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Capacity and Coverage Enhancements of MIMO WLANs in Realistic Environments

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Abstract — Recently, there has been an explosion of growth in research on MIMO systems, but little has been published characterising performance in realistic environments. This paper quantifies the performance of MIMO WLANs in outdoor environments, and compares performance between spatial multiplexing and space time block coding processing approaches. Packet Error Rate (PER) and throughput performance results are presented under different channel conditions. A WLAN physical layer simulator employing MIMO techniques and a propagation modelling tool are combined in order to evaluate the coverage and throughput enhancements of WLANs for the 2x2 and 4x4 MIMO cases.

I. INTRODUCTION

At present, Wireless Local Area Networks (WLANs) are being deployed around the world. Standards developed include IEEE 802.11a/g [1,2,14] based on orthogonal division multiple access (OFDM). It is likely that WLANs will become an important complementary technology to 3G cellular systems [3]. In [4,5], the spectrum efficiency benefits of deploying IEEE802.11a augmented with MIMO processing were investigated for both indoor and outdoor environments, continuing from the work in [3, 14]. This paper will present results for the outdoor case for MIMO WLANs.

A STBC is a simple and attractive space time coding scheme that was proposed by Alamouti [6]. STBC can enhance performance of WLANs by exploiting spatial diversity [7,8]. Spatial multiplexing [9] 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 in specific channel conditions. For this study, a WLAN physical layer simulator employing MIMO techniques [2,7,8] and an outdoor propagation modelling tool [10] were combined in order to evaluate the coverage and throughput of WLANs for the 2x2 and 4x4 MIMO cases in realistic environments. 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. SPACE TIME BLOCK CODING AND SPATIAL MULTIPLEXING

The physical layers of 802.11a [1] and 802.11g [14] are based on the use of OFDM. The physical layer provides several modes each with a different coding and modulation configuration (Mode1: BPSK 1/2 rate, Mode2: BPSK 3/4 rate,

Mode3: QPSK 1/2 rate, Mode4: QPSK 3/4 rate, Mode5: 16QAM 1/2 rate, Mode6: 16QAM 3/4 rate, Mode7: 64QAM 3/4 rate).

In Alamouti's [6] STBC encoding scheme 2 signals are transmitted simultaneously from the 2 transmit antennas. The transmission matrix is given by:

$$G_2 = \begin{bmatrix} X_1 & X_2 \\ -X_2^* & X_1^* \end{bmatrix} \quad (1)$$

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. In [11], Tarokh proposed and evaluated the performance of STBC for the case of 3 and 4 transmit and receive antennas. In this work these codes are applied for an OFDM based WLAN system. Since we are interested in a 4Tx and 4Rx system, $G_{4,4}^h$ is of interest:

$$G_{4,4}^h = \begin{bmatrix} X_1 & X_2 & X_3/\sqrt{2} & X_3/\sqrt{2} \\ -X_2^* & X_1^* & X_3/\sqrt{2} & -X_3/\sqrt{2} \\ X_3^*/\sqrt{2} & X_3^*/\sqrt{2} & (-X_1 - X_1^* + X_2 - X_2^*)/2 & (-X_2 - X_1^* + X_1 - X_2^*)/2 \\ X_3^*/\sqrt{2} & -X_3^*/\sqrt{2} & (X_1 - X_1^* + X_2 + X_2^*)/2 & -(X_2 + X_1^* + X_1 - X_2^*)/2 \end{bmatrix} \quad (2)$$

Note that in the case of $G_{4,4}^h$, the throughput of every mode is reduced since it is a 3/4 rate code.

Spatial multiplexing, also known as Bell Laboratories Layered Space Time Architecture (BLAST), represents a direct exploitation of the available space-time resources. The first version of BLAST proposed in the literature is Diagonal BLAST (D-BLAST) [9] which has a diagonal layering space-time coding process with sequential nulling and interference cancellation decoding. Vertical BLAST [12] on the other hand uses a horizontal layering space-time structure. Linear processing detection techniques include zero forcing (ZF) and minimum mean squared (MMSE). In this study an MMSE detection algorithm was used [4].

III. SIMULATION METHOD

A WLAN physical layer simulator employing MIMO techniques and a propagation modelling tool have been combined and extended in order to evaluate the coverage and throughput of hot spot WLANs employing STBC and SM for the 2x2 and 4x4 MIMO cases. To analyse the throughput over a large area would require a great deal of processing time if the physical layer simulator was run at every point on the grid. Instead an efficient method that maps channel characteristics onto performance is described in this section.

