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Mobile WiMAX: Downlink Performance Analysis with Adaptive MIMO Switching

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Abstract—The WiMAX standard has emerged to harmonise the wide variety of Broadband Wireless Access (BWA) technologies. The recent mobile WiMAX standard (802.16e) supports broadband applications to mobile terminals and laptops in urban environments. Mobile WiMAX supports a full range of multiple-input multiple-output (MIMO) techniques including space time block coding (STBC), spatial multiplexing (SM) and eigen-beamforming (EB). This paper compares the performance of the above schemes in terms of achievable throughput and operating range. Simulated packet error rate (PER) and throughput results are presented for each MIMO technique, and for a range of modulation and coding rates. Based on a typical link-budget, the expected throughput for each scheme is computed as a function of the basestation-terminal separation distance. The paper highlights the use of Adaptive MIMO Switching (AMS) in mobile WiMAX. The SNR switching points between each MIMO mode is determined and their dependency on channel spatial correlation is demonstrated. Finally the operating range of the different MIMO schemes is determined (based on a 10% PER) for a mobile WiMAX system. The use of eigen-beamforming together with AMS is shown to offer significant performance benefits in terms of robustness, capacity and operating range. For the scenario under test, the use of eigen-beamforming (based on the dominant eigen-mode) extends the operating range by 16%, and doubles the received data rate for 65% of locations.

Index Terms—802.16e, WiMAX, MIMO, AMS, Beamforming

I. INTRODUCTION

The first WiMAX systems were based on the IEEE 802.16-2004 standard [1]. This targeted fixed broadband wireless applications via the installation of Customer Premises Equipment (CPE). In December, 2005 the IEEE completed the 802.16e-2005 [2] amendment, which added new features to support mobile applications.

Mobile WiMAX extends the original OFDM PHY layer to offer efficient multiple-access using scalable OFDMA. Data streams to and from individual user equipment are multiplexed to groups of subchannels on the downlink and uplink. By adopting a scalable PHY architecture, mobile WiMAX is able to support a wide range of bandwidths. The scalability is implemented by varying the FFT size from 128 to 512, 1024, and 2048 to support channel bandwidths of 1.25 MHz, 5 MHz, 10 MHz, and 20 MHz respectively.

Power and spectral efficiency are vital since bandwidth is limited and user demand for high data rate applications continues to grow. One way to improve link capacity, and potentially increase spectral efficiency, is the application of MIMO. The combination of OFDM and MIMO enables the frequency selective MIMO channel to be separated into many flat fading channels. This allows equalisation to be performed in the frequency domain on a sub-carrier by sub-carrier basis.

Mobile WiMAX supports a full-range of smart antenna techniques, including eigen-beamforming (EB), spatial transmit diversity and spatial multiplexing (SM). EB operates at the sub-carrier level and converts the flat-fading MIMO channel into a set of independent scalar channels. This is achieved by applying transmit and receive beam weights. To compute the required array weights full knowledge of the Channel State Information (CSI) is necessary at the transmitter [3].

Spatial transmit diversity is achieved in the mobile WiMAX standard by applying Alamouti's Space-Time Block Codes (STBC) on the Downlink (DL) [4], and Space-Frequency Block Codes (SFBC) on the Uplink (UL) [5]. SM can also be employed on the DL and UL to increase the error-free peak throughput [6].

In this paper we investigate the downlink performance of mobile WiMAX in an urban microcell. In particular, STBC, SM and EB are used to enhance performance (relative to the single antenna case). Packet Error Rate (PER) and throughput results are presented for spatially correlated and uncorrelated channels. Finally, for each scheme, the expected throughput is calculated as a function of operating range (using a typical link budget). Adaptive MIMO Switching (AMS) is used to determine the most appropriate technique as a function of range, throughput and PER.

II. MOBILE WiMAX PHY DESCRIPTION

The mobile WiMAX standard builds on the principles of OFDM by adopting a Scalable OFDMA-based PHY layer (SOFDMA). The FFT size scales with bandwidth to maintain a fixed sub-carrier frequency spacing of 10.94 kHz. This ensures a fixed OFDMA symbol duration. Since the basic resource unit (i.e. the OFDMA symbol duration) is fixed, the impact of bandwidth scaling is minimized to the upper layers. Table I shows the relevant parameters for the mobile WiMAX OFDMA PHY. Table II summarises the OFDMA simulation parameters.

