Throughput Enhancement of OFDM based WLANs Using Space Time Block Codes and Time Domain Least Squares Channel Estimation

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Abstract

HIPERLAN/2, 802.11a, 802.11g and HiSWANa 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) techniques are considered as a means of enhancing the performance of COFDM WLANs. To perform channel estimation for multiple transmit and receive antennas, it is necessary to make transmitted pilot signals orthogonal in space and time. This was achieved using a Hadamard design. A time domain least square channel estimator was used to achieve high performance. Packet Error Rate (PER) performance results for the case of 2Tx and 2Rx antennas are presented and throughput enhancements are evaluated. It is observed that STBC doubles the link throughput for low SNR values. For the case of an 802.11a/g network, results for different packet lengths are also presented.

Introduction

At present, Wireless Local Area Networks (WLANs) supporting broadband multimedia communication are being developed and standardized around the world. Standards include HIPERLAN/2 [1], defined by ETSI BRAN, 802.11a [2] and 802.11g [3] defined by the IEEE and HiSWANa [4] defined by ARIB MMAC. These systems all provide channel adaptive data rates up to 54 Mbps (in a 20 MHz channel spacing) in the 5GHz and 2.4GHz - for the case of 802.11g - radio bands.

In order to enhance performance, multiple transmit and receive antennas can be used to provide diversity. Space Time Block Coding (STBC) is a simple and attractive space time coding scheme that was proposed by Alamouti [5]. It requires only a little additional complexity and is suitable for the slow fading environments in which WLANs will be 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 [6-8]. In this paper, link throughput results will be presented for the case of 2 transmit and 2 receive antennas with a time domain Least Squares (LS) channel estimation. It will be shown that link throughput is doubled for SNR values up to ~20dB when STBC are used. In [9], a number of channel estimation techniques were examined and compared. In this paper, to perform channel estimation for multiple transmit and receive antennas, a Hadamard design for the pilots was chosen to make them orthogonal in space and time. Results are presented for both time domain and frequency domain LS channel estimators and the time domain LS is shown to achieve superior performance in accordance with [9].

In 802.11a/g systems the packet size is not constant but can vary with a maximum payload usually up to 1500 bytes [15]. For the case of IEEE 802.11a/g, systems, PER results are also shown for different packet lengths.

WLAN Physical Layers

The physical layers of HIPERLAN/2, 802.11a, 802.11g and HiSWANa are based on the use of Orthogonal Frequency Division Multiplexing (OFDM). OFDM is used to combat frequency selective fading and to randomize the burst errors caused by a wideband-fading channel. The OFDM modulation 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 extension. When the guard interval is longer than the excess delay of the radio channel, ISI is eliminated. In that case, the signal received after the FFT can be written as:

$$y_k = H_k x_k + n_k \qquad (1)$$

where y_k is the received signal at a given subcarrier k, H_k is the frequency response of the channel at the k^{th} subcarrier, n_k represents complex Additive White Gaussian Noise (AWGN), and x_k is the transmitted signal at subcarrier k.

Importantly, the physical layer provides several modes (Table 1) each with a different coding and modulation configuration. These are selected by a *link adaptation* scheme. A simple approximation of 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. In the case where a simple link adaptation scheme is used, the mode with the highest throughput can be chosen for each instantaneous SNR value. Physical layer details can be found in [14, 15].

Table 1: Mode dependent parameters

Mode	Modulation	Coding Rate R	Bit rate [Mbit/s]
1	BPSK	1/2	6
2	BPSK	3/4	9
3	QPSK	1/2	12
4	QPSK	3/4	18
5 (802.11a/g)	16QAM	1/2	24
5 (H2/Ha)	16QAM	9/16	27
6	16QAM	3/4	36
7	64QAM	3/4	54
8 (802.11a/g)	64QAM	2/3	48

Space Time Block Coding

In [5] Alamouti proposed a simple transmit diversity scheme which was generalized by Tarokh [10] to form the class of Space-Time Block Codes (STBC). These codes achieve the same diversity advantage as maximal ratio receive combining (allowing for a -3dB offset for the case of 2 Tx antennas due to power normalization) [11]. In [12], Lee and Williams applied a 2Tx-1Rx antenna, transmit diversity scheme to OFDM in order to achieve diversity gain over frequency selective fading channels.