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. PER and throughput results have been produced for a number of channel scenarios with different parameters; SNR, RMS delay spread, K-factor and angular spread (the latter parameter affecting the correlation between the antenna links). Based on these results and the output from the propagation tool, at every point in a specific environment the appropriate channel scenario can be identified and hence the available throughput can be estimated. Link level simulations were performed over all channel scenarios for STBC and spatial multiplexing to generate the throughput mapping. The process is discussed in more detail in the following paragraphs.

A. Channel Scenarios

The link level simulations were conducted for 27 MIMO statistical channel scenarios with different parameters [4]. In order to define those channels we examined the channels specified by ETSI BRAN, channel measurements and channel observations from the propagation tools.

TABLE I. CHANNEL SCENARIOS

Channel Scenario	RMS delay spread	K factor	Angular width
H 20 0 60	20 ns	Rayleigh	60°
H 20 0 90	20 ns	Rayleigh	90°
H 20 0 360	20 ns	Rayleigh	360°
H 20 5 60	20 ns	5 dB	60°
H 20 5 90	20 ns	5 dB	90°
H 20 5 360	20 ns	5 dB	360°
H 20 10 60	20 ns	10 dB	60°
H 20 10 90	20 ns	10 dB	90°
H 20 10 360	20 ns	10 dB	360°
H 50 0 60	50 ns	Rayleigh	60°
H 50 0 90	50 ns	Rayleigh	90°
H 50 0 360	50 ns	Rayleigh	360°
H 50 5 60	50 ns	5 dB	60°
H 50 5 90	50 ns	5 dB	90°
H 50 5 360	50 ns	5 dB	360°
H 50 10 60	50 ns	10 dB	60°
H 50 10 90	50 ns	10 dB	90°
H 50 10 360	50 ns	10 dB	360°
H 150 0 60	150 ns	Rayleigh	60°
H 150 0 90	150 ns	Rayleigh	90°
H 150 0 360	150 ns	Rayleigh	360°
H 150 5 60	150 ns	5 dB	60°
H 150 5 90	150 ns	5 dB	90°
H 150 5 360	150 ns	5 dB	360°
H 150 10 60	150 ns	10 dB	60°
H 150 10 90	150 ns	10 dB	90°
H 150 10 360	150 ns	10 dB	360°

Table I 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 is not the RMS angular spread.

B. Performance evaluation metric (determinant)

Instead of using the observed angular spread, another metric can be used that describes the capacity of the channel and includes the effect of antenna configuration. This way our results will not depend on a specific antenna configuration, and is more generic. After careful consideration, the metric below was chosen where \mathbf{H} is the channel matrix [13]:

$$K_D = E \left\{ \det[\mathbf{H}\mathbf{H}^H] \right\} \quad (3)$$

The above metric gives us a measure of the capacity of the channel which does not depend on SNR.

C. Classification procedure

Finally, in order to classify the channel between two points in the environment, three parameters are 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. A decision based solely on the capacity of the channel would not have been very accurate, since the capacity can be affected from a number of parameters. As we will see later on, each parameter of the channel scenarios will affect the physical layer performance differently depending on the MIMO algorithm employed.

IV. PERFORMANCE RESULTS

A. PER and Throughput Performance of STBC

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 was 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 and spatial multiplexing performance under different channel conditions. The reader is referred to [7,8] for more information on the gains achieved with STBC and spatial multiplexing compared to single antenna systems.

The effect of the Rician K-factor and the angular width on the PER vs. average SNR performance was studied for the cases of 2x2 and 4x4 STBC 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 improve 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 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. As expected, the 4x4 configuration provides better PER performance results due to the increased diversity offered.

Significant throughput enhancements can be achieved when STBC are employed compared to the 1x1 case, especially for low SNRs. It was observed, that for low SNR values the 4x4 system provides better throughput 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 ($\frac{3}{4}$ code). The maximum throughput that can be achieved with the 4x4 STBC is 40.5 Mbps.

