Adaptive MIMO Transmission Techniques for Broadband Wireless Communication Systems

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ABSTRACT

Link adaptation is a way to increase data rates in wireless systems by adapting transmission parameters such as the modulation and coding rate. While link adaptation in single antenna systems is now mature, its application to multiple-input multiple-output communication links, presented in several emerging wireless standards, has been challenging. The main reason is that the space-time transmission strategy can also be adjusted in MIMO communication links, introducing a new dimension for adaptation. This means that practical MIMO link adaptation algorithms must also provide a dynamic adaptation between diversity and multiplexing modes of operation. This article reviews a recently proposed framework for adaptive MIMO architectures and shows how to use this framework to reduce adaptive control overhead. We also discuss practical implementation issues. Simulations in an IEEE 802.16e (mobile WiMAX) system illustrate the framework's potential improvements in data rates.

INTRODUCTION

The evolution of cellular communication systems from narrowband to broadband has resulted in a shift in system design performance measures. The top performance metric for narrowband systems supporting voice telephony is the number of users that can be supported under certain grade-of-service constraints. Advanced voice codecs, and techniques like power control and later interference cancellation were used to support higher numbers of users. Performance measures in broadband systems shifted as a result of the growing interest in wireless Internet access. Most cellular systems are now evaluated in terms of data-centric per-link performance, like the average or peak data rate. A suite of new technologies including multiple-input multiple-output (MIMO) communication and powerful error correcting codes have been suggested to increase the achievable spectral efficiency, resulting in high average and peak data rates.

Link adaptation has an important role in broadband wireless communication systems. Traditionally, link adaptation refers to the concept of adjusting transmit parameters like the modulation order and coding rate dynamically according to channel conditions. When the channel is good, higher-order modulation and higher code rates are chosen, while when the channel is bad, less efficient lower-order modulation and lower code rates are used. While link adaptation has been studied extensively, its direct application to MIMO communication links is challenging [1]. The main reason is that in MIMO links, there are many different spatial transmission strategies that offer different degrees of multiplexing and diversity performance [2], even with the same overall data rate. This makes the design of link adaptation algorithms more challenging due to the increase in the overall number of adaptation modes and the problem of distinguishing between different spatial modes with the same data rate yet different error rate performance in a given channel realization.

This article reviews the challenges associated with adaptive MIMO transmission. It also suggests a framework for devising practical adaptive MIMO architectures. The key idea is to limit spatial transmit modes to a small subset. The spatial adaptation is then combined with conventional adaptive modulation and coding (AMC). To reduce adaptive control overhead, a procedure is proposed for eliminating modes of operation with similar performance. To make the discussion concrete and directly applicable to the IEEE 802.16e standard [3], the specific case of switching between three open-loop MIMO transmission methods is considered: diversity, hybrid, and multiplexing. Diversity methods are employed to increase link robustness, resulting in better coverage. Hybrid techniques, by using both diversity and multiplexing methods, achieve higher data rates and provide good diversity advantage. Multiplexing schemes are also used to enhance spec-