TABLE I - OFDMA PHY PARAMETERS

Parameter	Value			
FFT size	128	512	1024	2048
Channel bandwidth (MHz)	1.25	5	10	20
Subcarrier frequency spacing (kHz)	10.94			
Useful symbol period (μs)	91.4			
Guard Time	1/32, 1/16, 1/8, 1/4			

Fig. 1 shows the block diagram of our MIMO enabled WiMAX simulator. The channel coding stage includes randomization, convolutional coding (native code rate is $1/2$) and puncturing to produce higher code rates.

TABLE II - OFDMA PARAMETERS

Parameter	Value
Channel bandwidth (MHz)	5
Sampling frequency F_s (MHz)	5.6
Sampling period $1 / F_s$ (μ s)	0.18
Subcarrier frequency spacing $\Delta f = F_s / N_{FFT}$ (kHz)	10.94
Useful symbol period $T_b = 1 / \Delta f$ (μ s)	91.4
Guard Time $T_g = T_b / 8$ (μ s)	11.4
OFDMA symbol duration $T_s = T_b + T_g$ (μ s)	102.9
	DL PUSC UL PUSC
Number of used subcarriers (N_{used})	421409
Number of pilot subcarriers	60136
Number of data subcarriers	360272
Number of data subcarriers/subchannel	2416
Number of subchannels	1517
Number of users (N_{users})	33
Number of subchannels/user	54

Fig. 1. Mobile WiMAX functional stages

A block interleaver is used to interleave the encoded bits onto separated subcarriers, thus minimizing the impact of burst errors. Once the data has been modulated (using QPSK, 16QAM, or 64QAM) the data is mapped by segmenting the sequence of modulation symbols into a sequence of slots (using the minimum data allocation unit) and then mapping these slots into a data region. This is performed such that the lowest numbered slot occupies the lowest numbered (logical) subchannel among the allocated subchannels. The mapping of slots continues vertically to the edge of the data region (defined as a group of contiguous logical subchannels), and then moves to the next available OFDMA slot.

Once the MIMO processing has been applied the data symbols are mapped to a data region and assigned to their corresponding logical subcarriers. These logical subcarriers are allocated to physical subcarriers using a specific sub-carrier permutation. Pilots are also inserted at this point. The final stage is to convert the data into a time-domain analogue form for use by the radio front end. A guard interval is also inserted at this stage.

Our simulation supports a number of link-speeds (see Table III for details). The peak data rate D is calculated as below:

$$D = N_D N_b R_{FEC} R_{STC} / T_s$$

where N_D , N_b , R_{FEC} , R_{STC} and T_s denote the number of assigned data subcarriers to each user, the bits per sub-carrier, the forward error correction (FEC) coding rate, the space-time coding rate, and the OFDMA symbol duration respectively.

TABLE III - MIMO MOBILE WiMAX LINK SPEEDS

Mode (Link-Speed)	No. of coded bits per subchannel DL/UL	No. of data bits per subchannel DL/UL	STBC 2x2 DL/UL bit rate/user (Mbps)	SM 2x2 DL/UL bit rate/user (Mbps)
QPSK 1/2	48/32	24/16	1.17/0.62	2.34/1.24
QPSK 3/4	48/32	36/24	1.75/0.93	3.5/1.86
16 QAM 1/2	96/64	48/32	2.33/1.24	4.66/2.49
16 QAM 3/4	96/64	72/48	3.50/1.87	7/3.73
64 QAM 1/2	144/96	72/48	3.50/1.87	7/3.73
64 QAM 2/3	144/96	96/64	4.66/2.49	9.33/4.98
64 QAM 3/4	144/96	108/72	5.25/2.80	10.50/5.60

III. MIMO WIDEBAND CHANNEL MODEL

Based on the ETSI 3GPP2 spatial channel model (SCM) [7], an urban micro tapped delay line (TDL) model was generated for use in this analysis. The TDL comprises 6 taps with non-uniform delays. The Mobile Station (MS) velocity is assumed to be 40 km/h. The antenna element separation is half a wavelength. A 3 sector base station (BS) is assumed and the channel was generated for 3 MS. The resulting spatial correlation coefficient ρ is 0.16 (highly uncorrelated) for one MS and 0.8 (highly correlated) for the other two MS. The channel has the following parameters:

