Diversity, Interference Cancellation and Spatial Multiplexing in MIMO Mobile WiMAX Systems

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Abstract – **Multiple input multiple output (MIMO) techniques are an essential part of the IEEE 802.16e - 2005 specifications, which form the basis of mobile WiMAX systems. In this paper, we first discuss the tradeoffs between diversity, interference cancellation and spatial multiplexing in MIMO systems, and we compare optimum combining (OC), maximum-ratio combining (MRC) and interference cancellation for different numbers of receive antennas. Then, we focus on the two mandatory MIMO profiles in the IEEE specifications (Alamouti's STC and the 2x2 spatial multiplexing scheme) and compare them when the first is combined with MRC at the receiver. The analysis obtained using the ITU pedestrian B channel in ideal conditions indicates that the two schemes lead to similar performance when they are operated at the same spectral efficiency.**

I. INTRODUCTION

Mobile WiMAX systems are based on the IEEE 802.16e-2005 specifications [1], which define a physical (PHY) layer and a medium access control (MAC) layer for broadband wireless access systems. In fact, these specifications include three different PHY layers: Single-carrier transmission (SCT), orthogonal frequency-division multiplexing (OFDM), and orthogonal frequency-division multiple access (OFDMA), the first two being pure TDMA systems. From these three PHY layers, OFDMA has been selected by the WiMAX Forum as the basic technology for portable and mobile services.

Compared to TDMA-based systems, OFDMA leads to a significant cell range extension on the uplink (from mobile stations to base station), because the transmit power is concentrated on a small number of carriers and the signal-to-noise ratio (SNR) at the receiver input is increased. Cell range extension is also achievable on the downlink (from base station to mobile stations) by allocating more power to carrier groups assigned to distant users. Another interesting feature of OFDMA is that it eases the deployment of networks with a frequency reuse factor of 1, thus eliminating the need for frequency planning.

Since radio resources are scarce and data rate requirements keep increasing, spectral efficiency is a stringent requirement in present and future wireless communications systems. On the other hand, random fluctuations in the wireless channel preclude the continuous use of highly bandwidth-efficient modulation, and therefore adaptive modulation and coding (AMC) has become a standard approach in recently developed wireless standards, including WiMAX. The idea behind AMC is to dynamically adapt the modulation and coding scheme to the channel conditions to achieve the highest spectral efficiency at all times [2, Chapter 9].

Another way of increasing spectral efficiency is to use multiple antennas at the transmitter and at the receiver. In general, multiple-antenna techniques can be used for different purposes including spatial diversity, interference cancellation, and spatial multiplexing to increase the transmitted data rate. Also, different tradeoffs can be made between these features. From the different MIMO profiles included in the IEEE 802.16e-2005 specifications, the WiMAX Forum has selected two profiles for use on the downlink. One of them is based on the space–time code (STC) proposed by Alamouti for transmit diversity [3], and the other is a 2x2 spatial multiplexing scheme [4]. These profiles can also be used on the uplink, but their implementation is only optional.

The purpose of this paper is two-fold: The first is to discuss the tradeoffs between spatial diversity, interference cancellation and spatial multiplexing in MIMO systems. The second is to analyze the two MIMO options included in the specifications of mobile WiMAX systems. The paper is organized as follows: In the next section, we discuss the spatial diversity, interference cancellation, and spatial multiplexing tradeoffs in MIMO systems. Then, in Section III, we describe Alamouti's STC and the 2x2 spatial multiplexing scheme, which are the two MIMO schemes included in the mobile WiMAX system specifications. In Section IV, we analyze the performance of the two MIMO schemes and we compare them at the same spectral efficiency using the modulations and convolutional code rates included in the specifications. Finally, we summarize our results and give our conclusions in Section V.