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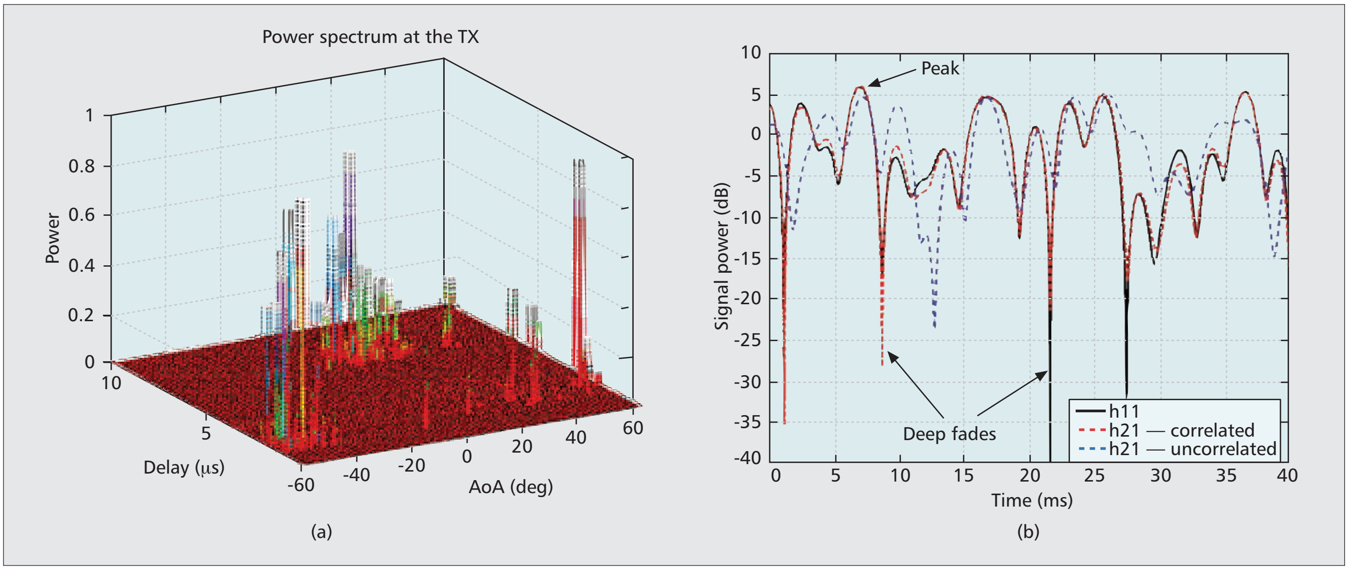

(a) (b)

Figure 1. *Signal power: a) power angle/delay profile of typical spatially correlated channel environments; b) signal power measured at two different antennas of a MIMO array, with and without channel spatial correlation. The temporal channel fading is due to Doppler effects.*

tral efficiency, when the channel is characterized by good quality and a large number of degrees of freedom. Simulations based on parameters from the IEEE 802.16e standard illustrate expected performance improvements in different channel scenarios. Compared with prior overviews of MIMO link adaptation [1], we suggest, based on our prior work [4–7], a concrete adaptation strategy. We show how to reduce the number of adaptive modes. We present simulation results for a current broadband wireless access system, and we highlight practical implementation issues.

FUNDAMENTALS OF ADAPTIVE MIMO SYSTEMS

The difference between conventional adaptive modulation and adaptive MIMO transmission is that it is also possible to switch between different spatial signaling techniques in response to changing conditions of the propagation channel. In this section we provide background on the wireless channel as we describe the fundamentals of adaptive MIMO transmission as well as representative MIMO strategies. We define the MIMO mode and suggest the adaptive MIMO framework.

BACKGROUND ON MIMO WIRELESS CHANNELS

In typical wireless communication systems, the signal measured at the receiver consists of multiple copies of the same transmit signal produced by different paths in the propagation environment. The multipaths cause different wavefronts to impinge, with uncorrelated phases, on the receive antenna. The wavefronts add up constructively or destructively, yielding, over time (time selectivity), fluctuations (i.e., peaks or fades) in the signal strength. In wideband transmissions, the relative delay of different propagation paths may be greater than the symbol period, resulting in channel fluctuation in the frequency domain. This fading effect is known as *frequency selectivity* and the rate of variation of the channel gain in frequency is a function of the delay spread of the multipaths.

When the transmitter or receiver is equipped with multiple antennas, the signals received at different elements of the arrays may fade independently; such a channel is characterized by its *spatial selectivity*. The spatial selectivity depends on both the physical characteristics of the channel (i.e., the spatial distribution of the impinging wavefronts) and array properties (i.e., antenna spacing, cross-polarization, and antenna radiation patterns). The spatial distribution of the multipaths determines the power angle spectrum of the channel, characterized in part by the angle spread or variance of the angular spectrum. The larger the angle spread, the higher the probability that multiple wavefronts add up with different phases at different antennas of the MIMO array. These in turn produce low correlated signals. Another channel effect that has impact on the spatial selectivity is the line-of-sight (LOS) component. When the LOS component is dominant, the signals measured at different antennas are equally strong over time, resulting in reduced number of degrees of freedom in the spatial domain.

