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Throughput and Coverage of WLANs Employing STBC under Different Channel Conditions

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Abstract—**HIPERLAN/2 and 802.11a/g WLANs employ Coded Orthogonal Frequency Division Multiplexing (COFDM) to 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. Packet Error Rate (PER) and throughput performance results are presented under different channel conditions. A WLAN physical layer simulator employing STBC and a propagation modelling tool are combined in order to evaluate the coverage and throughput of hot spot WLANs employing STBC for the 2x2 and 4x4 MIMO cases. Results showed that STBC can provide good performance, even at high K factors and under correlated channels. Throughput is significantly enhanced throughout the environment when STBC are employed.**

Keywords-Space Time Coding, WLANs, OFDM, correlation

I. INTRODUCTION

At present, Wireless Local Area Networks (WLANs) supporting broadband multimedia communications are being deployed around the world. Standards include IEEE 802.11a/g [1], and HIPERLAN/2 [2]. These systems provide channel adaptive data rates up to 54 Mbps in a 20 MHz channel spacing. It is likely that WLANs will become an important complementary technology to 3G cellular systems and will typically be used to provide 'hot-spot' coverage.

In [3], we quantified the throughput benefits offered to a cellular network using WLAN technology. In this paper, we expand our analysis for the case where WLANs employ STBC. In order to enhance performance, multiple transmit and receive antennas can be used to provide diversity. STBC is a simple and attractive space time coding scheme that was proposed by Alamouti [6]. It requires only a little additional complexity and is suitable for the slow fading environments in which WLANs are deployed.

A WLAN physical layer simulator employing STBC [2-4] and a propagation modelling tool [5] are combined in order to evaluate the coverage and throughput of hot spot WLANs employing STBC for the 2x2 and 4x4 MIMO cases. PER and throughput results are produced for a number of channel scenarios with different parameters such as rms delay spread, K-factor and angular spread (the latter parameter affecting the correlation between the antenna links). Based on these results and the coverage observed the available throughput can be estimated at every point in a specific environment.

II. WLAN PHYSICAL LAYER

The physical layers of HIPERLAN/2, 802.11a and 802.11g are based on the use of COFDM. COFDM 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 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:

$$Y_k = H_k X_k + N_k \tag{1}$$

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.

TABLE I. 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 (H/2)	16QAM	9/16	27
6	16QAM	3/4	36
7	64QAM	3/4	54
8 (802.11a/g)	64QAM	2/3	48

Importantly, the physical layer provides several modes (Table I), 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 [2,8].

III. SPACE TIME BLOCK CODING

A. 2x2 MIMO case

In [6] Alamouti proposed a simple transmit diversity scheme which was generalized by Tarokh [7] to form the class of Space Time Block Codes. These codes achieve the same diversity advantage as maximal ratio receive combining [9]. The transmit diversity scheme can be easily applied to OFDM in order to achieve a diversity gain over frequency selective fading channels. In Alamouti's encoding scheme 2 signals are transmitted simultaneously from the 2 transmit antennas. The transmission matrix is given by [6,4]:

$$G_2=\begin{bmatrix} X_1 & X_2 \\ -X_2^* & X_1^* \end{bmatrix} \quad (2)$$

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. At the first antenna, for the k^{th} subcarrier, X_1 is transmitted during the first symbol period followed by $-X_2^*$ in the second symbol period. At the second antenna, X_2 is transmitted during the first symbol period followed by X_1^* in the second symbol period.

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

$$\begin{aligned} Y_1&=H_1X_1+H_2X_2+N_1 \\ Y_2&=-H_1X_2^*+H_2X_1^*+N_2 \end{aligned} \quad (3)$$

where N_1, N_2 represent AWGN and H_1 and H_2 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 constant during the period of two OFDM symbols. This is reasonable for the OFDM parameters specified for WLANs.

After channel estimation, the channel parameters are known to the receiver, and the signals Y_1, Y_2 can be combined at the receiver according to:

$$\begin{aligned} S_1&=H_1^*Y_1+H_2Y_2^* \\ S_2&=H_2^*Y_1-H_1Y_2^* \end{aligned} \quad (4)$$

Substituting for Y_1, Y_2 from (3), the combined signals can be written as:

$$\begin{aligned} S_1&=(|H_1|^2+|H_2|^2)X_1+H_1^*N_1+H_2N_2^* \\ S_2&=(|H_1|^2+|H_2|^2)X_2+H_2^*N_1-H_1N_2^* \end{aligned} \quad (5)$$

In order to perform soft decision Viterbi decoding, the Channel State Information (CSI) of all channels and for all subcarriers is passed to the decoder.