B. PER and Throughput Performance of SM

The effect of K-factor and angular spread were also studied for the 2x2 and 4x4 SM systems and the PER performances are shown in Figure 3(a) and (b). It was shown earlier that the performance of the STBC systems improved for increasing K-factor. The opposite behaviour is observed however for spatial multiplexing systems. 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. The increase in correlation between antennas decreases the amount of spatial diversity that can be utilized. Since SM systems rely on spatial diversity to recover the transmitted message, this performance degradation is inevitable. Increased correlation results in making certain spatial channels weak, thus decreasing performance. However, as far as the angular spread is concerned, the same trend as with STBC is observed, i.e. the performance is worst in channels with low angular spread since the channels are more correlated.

The performances of different modes in channels with high delay spreads were also investigated. Figure 4 shows the performance of modes 3 and 5 for the 2x2 SM systems. As

illustrated in Figure 4, for channels with high angular spread and RMS delay spread there is performance improvement on the lower transmission modes (Figure 4a). However, higher modes experience an error floor in channels with high RMS delay spread (Figure 4b) since ISI is introduced (when the excess delay of the channel is larger than the guard interval).

As far as the difference in performance between the 2x2 and 4x4 cases is concerned, 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. The SM 4x4 case can reach a maximum throughput of 216Mbps compared to a maximum of 108Mbps for the 2x2 case. These values are significantly higher than the 54 Mbps maximum throughput of the SISO case. However, these throughputs can only be achieved under certain channel conditions such as low RMS delay spreads and high angular spread. A high K-factor or a low angular spread will result in performance degradation resulting in high throughputs being achieved only at very high values of SNR as will be shown in the next section. The performance degradation is greater for the 4x4 case for the reasons discussed above. Note that all the throughput values, presented in the next section, are at the physical layer and throughput will be considerably reduced after the MAC (medium access control) due to overheads [2].

C. Coverage and Throughput Maps

In this section, the performance of SISO, 2x2 MIMO and 4x4 MIMO in terms of maximum achievable throughput and SM/STBC modes will be assessed in an outdoor environment using ray-tracing data. The ray tracing propagation modelling tool [10] was employed to provide a point-to-multipoint characterisation of the MIMO radio channel at 5.2GHz, in the indoor WLAN environment for the AP (access point) locations. The outdoor analysis is performed over a 200m x 200m area of Bristol city centre. Ray-tracing predictions at 5.2GHz are generated for this area for a hotspot-type transmitter location (5m above ground) with transmit EIRP of 25dBm. The mobile terminals are located at 1.5m above ground, and both transmit and receive antennas are vertically polarised $\lambda/2$ dipoles. In these results power control has not been used. From the spatial-temporal dispersion information obtained from the ray tracing tool, channel characteristics such as path loss (and received power), RMS delay spread, K-factor and angular spread are predicted for every link. Using the channel dispersion information (complex channel impulse response and arrival angles) as well as the knowledge of the relative positions of the antenna elements for each array configuration, the wideband MIMO channel response matrices (\mathbf{H}) were generated for every link. The channel matrices were then averaged over the entire bandwidth and used in Equation (3) to calculate the determinant metric.

Based on the predicted coverage (SNR) and channel characteristics, as well as the PER and throughput performance of the WLANs in different channel conditions

(presented in the preceding sections), it is possible to evaluate the maximum achievable data rates throughout the coverage area. Coverage, throughput and mode maps were produced for both STBC and SM for the specific outdoor environment and for the 2x2 and 4x4 cases. A uniform linear array antenna configuration is considered.

In the SISO case (Figure 5), 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. For the STBC cases, (Figure 6), mode 7 was used in the majority of the locations in both 2x2 and 4x4 MIMO cases. This is due to the diversity offered by STBC, which enables those systems to work at very low SNR values. In effect, STBC can offer range extensions (or a reduction in transmit power) since most of the coverage at that range is provided by mode 7. For the 2x2 case 54Mbps is achieved over most of the area whereas for the 4x4 case 40.5Mbps was achieved throughout the coverage area. Note that the throughput reduction occurs because the 4x4 code is not full rate.

Contrary to STBC, a number of different modes were used in the SM system (Figure 7). For the 2x2 case, mode 7 can be supported in a very limited number of locations due to high correlations and the low immunity of SM to high correlation levels. In most LOS locations, mode 6 is used however lower modes are used further from the AP (lower SNRs). For the 4x4 case, SM performs poorly, offering mainly modes 3 and 1 throughout the area. This is due to the high correlation; hence a lot of transmitted signals cannot be detected. The resulting throughput for 2x2 SM is shown in Figure 8(a). Figures 8(b) compares the SM and STBC techniques for the 2x2 case in terms of the offered throughput. The blue areas correspond to locations where SM offers better throughput than STBC and the opposite is true for the red areas. It can be seen that for the 2x2 case, SM performs better in locations which are near the AP (due to the high SNR values) whereas STBC give higher throughputs than SM for areas further away from the AP (since STBC perform well even at low SNR values due to diversity). A smart MIMO system (that has knowledge of the channel parameters – for example TDD in WLANs) could adapt the MIMO technique, depending on the environment.