Figure 1a shows the power angle/delay profile of typical outdoor channel environments. With different delays, the wavefronts impinge on the antenna array from different angles of arrival (ranging between –60° and 60° with respect to the broadside direction of the uniform linear array). The impinging rays are clustered around a few angles and delays. Each cluster identifies the energy coming from one specific scattering object in the propagation environment. In more general scenarios, the higher the number and angle spread of the clusters, the lower the channel spatial correlation. Figure 1b shows the effect of the spatial correlation on the signal power measured at two different antennas of the array. In the presence of low spatial correlation (i.e., large antenna spacing), the received signals h11 and h21 fade independently, resulting in

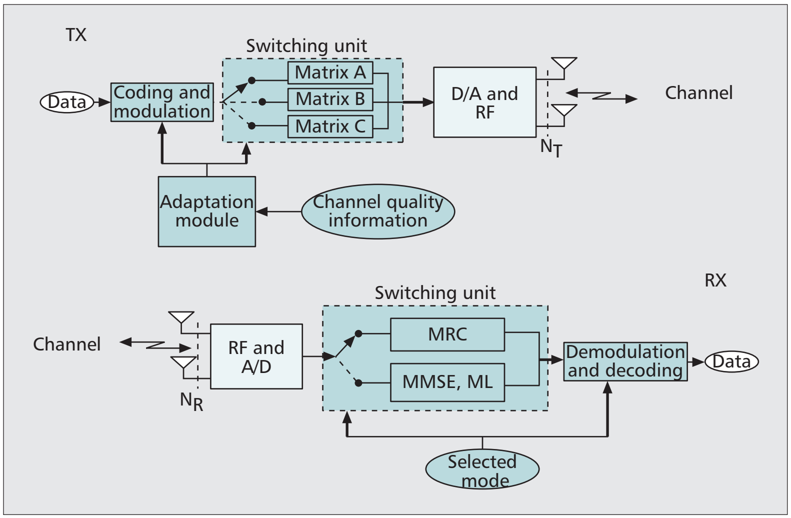

Figure 2. *Block diagram of adaptive MIMO communication systems.*

higher spatial diversity. We explain this phenomenon later in this section.

In practical systems, we can improve link performance by exploiting the channel time, frequency, and spatial selectivity with adaptive MIMO techniques. Adaptive MIMO systems that exploit time and frequency selectivity have been described already in [1]. In this article we focus only on spatial selectivity. To combat signal fading and enhance signal throughput, adaptive MIMO systems switch between robust or high-data-rate signaling solutions (consisting of different combinations of modulation/coding and MIMO schemes).

MODULATION AND CODING SCHEMES

Multiple modulation orders and forward error correction (FEC) codes are defined in typical standard wireless communication systems to enable link adaptation. The current wireless standards employing MIMO technology (i.e., IEEE 802.11n, IEEE 802.16e, and 3GPP Long Term Evolution) define different sets of modulation orders and coding rates. These are generally combined in predefined modulation/coding schemes (MCSs).

As an example, the IEEE 802.16e standard defines three modulation schemes: quaternary phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM [3, 8]. Additionally, various FEC coding techniques are possible, such as convolutional codes (CCs), convolutional turbo codes (CTCs), and low density parity check (LDPC) codes. A few coding rates are considered: 1/2, 2/3, 3/4, and 5/6 (the rate 5/6 code is used only for CTCs). Based on the above modulation orders and code rates, the IEEE 802.16e standard uses lookup tables with predefined sets.

MIMO METHODS

There are sophisticated space-time coding schemes for MIMO systems for different modulation and code rates. Unfortunately, these approaches, especially difficult in evaluating link performance, are not amenable to link adaptation. As a result, most current standards suggest spatial transmission mappings that can be used to decouple the choice of modulation and code rate from the MIMO method [9]. These mappings are either open loop, independent of the channel, or closed loop, designed as a function of the channel. In this article we consider only open-loop mappings, although the results can extend to closed loop techniques when combined with limited feedback techniques [10].

