MIMO Link Adaptation in Mobile WiMAX Systems

Bertrand Muquet(1), Ezio Biglieri(2) and Hikmet Sari(1),(3)
(1) Sequans Communications, Bat. Citicenter, 19 Le Parvis, 92073 Paris La Défense, France
(2) Universitat Pompeu Fabra, Passeig de Circumval.lació 8, E-08003 Barcelona, Spain
(3) Supélec, Plateau de Moulon, 1-3 Rue Joliot Curie, 91190 Gif sur Yvette, France

Abstract – **Mobile WiMAX systems are based on the IEEE 802.16e specifications, which include two mandatory MIMO profiles for the downlink. One of these is Alamouti's space-time code (STC) for transmit diversity, and the other is a 2x2 spatial multiplexing MIMO scheme. In this paper, we compare the two schemes assuming that the latter employs maximum-likelihood detection. The analysis shows that at the same spectral efficiency, Alamouti's STC combined with maximum-ratio combining (MRC) at the receiver significantly outperforms the 2x2 spatial multiplexing scheme at high values of the signal-to-noise ratio (SNR). Next, selection of a MIMO option is included in link adaptation to maximize network capacity, and operating SNR regions are determined for different modulation, coding and MIMO combinations.**

I. INTRODUCTION

Mobile WiMAX systems are based on the IEEE 802.16e-2005 standard [1], which defines a physical (PHY) layer and a medium access control (MAC) layer for broadband wireless access systems operating at frequencies below 11 GHz. The IEEE 802.16e-2005 specifications actually define three different PHY layers: Single-carrier transmission, orthogonal frequency-division multiplexing (OFDM), and orthogonal frequency-division multiple access (OFDMA). The multiple access technique used in the first two of these PHY specifications is pure TDMA, but the third mode uses both the time and frequency dimensions for resource allocation. From these three PHY technologies, OFDMA has been selected by the WiMAX Forum as the basic technology for portable and mobile services.

Compared to TDMA-based systems, it is known that OFDMA leads to a significant cell range extension on the uplink (from mobile stations to base station). This is due to the fact that the transmit power of the mobile station is concentrated in a small portion of the channel bandwidth 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].

An additional dimension to modulation and coding aimed at increasing spectral efficiency is the space dimension, i.e., the use of multiple antennas at the transmitter and receiver. More generally, multiple-antenna techniques can be used to increase diversity and improve the bit error rate (BER) performance of wireless systems, increase the transmitted data rate through spatial multiplexing, or trade off both. The WiMAX Forum has selected two different multiple antenna 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. These profiles can also be used on the uplink, but their implementation is only optional.

This paper analyzes the MIMO options included in the specifications of mobile WiMAX systems. In the next section, we first describe Alamouti's STC and its combination with maximum ratio combining (MRC) at the receiver. Next, we describe 2x2 spatial multiplexing and discuss the receiver issues. In Section III, we compare the two MIMO options when they are operated at the same spectral efficiency. In Section IV, we combine the MIMO options with adaptive modulation and coding and determine the SNR thresholds of operating regions. Finally, we summarize our results and give our conclusions in Section V.

II. MULTIPLE ANTENNAS 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 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:

$$r_1 = h_1 s_1 + h_2 s_2 + n_1 \tag{1.a}$$

$$r_2 = h_1 s_2^* - h_2 s_1^* + n_2 \tag{1.b}$$

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:

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

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

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:

$$r_{11} = h_{11} s_1 + h_{12} s_2 + n_{11} \tag{3.a}$$

$$r_{12} = h_{11} s_2^* - h_{12} s_1^* + n_{12} \tag{3.b}$$

for the first receive antenna, and

$$r_{21} = h_{21} s_1 + h_{22} s_2 + n_{21} \tag{4.a}$$

$$r_{22} = h_{21} s_2^* - h_{22} s_1^* + n_{22} \tag{4.b}$$

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:

$$\begin{aligned} x_1 &= h_{11}^* r_{11} - h_{12} r_{12}^* + h_{21}^* r_{21} - h_{22} r_{22}^* \\ &= \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_1 + \eta_1 \end{aligned} \tag{5.a}$$

and

$$\begin{aligned} x_2 &= h_{12}^* r_{11} + h_{11} r_{12}^* + h_{22}^* r_{21} + h_{21} r_{22}^* \\ &= \left(|h_{11}|^2 + |h_{12}|^2 + |h_{21}|^2 + |h_{22}|^2\right) s_2 + \eta_2 \end{aligned} \tag{5.b}$$

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 2x2 system.

