# Overview of Rate Adaptation Algorithms Based on MIMO Technology in WiMAX Networks

Tsz Ho Chan
Department of Computer Science and Engineering
The Hong Kong University of Science and Technology, Hong Kong
Email: cscth@cse.ust.hk

Chui Ying Cheung
Department of Computer Science and Engineering
The University of Washington, Seattle
Email: cherie@cs.washington.edu

Mounir Hamdi
Department of Computer Science and Engineering
The Hong Kong University of Science and Technology, Hong Kong
Email: hamdi@cse.ust.hk

Maode Ma
School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore
Email: Maode_Ma@pmail.ntu.edu.sg

***Abstract*—Wireless communication technology has been evolving over the years. From the 2.5G era where the General Packet Radio Service (GPRS) offered very low data rates of 171.2 Kbps to the 3.5G era where the High-Speed Downlink Packet Access (HSDPA) offered data rates of 10.8 Mbps, the increased data rates can support the delivery of richer mobile multimedia contents to end-users. With the growing demand in data throughput, the IEEE 802.16e promises to deliver high data rates over large areas to a large number of users in the near future. This exciting technology can rapidly provide broadband access to locations in the world's rural areas where broadband is currently unavailable, as well as competing for urban market share. In this paper, we will investigate the research issues in devising rate adaptation algorithms at the WiMAX PHY and MAC layers. We will propose a framework in which the PHY layer metrics can be passed into the MAC layer under practical simulation environment.**[1]

## I. Introduction

Broadband wireless communication networks have been developing for many years. From the 2.5G GPRS technology to the 3.5G HSDPA technology, the data rates have grown around a hundred times theoretically. However, the data rate is still low compared with the traditional wired networks such as IEEE 802.3 Ethernet. The IEEE 802.11n standard was developed to provide data rates of over 240 Mbps theoretically for local area network. In order to cover large area in metropolitan scale, the IEEE 802.16 (WiMAX) standard was developed and ratified as the IEEE 802.16d [1] standard in June 2004. In December 2005, enhancements were made on the WMANs mobility support to WiMAX and it was officially approved as the IEEE 802.16e [2] standard.

The WiMAX standard identifies two major groups of frequency bands. The 10-66 GHz licensed bands and the frequency bands below 11GHz. The 10-66 GHz licensed band has typical channel bandwidths of 25 MHz or 28 MHz and a raw data rate over 120 Mbps. Since the wavelength is short, line-of-sight (LOS) is required and so it is suitable for point-to-multipoint (PMP) access serving applications in office environment. The frequency bands below 11 GHz can further be classified as licensed or license-exempt bands. Since the wavelength is longer, LOS is not necessary but the multipath effect becomes significant. For the license-exempt band, since it allows the existence of other primary devices utilizing the same radio spectrum (primarily 5-6 GHz), additional interference and co-existence issues are introduced. The PHY and MAC layers have to incorporate additional mechanisms such as dynamic frequency selection (DFS) to cope with the interference and co-existence issues. The IEEE 802.16e standard defines the mobile WMANs for combined fixed and mobile broad bandwidth access supporting subscriber stations moving at vehicular speeds operating in licensed bands below 6 GHz.

With the enhancements on mobility support, WiMAX systems can provide broadband wireless access with higher data rates (around 70 Mbps) and mobility. It can compete with existing wired systems such as coaxial systems using cable modems and digital subscriber line (DSL) links. Regarding data rates support, one important issue in the WiMAX networks is to develop efficient algorithms supporting data rate adaptation. The WiMAX standard has specified different modulation schemes and messages format for systems to deliver broadband service. However, the policy on how and which modulation scheme should be used under various link conditions has not been specified in the standard. It has provided a wide space for researchers to develop and evaluate different data rate adaptation algorithms to enhance the performance of WiMAX systems.