To illustrate our approach, we consider three open-loop MIMO transmission mapping matrices defined in the IEEE 802.16e standard: *Matrix A*, exploiting only diversity; *Matrix B*, combining diversity and spatial multiplexing; and *Matrix C*, employing only spatial multiplexing [8]. We consider the practical case of four transmit antennas, but similar techniques can be applied to lower-order MIMO systems as well. We briefly review these schemes and outline their properties below.

Diversity (Matrix A) — Space-time block codes (STBCs) efficiently exploit transmit diversity to combat channel fading while keeping low decoding complexity. A number of STBCs for four-transmit-antenna systems have been proposed thus far. A rate 3/4 full-diversity code was presented in [11], while [12] proposed a rate one quasi-orthogonal STBC not yielding full diversity. There are several examples of space-time codes that achieve full diversity and rate one with relatively high complexities. Note that Matrix A is an example of orthogonal STBC.

Hybrid (Matrix B) — This method combines diversity and spatial multiplexing by encoding two transmit signal streams across the four antennas [13]. In particular, two Alamouti codes are run in parallel over two different sets of antennas, enabling rate two transmissions. To decode the data, zero forcing (ZF), minimum mean square error (MMSE), or maximum likelihood (ML) receivers can be employed.

Spatial Multiplexing (Matrix C) — Spatial multiplexing systems transmit multiple independent parallel data streams to enhance spectral efficiency over wireless channels characterized by rich scattering. The receive streams can be decoded through linear (i.e., ZF or MMSE) or nonlinear receivers. In general, nonlinear receivers yield better error rate performance, at the cost of higher computational complexity [14]. Typical examples of nonlinear receivers are successive interference cancellation (SIC) and ML.

ADAPTIVE MIMO FRAMEWORK

A decoupled framework for adaptive MIMO transmission is depicted in Fig. 2. The general adaptation mechanism can be summarized as follows. The receiver estimates the channel quality information (CQI) and sends it back to the transmitter; the transmitter processes the CQI and selects the best transmission mode (i.e., combination of MCS and MIMO method); the receiver is informed of the new selected mode via a low-rate control channel and adaptively switches between different receivers, depending on the selected mode. Alternatively, the receiver may estimate the optimal transmission mode based on the CQI and send it back to the transmitter.

One of the key design challenges of adaptive MIMO architectures is to define efficient adaptation modules that use a minimal amount of feedback information. Different adaptation criteria can be defined to exploit the time, frequency, and spatial selectivity of the wireless channel. We later present different adaptive methods designed to enhance throughput or produce diversity gain, and discuss their performance results.

DEFINITION OF THE MIMO TRANSMISSION MODES

Adaptive MIMO architectures utilize different combinations of MCSs and MIMO methods to enable transmissions over a wireless link. For the sake of simplicity, we assume QPSK, 16-QAM, and 64-QAM as modulation orders, and 1/2, 2/3, and 3/4 as code rates. We labeled MCS ID 1 for QPSK with code rate 1/2 and increased the index to the order of 8. For systems employing the eight MCSs and three MIMO methods described above, it is possible to define the set of 24 transmission modes reported in Table 1, ordered according to increasing values of peak spectral efficiency. In practice, it is desirable to reduce the number of modes to keep the number of control bits to a minimum. One solution is to discard modes that provide the same throughput at a worse error rate.

For example, Fig. 3 shows that mode 15 in Table 1 requires higher signal-to-noise ratio (SNR) than mode 14 to achieve the same throughput (due to worse bit error rate [BER]). The number of modes in Table 1 can therefore be reduced to 16, allowing the control information to be encoded over 4 bits. In systems with low-rate control channels, it is possible, as depicted in Fig. 3, to reduce the number of modes to eight such that only 3 bits are required for the control messages.