In Alamouti's encoding scheme two signals are transmitted simultaneously from the 2 transmit antennas. The transmission matrix is given by [5,10-13]:

$$X=\begin{bmatrix} x_{1,k} & -x_{2,k}^{*} \\ x_{2,k} & x_{1,k}^{*} \end{bmatrix} \qquad (2)$$

where in the case of OFDM, $x_{1,k}, x_{2,k}$ 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 [12]. At the first antenna, for the k^{th} subcarrier, $x_{1,k}$ is transmitted during the first symbol period followed by $-x_{2,k}^{*}$ in the second symbol period. At the second antenna, $x_{2,k}$ is transmitted during the first symbol period followed by $x_{1,k}^{*}$ in the second symbol period.

At receive antenna 1, after the DFT and the cyclic prefix removal, the received signals are given by [5,12]:

$$\begin{aligned} y_{1,k} &= x_{1,k} H_{1,k} + x_{2,k} H_{2,k} + n_{1,k} \\ y_{2,k} &= -x_{2,k}^{*} H_{1,k} + x_{1,k}^{*} H_{2,k} + n_{2,k} \end{aligned} \qquad (3)$$

where $n_{1,k}$, $n_{2,k}$ represent AWGN and $H_{1,k}$ and $H_{2,k}$ are the frequency responses, at a given subcarrier k, of the channels between Tx1 and Rx1 and Tx2 and Rx1 respectively. It is assumed that the channel responses are uncorrelated and constant during the period of two OFDM symbols. This is reasonable for the OFDM parameters specified for the WLANs.

After channel estimation, the channel parameters are known to the receiver, and the signals $y_{1,k}$, $y_{2,k}$ can be combined at the receiver according to [12]:

$$\begin{aligned} s_{1,k} &= y_{1,k} H_{1,k}^{*} + y_{2,k}^{*} H_{2,k} \\ s_{2,k} &= y_{1,k} H_{2,k}^{*} - y_{2,k}^{*} H_{1,k} \end{aligned} \qquad (4)$$

Substituting for $y_{1,k}$, $y_{2,k}$ from (3), the combined signals can be written as [5,12]:

$$\begin{aligned} s_{1,k} &= x_{1,k}\left(|H_{1,k}|^{2} + |H_{2,k}|^{2} \right) + n_{1,k} H_{1,k}^{*} + n_{2,k}^{*} H_{2,k} \\ s_{2,k} &= x_{2,k}\left(|H_{1,k}|^{2} + |H_{2,k}|^{2} \right) + n_{1,k} H_{2,k}^{*} - n_{2,k}^{*} H_{1,k} \end{aligned} \qquad (5)$$

In order to perform soft decision Viterbi decoding, the Channel State Information of both channels and for all subcarriers ($H_{1,k}$, $H_{2,k}$) is passed to the decoder in order to calculate the metric.

For the case of 1 Rx antenna, the above scheme is similar to that of two branch maximal ratio receive combining (MRRC). For the case of 2 Rx antennas, the signal from the two receivers are combined and the scheme performs similar to four branch MRRC. However, the Alamouti scheme has a 3 dB power loss compared to MRRC because each transmit antenna transmits half the power so that the average received power is the same when comparing receive diversity with transmit diversity [11,12].

Channel Estimation

To perform channel estimation, OFDM based WLANs use two consecutive pilot OFDM symbols in the preamble. In order to avoid adding additional overhead when 2 transmit and 2 receive antennas are employed, two pilot OFDM symbols will be transmitted from each transmit antenna. In order for this to work, the pilot symbols must be orthogonal. One family of pilots whose orthogonality is obtained jointly in space and time dimensions is the set of Orthogonal Space-Time Pilot Matrices (OSTPM) [9]. Such matrices are the STBC matrices - see equation (2) - and the Hadamard matrices [9]. In this paper, a Hadamard matrix will be used to transmit the real pilot symbols according to:

$$X=\begin{bmatrix} x_{1,k} & x_{1,k} \\ x_{1,k} & -x_{1,k} \end{bmatrix} \qquad (6)$$

Using this set of pilots the channels can be easily separated at the receiver by a linear combination of the received pilots [9]. Hence, the channel parameters can be computed independently for each transmit antenna according to:

$$\begin{aligned} r_{1,k} &= x_{1,k} H_{1,k} + x_{1,k} H_{2,k} + n_{1,k} \\ r_{2,k} &= x_{1,k} H_{1,k} - x_{1,k} H_{2,k} + n_{2,k} \end{aligned} \qquad (7)$$

$$\begin{aligned} s_{1,k} &= r_{1,k} + r_{2,k} = 2x_{1,k} H_{1,k} + n_{1,k} + n_{2,k} \\ s_{2,k} &= r_{1,k} - r_{2,k} = 2x_{1,k} H_{2,k} + n_{1,k} - n_{2,k} \end{aligned} \qquad (8)$$

where $r_{1,k}$, $r_{2,k}$ are the received pilots. This way, the channel parameters can be directly estimated in the frequency domain in the least square (FD LS) sense by inverting equation (8). This is similar to the 1 transmit, 1 receive case (see equation (1)).

