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Receive Diversity versus Space Time Block Codes in IEEE 802.11a and ETSI Hiperlan/2

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Abstract – The aim of this study is to enhance the performance of the current 802.11a and Hiperlan/2 standards by employing multiple antennas at the transmitter, receiver or both. These systems use coded orthogonal frequency division multiplexing (COFDM) technology and provide channel adaptive data rates of up to 54 Mbits/s. However, the performance of both standards can be improved, especially in environments with high root mean square (RMS) delay spread where uncoded data suffers from significant interchannel interference. Current techniques such as receive diversity and space time block codes are presented as a simple solution to enhance these standards. This paper explains the characteristics of these technique and results are presented in order to discuss their merits and demerits. The paper also determines which technique offers the highest performance without the addition of significant complexity at the receiver.

I. INTRODUCTION

802.11a is a North American standard defined by the IEEE[1] while Hiperlan/2[2] is a similar European system defined by the European Telecommunications Standard Institute (ETSI). Both of these standards belong to the family of wireless local area networks (WLANs) where there is no need to physically “plug” into the network in order to access data, the Internet, video conferencing and/or other terminals. However, high data rates are still required in order to offer similar services to a wired LAN.

Traditionally, one transmit and one receive antenna has been used in order to create a communication link between terminals. However, if more than one channel is established between the transmitter and receiver, such that the individual channels suffer independent and uncorrelated fading, then the effects of the channel can be reduced [3] and thus the performance of the current standards can be enhanced.

Multiple channels can be achieved using multiple antennas at the transmitter and/or receiver; the antennas can be polarised and/or spatially separated to ensure decorrelation. Diversity can be generated from these independent and uncorrelated channels by combining the independent links using a number of techniques. This paper investigates the possibility of employing diversity techniques and space time block codes (ST-BC) in the 802.11a and Hiperlan/2 standards in order to improve their performance, thus enabling the most promising technique to be proposed as a future WLAN enhancement.

II. PHYSICAL LAYER

Hiperlan/2 and 802.11a operate using coded orthogonal frequency division multiplexing (COFDM) in the 5GHz band. The two standards have been designed to operate in an indoor environment where high data rates and limited user mobility are expected. A nominal data rate of 20Mbit/s was specified without compromising reliability. However, in more

favourable channel conditions the system uses link adaption to enable data rates up to 54Mbit/s using a 64-QAM transmission mode that is optional in 802.11a but compulsory in Hiperlan/2. These standards differ primarily at the MAC layer [3]. Since this study is concerned only with the physical layer, the results are applicable to both standards.

OFDM is used to combat frequency selective fading in the channel and to randomise the bit errors over frequency sub-bands. OFDM is a wideband modulation scheme that transmits data on a large number of narrowband sub-bands.

III. BASEBAND MODEL

In the baseband model modulated symbols at the transmitter can be represented as:

$$x(t) = x_I(t) + jx_Q(t) \quad (1)$$

where $x(t)$ represents a complex modulated COFDM symbol at time t , x_I the in-phase component and x_Q the quadrature component. The received complex baseband symbol for the i th branch is given by:

$$u_{i th} = c_{i th}(t)x(t) + n_{i th}(t) \quad (2)$$

where $c_{i th}(t)$ denotes the fading distortion on the i th branch caused by the channel and $n_{i th}(t)$ represents the complex additive white Gaussian noise (AWGN) at the i th branch of the receiver.

The estimated fading distortion is calculated by comparing the received training sequence, distorted by the channel, with the original training sequence [4]. To remove the phase rotation introduced by the fading channel the received signal is multiplied by the complex conjugate of the estimated phase distortion term:

$$v_{i th} = u_{i th}(t)\exp(-j\tilde{\theta}_{i th}(t)) \quad (3)$$

where $\tilde{\theta}_{i th}$ represents the estimated phase distortion. The amplitude distortion of the i th branch is removed as described in the following section.

IV. SPACE RECEIVE DIVERSITY

Space receive diversity achieves independent transmission paths by spatially uncorrelating the antennas at the receiver. The signal is transmitted using a single antenna and received across n antennas.