Mode ID	Modulation	Code rate	MIMO mode	Peak rate (b/s/Hz)
1	QPSK	1/2	Matrix A	1
2	QPSK	2/3	Matrix A	1.3
3	QPSK	3/4	Matrix A	1.5
4	16-QAM	1/2	Matrix A	2
5	QPSK	1/2	Matrix B	2
6	16-QAM	2/3	Matrix A	2.7
7	QPSK	2/3	Matrix B	2.7
8	16-QAM	3/4	Matrix A	3
9	QPSK	3/4	Matrix B	3
10	64-QAM	2/3	Matrix A	4
11	16-QAM	1/2	Matrix B	4
12	QPSK	1/2	Matrix C	4
13	64-QAM	3/4	Matrix A	4.5
14	16-QAM	2/3	Matrix B	5.3
15	QPSK	2/3	Matrix C	5.3
16	16-QAM	3/4	Matrix B	6
17	QPSK	3/4	Matrix C	6
18	64-QAM	2/3	Matrix B	8
19	16-QAM	1/2	Matrix C	8
20	64-QAM	3/4	Matrix B	9
21	16-QAM	2/3	Matrix C	10.7
22	16-QAM	3/4	Matrix C	12
23	64-QAM	2/3	Matrix C	16
24	64-QAM	3/4	Matrix C	18

Table 1. *MIMO transmission modes and corresponding values of spectral efficiency.*

ADAPTIVE MIMO TRANSMISSION TECHNIQUES

In MIMO systems it is possible to exploit the channel spatial selectivity by switching between different transmission modes as a means to improve system performance. Adaptive MIMO switching methods can be designed to increase throughput for a predefined target error rate or reduce the error rate performance for a fixed transmission rate. We now describe these two approaches and define practical adaptation criteria.

THROUGHPUT-BASED ADAPTIVE METHODS

AMC is used to jointly adapt the modulation order and coding rate to the changing channel conditions, while satisfying the fixed power constraint. AMC is conceived to enhance spectral efficiency while satisfying a predefined target error rate performance. In practice, AMC techniques utilize robust MCSs when the channel experiences deep fades, and switch to higher-order MCSs as the channel quality improves. In MIMO systems, the spatial components of the channel can also be exploited by switching between different transmission modes. A general criterion is to employ robust diversity methods (e.g., orthogonal STBC, beamforming) for channels with high spatial correlation and to employ high data rate spatial multiplexing methods in channels with low correlation.

To gain intuition on this throughput-based adaptive mechanism, we consider three practical channel scenarios in the context of wireless metropolitan area networks (WMANs). The first scenario is characterized by one strong LOS component and no scattering. Since the channel has only one dominant spatial component due to the strong LOS component, the user who is starved of diversity and robust methods (i.e., Matrix A) would be selected by the adaptive algorithm. The second channel scenario is characterized by a poor scattering environment (i.e., non-LOS [NLOS] and low angular spread), in which only a few degrees of freedom are available to transmit parallel streams over the wireless link. In this case, the user would require hybrid methods (i.e., Matrix B)