In this paper, we will investigate the research issues in deriving rate adaptation algorithms of WiMAX. We will propose a framework in which the PHY layer metrics can be passed into the MAC layer in a practical simulation environment for the research on rate adaptation algorithms. Section II gives a comprehensive overview of the WiMAX physical layer and the MAC layer. Section III discusses various research issues on the MIMO-based rate adaptation algorithms. Section IV presents our simulation framework for rate adaptation algorithms and

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evaluate the simulation results on MIMO-based WiMAX PHY layer. Lastly, section V concludes this paper.

## II. WiMAX Physical and MAC Layer Techniques

The WiMAX physical (PHY) layer protocol specifies the electrical specification, collision control and timing dynamics of hardware such as antennas. It defines the conversion between the data bits from upper layer and the corresponding electrical signals transmitting over the air. The standard identifies two entities in a WiMAX network, the base stations (BSs) and the subscriber stations (SSs). The standard specifies five air interfaces for the PHY layer allowing flexibility for the service providers to optimize system deployments:

- WirelessMAN-SC: A single-carrier modulated air interface for 10-66 GHz frequency bands.
- WirelessMAN-SCa: A single-carrier modulated air interface for licensed bands below 11 GHz.
- WirelessMAN-OFDM: An orthogonal-frequency division multiplexing scheme which consists of 256 orthogonal carriers for licensed bands below 11 GHz.
- WirelessMAN-OFDMA: An OFDM scheme with 2048 carriers for licensed bands below 11 GHz. Multiple access for SSs is achieved by assigning each SS a subset of the 2048 carriers.
- WirelessHUMAN: Wireless High-speed Unlicensed Metropolitan Area Networks. It is used for license-exempt bands below 11 GHz. The SCa, OFDM and OFDMA modulation schemes can be applied with additional DFS mechanism to ensure there is no harmful interference to the primary devices identified by the regulation.

The first four air interfaces support both the time-division duplexing (TDD) and frequency-duplexing (FDD) while the WirelessHUMAN air interface supports only TDD. Both TDD and FDD configurations adopt an adaptive burst profiling framing mechanism where transmission parameters such as modulation and coding schemes (MCS) can be adjusted individually to each SS on a frame-by-frame basis. The uplink (UL) PHY is based on a combination of time-division-multiple-access (TDMA) and demand-assigned-multiple-access (DAMA) where the channel is divided into a number of time slots. The downlink (DL) channel is TDM at the BS where the MAC protocol data unit (PDU) for each SS is multiplexed onto a single stream of data and is received by all SSs within the coverage sector of the BS.

The WiMAX medium access control (MAC) layer protocol describes and specifies the issues of message composition and transmission, services provisioning, resources allocation and connection maintenance. The standard has defined frameworks supporting both the point to multipoint (PMP) and the Mesh topologies. In the PMP mode operation, within a given frequency channel and coverage of the BS sector, all SSs in the downlink receive the same transmission, or parts of it. The BS is the only transmitter operating in this direction. So it transmits without having to coordinate with other stations. The downlink is used for the information broadcasting. In cases where the message DL-MAP does not explicitly indicate that a portion of the downlink subframe is for a specific SS, all SSs are able to listen to that portion. The SSs check the connection identifiers (CIDs) in the received protocol data units (PDUs) and retain only those PDUs addressed to them. SSs share the uplink to the BS on a demand basis. Depending on the class of service at the SSs, the SSs may be issued continuing rights to transmit or the transmission rights granted by the BS after receipt of requests from SSs. In addition to individually addressed messages, messages may also be sent by multicast to group of selected SSs and broadcast to all SSs. In each sector, SSs are controlled by the transmission protocol at MAC layer. And they are enabled to receive services to be tailored to the delay and bandwidth requirements of each application. It is accomplished by five types of uplink sharing schemes, which are unsolicited bandwidth grants, polling, and bandwidth requests contention. The IEEE 802.16e standard has also defined a set of schemes to support mobility for the ranging, handover process, power control and sleeping of mobile WiMAX devices.