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 signals 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 at half the power so that the average received power is the same when comparing receive diversity with transmit diversity.

B. 4x4 MIMO case

In [7], Tarokh proposed and evaluated the performance of STBC for the case of 3 and 4 transmit and receive antennas. For complex constellations, STBC can be constructed for any number of transmit antennas, and again these codes have remarkably simple decoding algorithms based only on linear processing at the receiver. For two antennas STBC provide full spatial diversity and represent a rate one code. For more than two antennas, they provide full spatial diversity and half of the maximum possible transmission rate allowed by the theory of space–time coding (½ rate codes). For complex constellations and for the specific cases of three and four transmit antennas, these diversity schemes were improved in [7] to provide ¾ of the maximum possible transmission rate. In this work these codes (G^h_3 and G^h_4 [7]) are applied for an OFDM based WLAN system. Since we are interested in a 4Tx and 4Rx system, G^h_4 is of interest:

$$G^h_4=\begin{bmatrix} X_1 & X_2 & X_3/\sqrt{2} & X_3/\sqrt{2} \\ -X_2^* & X_1^* & X_3/\sqrt{2} & -X_3/\sqrt{2} \\ X_3^*/\sqrt{2} & X_3^*/\sqrt{2} & (-X_1-X_1^*+X_2-X_2^*)/2 & (-X_2-X_1^*+X_1-X_2^*)/2 \\ X_3^*/\sqrt{2} & -X_3^*/\sqrt{2} & (X_1-X_1^*+X_2+X_2^*)/2 & -(X_2+X_1^*+X_1-X_2^*)/2 \end{bmatrix} \quad (6)$$

where in the case of OFDM, X_1, X_2 X_3, are consecutive vectors before the IDFT operation. For the case of G^h_4, after channel estimation, the channel parameters are known to the receiver, and the received signals Y_1, Y_2, Y_3, Y_4 can be combined at the receiver according to:

$$\begin{aligned} S_1&=H_1^*Y_1+H_2Y_2^*+(H_3^*-H_4^*)(Y_4-Y_3)/2-(H_3+H_4)(Y_4+Y_3)^*/2 \quad (7) \\ S_2&=H_2^*Y_1-H_1Y_2^*+(H_3^*-H_4^*)(Y_4+Y_3)/2+(H_3+H_4)(Y_4-Y_3)^*/2 \\ S_3&=H_3^*(Y_1+Y_2)/\sqrt{2}+H_4^*(Y_1-Y_2)/\sqrt{2}+(H_1+H_2)Y_3^*/\sqrt{2}+(H_1-H_2)Y_4^*/\sqrt{2} \end{aligned}$$

For the case of 1 Rx antenna, the above scheme is similar to that of four branch maximal ratio receive combining (MRRC) – however, again the power is equally divided across the 4 Tx antennas, so a 6 dB deference is expected. For the case of 4 Rx antennas, the signals from the four receivers are combined and the scheme performs similarly to sixteen branch MRRC. Note that in the case of G^h_4, the throughput of every mode is reduced since it is a ¾ rate code. Additionally, the channel has to remain constant for 4 OFDM symbols, something which is still reasonable for WLAN systems where the coherence time is usually of the order of 2-10ms.

IV. SIMULATION SETUP

WLAN systems are deployed in a wide range of environments such as offices, exhibition halls, home and outdoor environments. For the purpose of link level simulations a number of channel scenarios that represent the most probable environments for WLAN operation in the 5GHz region were defined. These scenarios corresponded to different values of rms delay spread, K factor and angular spread (resulting in different correlations between the antenna links). Link level simulations were performed over all channel scenarios for STBC to obtain PER and throughput results and to derive the throughput maps of an outdoor environment as explained below.