A popular form of receive diversity processing is known as selection diversity [5], where the algorithm selects the branch with the highest short-term average power. Thus the single most appropriate branch is always selected.

Equal gain and maximal ratio combining [6] are two more sophisticated combining strategies where all of the signal inputs are individually weighted and summed.

The component branch symbols $v_{ith}(t)$ are weighted by $a_{ith}(t)$ prior to their summation as shown in equation 4. The particular weight is chosen depending on the algorithm used:

$$s(t) = \sum_{i=1}^B a_{ith}(t) v_{ith}(t) \quad (4)$$

For selective combining only the strongest signal is selected, therefore:

$$a_{ith}(t) = \frac{1}{\tilde{r}_{ith}(t)} \quad \tilde{r}_{ith}(t) = \max\{\tilde{r}_1(t), \tilde{r}_2(t), \dots, \tilde{r}_B(t)\} \quad (5)$$

For Equal Gain Combining, all of the sub-bands are simply cophased and summed and the resulting value is then normalised:

$$a_{ith}(t) = \frac{1}{\sum_{j=1}^B \tilde{r}_j(t)} \quad (6)$$

For Maximal Ratio Combining the sub-bands are weighted according to their signal strength so that the weak branches are suppressed while the strong branches are enhanced, as shown in equation 7.

$$a_{ith}(t) = \frac{\tilde{r}_{ith}(t)}{\sum_{j=1}^B \tilde{r}_j(t)} \quad (7)$$

V. SPACE TIME BLOCK CODES

Space-time coding is a technique based on transmit diversity. The data is encoded by a channel encoder and the coded symbols are transmitted orthogonally using uncorrelated antennas. It is a bandwidth and power efficient method of communication over fading channels that realizes the benefits of multiple transmit antennas.

A simple case of ST-BC was proposed by Alamouti [7] and consists of two antennas at the transmitter and n at the receiver. With this technique the data is encoded in time and space and can therefore be considered as a space-time block code.

The simple case of two antennas at the transmitter and one at the receiver is considered in this paper. At a given time t , for a given sub-band k , $s_{1,k}$ and $s_{2,k}$ are transmitted from antennas one and two respectively. In the following OFDM symbol $(t+T)$ and for the k th sub-band, $-s_{2,k}^*$ is transmitted from antenna one while antenna two transmits $s_{1,k}^*$, where $s_{1,k}^*$ and $s_{2,k}^*$ represent the complex conjugates of s_1 and s_2 . The k th sub-band channels between the transmitting antennas and the receiving antenna can be expressed as follows:

$$\begin{aligned} h_{1,k}(t) &= h_{1,k}(t+T) = \alpha_1 \exp(j\theta_1) \\ h_{2,k}(t) &= h_{2,k}(t+T) = \alpha_2 \exp(j\theta_2) \end{aligned} \quad (8)$$

The channels can be modelled as multiplicative distortion in the frequency domain, where $h_{1,k}$ and $h_{2,k}$ represent the channel k th sub-band gain between the receiving antenna and transmit antennas one and two respectively. A quasi-static channel is assumed so that during the transmission of two sub-band symbols at times t and $(t+T)$, the channel can be considered static. After each pair of OFDM symbols have been sent, the channel gains are updated with a new pair of uncorrelated gains.

AWGN is added at the receiver. The signal arriving at the receive antenna is a noisy superposition of the faded version of transmit OFDM symbols. After passing through the FFT process, the following received signals can be generated:

$$\begin{aligned} r_{1,k} &= s_{1,k} h_{1,k} + s_{2,k} h_{2,k} + n_{1,k} \\ r_{2,k} &= -s_{2,k}^* h_{1,k} + s_{1,k}^* h_{2,k} + n_{2,k} \end{aligned} \quad (9)$$

where $r_{1,k}$ and $r_{2,k}$ are the received symbols on the k th OFDM sub-band at time t and $(t+T)$ respectively and $n_{1,k}$ and $n_{2,k}$ represent uncorrelated complex random AWGN samples. In order to recover the original data from the k th sub-band, the following step is performed:

$$\begin{aligned} \tilde{s}_{1,k} &= r_{1,k} h_{1,k}^* + r_{2,k}^* h_{2,k} \\ \tilde{s}_{2,k} &= r_{1,k} h_{2,k}^* - r_{2,k}^* h_{1,k} \end{aligned} \quad (10)$$

where $\tilde{s}_{1,k}$ and $\tilde{s}_{2,k}$ represent soft estimated versions of $s_{1,k}$ and $s_{2,k}$ respectively.