However, OFDM based WLANs standards use 12 virtual subcarriers at the edge of the band and only K=52 subcarriers are used for transmission. Additionally, in order to prevent ISI, a guard interval, G, of 16 is used. This means that the channel impulse response is expected to have less than 16 coefficients. If we denote $F^{[K,G]}$ the truncated 64 Fourier matrix, in which the rows correspond to the K observed subcarriers and only the first G columns are kept, equation (8) can be written as:

$$\begin{aligned} S_1 &= 2X_1 H_1+N_1+N_2=2X_1 F^{[K,G]}h_1^{[G]}+N_1+N_2 \\ S_2 &= 2X_1 H_2+N_1+N_2=2X_1 F^{[K,G]}h_2^{[G]}+N_1+N_2 \end{aligned} \qquad (9)$$

where $X_1=\mathrm{diag}(\{x_{1,k}\}_{k=0:K-1})$, N_1, N_2 are AWGN vectors, $H_1=[H_{1,0} \ldots H_{1,K-1}]^T$ and $H_2=[H_{2,0} \ldots H_{2,K-1}]^T$ and $h_1^{[G]}$, $h_2^{[G]}$ are the time domain channel impulse response vectors.

The time domain least square (TD LS) estimator of the frequency coefficients is given by:

$$\begin{aligned} H_{1,TD\,LS} &= F^{[K,G]}\,[2X_1F^{[K,G]}]^{\dagger}\,S_1 \\ H_{2,TD\,LS} &= F^{[K,G]}\,[2X_1F^{[K,G]}]^{\dagger}\,S_2 \end{aligned} \qquad (10)$$

where the Moore-Penrose pseudo-inverse of a matrix A is denoted $A^{\dagger}$. The TD LS channel estimator requires some additional complexity since it is obtained by projecting the FD LS solution in the time domain by using $(F^{[K,G]})^{\dagger}$ [9]. However, performance is significantly improved, as can be observed from the results presented in the next section. Equation (10), can be seen as a form of filtering of the channel coefficients, since we know that the channel impulse response has less than 16 coefficients.

Performance Results

A detailed PHY layer software simulator of HIPERLAN/2 and 802.11a/g has been developed previously by the authors [15]. This simulator was enhanced by adding STBC and different channel estimation options.

Figure 1, shows the PER performance of mode 3 versus SNR with STBC for the cases of time domain least square (TD LS) estimation, frequency domain least square (FD LS) estimation and ideal channel estimation. Results are shown for 2 transmit and 1 receive antenna and for 2 transmit and 2 receive antennas for a packet size of 54 bytes (HIPERLAN/2 size packet) for channel model A as specified by ERSI BRAN [16]. It can be observed that the performance of the TD LS estimation is close to the ideal channel estimation case, with ~2dB degredation for the case of 2Tx and 2Rx at a PER=10^{-3}. The FD LS estimation results in ~4dB degredation in performance relative to the ideal channel estimation.

Figure 2, shows the perfeormance enhancement of mode 4 for 2 transmit and 1 receive antenna and for 2 transmit and 2 receive antennas for a packet size of 54 bytes. It can be observed that the performance is significantly improved for both the cases of 2Tx, 1Rx and 2Tx, 2Rx antennas. It can be seen that the proposed STBC provides ~5dB gain at a PER of 10^{-2} for the case of 2Tx and 1Rx antennas and a further 5.5dB gain for the case of 2Tx and 2Rx antennas for TD LS channel estimation. For FD LS these gains are reduced by around 2dB. Thus, TD LS channel estimation will be used for the remainder of the results presented in this paper.

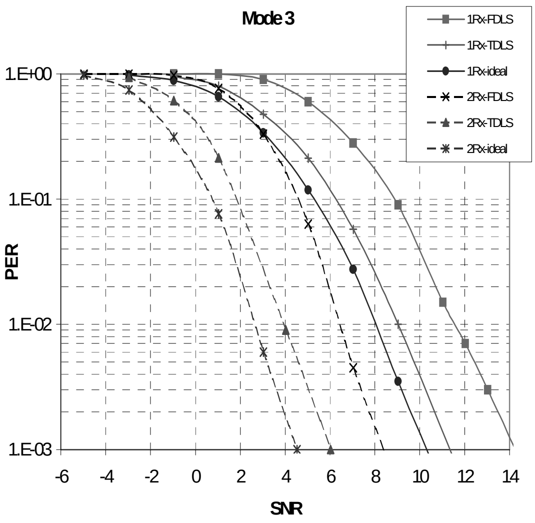

Figure 1: PER Performance for mode 3 using STBC with 2Tx, 1Rx and 2Tx, 2Rx antennas for FD LS and TD LS channel estimation.