II. MIMO PROCESSING TRADEOFFS

The multiple antennas inherent to MIMO systems can be exploited in several ways to improve performance. The use of MIMO in wireless standards, including WIMAX, is mainly motivated by the increased data rates obtained through spatial multiplexing across the multiple antennas. In particular, with N antennas at the transmitter and M antennas at the receiver, $\min(N,M)$ independent data streams can be supported, leading to a roughly N-fold increase in data rate over single antenna systems [2, Chapter 10]. Alternatively, diversity combining of the transmit and receive antenna signals can be used to reduce the impact of multipath fading on bit error probability. In particular, in Rayleigh fading BPSK modulation with one antenna at both the transmitter and receiver (single-input single-ouput, or SISO) has a bit error probability given by $P_e \propto SNR^{-1}$, where SNR is the averaged received signal-to-noise ratio at the receiver. In a system with multiple antennas, transmit and/or receive diversity causes the slope of the bit error probability curve to increase, leading to a bit error probability given by $P_e \propto SNR^{-d}$, where d is defined as the *diversity gain* of the system. For SISO systems $d = 1$, whereas for MIMO systems with N transmit and M receive antennas under maximal ratio combining (MRC), $d = NM$, an NM-fold diversity gain. Diversity gain is in addition to *array gain,* which equals the increase in average receive SNR due to the noise averaging that results from coherent combination of received signals, even in the absence of fading.

Multiple antennas cannot achieve multiplexing and diversity simultaneously: If some antennas are used for multiplexing they cannot be used for diversity, and vice versa. Hence there is a fundamental performance tradeoff in how antennas are used. This tradeoff was characterized in [5], where it was shown that in the asymptotic limit of high SNR, the diversity/multiplexing performance tradeoff is piecewise linear. In particular, let r represent the multiplexing gain – the multiplicative increase in data rate of the MIMO system over a SISO system – that is associated with the subset of transmit and receive antennas used to create independent data streams in space. Let $d^*(r)$ represents the diversity gain from the remaining antennas. As stated above, if all antennas are used for diversity, then there is no multiplexing gain, so $r = 0$ and $d^*(r) = NM$. At the other extreme, if all antennas are used for spatial multiplexing then $r = \min(N,M)$ and, since no antennas remain for diversity combining, $d^*(r) = 0$. In [5] it was shown there is a piecewise linear relationship between r and $d^*(r)$ as shown in Figure 1. This result implies that the diversity and multiplexing gains are effectively decoupled; the subset of antennas assigned to diversity combining results in the same diversity gain as if these were the only antennas in the system, and similarly for the subset of antennas used for multiplexing. While the analysis in [5] is asymptotic in nature and based on information-theoretic arguments, practical space-time codes have been developed in [6] that achieve the diversity-multiplexing tradeoff depicted in Figure 1 at moderate SNRs.

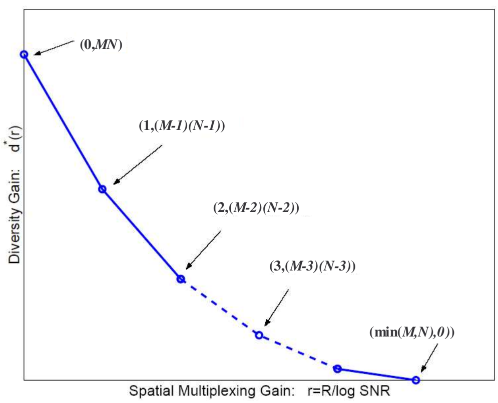

Figure 1. Diversity/Multiplexing Tradeoffs in MIMO

The optimal operating point on the curve in Figure 1, i.e. how many antennas should be used for multiplexing and how many should be used for diversity, depends on the performance metric of interest. Qualitatively, if a low probability of error is more important than high data rates, more antennas will be used for diversity, whereas if data rate is of utmost importance, more antennas will be used for multiplexing. Optimization of throughput and end-to-end distortion by finding the best operating point on the diversity/multiplexing tradeoff curve has been analyzed in [7]. This work also extends the diversity/multiplexing tradeoff to include the delay introduced by retransmitting packets received in error, a form of time-diversity that increases diversity gain at the expense of delay.