B. Spatial Multiplexing

The second multiple antenna profile included in WiMAX systems is the 2x2 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.

To describe the 2x2 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

$$r_1 = h_{11} s_1 + h_{12} s_2 + n_1 \tag{6.a}$$

$$r_2 = h_{21} s_1 + h_{22} s_2 + n_2 \tag{6.b}$$

which can be written in matrix form as:

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \tag{7}$$

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:

$$D(s_1, s_2) = \left\{ |r_1 - h_{11} s_1 - h_{12} s_2|^2 + |r_2 - h_{21} s_1 - h_{22} s_2|^2 \right\} \tag{8}$$

The complexity of the ML detector grows exponentially with the size of the signal constellation, and this motivates the use of simpler suboptimum detectors in practical applications. Among those are [4] - [7]:

1. Zero-forcing (ZF) detectors, which invert the channel matrix. The ZF receiver has a very small complexity that does not depend on the modulation. However, it does not exploit completely the system diversity and suffers from poor performance at low SNR.

2. Minimum mean-square error (MMSE) detectors, which reduce the combined effect of interference between the two parallel channels and additive noise. The MMSE receiver slightly improves the performance of the ZF receiver, but it requires knowledge of the SNR, which can be impractical. Besides, it does not exploit completely the channel diversity either.
3. Decision-feedback receivers, which make a decision on one of the symbols and subtract its interference on the other symbol based on that decision. These receivers offer improved performance when compared to ZF and MMSE receivers, but they are prone to error propagation and still lack optimality, which may lead to large performance losses.
4. Sphere detectors, which reduce the number of symbol values used in the ML detector. Note that this type of detectors may preserve optimality while reducing implementation complexity.

III. PERFORMANCE ANALYSIS

Since the Alamouti/MRC scheme has 4th-order diversity and the 2x2 spatial multiplexing scheme has 2nd-order diversity, the former obviously has better BER performance (at high SNR) when the same modulation and coding schemes are used in both systems. Consequently, the Alamouti/MRC scheme can use a higher-level modulation if the two schemes are required to give the same BER performance. 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 2x2 spatial multiplexing scheme with a modulation transmitting *m* bits per symbol.) We have made such a performance comparison using different types of channels. Fig. 1 shows the results on an uncorrelated Rayleigh fading channel when the Alamouti/MRC scheme uses 16-QAM and the spatial multiplexing scheme uses QPSK (4 bits per symbol period in both cases).

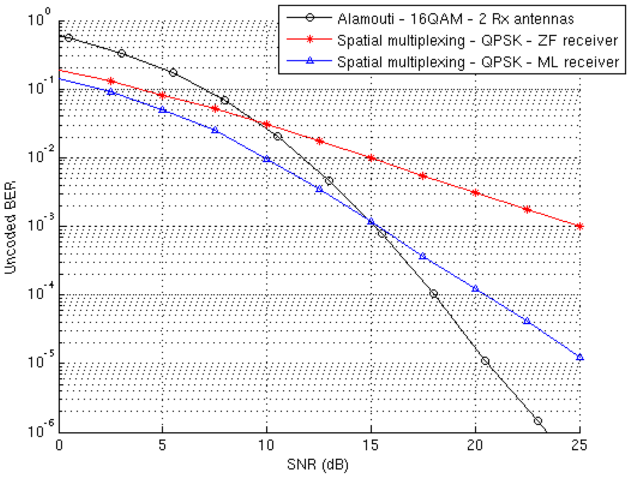

Figure 1. Comparison of Alamouti/MRC with 2x2 spatial multiplexing.

