Novel Antenna Configurations for Wireless Broadband Vehicular Communications

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***Abstract*—In this paper, mobile WiMAX trials are analysed to investigate the vehicular down-link performance for a number of on-car antenna configurations. The directionality and optimum polarization of the vehicular antennas are shown to improve both the range and throughput of the system. These improvements are attributed to the additional directive gain, and the reduced multi-input multi-output spatial correlation that results from orthogonal polarization. The mobile-WiMAX trials cover an urban vehicular scenario using a 2x2 MIMO system configuration. Results show that the throughput can be doubled for a wide range of received SNR levels (via STBC or SM) when a pair of directional dual polarized antennas are used at the vehicle (compared to omni-directional devices).**

Keywords-Directional Antenna; MIMO; WiMAX; Vehicular Communications; Polariation

I. INTRODUCTION

Broadband wireless connectivity is currently attracting considerable interest, and recently this has extended to vehicular applications. Previous work has explored the performance of on-car antennas with the WiFi standard [1, 2]. In this paper we analyse the vehicular performance of the mobile worldwide interoperability for microwave access (WiMAX) standard. Our work is based on experimental data collected from an urban environment using a carrier-class mobile-WiMAX base station (BS). The aim of the trial was to measure the performance improvements achieved in practice with novel multi-antenna configurations on the vehicle. The trial aimed to evaluate the ability of the WiMAX standard to support broadband services to mobile users travelling at vehicular speeds.

The paper begins with a short overview of antenna and propagation theory. The experimental configuration is presented in Section III. In Section IV, experimental results are reported for a 2x2 MIMO system. Recommendations are then given regarding the on-car antenna configuration at the mobile receiver. Finally, conclusions are presented in Section V.

II. ANTENNA AND PROPAGATION PRINCIPLES

Although antenna and propagation theory is well developed, both still attract considerable research interest. This is largely due to the development of new applications, such as the extension of broadband wireless to vehicles.

Most mobile wireless devices use omni-directional antennas since their radiation pattern allows signal reception from any direction in the azimuth plane (with uniform sensitivity). However, when antennas with directive radiation patterns are used, their orientation becomes important. In the real world, multipath components (MPCs) do not arrive with a uniform azimuth distribution, instead they tend to cluster from a number of specific directions. It was shown in [3] that the received signal power with any directive antenna is constant, regardless of its azimuth orientation, providing the arriving MPCs follow a uniform azimuth distribution. However, in a more realistic clustered environment, the orientation of the antennas is important in maximising the signal level. Even though a narrow beamwidth antenna limits reception to a small range of azimuth angles, the greater directional gain more than compensates providing the device is optimally orientated relative to the cluster.

When directional transmit and receive antennas are used, the total gain of the (correctly aligned) antennas will exceed any losses attributed to spatial filtering; hence a substantial gain can be introduced into the link-budget. Correct alignment is easy to achieve in line of sight (LoS) conditions (the two antennas are directed towards one another), however in Non-LoS conditions (with clustered MPCs), the correct alignment is more difficult to determine and will vary with mobile location and orientation.

Looking at the experimental results published by Lee, Parsons et al. [4, 5] (among others), we can conclude that the received power in the elevation plane is commonly focussed in a narrow range of elevation angles. It follows that the elevation angle distribution rarely follows a uniform distribution. Hence, it is preferable to install a high gain omni-directional antenna at the receiver, since these devices suppress vertically their radiation patterns. This type of radiation pattern increases the antenna gain, but its sensitivity is limited for a narrow range of angles in the elevation plane. It also follows that high-gain antennas will be desirable at the transmitter (depending on the height and distance between the two antennas and the maximum allowed effective isotropic radiated power (EIRP) imposed by the regulatory framework).

For vehicular applications there are specific environment and propagation characteristics that can be considered when designing the antenna system. The first common characteristic is the fact that all vehicles move forward with a fixed orientation relative to their direction of motion. The second characteristic is the clustering seen in the azimuth plane. On the downlink, the arriving MPCs tend to cluster around the front and rear of the vehicle. For a motorway scenario, this occurs due to the physical dimensions of the

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structure (i.e., a long and straight road with clutter to the sides). For vehicular applications in built-up areas, the buildings along both sides of the road create a waveguide effect that focuses the MPCs into the front and/or back of the vehicle. As a result, it is desirable to employ two (or more) narrow beam antennas aligned to the front and back of the vehicle respectively. This design takes advantage of the vehicular environment and offers a signal that has reduced Doppler spread. The solution also has the advantage of avoiding additional complexity at the BS or MT. The directive antenna beams provide increased antenna gain in the wanted directions, and this can be used to extend range.