In addition to spatial multiplexing and diversity, multiple antennas can also be used for interference reduction or cancellation. Antenna arrays can use phased-array techniques to provide directional gain, which can be tightly controlled with a sufficient number of antenna elements. Phased-array techniques work by adapting the phase of each antenna element in the array, which changes the angular locations of the antenna beams (angles with large gain) and nulls (angles with small gain).. For a receive antenna array with N antennas, N nulls can be formed to significantly reduce the received power of N separate interferers. If there are $N_I < N$ interferers, then the N_I interferers can be cancelled out using N_I antennas in a phased array, and the remaining $N - N_I$ antennas can be used for diversity or multiplexing gain. Note that directional antennas must know the angular location of the desired and interfering signals to provide high or low gains in the appropriate directions, and tracking of user locations can be a significant impediment in highly mobile systems.

An alternative to interference cancellation is interference reduction through diversity combining. Specifically, in addition to reducing the impact of multipath fading, diversity combining can also be used to optimally combine signals at different antennas to reduce interference. It is well known that MRC is the optimal combining technique in the absence of interference to maximize SNR at the combiner output [2, Chapter 7]. A more general technique called *optimal combining* follows the same principle for systems with both interference and fading to maximizing the average signal-to-interference-plus-noise power ratio (SINR) [8]. In fact, at the extreme, optimal combining reduces to either MRC or IC: When interference dominates SINR degradation, OC reduces to IC and when fading dominates the SINR, OC reduces to MRC to optimally mitigate fading. Note that optimal combining requires knowledge of all desired and interferer channel gains at each antenna, which are often difficult to estimate.

A complete performance analysis of MRC and OC in MIMO systems with fading and interference assuming multiple receive antennas and a single transmit antenna was undertaken in [9]. While the same techniques can be used to analyze performance under multiple transmit antennas, the mathematics become more involved. The main idea behind the analysis is to investigate the optimal weights for the received signal at all antennas to maximize SNR or SINR. The received signal vector across all antennas after weighting is given by

$$\boldsymbol{r} = H_D w_t b_s + \sum_{i=1}^{L} \sqrt{\Omega_i} h_i b_i + \boldsymbol{n}, \quad (1)$$

where H_D is the vector of receive antenna channel gains for the desired signal, w_t is the vector of weights at the transmitter, b_s is the transmitted symbol of interest, b_i is the symbol of the ith interfering signal, h_i is the gain of the ith interfering signal, and Ω_i is the power of the ith interference signal relative to the desired signal. The combiner output is then

$$y = w_{\boldsymbol{r}}^{\boldsymbol{H}} \boldsymbol{r}, \quad (2)$$

where w_r are the antenna weights at the transmitter. In MRC, the weights w_r yield the maximum SNR of y, and in OC the weights maximize the SINR of y. For MRC the weights are well-known to be $w_t = \sqrt{\Omega_D}\boldsymbol{u}$ and $w_r = H_D \boldsymbol{u}$.

It can be shown [9] that the SINR of y assuming weights associated with MRC is given by

$$\gamma = \frac{\Omega_D \lambda}{\sum_{i=1}^{L} \Omega_i \chi_i + \sigma^2}, \quad (3)$$

where λ is the maximum eigenvalue of the matrix $H_D^H H_D$ and the χ_i are exponential random variables with unit mean. The SINR distribution thus depends on the distribution of λ and the power of the interferers.

In [9], a closed-form expression for the outage probability of γ is obtained based on the moment-generating function (MGF) of the sum of the interferers $\chi = \sum_i \Omega_i \chi_i$. Differentiating this outage probability yields the distribution of γ. This distribution is then used to obtain the probability of bit error via an MGF analysis assuming any fading distribution on both the desired signal and the interferers.

For OC the received signal is given by

$$y_r = \boldsymbol{w}^H \boldsymbol{c}_s b_s + \sqrt{P_I} \sum_{i=1}^{L} w^H c_i b_i \quad (4)$$

where c_s is the fading on the symbol b_s of interest, c_i is the fading on the symbol b_i of the ith interferer, and P_I is the weighted power of the interferers. From [8] the optimal weights for OC are given by the vector

$$\boldsymbol{w} = gR^{-1}\boldsymbol{c}_s \quad (5)$$

where g is an arbitrary constant and $R = \sum_i c_i c_i^H$ is a Wishart distributed matrix, resulting in SINR $\gamma = P_i^{-1}\boldsymbol{c}_s^H R^{-1}\boldsymbol{c}_s$. The distribution of outage probability associated with this SINR, conditioned on the fading values for the desired and interfering signals, is shown in [10] to be gamma-distributed. The unconditional distribution is obtained in [8] via a MGF analysis, similar to the case of MRC.

