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Multiple Antenna Techniques in WiMAX Systems

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Abstract. Multiple antenna systems can offer significant improvements in system performance due to their ability to exploit multipath signal propagation and take advantage of its random nature in order to achieve diversity or spatial multiplexing gain. As such, they are very suitable for implementation in WiMAX (Worldwide Interoperability for Microwave Access) systems to improve its performance in harsh urban and indoor environments. WiMAX physical layer is based on Orthogonal Frequency Division Multiplexing (OFDM), which is very robust to multipath propagation and enables straightforward usage of MIMO techniques. In this paper multiple antenna techniques and their use in Fixed and Mobile WiMAX systems are discussed. We present test results, collected with field measurements during a Fixed WiMAX system deployment, and describe results obtained by applying a channel simulator whose parameters are tuned according to field measurement data. A performance comparison between STC (Space-Time Coding) and non-STC operation mode is analyzed for different coding and modulation schemes specified in the standard.

Keywords: multiple antennas, WiMAX, space-time coding, spatial multiplexing, OFDM

Uporaba večantenskih sistemov v omrežjih WiMAX

Povzetek. Večantenski sistemi omogočajo znatno izboljšanje učinkovitosti brezžičnega komunikacijskega sistema, saj izkoriščajo lastnost, kot je širjenje signala po več poteh, v svojo korist, tako da izrabljajo naključnost oziroma nekoreliranost teh poti za prostorsko ločevanje sočasno poslanih signalov. Kot taki so ti sistemi zelo primerni za implementacijo v sistemih WiMAX, ki na fizični ravni uporabljajo tehnologijo OFDM, odporno proti širjenju signala po več poteh. V prispevku sta podana pregled tehnik v več-antenskih sistemih in njihova uporaba v fiksnih in mobilnih sistemih WiMAX. Predstavljeni so tudi rezultati meritev na terenu in laboratorijskih meritev. V laboratorijskih meritvah smo uporabili simulator radijskega kanala s parametri radijskega kanala, pridobljenimi z meritvami na terenu. Izvedli smo primerjavo učinkovitosti dveh načinov delovanja, in sicer z uporabo in brez uporabe prostorsko-časovnega kodiranja. Primerjavo smo opravili za različne kodno-modulacijske sheme, ki so predpisane v standardu.

Ključne besede: večantenski sistemi, WiMAX, prostorsko-časovno kodiranje, prostorski multipleks, OFDM (ortogonalno frekvenčno multipleksiranje)

1 Introduction

The main attributes that are desired in a modern communication system are high spectral efficiency and high data rate, along with high quality of service (QoS) - meaning low outage probability, low bit error rate, etc. - and wide coverage. However, a wireless channel presents a very hostile and difficult environment for provision of such attributes. There are various drawbacks, such as signal attenuation due to path loss, limited bandwidth, co-channel interference (CCI) due to the presence of other users and, most importantly, severe fluctuations in signal level, referred to as fading [1]. Fading is a result of multipath propagation and the Doppler spread which is caused by the mobility of the user as well as variations in the environment.

Two main solutions to the above problem are typically proposed by modern standards. The first is adaptive coding and modulation (ACM), which is based on the concept that the coding and modulation scheme adapts dynamically to the channel conditions. The second is the use of multiple antennas at the transmitter and receiver. While ACM can cope with slow fading, multiple antenna techniques can also combat fast fading. Optimal performance can be obtained by taking advantage of both solutions.

Multiple input multiple output (MIMO) systems exploit multipath propagation and random signal fading to increase the system performance without extra bandwidth and power costs. There are four different benefits offered by MIMO systems: diversity gain, spatial multiplexing gain, array gain, and interference reduction. The use of MIMO techniques is also included in Fixed and Mobile WiMAX (Worldwide Interoperability for Microwave Access) system profiles. Several multiple antenna options are supported, enabling the exploitation of all the above stated benefits.

The paper is organized as follows: first we present a short overview of multiple antenna techniques and their main benefits. In Section 3, the IEEE 802.16 standard is

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discussed briefly and in Section 4 the use of multiple antennas in WiMAX systems, as described in the standard, is explored. In Section 5, results obtained from field and laboratory measurements are compared with those from theory, as discussed in previous sections. Conclusions are presented in Section 6.