III. Experimental Configuration

In the trial, the propagation environment surrounding the WiMAX BS consists of industrial buildings and a housing development (with building heights ranging from 10 to 20m). The BS is located at the centre of the concentric circles shown in Fig. 1, on the roof of a large office building. With the exception of one large building (40m x 40m x 15m tall), located 200m from the BS, all other buildings are located between 500m and 1500m from the BS. A number of tall trees (10m-15m) exist in this environment and these affect a small part of the route under test in this trial (with an extra 15-20 dB loss at point C). The BS was professionally installed and equipped with four high-gain sector antennas. All measurements were taken in the area covered by a single (90 degree) sector. Fig. 1 shows the 3.5km route (travelling away and back to point A) covered in this trial. The maximum BS-MT separation distance was 1350m (the U-turn in Fig. 1).

The route is close to the boresight of the antenna sector in use; and therefore it is assumed that there is no significant difference in the Tx gain throughout the drive test. As can be observed from the spot path loss exponent values shown in Fig. 1, the drive test covered LoS areas close to the BS and NLoS out to the cell edge. The path loss exponent was found to lie between 2 and 3.4. All drive tests started from point *A*, passed through points *B, C,* and *D,* and then reached point *E* (the U-turn). From point *E*, the vehicle returned to point *C* and then back to the start (*A*) via point *F*.

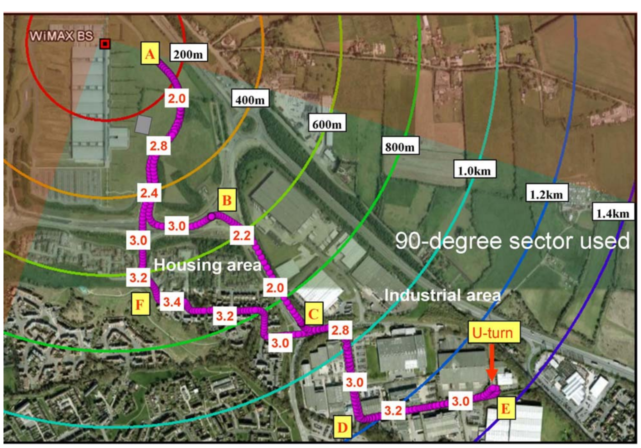

Figure 1. Drive tests and local path loss exponent values near the WiMAX BS

During the experiment it was possible to configure most of the BS parameters (details are given in Chapter 6 of [2]). This allowed the collection of data using each of the available modulation and coding schemes in the WiMAX standard. These tests were repeated using all the available transmission techniques (single input multiple output (SIMO), space time block coding (STBC) and spatial multiplexing (SM)). The performance analysis presented here is based on the data collected using MIMO (2x2) with adaptive modulation and coding (AMC), and adaptive MIMO switching (AMS) enabled. The use of different antenna configurations at the vehicle was also tested using a pair of omni-directional antennas, and a pair of 60-degree directional antennas, at various polarizations.

IV. Performance Analysis

A. RSSI/Range Improvements

Compared to our previous WiMAX trials [6], this BS supports operation at much longer separation distances. The main reason for this extended range is the additional 14.5dB gain in the sector antenna used at the BS, which increased the BS EIRP from 32dBm to 46.5dBm. Additionally, the increase in range, as well as in the data rates supported in the cell, is attributed to the following three factors: 1) the BS antennas were installed higher than the rest of the buildings and trees in the area, 2) the use of STBC [7] or SM at the BS, and 3) the support of two-branch maximum ratio combining (MRC) at the vehicle (with external on-car antennas). The receiver minimum sensitivity in a 5MHz channel (as used here) was -85dBm [8]. These low RF signal levels were experienced by the MT at NLoS distances of 1km and beyond (with path loss exponent of 2.8 to 3). Using QPSK ½ and ¾ rate codes together with the diversity gain offered by STBC, data rates close to 1Mbps were observed at 1360m from the BS (the U-turn at point *E*).