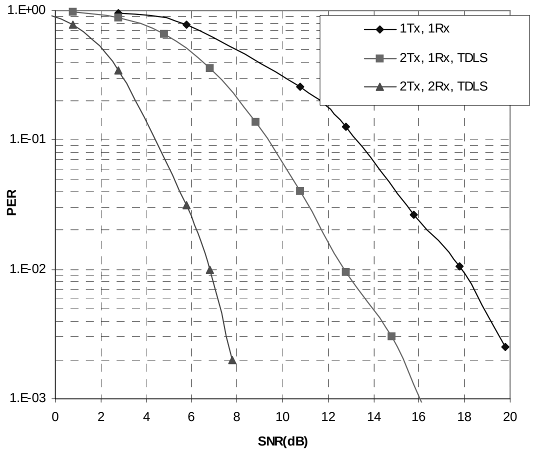

Figure 2: PER Performance enhancement for mode 4 using STBC with 2Tx, 1Rx and 2Tx, 2Rx antennas and TD LS channel estimation.

Figures 3 and 4 show the PER performances for all modes for the cases of a standard HIPERLAN/2 modem (with 1Tx and 1Rx) and for the case of 2Tx and 2Rx antennas with STBC respectively. It can be seen that performance is significantly enhanced, providing gains of 8.5-10.5 dB depending on the mode (and channel model). Modes 2, 4 and 6 (3/4 rate modes with puncturing) exhibit the most benefit. Table 2, summarises the STBC gains achieved at a PER= 10^{-2}.

For 802.11a/g systems the packet size is not constant but can vary with a maximum payload usually up to 1500 bytes [15]. Figure 5, shows the PER performance for 802.11a/g for different packet sizes. As expected, there is a degredation in performance as the packet size increases but performance with STBC is significantly enhanced for all packet sizes. Hence, all the link throughput enhancements that will be shown for HIPERLAN/2 are valid for the 802.11a/g WLANs.

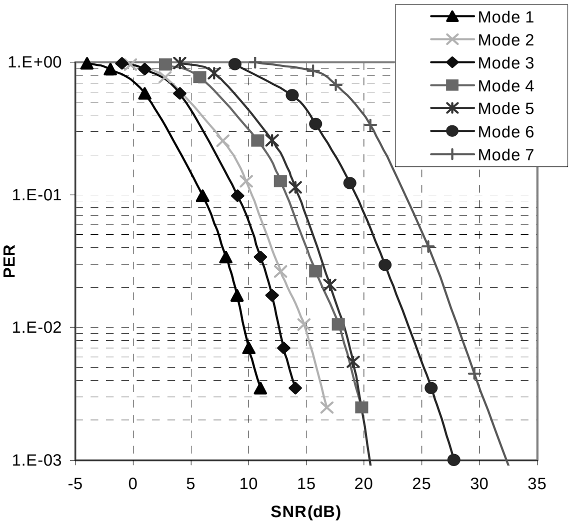

Figure 3: PER Performance of a standard HIPERLAN/2 system.

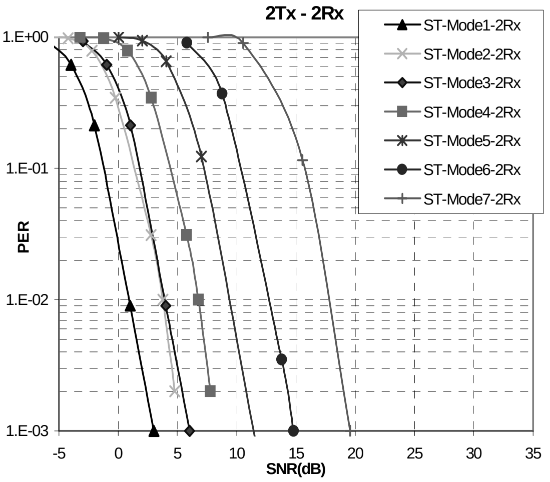

Figure 4: PER Performance using STBC with 2Tx, 2Rx antennas and TD LS channel estimation.

Table 2: STBC Gain at PER=10^{-2}

Mode	Gain (dB)
1	8.5
2	10.5
3	8.5
4	10.5
5	9
6	9.5
7	10

Figures 6 and 7 show the link throughput for the case of a standard HIPERLAN/2 modem and for the case of 2Tx and 2Rx antennas with STBC respectively. A simple link adaptaion scheme where the mode with the highest throughput is chosen for each instantaneous SNR value is assumed.