2 Overview of multiple antenna techniques

MIMO systems are wireless systems equipped with multiple antennas at the receiver and transmitter. The great interest in MIMO systems is due to their ability to increase system capacity or reliability without any increase in transmitting power or bandwidth. MIMO technology makes use of the spatial dimension by taking advantage of multipath propagation channel characteristics.

Spectral efficiency can be increased by the simultaneous transmission of data over different antennas using random fading as the means of signal separation. On the other hand increase in system reliability is achieved, with the insertion of redundancy, by transmitting multiple copies of the same signal over different propagation paths, thus achieving spatial diversity gain.

Suppose we have a MIMO system with M transmit and N receive antennas, then there are $M \times N$ subchannels between the transmitter and the receiver. Assuming frequency non-selective or flat fading, the received signal can be expressed as:

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{n}, \tag{1}$$

where $\boldsymbol{H}$ is the $N \times M$ dimensional channel matrix with complex coefficients h_{ij} that represent the channel response between the *j-th* transmit and *i-th* receive antenna, $\boldsymbol{y}$ and $\boldsymbol{x}$ are the received and transmitted vectors respectively, and $\boldsymbol{n}$ is the noise vector.

In Single Input Single Output (SISO) systems, capacity grows logarithmically with signal-to-noise ratio (SNR). In [2], Telatar has shown that the capacity of MIMO systems, compared to SISO systems, grows linearly with the number of independent subchannels, which equals the rank of channel matrix $\boldsymbol{H}$ and can be at most $min(M,N)$. The increase in capacity, compared to that of the SISO system, is referred to as spatial multiplexing gain.

Alternatively, a diversity gain of $M \times N$ can be achieved by assuming $M \times N$ random fading propagation paths [3]. Diversity techniques are based on the assumption that there is low probability of all paths being in a deep fade. Hence, diversity gain decreases the fluctuations in received signal power, which mitigates fading effects. Diversity gain d tells us how fast the decoding error probability P_e decays with the increase of SNR:

$$P_e \propto (SNR)^{-d} \tag{2}$$

Besides spatial multiplexing and diversity gain, other significant benefits, such as array gain or interference cancellation/avoidance, can be achieved. Array gain is the increase in SNR due to coherent combining of signals at the receiver and can be achieved, even in a highly correlated channel, either at the transmitter or receiver side, providing that the channel response is known at the respective side. Interference cancellation is important in cellular multi-user systems, since the presence of subscribers using the same frequency band causes CCI. The interference can be mitigated by spatially separating signals to/from different users. Application of such a method at the transmitter is called beamforming. It is used at the base station (BS) side and enables better frequency reuse and thus increases the overall capacity of the cellular system. However, it is not possible to exploit these benefits simultaneously to the full, due to conflicting demands on the spatial degrees of freedom. A certain trade-off between possible gains must be taken into account, based on the system requirements. The maximum trade-off between the two principal gains (spatial diversity and multiplexing) is a piecewise linear function [4], showing that, if maximum spatial multiplexing gain is to be achieved, no diversity gain can be exploited, and vice versa.

2.1 Systems exploiting spatial diversity

- **Receive diversity**

The optimal receive diversity technique in a Rayleigh channel is Maximal Ratio Combining (MRC), where the output is *the* weighted sum of all received signal components. The weights are chosen based on the SNR of the respective signal component, so that the average SNR of the combined signal is maximized. MRC yields the maximum diversity order N, assuming N receive antennas [1].

Other receive diversity techniques are Equal Gain Combining (EGC), where all signal branches are weighted with the same factor, and Selection Combining (SC), where only a subset of antennas are used for diversity combining.

- **Space-time coding (STC)**

The dual technique known as transmit diversity can be used at the transmitter side if the channel state is known at the transmitter, which is not usually the case. Hence, another coding technique that requires no channel state information at the transmitter is applied in order to achieve diversity gain. It exploits space and time diversity and is referred to as space-time coding (STC).