VI. SIMULATED RESULTS AND DISCUSSION

The results presented here are for ETSI channel A, as shown in table I [8]. Channel A represents an indoor environment where there is no line of sight and the multipath follows a Rayleigh distribution. The RMS delay spread is 50ns and the maximum excess delay spread is 390ns, thus the 800 ns guard interval specified by the standards will protect the data from inter-carrier interference (ICI). Channel A was chosen since it has the smallest RMS delay spread and thus the transmitted signal will suffer less from selective fading, causing the system to perform worse than the higher RMS delay spread scenarios.

The packet length is different in the two standards, with 802.11a having a longer packet structure and thus the packet error rate (PER) versus signal to noise ratio (SNR) results are slightly worse than for Hiperlan/2 (around 2dB) [3]. Only PER results for the 802.11a standard are presented here.

TABLE I. CHANNEL MODELS

Name	RMS delay spread	Characteristic	Environment
A	50ns	Rayleigh	Office NLOS
B	100ns	Rayleigh	NLOS
C	150ns	Rayleigh	NLOS
D	140ns	Ricean	LOS
E	250ns	Rayleigh	NLOS

Figure 1 shows results for $\frac{3}{4}$ rate convolutional encoded QPSK and 64QAM with ST-BC (2Tx-1Rx and 2Tx-2Rx) compared to the single input single output (SISO) case. We observe that the performance improves as the number of antennas at the receiver increases. As shown in table II, it is

observed for a target PER of 10^{-2} that QPSK 2Tx-2Rx achieves a gain of 8dB over the SISO case. For the same target, 2Tx-1Rx achieves approximately 3.4dB gain over the SISO case (see Table II). However, it can be observed that at a large PER (50%) the gain reduces to 0.2dB and 3.6dB respectively relative to the SISO case. The gain of ST-BC will therefore be maximised for error sensitive applications requiring low values of PER.

Figure 1. PER performance for ST-BC

TABLE II. ST-BC QPSK

PER	1Tx-1Rx	2Tx-1Rx	2Tx-2Rx
$5 \cdot 10^{-1}$ (50%)	9.9dB	9.7dB	6.3dB
10^{-1} (10%)	15.7dB	13.7dB	9.8dB
10^{-2} (1%)	20.6dB	17.2dB	12.6dB

Figure 2 shows the PER performance for all the different receive diversity techniques for QPSK and 64QAM in a 1Tx-2Rx scenario. Maximum ratio combining performs better than equal gain and selective combining at the expense of higher receiver complexity. This trend occurs for all transmission modes. For the 1% target PER, for both modes, the gain of maximum ratio combining over the equal gain technique is minimal (approximately 1dB), but 2-3dB better than selective combining.

Figure 2. PER performance for the different Receive Diversity techniques

Figure 3 compares the performance of maximum ratio combining for different numbers of receive antennas. As shown in table II it is possible to observe that for a PER target of 1% the gain obtained by placing 2 antennas at the receiver instead of at the transmitter (ST-BC) gives a 3.5 dB gain (see

table III). The performance penalty of ST-BC relative to space receive diversity is due to the fact that half the power is used to transmit redundant data. The gain difference decreases with the number of antennas at the receiver. From these results, the SNR gain is clearly not linearly related to the number of receive antennas. As in the ST-BC case, greater gains are obtained at smaller PER targets (see table III).