When SS registers to a BS, one transport connection is associated with one scheduling service. The IEEE 802.16e standard has defined five scheduling services:

- Unsolicited Grant Service (UGS)
- Real-time Polling Service (rtPS)
- Extended rtPS (ertPS)
- Non-real-time Polling Service (nrtPS)
- Best Effort (BE)

The transmission scheme at the MAC layer is connection-oriented. All data communications are defined in the context of a connection. Service flows can be provisioned at an SS and connections are associated with these service flows, each of which is to provide transmission service with requested bandwidth to a connection. The service flow defines the QoS parameters for the PDUs that are exchanged on the connection. The concept of a service flow on a connection is the key issue to the operation of the MAC protocol. Service flows provide a mechanism for uplink and downlink QoS management as bandwidth allocation processes. An SS requests uplink bandwidth for each connection. Bandwidth is granted by the BS to an SS as an aggregate of grants in response to each connection requests from the SS.

## III. Research Issues on the MIMO Based Rate Adaptation Algorithms

Limited frequency bandwidth and multipath fading have long been problems to wireless communication. Larger bandwidth can provide higher data transmission rates while multipath fading over the air channel causes signal quality degradation and hence lower the overall achievable throughput. To mitigate the signal quality degradation issue, increasing transmitted power level may be needed. However, the transmitted power is regulated and it has to comply with various standards in different countries. Therefore, the data transmission rates cannot be increased easily by that approach. With the advancement of wireless communication technology, the emerging

Multiple-Input-Multiple-Output (MIMO) technology provides a promising solution to improve the data transmission rates. This section discusses various research issues on MIMO-based rate adaptation algorithms.

### *A. Physical Layer Enhancement by MIMO: Spatial Diversity vs Spatial Multiplexing*

It has been a hot research topic in the field of wireless communication since the first literature on MIMO was released around twenty years ago. Hundreds of papers were published regarding different aspects of MIMO such as coding schemes and performance analysis. However, it was not until last two to three years did the MIMO-based routers appear in the consumer market. MIMO systems exploit spatial diversity by using multiple antennas at the transmitter side or the receiver side of the communication link. The multipath property of wireless signals transmission becomes an important basis in constructing theories of MIMO. The WiMAX standard has specified the adoption of MIMO techniques as an optional feature for WiMAX systems where at most four antennas are supported at a WiMAX device. The gain in spatial diversity provided by the MIMO technique improves the robustness to channel fading and hence WiMAX BSs and SSs can communicate in higher data rates as compared with a WiMAX system using a single antenna only.

In a MIMO-based WiMAX system, each antenna can be treated as one spatial stream basically. A higher level MCS requires higher SNR to maintain a small Bit Error Rate (BER). MIMO supports two modes of operation: spatial diversity for better signal quality and spatial multiplexing for higher throughput. These two MIMO modes can be configured by sending data over variable number of spatial streams. Since each WiMAX device supports up to four antennas, when the number of spatial streams is fewer than the number of transmit antennas, the remaining antennas can be exploited for diversity gain.

In general, Space Time Code (STC) is the technique to exploit spatial diversity. It consists of a set of coding algorithms which adjust and optimize the joint encoding across the transmit antennas aiming at increasing the reliability of a wireless link. Alamouti [3] proposed Space Time Block Code (STBC) which can be implemented in the DL of the WiMAX systems with 2x1 or 2x2 transmit-receive antennas at rate 1. STBC can be used in low delay spread environment and it enhances PER performance. STBC was later generalized to support arbitrary number of transmit antennas. Research has been conducting in the MIMO coding algorithms over the years. For example, Space Time Trellis codes (STTC) is another STC developed with improvements in coding, diversity gain and BER. The complexity of STTC lies on the non-linear decoding procedure at the receiver where a Viterbi decoder is used. This contrasts to the linear Maximum Likelihood (ML) scheme for the decoding of STBC.