V. CONCLUSIONS

In this paper, STBC and SM 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. Coverage and throughput maps have been produced showing that significant enhancements can be achieved in both cases. The potential channel capacity is strongly dependent on the channel characteristics. If there is no or limited diversity in the channel, some MIMO techniques will at best perform poorly, and could completely fail to operate. Therefore any application using such MIMO techniques that is likely to experience such poor channels, must have operating modes tolerant to such channel conditions

(i.e. not relying on spatial diversity) if communication capability is not to be lost. This study has shown that, for the algorithms investigated, STBCs are more able to maintain communication than SM when channels are strongly correlated. What is clear from the results is that SNR is a dominant factor in performance, and so system design must not lose sensitivity/gain while trying to minimise channel correlation. The capacity gain as a function of the number of antennas has been seen to be less than linear in realistic channels. As already noted, performance can degrade with larger numbers of antennas if the channel cannot support sufficient spatial modes for the algorithm being used. This degradation is more severe for the SM algorithms studied in this project.

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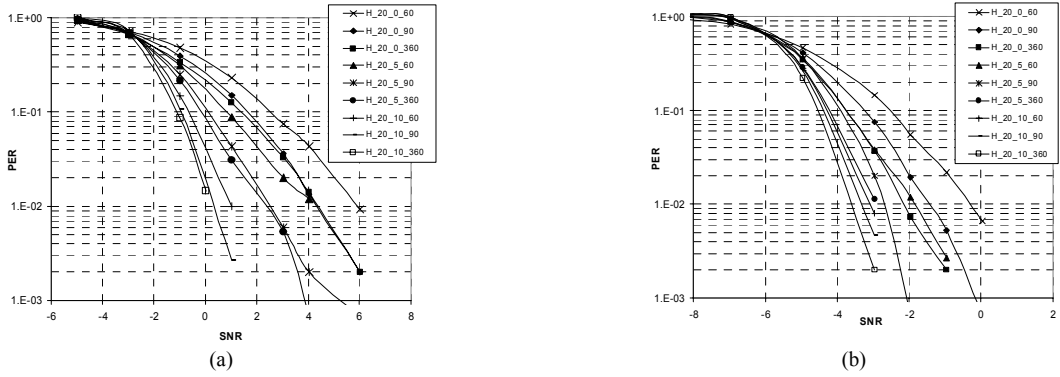


Figure 1. PER performance of STBC mode 3 for (a) the 2x2 and (b) the 4x4 cases with different K-factors and angular spreads

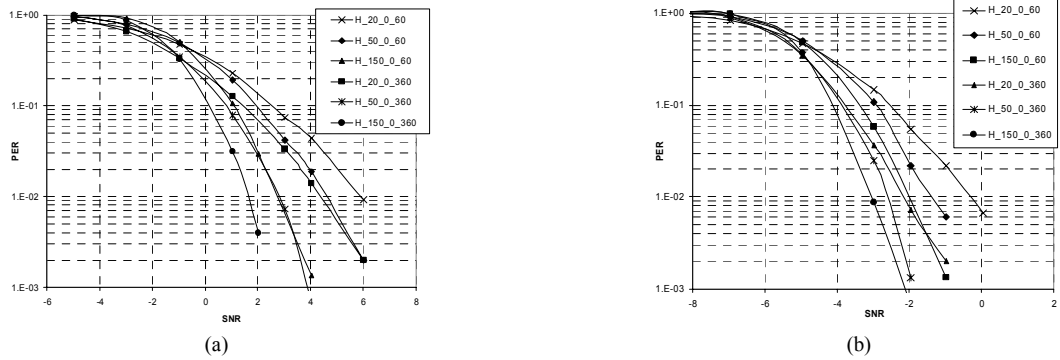


Figure 2. PER performance of STBC mode 3 for (a) the 2x2 and (b) the 4x4 MIMO cases with different delay and angular spread