An alternative to MRC and OC is interference cancellation through beam-steering, where array processing under N antennas can ideally null out N-1 interferers. If we assume perfect cancellation of the strongest N-1 interferers, then performance analysis reduces to finding the outage and bit error probabilities for the residual L-N-1 interferers that remain after cancellation. These distributions first require the order statistics for the strongest interferers, which are obtained in [11]. The MGF for the received signal and its corresponding pdf is then obtained in closed form, from which outage probability can be obtained. More details can be found in [8].

A performance comparison between OC, MRC, and IC is shown in Figure 2. These numerical results are based on an interference-dominated environment where noise is negligible, and equal-power Rayleigh-fading interferers. The figure shows the outage probability as a function of SIR at each antenna for 2, 3, and 4 receive antennas. Note that as expected, OC has the best performance, since it generalizes both MRC and IC. We also see that IC does worse than MRC except at low SIR, where interference dominates performance degradation and hence canceling interference is the correct strategy. At high SIRs, performance degradation due to multipath fading causes more degradation than interference and hence MRC leads to better performance than IC.

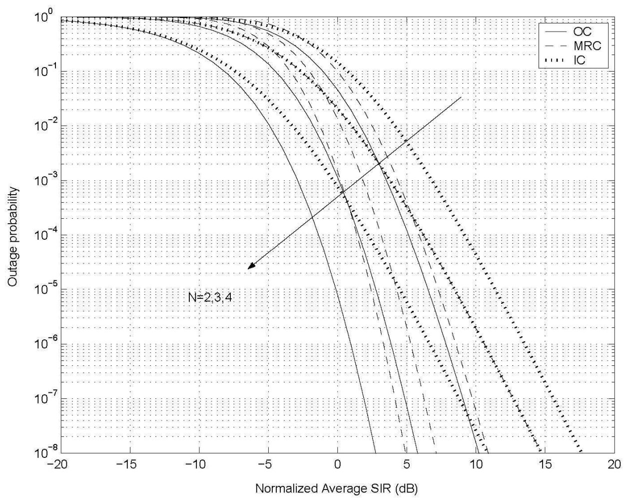

Figure 2. Performance comparison of OC, MRC and IC

III. MIMO SCHEMES IN WiMAX SYSTEMS

A. Transmit Diversity

The first multiple antenna profile is the simple STC scheme proposed by Alamouti [3] for transmit diversity. In the IEEE 802.16e-2005 specifications, this scheme is referred to as

Matrix A. Originally, Alamouti's STC was proposed to avoid the use of receive diversity on the downlink and keep the subscriber stations simple. In OFDMA-based WiMAX systems, this technique is applied subcarrier by subcarrier and can be described as follows:

Suppose that (s_1, s_2) represents a group of two consecutive symbols in the input data stream to be transmitted. During a first symbol period t_1, transmit (Tx) antenna 1 transmits symbol s_1 and Tx antenna 2 transmits symbol s_2. Next, during the second symbol period t_2, Tx antenna 1 transmits symbol s_2^* and Tx antenna 2 transmits symbol $-s_1^*$. Denoting the channel response from Tx1 to the receiver (Rx) by h_1 and the channel response from Tx2 to the receiver by h_2, the received signal samples corresponding to the symbol periods t_1 and t_2 can be written as:

$$r_1 = h_1 s_1 + h_2 s_2 + n_1 \tag{6.a}$$

$$r_2 = h_1 s_2^* - h_2 s_1^* + n_2 \tag{6.b}$$

where n_1 and n_2 are additive noise terms.

The receiver computes the following signals to estimate the symbols s_1 and s_2:

$$x_1 = h_1^* r_1 - h_2 r_2^* = \left(|h_1|^2 + |h_2|^2\right) s_1 + h_1^* n_1 - h_2 n_2^* \tag{7.a}$$

$$x_2 = h_2^* r_1 + h_1 r_2^* = \left(|h_1|^2 + |h_2|^2\right) s_2 + h_2^* n_1 + h_1 n_2^* \tag{7.b}$$

These expressions clearly show that x_1 (resp. x_2) can be sent to a threshold detector to estimate symbol s_1 (resp. symbol s_2) without interference from the other symbol. Moreover, since the useful signal coefficient is the sum of the squared moduli of two independent fading channels, these estimations benefit from perfect second-order diversity, equivalent to that of Rx diversity under maximum-ratio combining (MRC).