TABLE IV - 3GPP TDL CHANNEL PARAMETER

	Tap 1	Tap 2	Tap 3	Tap 4	Tap 5	Tap 6
Delay (ns)	0	210	470	760	845	910
Power (dB)	0	-1.8	-1.5	-7.2	-10	-13
K factor	0	0	0	0	0	0
Delay spread	279 ns					

IV. MIMO SCENARIOS DESCRIPTION

A. Space-Time Block Coding (STBC)

Our mobile WiMAX simulator implements the Alamouti scheme [4] on the DL to provide transmit and receive diversity. This scheme uses a transmission matrix $[s_1, -s_2^*; s_2, s_1^*]$, where s_1 and s_2 represents two consecutive OFDMA symbols.

B. Spatial Multiplexing (SM)

Mobile WiMAX supports SM (also known as BLAST) to increase the peak error-free data rate by transmitting separate data streams from each antenna. For those modes based on SM in our simulator, an MMSE receiver is used to remove the inter-stream interference on a per sub-carrier basis [6].

C. Eigen-beamforming

Eigen-beamforming uses knowledge of the CSI to create a set of orthogonal spatial filters. The spatial filters are used at the transmitter to direct the N data sub streams along the N orthogonal modes (or eigen-modes) of the channel so that they can be extracted without interference at the receiver. The value N is given by the minimum number of antennas at the transmitter or the receiver.

Eigen-beamforming is the optimal space-time processing technique since it maximises capacity by providing a full multiplexing gain whilst also extracting maximum diversity from the channel. The technique also offers a significant array (or beamforming) gain. This array gain is not achieved by open loop MIMO techniques that operate without prior

knowledge of the CSI.

The channel experienced by the k th sub-carrier is given by $H^k_{N_R \times N_T}$, where N_R and N_T indicate the number of receive and transmit antenna respectively. Using singular value decomposition (SVD) this can be written as

$$H^k_{N_R \times N_T} = U_{N_R \times N_R} \Sigma_{N_R \times N_T} V_{N_T \times N_T}^* \quad (1)$$

where $U_{N_R \times N_R}$ and $V_{N_T \times N_T}$ are unitary matrices, $*$ denotes matrix conjugate transposition. The matrix $\Sigma_{N_R \times N_T}$ is the diagonal matrix $\text{diag}(\sqrt{\lambda_1(k)}, \dots, \sqrt{\lambda_j(k)}, 0, \dots, 0)$ of the singular values of H^k .

U and V are unitary matrices, so pre-processing the transmitted signal vector X_k by linearly multiplying it by V and post-processing the received signal vector Y_k using U^* yields the estimate received signal R_k :

$$\begin{aligned} R_k &= U^* Y_k \\ &= U^* (H V X_k + n) \\ &= U^* (U \Sigma V^* V X_k) + n \\ &= U^* U \Sigma V^* V X_k + U^* n \\ &= \Sigma X_k + U^* n \end{aligned} \quad (2)$$

This removes all spatial interference without the need for further noise enhancing processing. It can be seen that the power gain of the j th channel is given by the j th eigenvalue λ_j and thus the maximum array gain is given by the magnitude of the maximum eigenvalue. If H is a zero mean spatially white matrix, it can be shown [8] that the diversity gain is $N_R N_T$ and the array gain lies between $\max(N_R, N_T)$ and $N_R N_T$.

Two eigen-beamforming schemes are investigated in this paper. The first maximises diversity by restricting the transmission of data symbols to the strongest eigen-mode. In this case all the transmit power is focused on the strongest spatial channel and the weaker spatial modes are unused (thus lowering the peak error-free data rate). This scenario is beneficial in highly correlated channels, where the mean array gain tends to $N_R N_T$ [9]. The second eigen-beamforming approach transmits data on all the spatial channels. This is used to maximise the error-free throughout, and is applicable to highly uncorrelated channels (where the weakest eigen-value is still sufficient for data transmission).

The main disadvantage of eigen-beamforming (compared to the earlier STBC and SM techniques) is the need for accurate CSI at the transmitter [10].