A. Classification of the model-based channels

Using the propagation modelling tool [5,3], MIMO channel characteristics were obtained for every point in an outdoor environment grid. Channel information included SNR values, MIMO channel response (H matrix), K-factor, rms delay spread and angular spread for all links between the AP and the MT over the coverage area. Using the above parameters it is possible to characterise the channel for a specific link and to then find the corresponding channel scenario from the ones defined. Additionally, the SNR value for that specific link is known. Since the throughput performance for a specific channel scenario and the SNR observed at that point (for a defined transmit power) are known, we are able to map the throughput that can be achieved at that point. This procedure was followed for all points in the coverage area, thus producing coverage and throughput maps.

B. Channel Scenarios

The link level simulations were conducted for 27 MIMO statistical channel scenarios with different parameters. In order to define those channels we examined the channels specified by ETSI BRAN, channel measurements and channel observations from the propagation tools. Table II presents the channel scenarios chosen. As can be seen, three values were chosen for the K-factor. The first corresponds to a Rayleigh scenario. This scenario can be observed in indoor and outdoor systems on which there is no LOS between the AP and the MT and the energy received at each time is made up of multiple paths of similar powers. The other two K-factor values chosen were 5 and 10 dB. These choices were based on the fact that measurements have shown that values of K-factor higher than 15 dB rarely occur in typical environments (indoor, outdoor). Therefore, taking into account the fact that we need to keep the number of parameters to a minimum, the three values mentioned above were thought to cover most real-life scenarios. Three cases were also selected for the rms delay spread. These were 20, 50 and 150ns. The first corresponds to indoor systems and cases in which the terminal is very close to the AP. The second case corresponds to indoor systems with high delay spread or outdoor hot-spots, and finally the third case corresponds to an outdoor case. As with the other two parameters, three values were also chosen for the angular width. These were 60, 90 and 360 degrees. The angular width (uniform distribution) will determine the correlation between the antennas. Note this in not the rms angular spread. The rms angular spread can be calculated from the angular width.

C. Performance evaluation metric (determinant)

Instead of using the observed angular spread, another metric can be used that describes the capacity of the channel. After careful consideration, the metric below was chosen where H is the channel matrix [10]:

$$K = E\{\det[\mathbf{H}\mathbf{H}^H]\} \quad (8)$$

D. Classification procedure

Finally, in order to classify the channel between two points in the environment, three parameters were considered. These are: the rms delay spread, the K-factor and the determinant metric that were observed in each link. After characterising the link, the throughput was calculated based on the throughput performance for the observed SNR.

TABLE II. CHANNEL SCENARIOS

Channel Scenario	rms delay spread	K factor	Angular width
H_20_0_60	20 ns	Rayleigh	60º
H_20_0_90	20 ns	Rayleigh	90º
H_20_0_360	20 ns	Rayleigh	360º
H_20_5_60	20 ns	5 dB	60º
H_20_5_90	20 ns	5 dB	90º
H_20_5_360	20 ns	5 dB	360º
H_20_10_60	20 ns	10 dB	60º
H_20_10_90	20 ns	10 dB	90º
H_20_10_360	20 ns	10 dB	360º
H_50_0_60	50 ns	Rayleigh	60º
H_50_0_90	50 ns	Rayleigh	90º
H_50_0_360	50 ns	Rayleigh	360º
H_50_5_60	50 ns	5 dB	60º
H_50_5_90	50 ns	5 dB	90º
H_50_5_360	50 ns	5 dB	360º
H_50_10_60	50 ns	10 dB	60º
H_50_10_90	50 ns	10 dB	90º
H_50_10_360	50 ns	10 dB	360º
H_150_0_60	150 ns	Rayleigh	60º
H_150_0_90	150 ns	Rayleigh	90º
H_150_0_360	150 ns	Rayleigh	360º
H_150_5_60	150 ns	5 dB	60º
H_150_5_90	150 ns	5 dB	90º
H_150_5_360	150 ns	5 dB	360º
H_150_10_60	150 ns	10 dB	60º
H_150_10_90	150 ns	10 dB	90º
H_150_10_360	150 ns	10 dB	360º

V. PERFORMANCE RESULTS

A. PER and Throughput Performance

Firstly, the PER and throughput performance for STBC over the 27 specified channels is presented. Due to the large number of performance results, a subset of the results were chosen to allow a comparison under different parameters. Results are presented for both the 2x2 and 4x4 antenna configurations. Note that due to space limitations, the PER performance of the 1x1 case is not shown here since we are only interested in comparing the STBC performance under different channel conditions. The reader is referred to [4] for more information on the gains achieved with STBC.