Alamouti's transmit diversity can also be combined with MRC when 2 antennas are used at the receiver. In this scheme, the received signal samples corresponding to the symbol periods t_1 and t_2 can be written as:

$$r_{11} = h_{11} s_1 + h_{12} s_2 + n_{11} \tag{8.a}$$

$$r_{12} = h_{11} s_2^* - h_{12} s_1^* + n_{12} \tag{8.b}$$

for the first receive antenna, and

$$r_{21} = h_{21} s_1 + h_{22} s_2 + n_{21} \tag{9.a}$$

$$r_{22} = h_{21} s_2^* - h_{22} s_1^* + n_{22} \tag{9.b}$$

for the second receive antenna. In these expressions, h_{ji} designates the channel response from Tx i to Rx j, with i, j = 1, 2, and n_{ji} designates the noise on the corresponding channel. This MIMO scheme does not give any spatial multiplexing gain, but it has 4th-order diversity, which can be fully recovered by a simple receiver. Indeed, the optimum receiver estimates the transmitted symbols s_1 and s_2 using:

$$x_1 = h_{11}^* r_{11} - h_{12} r_{12}^* + h_{21}^* r_{21} - h_{22} r_{22}^*$$
$$= \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_1 + \eta_1 \tag{10.a}$$

and

$$x_2 = h_{12}^* r_{11} + h_{11} r_{12}^* + h_{22}^* r_{21} + h_{21} r_{22}^*$$
$$= \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_2 + \eta_2 \tag{10.b}$$

with $\eta_1 = h_{11}^* n_{11} - h_{12} n_{12}^* + h_{21}^* n_{21} - h_{22} n_{22}^*$

and $\eta_2 = h_{12}^* n_{11} + h_{11} n_{12}^* + h_{22}^* n_{21} + h_{21} n_{22}^*$

These equations clearly show that the receiver fully recovers the fourth-order diversity of the 2×2 system.

B. Spatial Multiplexing

The second multiple antenna profile included in WiMAX systems is the 2×2 MIMO technique based on the so-called matrix $\mathbf{B} = (s_1, s_2)^T$. This system performs spatial multiplexing and does not offer any diversity gain from the Tx side. But it does offer a diversity gain of 2 on the receiver side when detected using maximum-likelihood (ML) detection [4].

To describe the 2×2 spatial multiplexing, we omit the time and frequency dimensions, leaving only the space dimension. The symbols transmitted by Tx1 and Tx2 in parallel are denoted as s_1 and s_2, respectively. Denoting by h_{ji} the channel response from Tx i to Rx j (i, j = 1, 2), the signals received by the two Rx antennas are given by

$$r_1 = h_{11} s_1 + h_{12} s_2 + n_1 \tag{11.a}$$

$$r_2 = h_{21} s_1 + h_{22} s_2 + n_2 \tag{11.b}$$

which can be written in matrix form as:

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \tag{12}$$

The ML detector makes an exhaustive search over all possible values of the transmitted symbols and decides in favor of (s_1, s_2) which minimizes the Euclidean distance:

$$D(s_1, s_2) = \left\{|r_1 - h_{11} s_1 - h_{12} s_2|^2 + |r_2 - h_{21} s_1 - h_{22} s_2|^2\right\} \tag{13}$$

IV. PERFORMANCE ANALYSIS

Since the Alamouti/MRC scheme has 4th-order diversity and the 2×2 spatial multiplexing scheme has 2nd-order diversity, the former can be expected to have a better BER performance (at high SNR) when the same modulation and coding schemes are used in both systems. But of utmost interest is a performance comparison between the two MIMO schemes when they are used at the same spectral efficiency. (Note that the Alamouti/MRC technique with a modulation scheme transmitting *2m* bits per symbol has the same spectral efficiency as the 2×2 spatial multiplexing scheme with a modulation transmitting *m* bits per symbol.) In a previous study [12], we made such a performance comparison between the two schemes when the Alamouti/MRC scheme uses 16-QAM and the spatial multiplexing scheme uses QPSK (4 bits per symbol period in both cases. The simulations were made using uncoded signal constellations and uncorrelated Rayleigh fading channels. The results confirmed that the Alamouti/MRC scheme indeed outperforms the 2×2 spatial multiplexing scheme at high SNR values.