V. DOWNLINK SIMULATION PERFORMANCE ANALYSIS

In this section SISO and MIMO ($N_T = N_R = 2$) PER and throughput results are presented using the Mobile WiMAX simulator and channel model described in sections II, III and IV. The BS transmits data simultaneously to the 3 MS, with each sharing a common OFDMA symbol. Perfect channel estimation and synchronisation is assumed. The link throughput for each user is estimated from the PER as

follows:

$$R = D(1 - \text{PER}) \quad (3)$$

where D represents the peak error-free transmission rate for the chosen link-speed (see section II). It should be noted that this link throughput calculation does not take into account the feedback overhead. In a realistic system, the throughput will be lower due to various overheads. The received power for a given terminal can be calculated as

$$P_R = P_T + G_T + G_R - P_L \quad (4)$$

where P_T represents the transmit power (43dBm), G_T and G_R represent the antenna gains of the basestation and mobile terminal respectively (15dBi and 0dBi), P_R represents the received power, and P_L denotes the path loss. The values quoted in brackets represent the numbers used in our link-budget. The thermal noise floor can be calculated as

$$N = 10 \log_{10}(\kappa F) + 10 \log_{10}(W) + NF \quad (5)$$

where $\kappa = 1.38 \times 10^{-23} \text{ J/Hz/K}$, F is the temperature in kelvin (300K), W is bandwidth in Hz, and NF is the receiver noise figure (7dB). The path-loss for a non line-of-sight urban channel is modelled here using the COST 231 Walfish-Ikegami model [7]

$$P_L(\text{dB}) = -55.9 + 38 \log_{10}(d) + (24.5 + 1.5 f_c / 925) \log_{10}(f_c) \quad (6)$$

where f_c is the carrier frequency in MHz and d is the BS to MS separation distance in metres.

A. Low Spatial Correlation ($\rho = 0.16$)

Fig. 2 compares the PER performance for each of the MIMO schemes in a channel with low spatial correlation. It can be seen that the PER performance of the SM eigen-beamforming technique (denoted SVD SM in the figure) offers a significant improvement when compared with SM, especially at the high channel coding rate. More specifically, at a PER of 10^{-2} , for 1/2 and 3/4 rate 16QAM the performance improvement is 7dB and 2.5dB. Compared to SM, for a coding rate of 3/4, SVD only provides an array gain; meanwhile for the 1/2 rate code the SVD scheme provides a much higher diversity order (equivalent to STBC). This agrees with [12] where the maximum diversity order of a coded SVD scheme is $N_R \times N_T$.

Fig. 2. PER vs. SNR MIMO modes comparison

Fig. 2 shows that the dominant eigen-mode curves

(denoted SVD DE) have the same gradient as the STBC curves, thus demonstrating an equivalent diversity order (equal to $N_R N_T$ for a perfectly uncorrelated channel). The dominant eigen-mode outperforms STBC in terms of PER vs SNR (both having the same peak error-free throughput). For a PER of 10^{-2} , the 1/2 rate 16QAM mode shows an improvement of approximately 2.5dB due to the array gain.

Fig. 3. Throughput vs. SNR MIMO mode comparison

Fig. 3 presents the expected throughput versus SNR for each of the MIMO modes. The throughputs have been calculated using (3); however any PER in excess of 10% is assumed to be too severe to maintain a practical data link. We observe that in order to achieve the same peak error-free throughput (2.4 Mbps) in the 1/2 rate 16QAM mode, the dominant eigen-mode transmission requires 6dB SNR which is 3dB less than STBC. The use of STBC and SVD DE improves system robustness but does not provide a peak error-free throughput enhancement. At the same mode 16QAM 1/2, the SVD SM is capable of doubling the peak error-free throughput at SNR values greater than 15dB. Standard SM (no prior CSI) achieves this throughput for SNR values beyond 25dB. The SM modes cannot provide throughput at lower SNR values (below 12dB for SM SVD and 15dB for standard SM) since the achieved PER exceeds 10%. To run at lower SNR values the SM system needs to switch to a lower modulation scheme, or must use a lower FEC rate (which reduces the peak throughput).

Fig. 4. Maximum throughput vs. distance for MIMO modes

Fig. 4 shows the throughput versus distance envelope for all of the MIMO modes for the low spatial correlation channel. The individual envelope was generated using adaptive modulation and coding (AMC) to increase and/or

decrease the link-speed depending on SNR, within each MIMO mode. Mobile WiMAX requires the use of AMS to select the best MIMO scheme. Fig. 4 clearly shows that SM eigen-beamforming is optimum for ranges up to 520m (i.e. above 15.6dB SNR) and dominant eigen-beamforming is optimum for longer distances. In the case of perfect channel knowledge, SM and STBC are not selected by the AMS algorithm. Each of the link-speeds included in the calculation of the envelope are shown in Fig. 5. This figure indicates the percentage of the overall range for which each link-speed operates for both SVD SM and SVD DE.