As explained earlier, no loss should be experienced in the received power when a directional antenna is used in a rich multipath environment (uniform Azimuth MPC spread). Losses will be experienced in a clustered environment if the directional antenna is orientated away from any cluster. However, if correctly aligned to the cluster, a considerable antenna gain is observed. In order to find out how often the MPC clusters fall outside the beamwidth of the vehicular antennas, the received signal strength indication (RSSI) levels were recorded with directional and omni-directional antennas for LoS and NLoS conditions. The omni-directional antennas were monopoles with a gain of 4dBi, while the 60-degree directional antennas were patch devices offering a peak gain of 8dBi in the boresight direction. The directional antennas were orientated to point towards the back of the vehicle. In both configurations the two Rx antennas were mounted on the roof of the vehicle, separated by 10 wavelengths. The antennas used + and – 45 degree (dual slant) polarization, similar to the BS antennas. Each antenna configuration on the vehicle was tested with two drive tests in order to demonstrate the repeatability of the results.

The RSSI levels from these tests are shown in Figs. 2 and 3. Fig. 2 shows the mean RSSI level as the vehicle moves away from the BS, whereas Fig. 3 shows the RSSI value as the vehicle returns to the BS from point *E*. It is clear from Fig. 2 that in LoS, or near-LoS conditions (at distances less than 250m and between 540 and 900m), the directive gain leads to a much stronger observed RSSI value. From Fig. 3 it is clear that although the directional antennas were pointing in 'random' directions (relative to the BS), the RSSI was almost always higher than the value recorded using the omni-directional devices. There were three short exceptions along the route (located near 200, 630 and 1200m away from the BS). This finding supports the concept of using directional antennas for vehicular communications. Such a configuration improves the received signal level, and hence the system performance (in terms of range, PER, throughput and supported user velocity) [2, 9].

B. *Capacity Enhancement*

From the MIMO capacity equation (in bps/Hz) shown in Equation (1), it is observed that when multiple antennas are used in a MIMO system, the RSSI (or SNR) is not the only metric that determines the capacity of the system [10]. Equation (1) assumes perfect knowledge of the channel state information (CSI) at the Rx, but not at the Tx. I_{NR} is the N_R *x* N_R identity matrix, and ρ is the mean SNR per received branch. N_T and N_R are the number of Tx and Rx antennas respectively, and H is the power normalised channel matrix.

$$C = \log_2\left[\det\left(I_{N_R} + \left(\frac{\rho}{N_T}\right) HH^*\right)\right] \tag{1}$$

It follows from Equation (1) that MIMO systems also require low fading envelope correlations between the multiple antenna branches in order to fully exploit the capabilities of SM and STBC [11]. Low fading envelope correlation increases the determinant of the MIMO channel matrix, which enhances the theoretic capacity of the system [12, 13]. In a fading channel, the ideal channel experiences independent and identically distributed (iid) fading on the elements of H [10].

It is well understood that high values of spatial correlation is commonly the reason why MIMO systems fail to achieve their maximum performance in LoS conditions, or in channels with a strong Rician *K-factor.* One solution proposed by Sarris and Nix in [14] solves this problem by using optimised antenna spacings that achieve orthogonality and maximise the LoS channel rank. However, the optimised spacing changes with Tx-Rx distance and this approach is not practical for the mobile WiMAX bands (2-5GHz) due to the prohibitively large antenna spacing required.

Fig. 4 shows a comparison of the DL throughput and the RSSI as a function of Tx-Rx separation distance when different antennas are installed on the vehicle. As observed from the path loss exponent in Fig. 1, a strong LoS component (e.g., n<2.4) was present at distances less than 250m, and between 540m and 900m. This is confirmed by the large differences in RSSI levels between the two types of Rx antennas, since the data shown in Fig. 4 was collected as the vehicle drove away from the BS (and the directional antennas pointed towards the back of the vehicle; mostly towards the BS). Therefore, when the vehicle passed through these locations (with the directive antennas installed) a much higher RSSI was recorded. However, looking at the throughput, it is clear that under LoS conditions the omni-directional antennas achieved a higher throughput (in both runs) even though the corresponding RSSI level was much lower. This can be explained by the use of co-polarized directional antennas, which result in higher spatial correlations between the Rx antennas when operating in LoS (relative to the omni-directional antennas).