STC codes are divided in two groups, namely Space-Time Trellis Codes (STTC) and Space-Time Block Codes (STBC) [3]. STTC perform symbol mapping via a trellis diagram, so that a modified Viterbi decoding algorithm can be used at the receiver. These codes achieve maximum diversity gain as well as coding gain, however, the decoding process is very complex when dealing with greater numbers of transmit antennas and higher modulation levels, because these are reflected in higher numbers of encoder states. For this reason the orthogonal STBC introduced by Alamouti [5] has gained in popularity, although no coding gain can be achieved. The scheme is composed of two transmit and an arbitrary number of receive antennas. The source data are encoded in two symbol periods. In the first interval, symbol s_1 is transmitted over the first antenna and symbol s_2 over the second. In the second interval, complex conjugated symbols are transmitted: $-s_2^*$ over the first antenna and s_1^* over the second. Decoding is performed with simple linear processing at the receiver side. Figure 1 depicts a 2×1 Alamouti STC scheme.

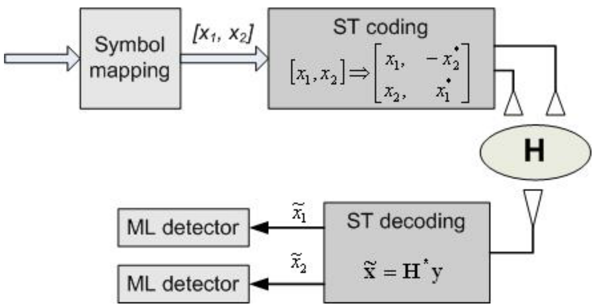

Figure 1: 2×1 Alamouti STC scheme

2.2 Systems exploiting spatial multiplexing

Systems exploiting spatial diversity require multiple antennas at one side of the communication channel only. However, if we want to achieve spatial multiplexing gain by simultaneously transmitting multiple data streams over different antennas, multiple antennas are required at both sides of the channel, since multiplexing gain can be at most *min(M,N)*.

In [6], Foschini proposed a layered space-time (LST) architecture referred to as V-BLAST (Vertical Bell labs LAyered Space-Time). The proposed scheme is shown in Figure 2. The input data stream is divided into *M* independent substreams which are then mapped into modulated signals and transmitted simultaneously over *M* transmit antennas, each using the same frequency band. By transmitting independent streams over each antenna, MIMO systems can offer a linear increase in data rate within the same bandwidth. Under suitable conditions, such as a rich scattering environment that results in an uncorrelated Rayleigh fading channel, the receiver can separate the data streams.

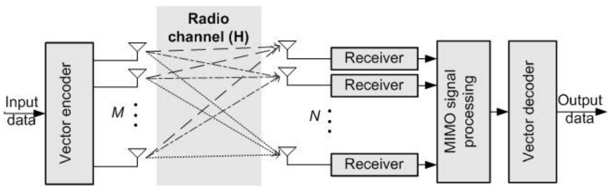

Figure 2: MIMO system diagram with uncoded spatial multiplexing

The efficiency of such a system is strongly dependent on the decoding algorithm selected, in which a compromise between complexity and optimality has to be made. The optimal decoding algorithm is Maximum Likelihood (ML) decoding. ML detection requires an exhaustive search over all possible combinations of transmitted symbols and is often computationally too demanding. Other, suboptimal, approaches are linear detection methods like Zero Forcing (ZF) or Minimum Mean Square Error (MMSE) [3], iterative approaches such as Successive Interference Cancellation (SIC) [7], and Sphere Detector [8].

2.3 Adaptive MIMO systems

In a time varying channel, a transmitter has to be able to adapt to the changes of the channel state in order to optimize its performance [9]. Beamforming is a precoding signal processing method used in multiple antenna systems, and allows the formation of the desired beam in order to improve the system performance by cancelling out the interfering signals and steering the beam in the direction of the chosen user. It is based on knowledge of the instantaneous channel state at the transmitter, and can thus be adapted to changes introduced into the channel [10]. Channel state information (CSI) can be obtained via reciprocity (in TDD systems) or via a return feedback link from the receiver. Under highly dynamic channel conditions this may not be possible, due to the delay in acquiring the CSI data. Moreover, the use of reciprocity in TDD system requires accurate calibration of all the elements in the communication path, which is not easy to achieve in practice.

The channel capacity would be optimally exploited if the MIMO system decided, dynamically, which of the three techniques (diversity, spatial multiplexing or beamforming) should be used.