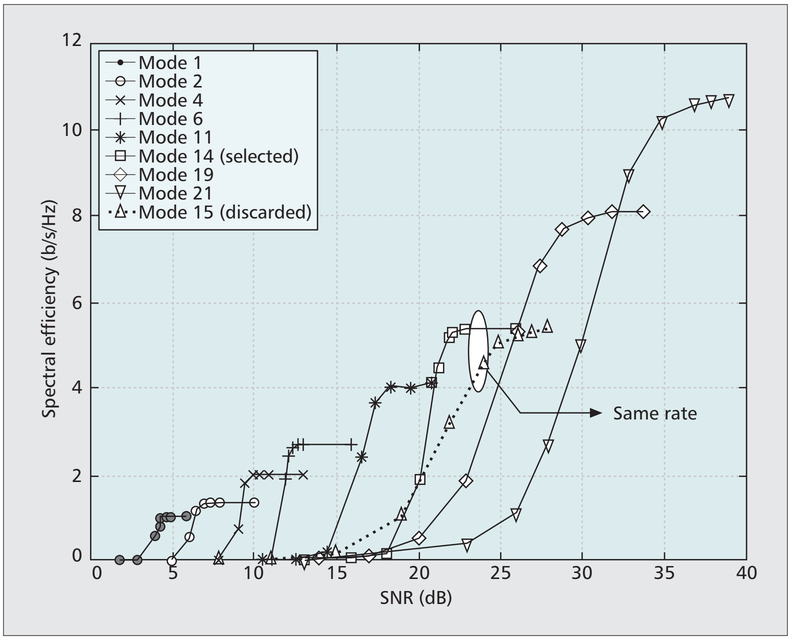

Figure 3. *Spectral efficiency of different MIMO modes in Table 1 (defined as combinations of MCSs and MIMO schemes) for practical 4 × 4 MIMO systems.*

to enhance throughput while maintaining good error rate performance. The third channel scenario is a rich scattering environment (i.e., high angular spread), for which adaptive MIMO algorithms would switch to multiplexing transmissions (i.e., Matrix C) to increase spectral efficiency.

As for conventional AMC schemes, the choice of the best MIMO transmission method also depends on the SNR. For example, users at the edge of the cell would be served with diversity methods as opposed to users close to the access point (e.g., in urban environments and NLOS), for which multiplexing methods would be preferable. Table 2 summarizes the MIMO methods to be used in different channel scenarios and SNR conditions.

Given the set of MIMO transmission modes in Table 1, the challenge now is to design methods to switch between modes depending on the channel conditions. The general criterion of throughput-based adaptive algorithms is to select the mode that yields the highest throughput while satisfying a predefined target rate. This adaptive method requires knowledge of the error rate performance of each mode, which is also a function of the channel spatial selectivity. For example, the average BER of spatial multiplexing modes (i.e., modes 12, 15, 17, 19, 21–24 in Table 1) is much higher in spatially correlated channels than in spatially selective channels. One way to estimate the error performance of different modes is to express their BER in closed form as a function of the channel parameters. For example, this has been done for bit-interleaved coded modulation (BICM) systems in [4, 15]. Unfortunately, these closed-form expressions are not available for all kinds of channels (e.g., with LOS) and MIMO transceivers.

An alternative method is to empirically precompute the error performance of the transmission modes for a set of typical propagation scenarios or *link quality regions*. The link quality regions are defined by quantized levels of time/frequency/space correlation and SNR values. Then the optimal *SNR switching thresholds*, corresponding to the predefined target error rate, are stored for different modes in lookup tables (LUTs). A general method to generate the LUTs is described in [1]; it accounts for the time and frequency selectivity of the channel. For spatially selective channels, the LUT can be constructed based on quantized spatial correlation scenarios as reported in Table 2.

In practical adaptive MIMO systems, the receiver first calculates the *link quality metrics*, consisting of average SNR and space selectivity indicators [5]. These metrics are then input into the LUT, which maps the link quality metrics into a link quality region. Then the average SNR is compared against the available SNR thresholds of the selected channel scenario to choose the optimal transmission mode, providing the highest throughput for the predefined target error rate. The mode selection information is then conveyed to the transmitter via a reliable low-rate feedback channel. This adaptive mechanism can be carried out on a frame-by-frame basis, by tracking the instantaneous channel quality. Alternatively, long-term adaptation can be employed to reduce the amount of control information, resulting in lower throughput performance. We discuss slow vs. fast adaptation in the next section.

Figure 4 shows the spectral efficiency achievable by throughput-based adaptive 2 × 2 MIMO systems with target BER of 10^{-6} in different propagation scenarios. Picocells are characterized by a number of scattering objects and high angular spread, resulting in low spatial correlation. On the other hand, macrocell environments are defined by low spatial correlation. In this case, the adaptive algorithm switches between orthogonal STBC and spatial multiplexing modes, based on statistical spatial channel quality information. We observe that the performance of the adaptive algorithm depends on the correlation scenario. 5 dB gains can be achieved in the high SNR regime by enabling adaptation based on the channel spatial correlation.