Spatial multiplexing (SM) is the technique for increasing throughput at a given SNR of a wireless channel. The WiMAX BS transmits independent data streams from each transmit antenna to SSs. Source data streams are multiplexed into N transmit antennas and they are sent to the WiMAX SSs with N receive antennas resulting a rate of N times higher. The Bell Labs Layered Space-Time (BLAST) scheme such as V-BLAST or D-BLAST sends parallel symbols streams from the transmitter to the receiver. The main disadvantage with SM schemes is that the channel has to be in good condition with high SNR. The decoding procedure at the WiMAX SS is simple and all the received signals can be recombined linearly such as by ML, Zero Forcing (ZF) or Minimum Mean Square Error (MMSE) methods.

A WiMAX BS can either use all its antennas to exploit spatial diversity or spatial diversity. [4] shows that it may not be an optimal case in terms of maximizing throughput if a WLAN system, which has more than two antennas, operates at the two extremes. [4] proposes a hybrid 4x4 scheme which combined spatial diversity and spatial multiplexing to provide both increased throughput and diversity to the system. Those papers give insight to the design of rate adaptation algorithms in the PHY layer. The WiMAX standard only specifies MIMO feedback messages framework and it does not define the exact implementation of different spatial diversity or spatial multiplexing techniques.

Research issues such as MIMO encoding and decoding using information theory, beamforming and channel capacity analysis are still carrying on in this vibrant and active research area. Advances in either of these aspects definitely influence the design and the choice of MCS and rate adaptation algorithms in MAC layer.

### *B. Closed-loop and Open-loop Link Adaptations in WiMAX*

The availability of the channel state information (CSI) categorizes MIMO systems into two categories and it affects the performance of the rate adaptation algorithms. The WiMAX standard has defined a PMP frame structure for DL and UL of SSs. It supports both open-loop and closed-loop link adaptive feedback from SSs to the BS. The closed loop operation assumes perfect CSI is available at the transmitter, either through explicit feedback from the receiver using specific control frames or through channel sounding and calculation between the transmitter and the receiver. However, the computation complexity at the precoding matrix [5] and the communication overhead are large and thus difficult to implement.

In closed-loop rate adaptation designs, the MIMO PHY scheme maximizes the data rate for a target BER. It selects a subset of the transmit antennas and chooses the best constellation which can be supported on each of the selected antennas. The selected rate setting is then sent back from the receiver to the transmitter in the MAC design. In open-loop rate adaptation designs, there is no feedback from the receiver to the transmitter and hence the transmitter does not have channel knowledge. It uses the same MCS and the same TX power for each spatial stream for data transmission. However, open-loop multi-antenna approach is easier in implementation, at an expense of the potential channel capacity utilization.

Research papers published specifically for WiMAX systems in this aspect has been extremely rare. It may be due to the absence of a suitable WiMAX simulator for the evaluation of the research in this area. [5] and [6] focus on the theoretical analysis on the closed-loop feedback and limited feedback mechanism in non-WiMAX context. It is expected that there will be more research work to be done in this area upon the availability of suitable simulation tools. The research trend in this area has been going to derive rate adaptation algorithms with limited channel feedback as suboptimal solutions to closed-loop feedback adaptation.

### *C. Channel Quality Measurement and Channel Characterization*

The WiMAX standard has provided a framework for BSs and SSs to obtain signal quality statistics during their communications. It has defined fields for the Received Signal Strength Indication (RSSI) and Carrier to Interference-plus-Noise Ratio (CINR) in the feedback response message body. The RSSI and CINR statistics, which are mandatory but vendor-specific in implementation, can aid BS assignment and burst adaptive profile selection. SSs can obtain RSSI measurement statistics from the OFDM DL preambles and then SSs shall report the updated mean and the standard deviation of the RSSI and CINR, in units of dBm and dB respectively, back to the BS via REP-RSP messages. With the RSSI and CINR statistics, the antenna at the BS can evaluate the channel quality and determine the transmission rate to be used in the DL to SSs.

There is little research in this area. Practically there is no paper released on rate adaptation algorithms using RSSI and CINR statistics in WiMAX systems. It may be due to the fact that there is no commercial product released to the consumer market and individual researchers could not evaluate the performance of their algorithms. Research on this area is limited to companies which develop WiMAX products.