3 IEEE 802.16 standard

WiMAX is a metropolitan area network (MAN) wireless technology planned to provide high-speed communication over the last mile. WiMAX is a system that conforms to IEEE 802.16, a wireless communication standard being standardized in IEEE.

For Fixed WiMAX, the 802.16-2004 (802.16d) [11] version of standard is used. In 2005, an upgrade to IEEE 802.16-2004 was approved under the form of IEEE

802.16e amendment, which adds mobility features to the original standard [12].

The organization responsible for certification and interoperability of 802.16 broadband wireless products is called WiMAX Forum. WiMAX Forum develops WiMAX system profiles that define the mandatory and optional features of the IEEE standard that are necessary to build a WiMAX compliant air interface that can be certified by the WiMAX Forum.

If we make a coarse comparison of the functionalities adopted in Fixed and Mobile WiMAX profiles, we note that the main difference is in a multiple access scheme and the support of mobility. Fixed WiMAX supports OFDM as a physical layer technology; however only one user can transmit at a time, while the multi-user access is done in the time domain. On the other hand, Mobile WiMAX supports Orthogonal Frequency Division Multiple Access (OFDMA), which enables multiple users to transmit simultaneously using different carriers. Nevertheless, sub-channelization can be implemented in Fixed WiMAX in order to achieve simultaneous multiple access in the uplink. Apart from that, 802.16e standard functionalities enable full mobility, in contrast to 802.16d, in which mobility support is limited to nomadic.

4 MIMO techniques in WiMAX systems

One of the many advantages of OFDM technology lies in its robustness to multipath and the ease with which the multiple-antenna techniques can be utilized to increase range and throughput [13]. Hence, WiMAX is ideally suited for operation in cluttered environments with high presence of signal scattering, where benefits of multiple antenna systems such as diversity and spatial multiplexing gain are significant.

4.1 Multiple antenna techniques in Fixed WiMAX

In Fixed WiMAX, the support of MIMO techniques is limited to a simple diversity scheme using 2×1 Alamouti STC code (3), which provides maximum transmit diversity gain for two antennas.

Support for Beamforming (AAS – Adaptive Antenna Systems) is also included in the 802.16-2004 OFDM-PHY; however, it is not used in practice in the Fixed WiMAX certified equipment.

4.2 Multiple antenna techniques in Mobile WiMAX

Four multiple antenna techniques are foreseen in Mobile WiMAX specifications, referred to as Matrix A, Matrix B, Adaptive Antenna Systems and collaborative MIMO.

- **Matrix A**

In Mobile WiMAX, the Alamouti STC scheme, proposed already in Fixed WiMAX system profile, is referred to as Matrix A:

$$A = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}, \tag{3}$$

where the rows represent the transmit antenna and the columns represent the symbol period. Matrix A with two transmit antennas is mandatory for Wave 2 certification of WiMAX systems, while other STBC schemes for three or four transmit antennas are optional.

The Alamouti diversity scheme increases system reliability by mitigating fluctuations in the received signal power, so Matrix A is very appropriate when the user is highly mobile, with rapid signal fading and multipath reception. The reduced fade margin allows the use of a higher modulation level, causing a certain increase in capacity as well.

- **Matrix B**

While MIMO Matrix A implements rate 1 STC, MIMO Matrix B uses spatial multiplexing. Support of Matrix B with two transmit antennas is mandatory for Wave 2 certification:

$$B = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}. \tag{4}$$

It is a 2×2 MIMO technique where each symbol is sent only once, so no redundancy is introduced during transmission. That means that no diversity gain can be achieved, but two symbols are sent in each symbol period, which, under suitable conditions, doubles the data rate. As explained in Section 2, spatial multiplexing requires at least as many receive antennas as the number of independent data streams, so in this scenario at least two receive antennas at the mobile station (MS) side are required.

The efficiency of Matrix B MIMO depends greatly on the presence of natural multipath, which implies independent fading of different paths. Under this condition two received signals are not correlated and can be successfully distinguished at the receiver. This kind of channel characteristic is common in dense urban areas while, in areas with LOS conditions and limited multipath, Matrix B will perform poorly due to high signal correlation.

Although Matrix B enables a significant capacity increase, the use of STC/MRC scheme (Matrix A in combination with MRC) offers better performance at low SNR. Since the capacity grows logarithmically with SNR, it proves more convenient to increase SNR in order to gain capacity as well as robustness. However, at high SNR, the linear nature of capacity growth enables Matrix B to outperform Matrix A.