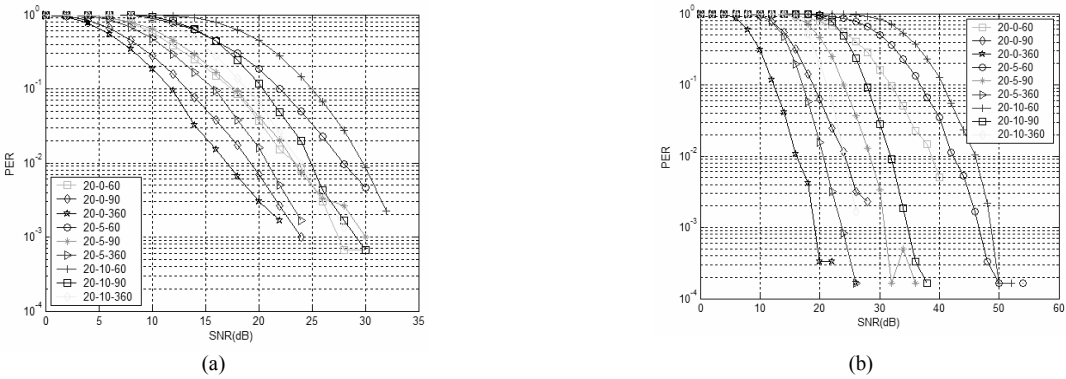


Figure 3. PER performance of SM mode 3 for (a) the 2x2 and (b) the 4x4 MIMO cases with different K-factor and angular spread