It can be observed that the ZF receiver does not exploit the diversity of the spatial multiplexing scheme and that the slope of its BER curve is only half that of the ML receiver. The other interesting observation is that the slope of the Alamouti/MRC scheme is twice as large as that of the spatial multiplexing ML receiver, which is due to the diversity factor of 4 for the former and of 2 for the latter. These results are in agreement with those reported in [8].

As predicted by the respective diversity gains of the two schemes, the results displayed in Fig. 1 confirm that at high SNR values, the simple Alamouti/MRC scheme with 16-QAM achieves better performance than the 2x2 spatial multiplexing MIMO system with QPSK and ML detection. However, since the WiMAX specifications have a limited number of modulation options, the Alamouti/MRC option can not always compete with 2x2 spatial multiplexing in terms of spectral efficiency. To maximize network capacity, the MIMO option needs to be selected as a function of the channel SNR in the same way as modulation and coding.

IV. MIMO LINK ADAPTATION

Before including the MIMO option in link adaptation, we recall the modulations and the basic code rates (denoted r) available in WiMAX system specifications:

- QPSK, r = 1/2 and r = 3/4
- 16-QAM, r = 1/2 and r = 3/4
- 64-QAM, r = 1/2 and r = 3/4

The code rates above correspond to the convolutional coding schemes included in the standard, and optional interleaving and other coding schemes such as convolutional turbo codes are not considered.

In single-antenna systems, link adaptation selects a signal constellation and a code rate as a function of the channel. This concept is called adaptive modulation and coding (AMC). The basic idea is to measure the channel quality (for instance by estimating the received power or the received SNR) at the mobile station. If the channel variations are sufficiently slow so that they are essentially constant over a period of time, the channel quality measurement can be fed back to the BS for link adaptation. The BS can then adapt the modulation and coding schemes to the channel and optimize the overall spectral efficiency subject to some performance criterion (for instance, the outage probability for a given packet error rate shall be smaller than a predetermined value).

Fig. 2 illustrates the AMC concept when the performance criterion is that the forward error correction (FEC) block error rate (FBER) must be smaller than 10^{-3}. For different combinations of the modulation and coding options that are available in the standard, the figure shows the SNR thresholds above which the performance criterion is met. (The SNR thresholds are computed for a system using MIMO matrix A at the transmitter, two antennas with MRC at the receiver, and the ITU Pedestrian Channel A corresponding to a speed of 3 km/hour.) For instance, 16QAM with code rate 1/2 cannot be used for SNR values below 7 dB, because it yields an FEC block error rate greater than 10^{-3}. Above this threshold, the modulation meets the performance criterion and leads to a spectral efficiency of 2 bits per symbol. Further, the figure shows that for SNR values exceeding 11dB, 16QAM can also be used with code rate 3/4 and this increases the spectral efficiency from 2 to 3 bits per symbol. Based on the SNR thresholds shown, AMC consists of using the modulation/ coding combination that leads to the highest throughput. The figure shows that some modulation/coding combinations are not useful on the considered channel for the performance criterion used. For instance, it is meaningless to use 64QAM with code rate 1/2, because 16QAM with code rate 3/4 gives the same spectral efficiency and has a lower SNR threshold.

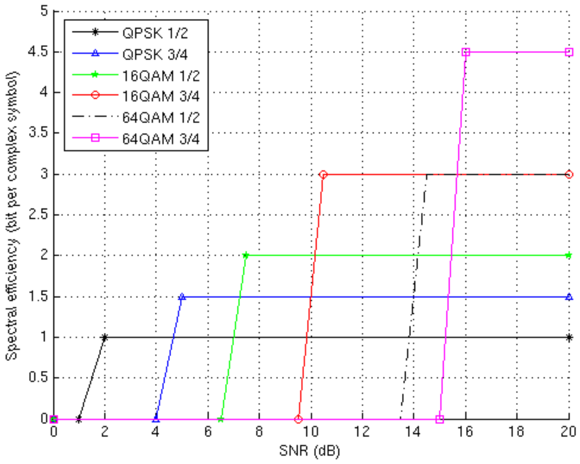

Figure 2. Operating SNR thresholds for adaptive modulation and coding (ITU pedestrian channel A, speed = 3 km/hour, FBER = 10^{-3}).