- **Adaptive Antenna Systems (AAS)**

If more than two antennas are implemented at the base station, the additional degrees of freedom can be utilized. AAS can use beamforming in order to shape the transmitted beam and to spatially separate different signals coming from different directions. Beamforming can be used, either in combination with either Matrix A or B or as a stand-alone technique, in order to separate signals from different users and decrease interference. Again, the channel state information has to be available at the transmitter, which can be a very demanding task, especially in a rapidly changing mobile environment.

In practice, beamforming is more appropriate when there is a predominant angle of arrival, so the system can form an appropriate radiation pattern. Thus it will not be very efficient in Rayleigh fading environments (high multipath and no LOS component).

- **Collaborative MIMO**

Collaborative MIMO is used in the uplink as a requisite for increased capacity of the system as a whole. It does not result in any per user data rate increase, but it can double the cumulative capacity of the sector. Collaborative MIMO uses Space-Division Multiple Access (SDMA), so that two subscriber stations, each equipped with a single antenna, can transmit simultaneously using the same OFDM subcarriers. This is similar to the spatial multiplexing used in downlink with Matrix B, except that the transmitters are well separated in space and thus the correlation is much lower.

5 WiMAX system measurements

In this section we describe test results of Telsima's indoor Fixed WiMAX deployments with MRC and STC in Bangalore, India. Based on the terrain measurements we have developed a dedicated channel model and have performed extensive tests of MRC and STC performance with the channel simulator in the laboratory.

Note that, at the base station side, cross-polarized antennas were used in order to exploit polarization diversity since operators prefer to install only a single antenna, instead of installing two BS antennas separated in space in order to exploit spatial diversity. The field measurements actually showed that the gains of STC and MRC obtained with one cross-polarized antenna at the BS were similar to those obtained with two spatially separated antennas.

5.1 Field measurements results

Figure 3 shows the average increase in CINR when STC is used in the downlink, compared to the normal operation. Each location index corresponds to one indoor test location. The increase in average carrier to interference-plus-noise ratio (CINR) is around 4.5 dB. A 3 dB increase in CINR is achieved due to a twofold increase in transmitted power. The remaining increase in CINR is due to lower frequency selectivity in STC mode than in simple SISO communication. Very similar results were also obtained for the MRC testing in the uplink, where the basic 3 dB gain is achieved due to coherent combination of the received signals.

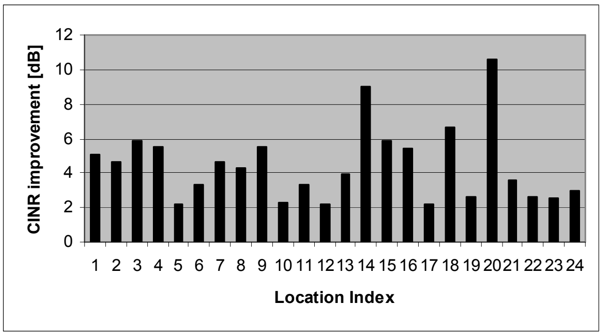

Figure 3: Average STC gain in CINR

High gains of average CINR can be achieved with STC (Figure 3); however, the gains measured at different locations can vary significantly. For some locations a gain of only 2 dB is achieved, while for other locations it is over 8 dB. This can be explained by the fact that, at some indoor subscriber station (SS) locations, the signal from the primary BS antenna is stronger than the one from the secondary antenna, while for other locations the signal from the secondary BS antenna is much stronger. Since the STC or MRC gain is actually a gain in dBs relative to the received CINR when only a primary transmit antenna is used, the gains are very different. Even a small change of the indoor modem antenna position results in a significant variation in gain. However, the most important observation in the field was that variation of the signal quality is much lower when STC or MRC is used. It was also established that the gains of STC and MRC are highest in locations where CINR is lowest, since at these locations the primary antenna signal is low.