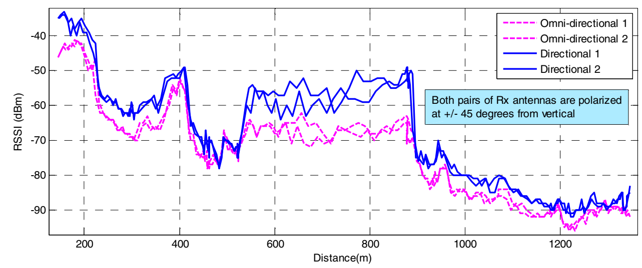

Figure 2. RSSI versus distance with different Rx antennas (driving away from the BS)

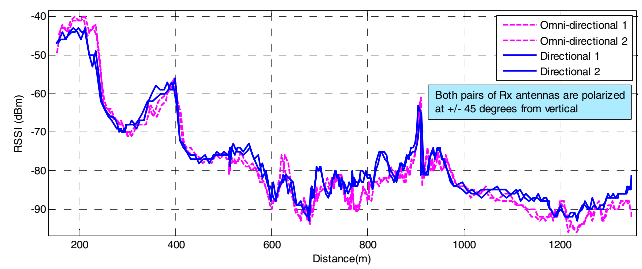

Figure 3. RSSI versus distance with different Rx antennas (driving towards the BS)

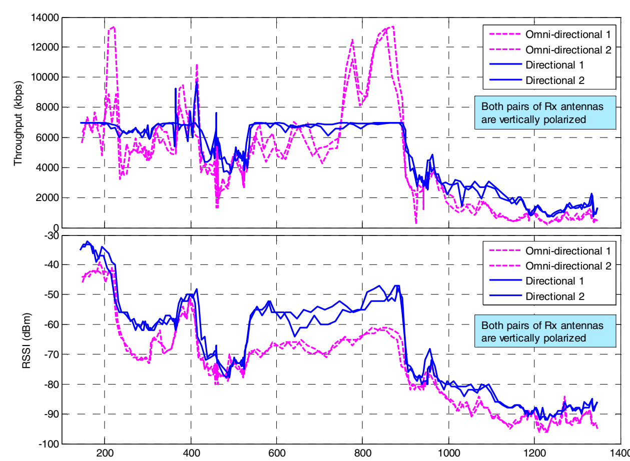

Figure 4. DL throughput and RSSI vs distance with diff. Rx antennas

Although the throughput results in Fig. 4 suggest that co-polarized directional antennas can limit the throughput of MIMO systems in LoS conditions, this can be avoided if other techniques are employed to further de-correlate the received fading envelopes. One way to achieve this is to use orthogonal polarizations at the receiver [15], in addition to the 10λ spatial separation (employed throughout the trials). This is confirmed by the throughput and the corresponding RSSI levels shown in Fig. 5 for the three different antenna configurations tested on the vehicle.

From Figs. 4 and 5 it is also observed that the directional antennas on the vehicle outperform the omni-directional ones in terms of RSSI. Additionally, when the directional devices are orthogonally polarized they outperform all the other configurations in terms of throughput. The increase in RSSI relative to the omni-directional case is due to the higher antenna gain, while the increase in throughput is achieved (with the use of SM rather than STBC) through further de-correlation of the received fading envelopes by incorporating orthogonal polarization in addition to the 10λ antenna spacing on the roof of the vehicle. Similar benefits from the use of dual polarized antennas were reported by Nabar et al. in [15] via simulation.

Although throughput is approximately doubled with a pair of directional dual-polarized Rx antennas (compared to the omni-directional antennas), Fig. 5 gives the impression of greater improvements in LoS conditions. This occurs since under these conditions the mean DL throughput increases from 6Mbps to more than 11Mbps, while in NLoS areas (e.g., for Tx-Rx distances > 1km) the mean throughput increases from 1Mbps to 2Mbps. This throughput (and spectral efficiency) improvement is the outcome of a 2x2 MIMO system operating in STBC mode for low SNR, and in SM mode for high SNR and low fading envelope correlations, as discussed in [16, 17].

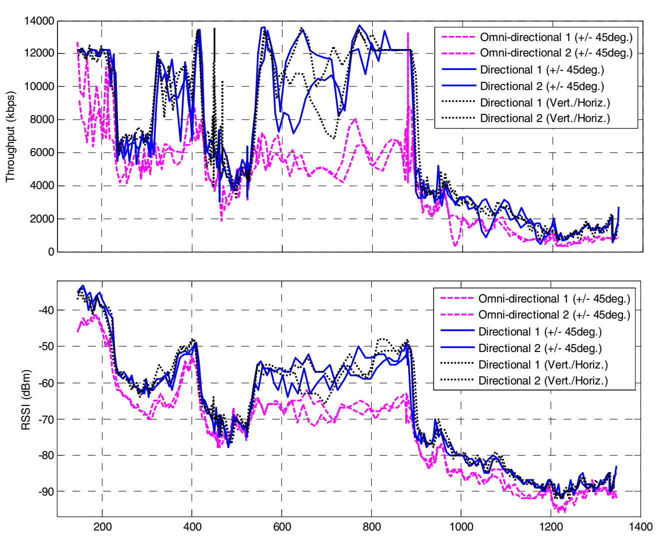

Figure 5. DL throughput and RSSI versus distance with dually polarized Rx antennas