The effect of the Rician K-factor and the angular width on the PER vs. SNR performance was studied for the cases of 2x2 and 4x4 MIMO systems. The results are shown in Figures 1(a) and (b) respectively. It can be seen that as the K-factor increases, the PER performance is also seen to increase since the channel becomes more Rician (resulting in less fading). Even though in channels with high K-factors the signals are more correlated, effectively reducing the spatial diversity of the system, STBC systems are able to cope with this decrease since a maximum of one symbol is transmitted per channel. This does not apply for systems employing spatial multiplexing where we observed that performance degrades for higher K factors. This behavior of STBC systems for high K-factor channels indicates that STBC can potentially be used efficiently in LOS environments. Another result that arises is the degradation in performance for channels with low angular spread. Low angular spread corresponds to a greater level of correlation between the antenna links resulting in lower performance.

Another factor that is expected to affect the performance of OFDM STBC systems is the rms delay spread. The PER performance of 2x2 and 4x4 systems are shown in Figure 2 for mode 3. From Figure 2 (a) and (b), it can be observed that the performance of both cases is increased for an increased rms delay spread. This is due to the fact that a high delay spread in the time domain corresponds to frequency selective fading in the frequency domain and therefore there is a higher degree of frequency diversity to be exploited by an OFDM system, thus resulting in higher performance.

Figures 3 (a) and (b) present PER performance results for all modes for channel H_20_0_360 (rms delay spread 20ns, Rayleigh, angular spread 360 degrees). As expected, in the same channel the different STBC transmission modes have different PER performances. These performance results are shown for the 2x2 and 4x4 cases. As expected, the 4x4 configuration provides better PER performance results due to the increased diversity offered.

Figures 4(a), (b) and (c), show the throughput performances on the same channel for all modes for the 1x1, 2x2 and 4x4 cases respectively. As expected [4], significant throughput enhancements can be achieved when STBC are employed compared to the 1x1 case, especially for low SNRs. It can also be seen that for low SNR values the 4x4 system performs better than the 2x2 system due to the higher diversity order (16 instead of 4). However for higher values of SNR, the 4x4 throughput performance is outperformed by the 2x2 system because the 4x4 STBC is not a full rate code (¾ code). The maximum throughput that can be achieved with the 4x4 STBC is 40.5 Mbps.

B. Coverage and Throughput Maps

The propagation modelling tool was employed to provide a point-to-multipoint analysis of the received signal level at 5.2GHz, in the outdoor WLAN environment for the AP (access point) locations. Additionally, channel characteristics such as rms delay spread, K-factor and angular spread can be predicted for every link. The outdoor analysis is performed over a 200m x 200m area of downtown Bristol. Ray-tracing predictions at 5.2GHz are generated for this area for a hotspot-type transmitter location (5m above the ground) with a transmit EIRP of 25dBm. The mobile terminals are located at 1.5m above ground, and both transmit and receive antennas are vertically polarized $\lambda/2$ dipoles. Based on the predicted coverage (Figure 5), the channel characteristics observed and the throughput performance of the WLANs in different channel conditions, it is possible to evaluate the maximum achievable data rates throughout the coverage area. The modes used in the SISO case and the offered throughputs are shown in Figure 6. It can be seen that mode 7 was used in the majority of LOS locations due to the high values of SNR in those areas. Modes 6 and 5 were also used in locations with lower SNR, resulting in lower throughputs as shown in Figure 7.

STBC were also used in the outdoor case and the results in terms of the mode used are shown in Figure 8 (a) and (b) for the 2x2 and 4x4 cases respectively. Mode 7 is supported throughout almost the entire area for both the 2x2 and 4x4 cases. This is due to the smaller SNR required by the STBC solution in order to provide coverage, and the strong immunity to correlation. As expected, in terms of throughput, the maximum throughput was achieved by both the 2x2 and 4x4 cases in most locations. It is obvious that range extension can also be supported, especially in the 4x4 case. Compared to the SISO case, STBC can provide higher throughputs throughout the coverage area.