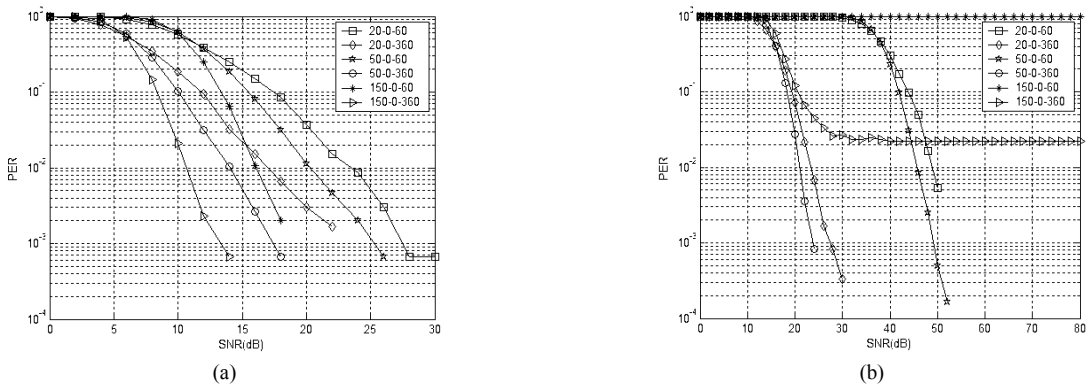


Figure 4. Performance of 2x2 MIMO (a) mode 3 and (b) mode 5

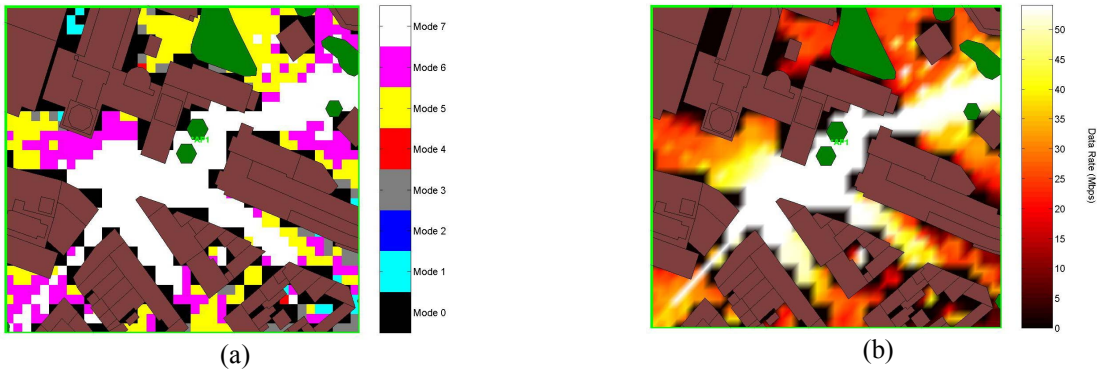


Figure 5. (a) SISO Modes and (b) SISO Throughput

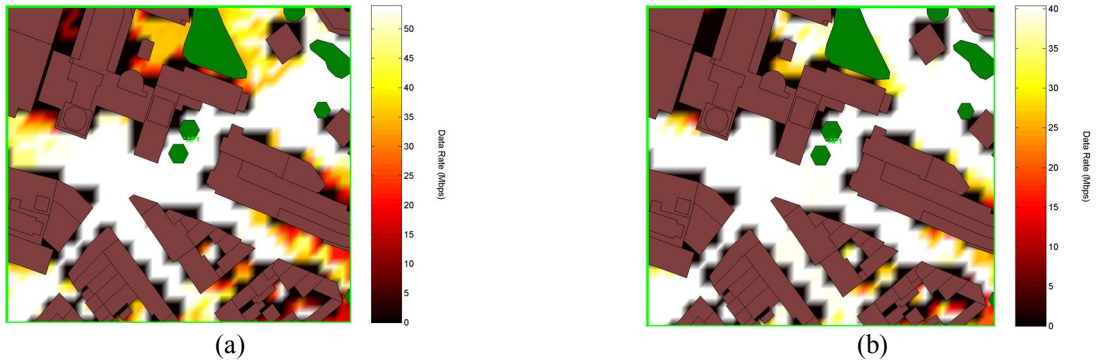


Figure 6. OFDM STBC throughput for the (a) 2x2 and (b) 4x4 cases

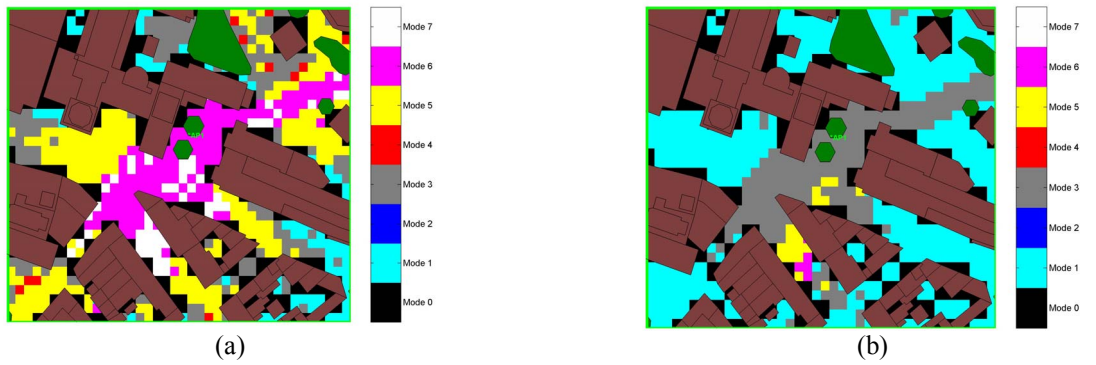


Figure 7. SM modes used in (a) 2x2 and (b) 4x4 MIMO cases

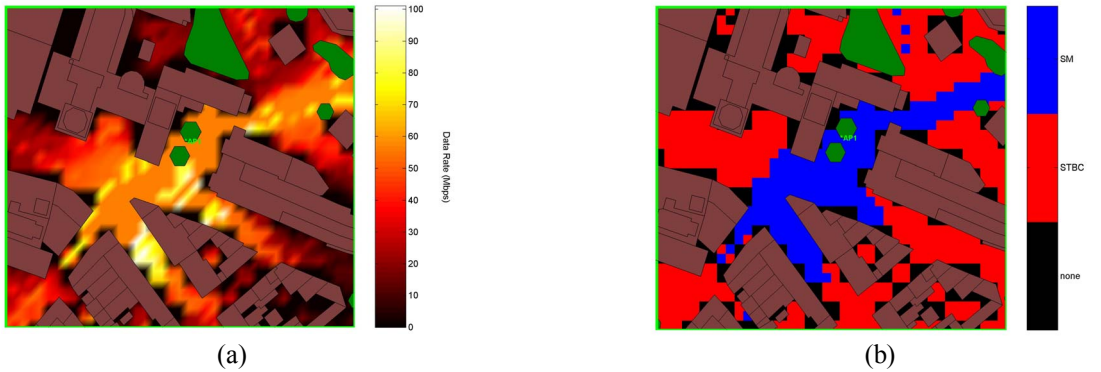


Figure 8. (a) OFDM SM throughput for the 2x2 case (b) best technique