Returning now to the MIMO options, the best way to handle them is to add the MIMO dimension to adaptive modulation and coding, and select the best combination through link adaptation. Fig. 3 shows the operating SNR thresholds of the 7 useful combinations for link adaptation over the ITU pedestrian channel A model.

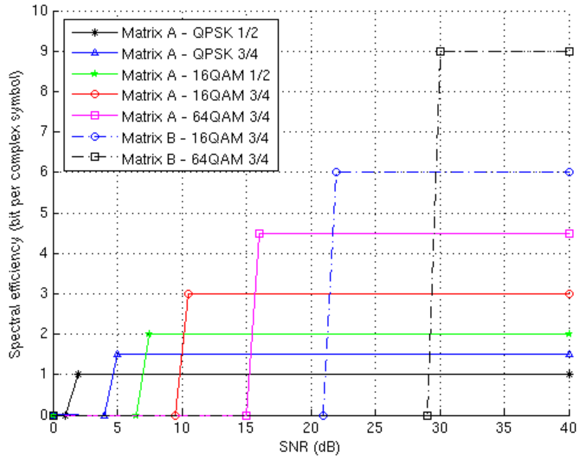

Figure 3. Operating SNR thresholds for adaptive modulation, coding and MIMO combinations (ITU pedestrian channel A, speed = 3 km/hour, FBER = 10^{-3}).

Based on the results of this figure, MIMO matrix B (spatial multiplexing) will be usable with 16QAM and code rate 3/4 at SNR values higher than 22 dB yielding a spectral efficiency of 6 bits per symbol. Furthermore, at SNR values higher than 30 dB, this system can use 64QAM and code rate 3/4 leading to a spectral efficiency of 9 bits per symbol. This represents a significant increase of throughput compared to a MIMO matrix A system whose spectral efficiency is limited to 4.5 bits per symbol in the considered system. From these results, we can conclude that the increase in cell capacity that is achievable with Matrix B is a function of user locations and the corresponding SNR values. We can also conclude that Matrix B does not lead to any cell range extension, because users near the cell edge typically have low SNR values and Matrix B cannot be used with high-level modulations for these users.

IV. CONCLUSIONS

WiMAX system specifications include many different features and options to make the best use of the wireless channel characteristics. These include adaptive modulation and coding, and multiple antenna techniques such as transmit/receive diversity and spatial multiplexing. In this paper, we have described the multiple antenna options and compared their performance. The results indicated that at the same spectral efficiency, Alamouti's STC (Matrix A) combined with MRC at the receiver achieves significantly better performance than 2x2 spatial multiplexing (Matrix B) at high SNR values. Next, we combined the MIMO option with adaptive modulation and coding so as to maximize the throughput by means of link adaptation. Using an ITU pedestrian channel model, we determined the operating SNR thresholds for different modulation, coding and MIMO combinations, and the regions where Matrix B can be used to increase cell capacity.

REFERENCES

[1] IEEE 802.16-2005: IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems – Amendment 2: Physical Layer and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, February 2006.

[2] A. Goldsmith, *Wireless Communications,* Cambridge University Press, 2005.

[3] S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451 – 1458, October 1998.

[4] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*, Cambridge University Press, 2005.

[5] E. Biglieri, R. Calderbank, T. Constantinides, A. Goldsmith, A. Paulraj, and H. V. Poor, *MIMO Wireless Communications.* Cambridge University Press, 2006

[6] E. Viterbo and E. Biglieri, "A Universal Lattice Decoder," Proc. 14th GRETSI Symposium, September 1993, Juan-les-Pins, France.

[7] M. O. Damen, A. Chkeif, and J.-C. Belfiore, "Lattice Codes Decoder for Space-Time Codes," *Electronics Letters*, vol. 4, pp. 161 – 163, May 2000.

[8] R. W. Heath, Jr. and A. J. Paulraj, "Switching Between Diversity and Multiplexing in MIMO Systems," *IEEE Trans. Commun.*, vol. 53, no. 6, pp. 962 – 968, June 2005.