VI. CONCLUSIONS

In this paper, STBC techniques were considered as a means of enhancing the performance and throughput of OFDM WLANs. PER performance results for the case of 2x2 and 4x4 antenna configurations under different channel conditions were presented. It was shown that STBC can provide good performance, even at high K-factors and under highly correlated channels. Coverage and throughput maps have been produced showing that significant enhancements can be achieved in both cases. STBC is a simple technique that can enhance the throughput of OFDM based WLANs and can also enhance the coverage area since lower SNR values are required.

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REFERENCES

[1] IEEE Std 802.11a/D7.0-1999, Part11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High Speed Physical Layer in the 5GHz Band..

[2] A. Doufexi, S. Armour, P. Karlsson, M. Butler, A. Nix, D. Bull, J. McGeehan, "A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless LAN Standards," IEEE Communications Magazine, May 2002, Vol. 40, No. 5.

[3] A. Doufexi E. Tameh, A. Molina, A. Nix, S. Armour "Hot Spot Wireless LANs to Enhance the Performance of "3G and Beyond" Cellular Networks", IEEE Communications Magazine, Vol.41 No.7, July 2003.

[4] A. Doufexi, A.Prado, S. Armour, A. Nix, M. Beach, "Use of Space Time Block Codes and Spatial Multiplexing using TDLS Channel Estimation to Enhance the Throughput of OFDM based WLANs", IEEE VTC Spring, Korea, April 2003.

[5] E. K. Tameh, A.R Nix, "A Mixed-Cell Propagation Model for Interference Prediction in a UMTS Network", IEEE VTC'01 Spring (Rhodes).

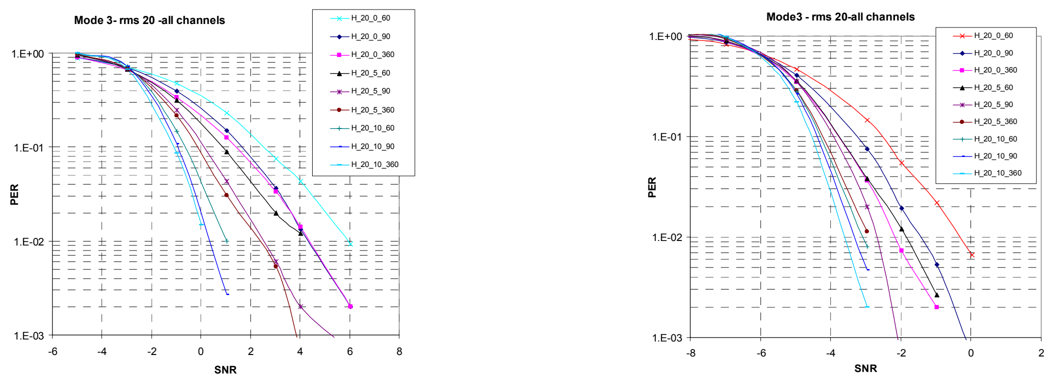
[6] M.Alamouti, "A simple transmit diversity technique for wireless communications", IEEE JSAC, Vol. 16, No.8, October 1998.

[7] V.Tarokh, H.Jafarkhani, A.R.Calderbank, "Space-time block coding for wireless communications: performance results", IEEE JSAC, Vol. 17 No. 3, March 1999, pp.451-460.

[8] A.Doufexi, S.Armour, P.Karlsson, A.Nix, D.Bull, "Throughput Performance of WLANs Operating at 5GHz Based on Link Simulations with Real and Statistical Channels," IEEE VTC'01 Spring (Rhodes).