An accurate channel model which captures the characteristics of the propagation environment allows the transmitter at the BS or SSs to have a better knowledge on the channel condition. It also helps in the channel capacity analysis and the design of MIMO coding techniques and rate adaptation algorithms which match the channel statistics. It remains an active and open research area on how to use the statistical data and characterize the MIMO channel so as to facilitate the choice of spatial multiplexing or spatial diversity techniques. [7] points out that most papers on the topic of MIMO use a statistical channel model which is an idealized abstraction of spatial propagation characteristics and assumes independent and identically distributed (i.i.d.) fading between different transmit-receive antenna pairs. The use of an idealized channel model helps in STC design since it is tractable in capacity analysis. However, the realistic capacity of MIMO channels can be substantially lower as the channel coefficients between different transmit-receive antenna pairs exhibit correlation due to clustered scattering in realistic environments. Parametric physical models, which explicitly model signals arriving from different directions, are another heuristic in the channel modeling research. Nevertheless, the physical channel parameters, such as angles of signals direction, introduce nonlinear dependence on the models and it increases the difficulty to calculate the channel capacity and to design STC.

Research in this topic aims at characterizing a channel accurately while preserving linear properties in the parameters of the models for analysis. [7] and [8] propose a virtual representation of MIMO fading channel by introducing pairwise-error probability (PEP), rank and eigenvalue characterization. It is expected such characterization could provide simpler parameters set to the upper layer and hence provide clues to rate adaptation algorithms in cross layer design.

## IV. A Practical Rate Adaptation Simulation Model for MIMO-based WiMAX Systems

In this section, we present our WiMAX rate adaptation simulation model and evaluate the results on the MIMO-based WiMAX PHY layer. Research on WiMAX PHY and MAC layers has been conducted for many years. However, focus of most published work has been given to either PHY enhancement without MIMO or MAC layer quality of service (QoS). Some research used OPNET to carry out WiMAX simulation but the simulation model does not take MIMO technique into account. Nevertheless, corporations, such as Intel and Nokia...etc, are actively engaged in development and deployment of MIMO-based WiMAX systems. The WiBro network in Korea is one of the examples. It is expected rate adaptation algorithms could be evaluated more easily upon the availability of commercial products.

### *A. Simulation Model Structure and Features*

We propose a MIMO-based WiMAX simulation model on the PHY layer based on the work of [9] on MIMO channel characterization and it could be used to evaluate rate adaptation algorithms in WiMAX for practical simulations. Fig. 1 shows the structure of our proposed simulation framework. The PHY model adopts the WirelessMAN-OFDM air interface specification. It is based on OFDM-256 modulation and designed for NLOS application. In OFDM-256, waveform is composed of 256 orthogonal carriers and so selective fading can be confined to a number of carriers which can be equalized easily. With the use of OFDM symbol time and a cyclic prefix, the inter-symbol interference (ISI) problems and the adaptive equalization problems can be handled.

Adaptive modulation allows a WiMAX system to adopt different MCS depending on the signal to noise ratio (SNR) of the radio link. Our simulation model is capable to perform Binary phase shift keying (BPSK), quaternary phase shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM) and 64-QAM which comply to the four mandatory modulation coding schemes specified in the WiMAX standard for uplink (DL) and downlink (DL) connections. Fig. 2 depicts the detailed structure of our simulation model on PHY layer at the transmitter side.