5.2 Laboratory measurements with a channel simulator

Based on the observations of signal variation, frequency selectivity and correlation in the field, we modified a standard SUI-3 channel model in order to simulate the non-LOS (NLOS) indoor Bangalore channel that was observed in Telsima's actual WiMAX network. There are three taps in the developed channel. The first is Rice distributed with Rice K factor 9. The second and third taps are Rayleigh distributed, with 5 dB attenuation relative to the first tap, and are delayed by 300 ns and 900 ns, respectively. This results in a strong frequency selective channel. The correlation of the channels corresponding to each BS antenna was set to 0.2. An Elektrobit Propsim C2 Wideband Radio Channel Simulator was used in the Telsima laboratory to simulate the channel.

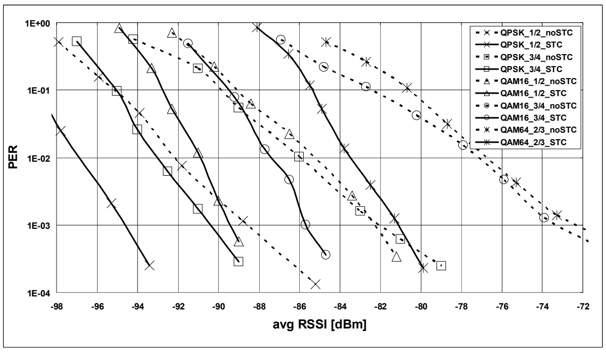

Figure 4: Packet Error Rate (PER) improvement with STC

The Packet Error Rate (PER) versus average input signal level (RSSI), for STC and normal non-STC (SISO) operations for different coding and modulation levels, is demonstrated in Figure 4. A channel bandwidth of 3.5 MHz was used and the packet size was 1460 Bytes. As shown in (2), the difference in gradient of the PER curves represents the diversity gain. The measurement results prove that high diversity gains are achieved, since the PER decay is much faster for STC operation. For the 16QAM ¾ scheme it can be seen that the gradient of the slope is nearly doubled, meaning that in this case a diversity gain close to 2 is achieved, which is the maximum possible gain achievable with two antennas.

From Figure 4 it can be estimated that for PER 10^{-2} the gains of STC are around 5 dB for QPSK ½, 7 dB for QPSK ¾, 5 dB for 16QAM ½, 10 dB for 16QAM ¾ and 7 dB for 64QAM ⅔. It may seem surprising that the gains and the slopes are so different for different modes of operation. The reason lies in the frequency selectivity. Since higher order modulations are more sensitive to frequency selectivity, the gains of STC are higher for those modulations. But, more importantly, the Forward Error Correction (FEC) adds robustness to frequency selectivity, utilizing frequency diversity. It can be seen clearly from Figure 4 that, in non-STC (SISO) operation, curves representing higher redundancy FEC modes are steeper than those for lower redundancy ones. This is because stronger FEC coding exploits frequency diversity better. For example, comparing non-STC QPSK ½ and QPSK ¾, it can be seen that QPSK ¾ performs quite poorly. Even more surprisingly, without STC at a lower PER area, the 16QAM ½ even outperforms the QPSK ¾, although it has higher spectral efficiency. The high redundancy FEC coding (e.g. ½) already effectively exploits the frequency diversity gain, so the gains of STC are lower for those modes.

6 Conclusion

Multiple antenna systems, their main characteristics and their use in both Fixed and Mobile WiMAX, have been briefly reviewed. The performance of Telsima's Fixed WiMAX system supporting STC in downlink and MRC in uplink has been described and analyzed.

The field results show a great improvement of signal quality with STC and MRC, but the gains differ greatly for different indoor locations. The average gain in CINR observed in the field was 4.5 dB and the highest over 10 dB.

Based on the results of field measurements, a dedicated channel model was developed in order to simulate the real propagation channel, either by computer or by hardware channel simulator. Laboratory measurements done with the channel simulator, using this model, showed that the gain of STC is highly dependent on the PER at which it is observed, and on the coding and modulation mode used.

The measurement results proved that diversity gain is achieved in all cases, since the PER slope is much steeper in STC mode. It was also revealed that, in general in a dynamic channel, the coding-modulation modes with higher redundancy perform much better than those with lower redundancy. Since the performance of lower redundancy codes is poor in such a demanding channel, the gains of STC and MRC are greatest for those modes. The highest gain measured was for 16QAM ¾, i.e. 10 dB at PER 10^{-2} and 12 dB at 10^{-3}.

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