Figure 3. PER performance for maximum ratio combining

TABLE III. RECEIVE DIVERSITY QPSK

PER	1Tx-1Rx	1Tx-2Rx	1Tx-3Rx	1Tx-4Rx
$5 \cdot 10^{-1}$ (50%)	9.9dB	6.1dB	5dB	3.2dB
10^{-1} (10%)	15.7dB	10.1dB	7.7dB	6.1dB
10^{-1} (1%)	20.6dB	13.7dB	11dB	8.4dB

VII. MEASURED CHANNEL RESULTS

Results were obtained using real measured channel data for the SISO case. The real channel data was taken using a Medav channel sounder in a series of offices in a building at the University of Bristol [9]. A configuration with 8 antenna elements at both the transmitter and the receiver was used. The transmit antenna array was placed at various locations around the office in order to obtain uncorrelated data sets. Figure 4 shows the results obtained for the real measured data relative to the simulated Channel A.

Figure 4. PER Performance in Real and simulated channel scenarios

For all modes, the performance using the real data was within 1dB of the simulated Channel A. The improved performance with the simulated channel relative to the real one can be

attributed to the fact that the real indoor environment suffers from smaller RMS delay spreads (~ 20 ns), hence the channel changes slowly across the sub-bands and frequency diversity cannot be so efficiently exploited.

VIII. CAPACITY ANALYSIS

The data rate versus SNR achieved by these standards can be estimated from the PER results as follows:

$$R = D \cdot (1 - PER) \quad (11)$$

where D is the nominal bit rate (Mbits/s) and R is the capacity. From the PER results, the range achieved by 802.11a was calculated for each of the different diversity techniques. In order to calculate the capacity, the SNR at the receiver can be calculated as follows:

$$SNR_{dB} = P_R - N \quad (12)$$

where P_R is the received power and N is the AWGN power calculated using :

$$N = 10 \log_{10}(K_B F) + 10 \log_{10}(B) + NF \quad (13)$$

where K is Boltzmann's constant $1.38e-20$ mW/Hz/Kelvin, F is the temperature in degrees Kelvin (300K), B is the bandwidth and NF is the receiver noise figure, set to 10dB in these simulations.

The received power was calculated as follows:

$$P_R = P_T - P_L \quad (14)$$

where P_T is the transmitted power (0dBm or 1mW) and P_L is the path loss. The path loss was calculated from:

$$P_L = G_T G_R + 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) + Fl + \alpha \cdot d \quad (15)$$

where G_T and G_R are the antenna gains (assumed to be 0 dBi), d is the distance travelled from the transmitter to the receiver, λ is the wavelength of the carrier frequency and Fl represents the path loss caused by a blocking wall (assumed to be 6dB). This wall ensures that the fading characteristics are Rayleigh, in agreement with ETSI channel A. The final parameter α represents extra attenuation in dB/m due to clutter in the operating environment.

Figure 5 shows the results for the SISO and ST-BC case, while figure 6 shows the results for space diversity. These results assume QPSK modulation over channel A.

For ST-BC, from figure 5 we can observe range improvements of 5.2m (2Tx-1Rx) and 12.9m (2Tx-2Rx) (relative to the SISO case) for a clutter attenuation of 0.1dB/m. This range was calculated based on a target data rate of 9Mbits/s, which translates to a PER of 50%. Clearly, although this throughput is still high, this type of link is only suitable for non time bounded data transfer. For systems needing to maximise throughput or minimise latency, a far lower PER target, somewhere in the region of 1%, is more suitable.

From table II we can obtain the SNR at which the system achieves a data rate of 9Mbit/s (from the 50% PER row).

Using equation 14, the receive sensitivity and maximum tolerable path loss for each ST-BC configuration can be calculated. For a 2Tx-2Rx system a path loss of 84.5dB can be tolerated. This drops to 80.9dB for the SISO case.

Figure 5. Range for ST-BC

Figure 6. Range for Space Receive Diversity

Figure 7 shows a set of path loss versus distance curves for clutter attenuation values in the range 0-1dB/m. From this figure we can deduce the range enhancement associated with any of our systems. The range extension is at its greatest when the clutter loss is zero, and at its least for environments with a high path loss versus distance gradient. For environments with an attenuation gradient of 1dB/m, the range extension associated with most SNR gains is almost negligible and the benefits of diversity are small.