Table I shows the supported rate combinations with the RS-CC rates in the simulator. The WiMAX standard does not

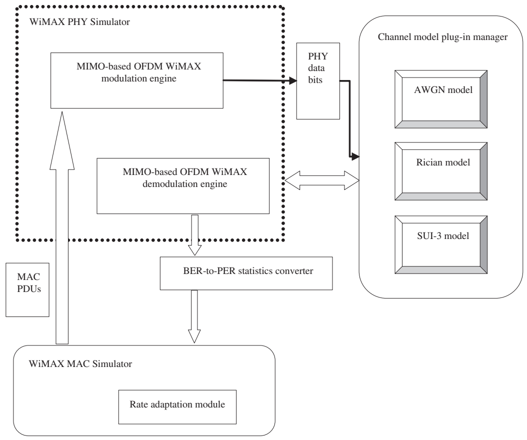


Fig. 1. Structure of the simulation framework

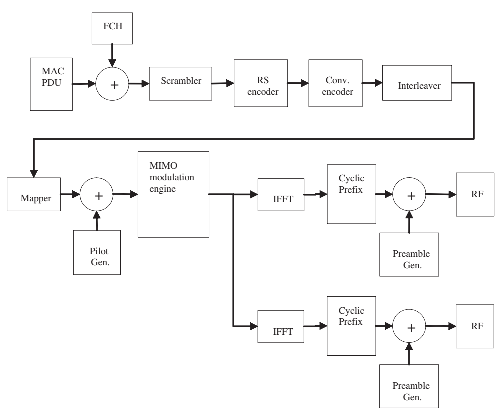


Fig. 2. Detailed structure of the simulation framework on PHY Tx side

TABLE I
RATE COMBINATIONS

| $RateID$ | $ModulationRS-CCrate$ |
|---|---|
| 0 | $BPSK1/2$ |
| 1 | $QPSK1/2$ |
| 2 | $QPSK3/4$ |
| 3 | $16-QAM1/2$ |
| 4 | $16-QAM3/4$ |
| 5 | $64-QAM2/3$ |
| 6 | $64-QAM3/4$ |

specify a channel modeling for practical simulation. It is up to researchers to decide which channel model to be adopted for their simulations. Our simulation model, with a plug-in interface, supports additive white Gaussian Noise (AWGN) channel model and Rician fading channel model. The support of SUI-3 channel will be left as future work.

### B. Simulation Results

As discussed in section III, there are various aspects of research issues which have to be considered in deriving rate adaptation algorithms. For example, methods such as Frobenius norm can be used to characterize a channel and its capacity at a given SNR. [9] proposes another method based on the Euclidean distance calculations to characterize the channel H with the use of the Demmel condition number. The paper proposes a fixed rate adaptation where the spatial modulation scheme is varied between the Alamouti MIMO diversity scheme with 16-QAM modulation and spatial multiplexing with 4-QAM transmit constellations. We have, based on the idea of using the Demmel condition number proposed in [9], extended and built our WiMAX PHY simulator. Three groups of channel matrix H which captures the essence of different channel conditions are simulated using the MCSs defined by the IEEE 802.16e standard with MIMO technology incorporated into the simulation. Alamouti STBC is used for spatial diversity while V-BLAST is used for spatial multiplexing as the MIMO technique.

### C. Discussion

In each figure, under the same MIMO technique, a higher MCS will shift the BER-eSNR curve to the right. This agrees to the fact that under a given target BER, a higher MCS would require higher SNR to achieve the same performance. Fig. 3 shows the simulation result where $\text{cond}_D(\text{H})=1$. The value is small and it implies the channel coefficients in the channel matrix H are more independent to each other. Either STBC or SM schemes results in similar BER. Therefore, spatial multiplexing shall be adopted in such case since the data rate can be boosted up. Fig. 4 and 5 show the simulation results where the $\text{cond}_D(\text{H})$ values become larger and larger (5 and 20). It is worthwhile to note that as the value goes higher,