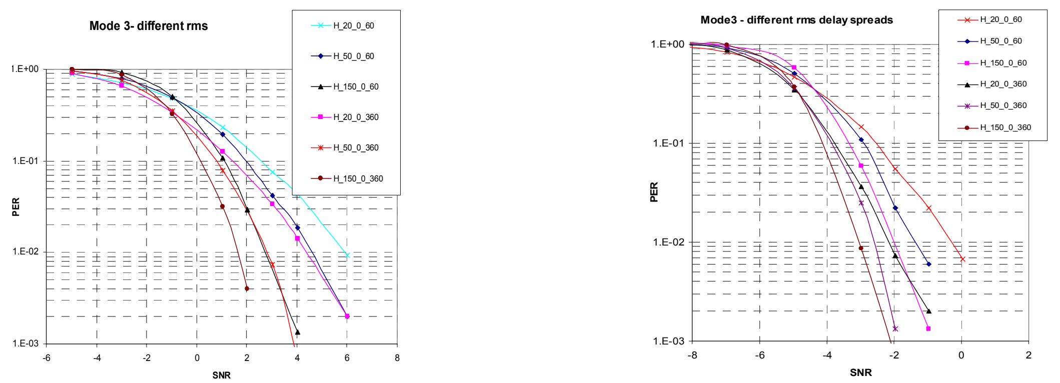
[9] B. Vucetic, "Space-Time Codes for High Speed Wireless Communications", Course on Space Time Codes, King's College London, November 2001.

[10] Oestges, C., Clerckx, B., Vanhoenacker-Janvier, D., and Paulraj, A.J., "Impact of Diagonal Correlations on MIMO Capacity: Application to Geometrical Scattering Models", IEEE VTC Fall, October 2003.



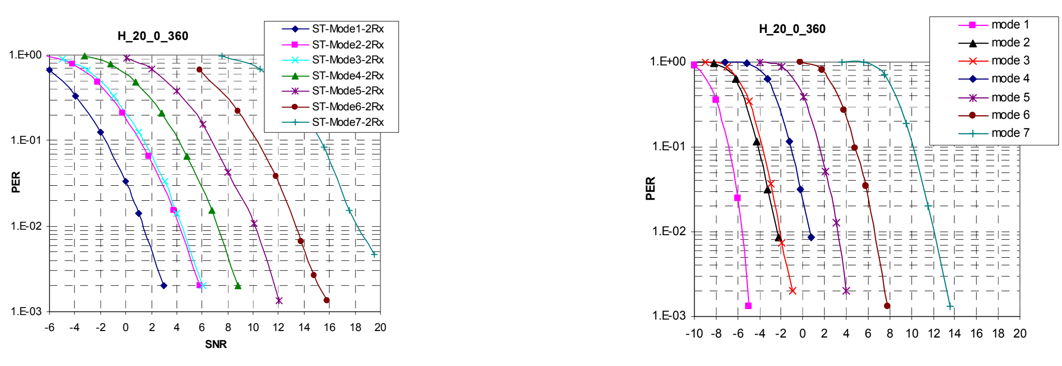
(a) (b)

Figure 1. PER performance of STBC mode 3 for (a) the 2x2 and (b) the 4x4 cases with different K-factors and angular spreads



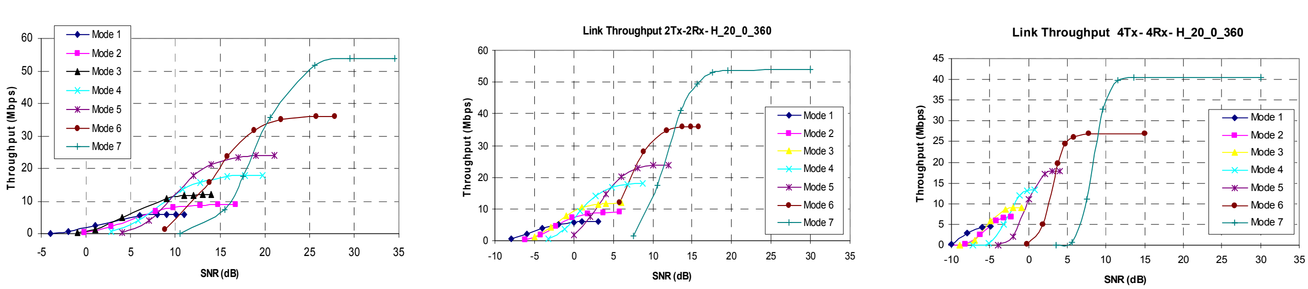
(a) (b)

Figure 2. PER performance of STBC mode 3 for (a) the 2x2 and (b) the 4x4 MIMO cases with different delay and angular spread