From figure 3 it was seen that space receive diversity improves the received SNR for a given target PER. Table III clearly demonstrates that the SNR gains were far higher at a low PER (1%) than at a high PER target (50%). The maximum tolerable path loss for any considered system can be obtained by subtracting the SNR quoted in tables II and III from the single antenna 50% PER value of 9.9dB. Next, this value is added to the reference loss of 80.82dB (SISO case). Clearly, systems operating at the 1% PER target require higher SNRs than when they operate at the 50% PER target, therefore they tolerate a smaller path loss. Although this reduces their operating range, we see that these are the types of system that benefit the most from ST-BC and receive diversity (see table IV).

However, if the environment suffers from a high attenuation factor (1dB/m) we can observe from figure 5 and 6 that the range enhancement is almost negligible for any PER target. In this situation, diversity offers little advantage. Figure 7 shows that for this kind of environment, a large increase in the amount of path loss that the system can tolerate translates into a very small range enhancement.

Table 4 shows the range enhancements and the tolerated path loss of the considered systems for two extreme environments, with the lowest clutter attenuation $\alpha = 0\text{dB/m}$ and with the highest $\alpha = 1\text{dB/m}$. We can observe that for both cases the relative range extension is greater for a low PER target although the operating range is reduced. In an operating environment where there is no clutter attenuation, the range enhancement is still fairly large at a target PER of 50% however this is an optimum situation and it is very likely that the system operates in a cluttered environment.

TABLE IV. RESULTS FOR DIFFERENT ARCHITECTURES.

Architecture	Distance(m)/Path Loss(dB)			
	$\alpha = 0\text{dB/m}$		$\alpha = 1\text{dB/m}$	
	1%	50%	1%	50%
1Tx-1Rx	7.2/70.2	24.5/80.9	3.7/70.2	8.1/80.9
2Tx-2Rx	17.5/78.2	48/84.5	6.7/78.2	11.2/84.5
1Tx-4Rx	31.3/82.4	54/87.6	9/82.4	11.8/87.6

Figure 7. Path loss versus distance

IX. CONCLUSIONS

This paper has compared the PER performance of non-standard compliant ST-BC and space receive diversity with compliant SISO 802.11a. The BER performance of Hiperlan/2 and 802.11a is near identical, however, the PER performance of the 802.11a is slightly worse due to the longer packet sizes involved at the MAC layer.

Both ST-BC and receive diversity offer a simple solution to combat the effects of fading and noise. However the PER results showed that receive diversity offers a larger gain than ST-BC at the cost of requiring multiple antennas at the receiver. This is especially true with system employing a fixed access point, where it is advantageous to concentrate complexity and therefore cost at the transmitter. In the likely case where the mobile terminal has a single antenna, space receive diversity can be used on the uplink (mobile terminal to access point) and ST-BC on the downlink.

The SNR gains, and therefore the gain in coverage, depend on the PER assumed for both techniques. The range enhancement was large (greater than 100% increase) if the system is required to operate at high data rates or low latencies (1% PER). This means that diversity as a method of range extension will be best suited to high reliability applications such as real-time audio and video applications where only small packet error rates are acceptable. Space receive diversity achieves a greater range enhancement than ST-BC. However, range enhancement was small for applications where high PER can be tolerated (such as delay insensitive applications or applications requiring data rates far lower than the offered rate).

For environments where path loss falls off rapidly with distance due to high clutter attenuation factors, a given diversity gain translates into a small range improvement. Diversity techniques in this operating environment offer very little benefit in terms of range enhancement.

We therefore conclude that space diversity techniques offer greater range enhancement than ST-BC at the expense of increased down-conversion and baseband processing complexity which leads to increased terminal cost. Both techniques are only of benefit when high data rates or low latencies are required and low amounts of clutter are present in the operating environment. Space receive techniques and ST-BC should both be considered for inclusion in future high data rate WLANs. The former for devices requiring large coverage and high data rates, and the latter for inclusion in fixed access point devices.

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