Channel scenario	Low SNR (< 15 dB)	Medium SNR (≃ 20 dB)	High SNR (> 25 dB)
LOS, H/L CSC	Matrix A	Matrix A	Matrix B
NLOS, H/L CSC	Matrix A	Matrix B	Matrix C

Table 2. *Selected MIMO transmission modes in different channel scenarios and SNR conditions. Each propagation scenario is characterized by given (high/low) channel spatial correlation and LOS component.*

DIVERSITY-BASED ADAPTIVE METHODS

The goal of diversity-based adaptive methods is to improve the error rate performance of wireless systems, resulting in higher robustness to fading and increased coverage. Diversity-based methods are enabled by switching between different MIMO modes to reduce the error rate for fixed-data-rate transmissions. To achieve the same data rate with different transmission modes, different MCSs are employed for the three MIMO schemes described above. For example, diversity-based methods can be applied to the following sets of modes characterized by the same values of peak spectral efficiency: {4, 5}, {6, 7}, {8, 9}, {10, 11, 12}, {14, 15}, {16, 17}, and {18, 19} in Table 1. As for throughput-based methods, the adaptation can be carried out at fast or slow rates.

One solution for instantaneous diversity-based adaptations was proposed in [6, 7]. In [6] an algorithm based on the minimum Euclidean distance was designed to switch between diversity and multiplexing schemes for 2 × 2 MIMO systems. A similar method was presented in [7] for 4 × 4 MIMO systems, enabling switching between Matrices A, B, and C. These methods, however, are based on theoretical bounds, yielding performance loss, especially for a large number of transmit antennas. Moreover, the computational complexity at the receiver is high because the minimum Euclidean distance has to be calculated on a frame-by-frame basis.

Alternatively, a stochastic approach can be employed as in [7]. In this case, the error rate performance is precomputed for different transmission modes. The optimal SNR switching thresholds are stored in LUTs for different propagation conditions, similar to the throughput-based method. Then the receiver estimates the channel quality and selects the mode yielding the lowest BER performance. As a case study, the authors considered the following three MIMO modes without FEC coding for simplicity: Mode A, with 256-QAM and Matrix A; Mode B, with 16-QAM and Matrix B; and Mode C with 4-QAM and Matrix C. All three modes are characterized by the same peak spectral efficiency value of 8 b/s/Hz. We observe that the diversity-based adaptive method switches between Modes C and B as the SNR level increases to improve the BER performance, resulting in diversity gain. In this case, Mode A is never selected for transmission due to its poor error rate performance. In 4 × 2 MIMO systems Mode C is not an option, since the number of receive antennas is lower than the number of transmit antennas. In this case, adaptive switching is enabled between Modes A and B.

JOINT DIVERSITY/THROUGHPUT-BASED ADAPTIVE METHODS

We showed that adaptive MIMO transmission methods can be designed to either increase throughput or provide diversity gains. For both these approaches we selected only a subset of modes from Table 1 to reduce the number of bits used for control information. Alternatively, it is possible to employ the whole set of modes in Table 1 in a joint diversity/throughput-based adaptive algorithm. In this case, the throughput-based method would be employed to enhance spectral efficiency for a predefined target error rate. It would, depending on the estimated link quality region, switch to modes with higher data rates. Moreover, within each link quality region, the joint adaptive algorithm would switch between modes with the same rate but different error rate performance. This would yield additional diversity gains, resulting in higher spectral efficiency.