A number of researchers have published work on dual polarization that suggests dual slant polarization outperforms vertical/horizontal polarization due to unbalanced received signals in the latter case [18-20]. Based on the results presented in Fig. 5, it is shown that the diversity and multiplexing gains are similar for both dual polarized receiver configurations, as in [21]. It is understandable for the signals received in a multipath environment using vertically and horizontally polarized antennas to be unbalanced if large differences exist in their radiation patterns. This is less likely to be experienced when dual slant polarization is used. This is illustrated in Fig. 6 which shows the radiation pattern of an antenna when polarized at different angles.

Furthermore, when dealing with directional antennas, in order to avoid the above problem and thus increase the achievable gain, all directional antennas should point in the same direction; otherwise the diversity (or multiplexing) gain may drop due to unbalanced received fading envelopes. Balanced links (i.e., with similar mean powers) help improve the performance of signal combining and diversity techniques at the receiver. If the links are also spatially de-correlated then a strong SM gain is also achieved.

Fig. 7 shows the mean PER over the drive test route with directional antennas at different polarizations. Although the mean RSSI is similar for the three configurations with directional antennas (see Fig. 4 and 5), it is clear that under LoS conditions the two vertically polarized directional Rx antennas give the lowest PER. This can be explained by the diversity gain offered by STBC (which helps maintain stability in the instantaneous RSSI and reduces the required fade margin [22]).

The results in Fig. 7 confirm that the high fading correlation caused by the co-polarized directive Rx antennas forces the BS to use STBC, rather than SM. Consequently, the mean PER is seen to drop from 20% down to 5% whenever a strong LoS component reaches the receiver (and hence STBC is used). These throughput and PER results suggest that the criterion behind the BS AMS algorithm is based on maximising the spectral efficiency (hence enabling the WiMAX network to accommodate more users, increase data rates, and increase revenue for network operators).

The above strategy is not surprising since the mobile WiMAX standard incorporates multiple antenna techniques in order to exploit rich multipath in urban environments. SM is used to increase throughput, while STBC is used to increase range and reliability [22, 23].

As shown in Fig. 8, a threshold PER of around 20% is used by the BS to switch to the best combination of MIMO mode and modulation scheme. In terms of mean PHY layer throughput, the BS supported data rates of between 0.5 and 9.2Mbps when omni-directional antennas were used on the vehicle. When the vehicle was equipped with directional antennas the throughput varied between 1.1 and 11.5Mbps

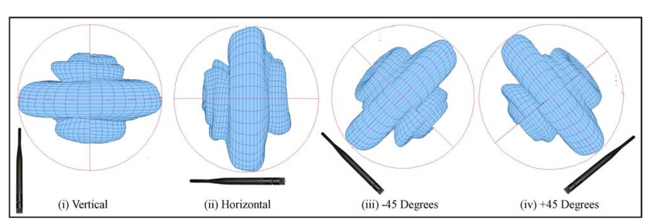

Figure 6. Antenna radiation patterns at diff. orientations (polarizations)

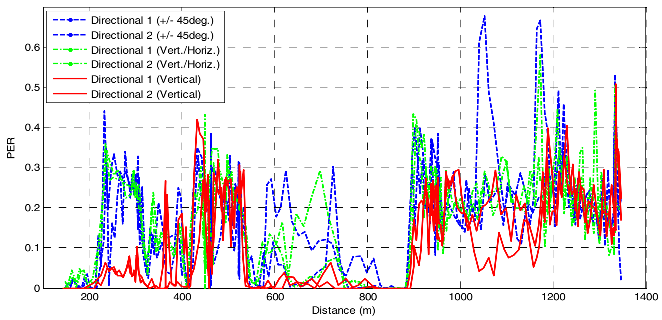

Figure 7. PER versus distance for directional Rx antennas

The achieved throughput depends on the SNR and the fading de-correlation in the matrix channel. Looking at the performance achieved with different pairs of antennas at the receiver (Fig. 8), it is seen that for an SNR of 24dB or less, the PER and throughput performance is similar (with the exception of PER values at SNR<9dB). However, at higher SNR values the directional antennas with orthogonal polarization provided the highest throughput (since this reduced the fading envelope correlation), whereas directional antennas using the same polarization achieved the lowest PER since STBC was then preferred over SM (due to the high spatial correlation of the resulting fading envelopes).