Fig. 5. Link-speed transitions over operating range for SVD SM (left) and SVD DE (right)

It should be noted that the maximum throughput in Fig. 4 (10.5Mbps) represents the throughput per user assuming fractional frequency reuse across the three sectors. The maximum range achieved in the simulation is 1.5 km. In more favourable environments, and with higher EIRP levels, the operating range can exceed this 1.5km range in NLoS [11].

B. High Spatial Correlation ($\rho=0.8$)

Fig. 6 compares the PER performance for all of the MIMO schemes in a highly correlated channel. The dominant eigen-mode transmission still shows the best performance. The fact that the gradients of the STBC and SVD DE curves are shallower in this scenario highlights the reduced diversity. Compared with the previous curves, at a PER of 10^{-2} using 1/2 rate 16QAM, the performance of SVD DE and STBC has degraded by 3dB. The performance of the SVD SM and SM modes have degraded by 2.5dB and 7dB, respectively. From this observation we note that SVD SM operates better than standard SM in the highly correlated channel.

Fig. 6. PER vs. SNR MIMO mode comparison (correlated channel)

Fig. 7 shows the throughput versus distance envelope for all of the MIMO modes in this highly correlated case. It can be seen that the cross-over point for the AMS algorithm has reduced to 440m (i.e., increased to 18.4dB SNR) due to the

drop in performance of the SM schemes.

Fig. 7. Maximum throughput vs. distance for MIMO modes

VI. OPERATING RANGE COMPARISON

Table V illustrates the maximum range achievable and the corresponding received SNR by using different MIMO schemes for low and high spatially correlated channels.

TABLE V - BS TO MS RANGE FOR ALL MIMO SCHEMES

MIMO Scheme	$\rho=0.16$		$\rho=0.8$	
	$d_{\max}$ (m)	SNR (dB)	$d_{\max}$ (m)	SNR (dB)
SISO	780	9	780	9
SM	640	12	450	18
STBC	1295	0.57	1201	1.82
SVD SM	780	9	650	12
SVD DE	1504	-1.89	1399	-0.71

It can be seen from this table that both eigen modes improve the maximum range achievable, even at lower SNR values when compared with their MIMO counterparts. Relative to STBC, the range of SVD DE is improved by 210m (16%). From Fig. 4 and 7 it can be seen that the throughput has been doubled by using dominant eigen-mode beamforming rather than STBC (between 800m and the maximum cell radius; which represents approximately 65% of the cell area).

VII. CONCLUSIONS

This paper has presented a detailed study of the throughput benefits of MIMO when applied to mobile WiMAX. The matrix channel was modelled using the well-known 3GPP spatial channel model. The simulation is fully compliant with the 802.16e-2006 standard. Throughput results were presented for all MIMO modes and all standardised link-speeds. At low SNR values it was found that dominant eigen-beamforming is the most robust MIMO mode. However, at higher SNR values (above 15.6dB when $\rho=0.16$) AMS must be used to switch to SM eigen-beamforming in order to maximise throughput. The switching point for AMS depends on the channel correlation.

One important point to note here is that the maximum operating range, as well as the AMS switching points, are dependent on assumption of a maximum tolerable PER of 10%. Different PER thresholds (corresponding to different QoS service flows) will modify the maximum range as well as the SNR switching points. This demonstrates the

importance of cross layer interaction when determining the AMS thresholds.

Our results clearly show that both eigen-beamforming schemes achieve higher throughput than traditional SM and STBC schemes. In reality the eigen-beamforming schemes suffer from an additional overhead as a result of CSI feedback. This reduces their overall error-free throughput relative to standard SM modes. As a result, and given the degradation that results from imperfect and delayed CSI, in practical implementations the AMS algorithm may select standard SM and STBC modes at some values of SNR. Further simulations are required in order to further quantify the effects of imperfect CSI, mobility, channel correlation and the impact of using of larger M , 'waterfilling' and AMC on the different eigen-modes.

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