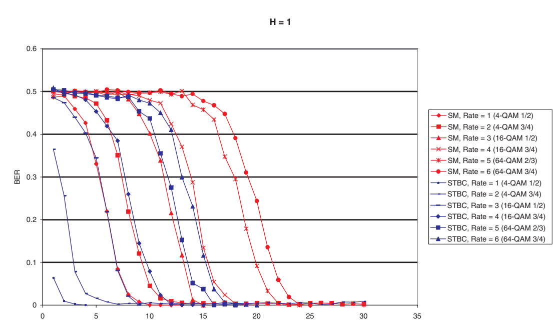


Fig. 3. $\text{cond}_D(\text{H})=1$

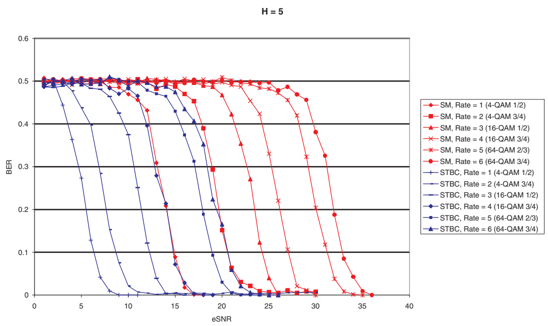


Fig. 4. $\text{cond}_D$(H)=5

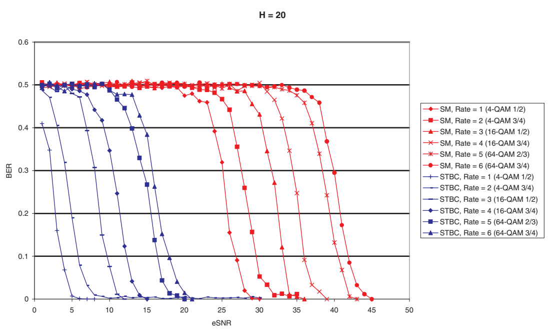


Fig. 5. $\text{cond}_D$(H)=20

the set of STBC curves and the set of SM curves start to separate from each other. The set of STBC curves goes to left while the set of SM curves goes to right. This suggests an observation that when the eSNR is high, SM with a higher MCS shall be adopted and when the eSNR is low, it is better to be more conservative to stay with the STBC scheme. A general observation is to use spatial multiplexing for achieving higher data throughput at high SNR regions as long as the packet error rates (PER) are small. When the channel quality is detected to be poorer, data transmission should be switched to exploit spatial diversity so that the transmission reliability can be increased at low SNR regions.

With the BER-eSNR data, the PER data can be output from the BER-PER converter using techniques proposed in [10]. An abstract PHY model can be built so that data is passed into the MAC layer simulator. In terms of practical rate adaptation algorithms, the complexity of the parameters passing from the PHY layer into the MAC layer should be small so that the computation in the WiMAX systems hardware is affordable without performance depreciation. Our simulation model makes use of the Demmel condition number to capture the channel characteristic and it satisfies such requirement.

From the simulation results, we may select some effective SNR thresholds to switch between different MCSs and MIMO coding techniques under different $\text{cond}_D$(H) values in the WiMAX PMP mode. The MAC layer of WiMAX adopts a request-grant approach and the rate information is defined in the Uplink Channel Descriptor (UCD) burst profile and the Downlink Channel Descriptor (DCD) burst profile. The exact MCS is specified inside the FEC code type field of the profiles. Rate adaptation algorithms in MAC layer simulator can be implemented based on the recently released WiMAX MAC layer in ns-2. In this paper, focus has been given on the WiMAX PHY research issues, MAC layer analysis will be left as future work. The direction can be on deriving a credit-based algorithm with reference to the RSSI statistics and the channel feedback data from the PHY layer. These algorithms, together with QoS research topics, can be evaluated thoroughly by using our proposed WiMAX PHY simulation model.

## V. Conclusion

In this paper, we have given a comprehensive overview on the IEEE 802.16e PHY and the MAC layers. We have also discussed the various research issues in deriving rate adaptation algorithms with the incorporation of the MIMO techniques. The major contribution in this paper is that we have demonstrated a practical simulation model for evaluating IEEE 802.16e rate adaptation algorithms with Alamouti STBC and V-BLAST as the MIMO techniques at the WiMAX PHY layer. Our model has made use of the Demmel condition values to address the channel characterization issue and has the advantage of reduced parameters set passed to the WiMAX MAC layer for practical and representative simulation.

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