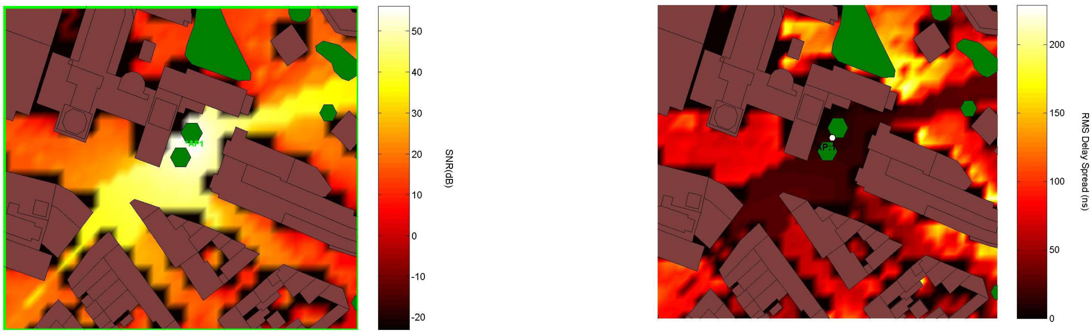
(a) (b)

Figure 3. PER vs. SNR performance of all modes in channel H_20_0_360 for the (a) 2x2 and (b) 4x4 MIMO cases



(a) (b) (c)

Figure 4. Throughputs for (a)the 1x1, (b) the 2x2 and (c) 4x4 cases for all modes (channel H_20_0_360)



(a) (b)

Figure 5. Area plots showing (a) the SNR (b) the delay spread

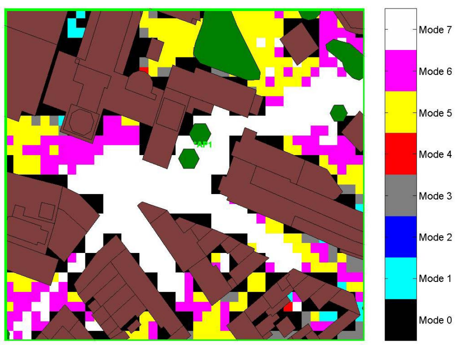


Figure 6. SISO modes

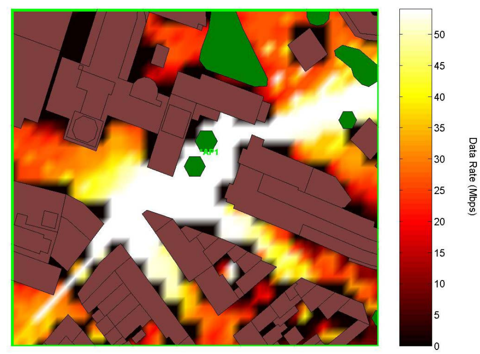
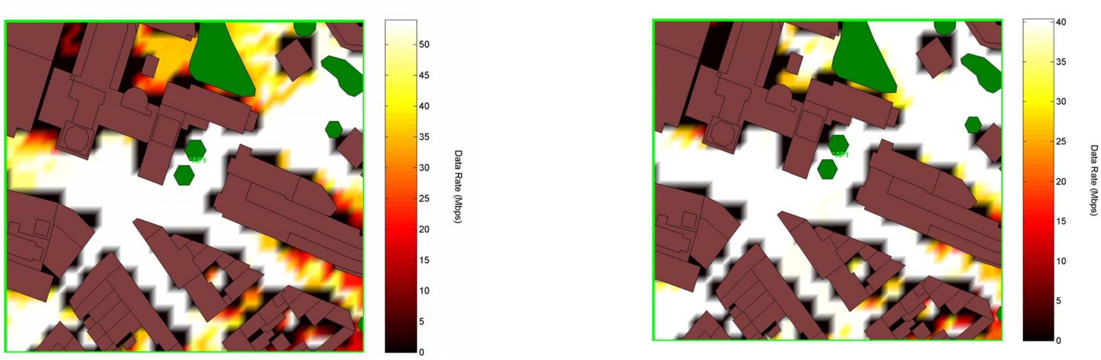


Figure 7. SISO throughput

(a) (b)

Figure 8. STBC modes used in (a) 2x2 and (b) 4x4 MIMO cases



(a) (b)

Figure 9. OFDM STBC throughput for the (a) 2x2 and (b) 4x4 case