In this paper, we report performance results obtained using the ITU Pedestrian Channel B [13] with pedestrian speed v = 3 km/h and assuming perfect channel state information and automatic gain control (AGC) at the receiver. We also assume perfect decorrelation between the different channels. Furthermore, the WiMAX convolutional turbo code and interleaver were included in the simulations. The BER vs. SNR results are depicted in Fig. 3 for the SISO channel, in Fig. 4 for MIMO Matrix A, and in Fig. 5 for MIMO Matrix B. Each figure shows 8 curves corresponding to the different modulations and convolutional code rates used.

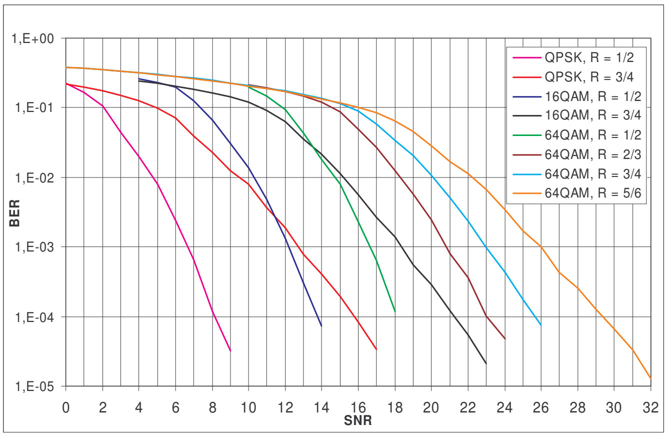

Figure 3. Performance of SISO systems on ITU Pedestrian B Channel with a pedestrian speed of 3 km/h.

Examining Fig. 4, we can observe that the three curves corresponding to the convolutional code rate R = 1/2 have identical slopes and that for each modulation the slopes of the BER curves are reduced with higher code rates. As a result, there is a crossover point between the curves corresponding to 16QAM R = 1/2 and QPSK R = 3/4, and the former gives better BER results at SNR values higher than 12 dB. The same observation holds for 64QAM R = 1/2 and 16QAM R = 3/4, where the crossover point is located at about 13.5 dB. Note that the latter two systems have identical spectral efficiencies (3 bits per channel use) and the results of Fig. 3 confirm that 64QAM R = 1/2 has superior performance.

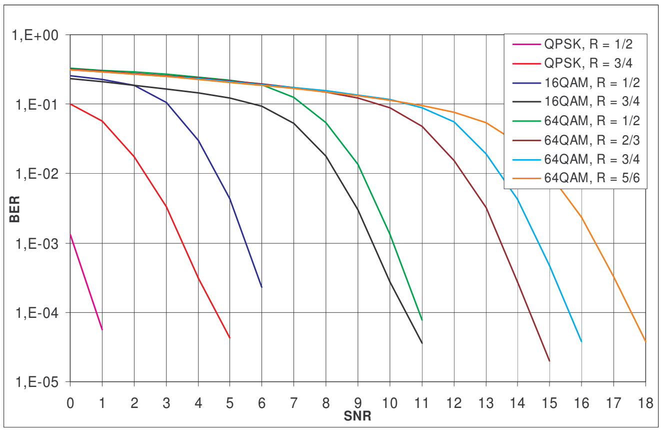

Figure 4. Performance of MIMO Matrix A systems (with MRC at the receiver) on ITU Pedestrian B Channel with a pedestrian speed of 3 km/h.