Table 3, summarises the throughput achieved with and without space time block codes. It can be seen that STBC doubles the link throughput for SNR values up to ~20 dB and throughput is higher than 50 Mbps for SNR values higher that 16 dB.

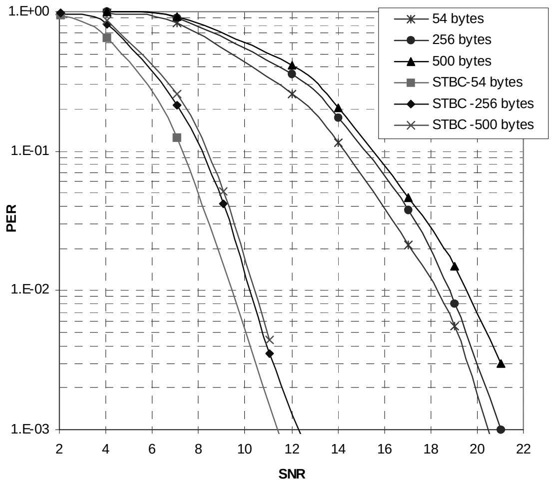

Figure 5: PER Performance for mode 5 using STBC with 2Tx, 2Rx antennas for different packet sizes.

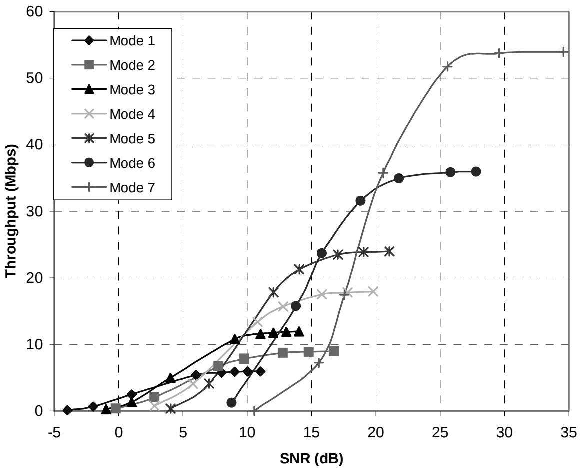

Figure 6: Link Throughput for HIPERLAN/2

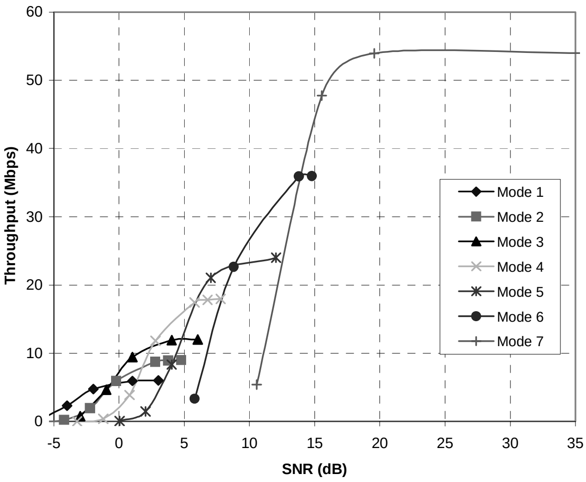

Figure 7: Link Throughput with STBC, 2Tx, 2Rx.

Table 3: Link Throughput with STBC

SNR(dB)	1Tx, 1Rx antenna	2Tx, 2Rx antennas
0	2 Mbps	7 Mbps
5	7 Mbps	16 Mbps
10	11 Mbps	26 Mbps
15	22 Mbps	45 Mbps
20	34 Mbps	54 Mbps
25	51 Mbps	54 Mbps

Conclusions

In this paper, space-time block coding (STBC) techniques were considered as a means of enhancing the performance and throughput of OFDM WLANs. To perform channel estimation for multiple transmit and receive antennas, a Hadamard design for the pilots was employed to achieve orthogonality in space and time. A time domain least square channel estimator was used to achieve superior performance. PER performance results for the case of 2Tx and 2Rx antennas and throughput enhancements were presented. Gains between 8.5-10.5 dB were observed at a PER of 10^{-2} when 2 antennas were used in both the transmitter and receiver. It was shown, that the link throughput was significantly increased (by up to 100% for lower SNRs) when STBC were used. For the case of a 802.11a/g network, results for different packet lengths were presented and it was shown that these systems would enjoy benefits from STBC similar to those of HIPERLAN/2.

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Acknowledgements

The authors wish to acknowledge the support of the IST SATURN and ROMANTIK projects which are funded by the European Union.