Although high throughputs were achieved in this trial it should be noted that the high observed PER (20% for an SNR of 27dB or less) makes this particular AMS strategy inappropriate for real-time applications such as conversational video or Voice Over IP (VOIP). High PER values are acceptable in many types of TCP application, such as web browsing and file transfer. At high PER, Medium Access Control (MAC) and/or Transport layer retransmissions introduce considerable delay and jitter into the link, and this adversely affects time-bounded applications.

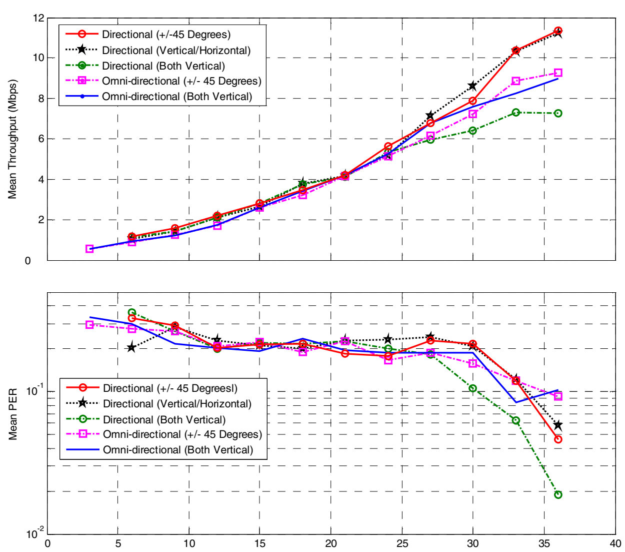

Figure 8. Measured mean PER and throughput for a 2x2 MIMO system with different antenna types and configurations at the vehicle (AMS and AMC are enabled)

Finally, the impact of vehicular antenna beamwidth and polarization on the selection of SM over STBC is demonstrated in Table I as a percentage of the total duration of the MIMO drive test in LoS and NLoS conditions. Once again, the throughput benefits gained by the use of directional antennas with orthogonal polarizations are shown in this table for LoS and NLoS channel conditions. The configuration of directional and co-polarized antennas supports the lowest use of SM. When using omni-directional antennas, orthogonal polarization does not affect the selection of SM over STBC, mainly since the correlation of the fading envelop is low due to the 10λ antenna spacing and the multipath environment, and secondly because of the lower SNR values due to the lower antenna gain (compared to the SNR seen with the directional Rx antennas).

TABLE I. SM USAGE FROM ALL MIMO DRIVE TESTS WITH AUTOMATIC MIMO SWITCHING ENABLED

Spatial-Multiplexing usage (%) in LoS and NLoS conditions with different Rx antenna configurations on the vehicle					
Rx antenna	Directional	Direct.	Direct.	Omni-direct.	Omni-direct.
Polari-zation	+/- 45 Deg.	Vert./ Horiz.	Both Vertical	+/- 45 Deg.	Both Vertical
LoS	77.52	85.52	37.93	56.08	59.65
NLoS	57.95	67.55	41.4	33.25	30.05

V. CONCLUSIONS

The real-world DL performance of a mobile WiMAX BS supporting multiple antenna technologies was reported in this paper. Performance was based on the measurement of PER and throughput via a number of drive tests. A range of different antenna configurations were used on the vehicle.

Results demonstrated that in all areas tested, directional antennas resulted in higher RSSI values. It was also verified (via practical measurement) that high SNR and low fading envelope correlations are required in order to achieve high spectral efficiency using SM transmission. Directional antennas at the vehicle were seen to result in higher SNR values as a result of the clustered channel and their higher directive gain. Orthogonal polarization was seen to support greater use of SM. This occurred since low fading envelope correlation was achieved via polarization and pattern diversity at the vehicle.

In terms of the supported (mean) PHY layer DL throughput, it was verified that a 2x2 MIMO system can support up to 11.5Mbps in a 5MHz channel at an SNR of 35dB (using SM mode), and 1Mbps at an SNR of 6dB (using STBC) when the type and orientation of the receiving antennas are carefully selected.

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