Next, comparing the results of Figs. 4 and 5, we can notice that the curves have higher slopes in Fig. 4, which is due to the order-4 diversity of the system at hand. We can also observe that the curves corresponding to lower code rates have higher slopes in both figures, but the crossover points are not located within the BER range displayed. As a general observation, the order-4 diversity associated to MIMO Matrix A with MRC at the receiver leads to a substantial BER performance improvement over the SISO system. More precisely, the SNR improvement at the BER of 10^{-4} is in the range of 7 – 7.5 dB for the code rate of 1/2 and in the range of 10 – 11.5 dB for the code rate of 3/4.

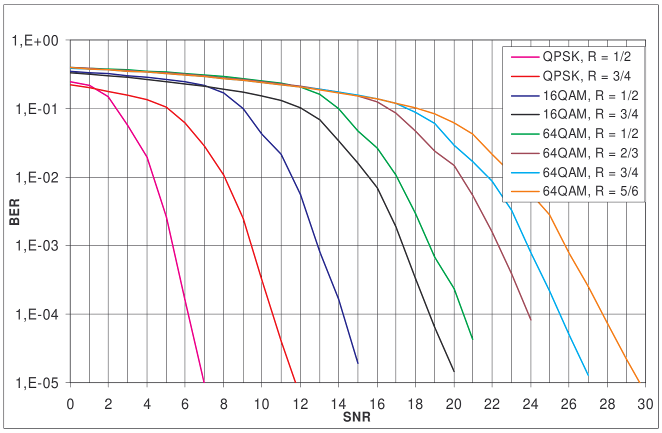

Figure 5. Performance of MIMO Matrix B systems on ITU Pedestrian B Channel with a pedestrian speed of 3 km/h.

Finally, a comparison of Figs. 4 and 5 allows us to quantify the figure of merit of the two MIMO schemes of interest. For a given modulation and coding scheme, Matrix B doubles the system spectral efficiency, but requires a significantly higher SNR value. For example, 64QAM with R = 1/2 requires an SNR of 11 dB to achieve a BER of 10^{-4} in a MIMO Matrix A system, while it requires an SNR of 20.5 dB to achieve the same BER in a MIMO Matrix B system.

To compare Matrix A and matrix B MIMO systems at the same spectral efficiency, we concentrate on the following 3 cases:

1. Matrix A system with 16QAM and R = 1/2 vs. Matrix B system with QPSK and R = 1/2.
2. Matrix A system with 16QAM and R = 3/4 vs. Matrix B system with QPSK and R = 3/4.
3. Matrix A system with 64QAM and R = 2/3 vs. Matrix B system with 16QAM and R = 1/2.

From Figs. 4 and 5, we can read that the two systems in (1) require an SNR of approximately 6.2 dB to achieve a BER of 10^{-4}. Similarly, the two systems in (2) require an SNR of 10.5 dB to achieve the same BER value. Finally, the two systems in (3) require an SNR of 14.4 dB to achieve the same BER. These results indicate that the two MIMO systems included in WiMAX specifications achieve the same performance on the channel at hand when they are used at the same spectral efficiency. Since the ML receiver is less complex to implement for MIMO Matrix A systems, these results suggest that Matrix A should be used whenever it complies with the spectral efficiency requirements. Also, Matrix A having a higher diversity than Matrix B, the slope of its BER curves is higher and this scheme can be expected to give better results at lower BER values. Another consideration which favors Matrix A is the robustness to the channel rank. But Matrix A has an upper limit of 5 on the number of information bits per channel use, while Matrix B can go up to 10 bits per channel use with sufficiently high SNR values.

V. Conclusions

In this paper, we have first discussed the diversity, interference cancellation and multiplexing gain tradeoffs in MIMO systems. Next, we have described the two MIMO schemes included in WiMAX system specifications and analyzed their performance using the ITU pedestrian B channel model with a pedestrian speed of 3 km/h and assuming perfect channel state information and uncorrelated channels. The results indicated that at the BER of 10^{-4} both systems lead to a performance improvement of 7 – 11 dB compared to the basic SISO system depending on the convolutional code rate used. They also indicated that at the BER of 10^{-4} the two MIMO systems lead to the same performance on this channel. At lower BER values, Matrix A can be expected to give superior performance due to the increased diversity order, but Matrix B increases throughput at SNR values which are compatible with operation of this MIMO scheme with 64-QAM.

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