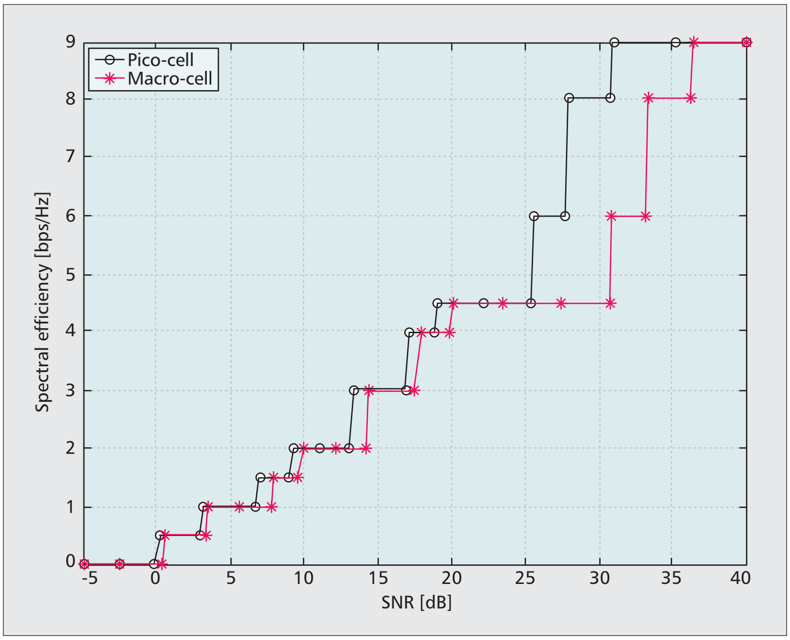

Figure 4. *Spectral efficiency of throughput-based adaptive 2 × 2 MIMO systems in different channel environments. The adaptive method switches between orthogonal STBC and spatial multiplexing.*

PRACTICAL IMPLEMENTATION ISSUES

There are several practical issues in the design of adaptive MIMO algorithms.

When the adaptation module is at the transmit side, the receiver needs to communicate the link quality metrics (i.e., average SNR and space selectivity indicators) to the transmitter, resulting in higher feedback overhead. The standard must have provisions for the appropriate kind of feedback. Alternatively, the adaptation module can be designed at the receiver so that only the MCS mode is fed back to the transmitter. This approach, however, results in a high-complexity receiver for the user terminal, but may allow more flexibility in the choice of terminal algorithms.

The number of control messages sent by the transmitter to enable mode switching is a function of the adaptation rate. In general, fast adaptation results in better system performance, since the algorithm is able to track the short-term channel variations. The high number of control messages, however, may become impractical for systems with low-rate control channels or in high Doppler. Statistical adaptation may be preferable. Statistical adaptation is close to optimum where there is a substantial amount of correlation in the channel.

It may be computationally expensive to precompute the LUTs for throughput-based adaptive methods via simulations. One way to reduce this complexity is to rely on theoretical performance analysis of BICM MIMO systems [4] and empirically derive from that the SNR switching thresholds for different link quality regions.

Given the significant performance gains and the low implementation complexity, we believe that adaptive transmission for MIMO communication systems is one of the most promising solutions for next-generation wireless networking.

Spatial multiplexing modes require high SNR to be selected by the adaptive algorithm, as shown in Table 2. In indoor environments (as for wireless local area networks), when the users are close to the access point (i.e., high SNR condition) and in the presence of rich scattering, adaptive switching to multiplexing mode is a practical solution to increase system throughput. On the other hand, in outdoor scenarios (as for typical cellular systems) the distribution of the SNR is centered at low values due to the adverse effect of path loss and the presence of users at the edge of the cell. In these conditions, adaptive MIMO algorithms may not provide satisfactory throughput performance. Other solutions such as precoding for multi-user MIMO systems may be a better way to increase the sum spectral efficiency.

CONCLUSIONS AND FUTURE WORK

This article outlines a general framework for enabling link adaptation techniques for MIMO communication systems. To date, the AMC and MIMO techniques have been separately and independently operated. In this article, however, we discuss methods by which those techniques can be jointly optimized to improve link performance and throughput. We explore various ways to capture the channel information and provide some guidelines on the system design. In this article we consider open-loop MIMO solutions including diversity, hybrid, and spatial multiplexing. Extensions to include closed-loop schemes are part of ongoing research. A particularly attractive area for future research is adaptive modulation with limited feedback, where the transmit precoders are quantized.

Given the significant performance gains and low implementation complexity, we believe that adaptive transmission for MIMO communication systems is one of the most promising solutions for next-generation wireless networking.

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