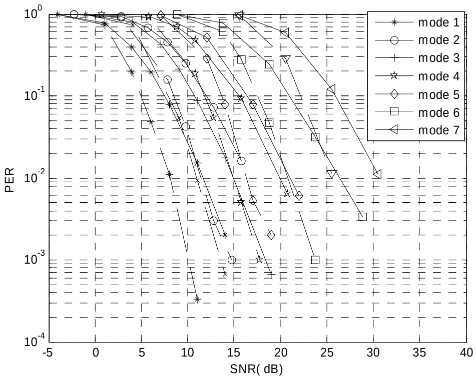

Figure 5. PER performance for 4x2 Hybrid sytem, ZF - solid lines standard spatial multiplexing, dash lines hybrid system

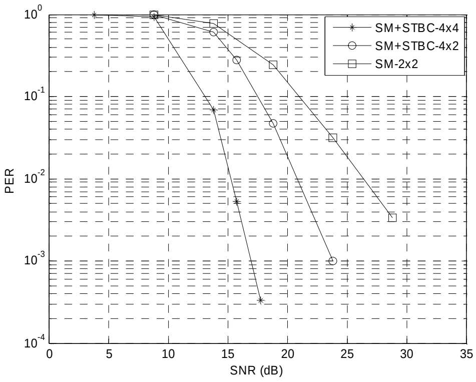

Figure 6. PER performance for 4x4 Hybrid sytem, ZF, mode 6

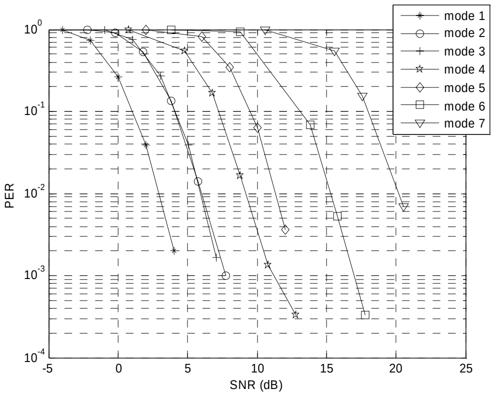

Figure 7. PER performance for 4x4 Hybrid sytem, ZF, all modes

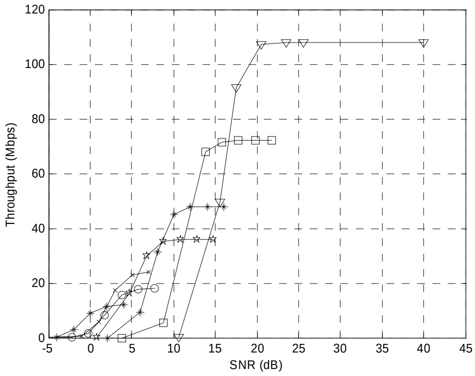

Figure 8. Link Throughput for hybrid scheme, ZF

C. *Performance for different channel conditions*

In this section we will examine how the hybrid scheme performs under correlated channel conditions. Figure 9, compares the performance of the hybrid scheme to that of standard Spatial Multiplexing for different channel conditions. It can be observed that not only does the hybrid scheme perform well even in correlated channels (decreasing the angular spread results in increased correlation between the antenna channels) but the gain is increased for more correlated channels. This can be seen in Table III that summarises the gains achieved at a PER of 10^{-2}.

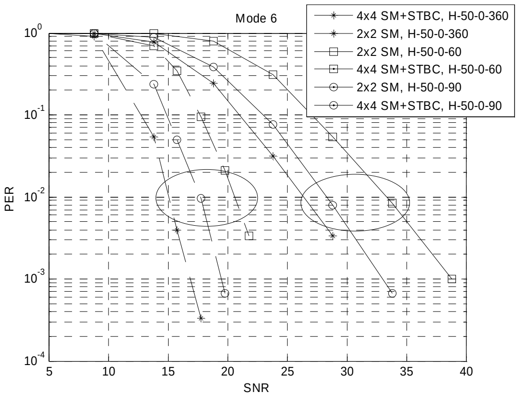

Figure 9. Hybrid Scheme versus standard Spatial Multiplexing for different channel conditions

TABLE II. THROUGHPUT ENHANCEMENT

SNR (dB)	Throughput Hybrid Scheme	Throughput , 2x2 Spatial Multiplexing
5	22 Mbps	9 Mbps
10	45 Mbps	20 Mbps
15	70 Mbps	38 Mbps
20	107 Mbps	60 Mbps
30	108 Mbps	107 Mbps

TABLE III. GAIN AT A PER=10^{-2}

Channel Scenario	Gain (dB)
H_50_0_60	12.5
H_50_0_90	11
H_50_0_360	11

VIII. CONCLUSIONS

In this paper a hybrid 4x4 scheme was investigated for next generation WLANs. This scheme combines spatial multiplexing and STBC to provide both increased throughput and diversity. Performance results for MIMO WLANs employing the hybrid MIMO technique were presented for both a 4x2 and a 4x4 configuration employing ZF detection. Packet Error Rate and throughput performance results under different channel conditions showed that the hybrid algorithm can provide enhanced performance relative to a standard spatial multiplexing approach. Gains of up to 12dB were observed at a PER of 10^{-2}. It was shown that the proposed scheme can provide double the throughput of a 2x2 spatial multiplexing system at low SNR values (similar to 4x4 spatial multiplexing –see Table II). In addition, the hybrid algorithm has the advantage of providing good performance even in correlated channels.

ACKNOWLWDGEMENTS

This work was done under the 3CR OSIRIS project at the University of Bristol.

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