A Link Adaptation Algorithm in MIMO-based WiMAX systems

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Abstract— **In order to extend the coverage of wireless communication to metropolitan scale, the Worldwide Interoperability for Microwave Access (WiMAX) standard was developed and ratified as the IEEE 802.16d standard in June 2004. The standard defines an adaptive modulation framework which allows a WiMAX system to communicate with various burst profiles according to the link quality. The selection mechanism of a suitable burst profile is left open for research. In this paper, we devised a novel link adaptation algorithm with dynamic threshold probing based on an extension of our previous work on a MIMO-based WiMAX systems simulation framework. Our algorithm was capable of quickly adapting to channel conditions using PHY layer metrics and MAC layer statistics. Evaluation showed that our algorithm could achieve high system throughput while minimizing the packet drop rate significantly.**

Index Terms— **WiMAX, link adaptation, MIMO, algorithm, cross-layer design**

I. INTRODUCTION

The Worldwide Interoperability for Microwave Access (WiMAX) standard was developed and ratified as the IEEE 802.16d [1] standard in June 2004. Enhancements were made to the standard on mobility support and it was officially approved as the IEEE 802.16e [2] standard in December 2005. With the advancement of antenna technology in recent years, the emerging Multiple-Input-Multiple-Output (MIMO) technology provides a promising solution to improve the robustness of data transmission while not sacrificing the transmission rates by exploiting spatial diversity. Space Time Code (STC) can be used to achieve higher resistance to interference so that the same modulation scheme can be used at lower SNR while Spatial Multiplexing (SM) can be used to achieve higher throughput by transmitting different streams of data in different antennas simultaneously. Forward error correction (FEC) code can be added to the data to further improve the robustness of transmission. In order to decide which modulation scheme to be adopted in the system during transmission, a number of link adaptation algorithms are devised to improve the performance of wireless systems.

Link adaptation plays a central role in regulating the utilization of the radio resources. There are three possible physical approaches to adapt to the varying link condition:

- Power adaptation: Higher transmit power could improve data reception at the receiver. However, high transmit power may lead to interference to other communication systems nearby when the network topology is considered. Algorithms in this category concern the best utilization of radio resources by regulating the transmit power at the transmitter. Higher power may be allocated for transmission under poor link condition.
- Frequencies adaptation: Noise and signal fading to the link is frequency-selective. Some wireless networks such as the IEEE 802.11a WLAN standard adopts the frequency-hopping spread spectrum mechanism. Algorithms in this category such as [3] use this method to switch between different frequency ranges.
- Modulation rate adaptation: Modulation coding schemes (MCSs) perform differently under various link conditions. For example, the binary phase shift keying (BPSK) works well in poor link condition while 64-quadrature amplitude modulation (64QAM) does not. 64QAM provides higher bandwidth efficiency than BPSK and it results in higher throughput to the system. When the link condition is poor, bandwidth efficiency is sacrificed for robust communication between the transmitter and the receiver.

Different MCSs and messages formats are specified in

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the WiMAX standard for the systems to deliver broadband service. However, the policy on how and which modulation scheme should be used under various link conditions are not specified. There is a wide research space to develop and evaluate different link adaptation algorithms for enhancing the performance of the WiMAX systems. In this paper, we will devise a link adaptation algorithm and analyze its performance at the MAC layer. The simulation is based on our extended work [4] in constructing a MIMO-based WiMAX simulation environment using well-known existing simulation tools. This paper is organized as follows: Section II gives a discussion on the related work. Section III devises a link adaptation algorithm for the MIMO-based WiMAX systems. Section IV gives an overview of our previous work in the PHY layer simulation framework and describes our new extension in the MAC layer for the performance evaluation of our algorithm. Section V presents and analyzes the simulation results. Lastly, section VI concludes this paper.

II. Related Work

Various design philosophies on the types of MIMO adaptive coding schemes are discussed in [5] and [6]. In particular, the majority of link adaptation algorithms in the WiMAX systems adopts a signal measurement based approach. [7] proposed a simple link adaptation algorithm which performed a fixed SNR threshold table lookup process to determine the suitable modulation rates in the WirelessMAN-SC air interface. The simulation was done using OPNET and MIMO model was not considered. The algorithm was based on the analysis of the Type 1 channel model with the DOCSIS MAC layer. [8] worked on the link adaptation algorithm in MIMO-based WiMAX systems. The paper was based on a simulation of the Alamouti's STC (Matrix A) and SM (Matrix B) models with the ITU pedestrian channel A model. However, the performance simulation at the MAC layer was not studied and the thresholds for the modulation rates selection were fixed. It may not be able to adapt to the varying channel condition in reality. [9] proposed a link adaptation algorithm for the SISO 802.16d systems. The algorithm adopts a sliding window approach to estimate the CINR values. The performance analysis was focused to the value of its sliding window size. Different modulation schemes were not considered and the performance analysis on the PHY and MAC layers were not studied. [10] worked on the performance evaluation of a MIMO-OFDM PHY layer in an outdoor environment. It proposed a SNR table lookup method with an additional dimension which considers the determinant of the channel matrix function $det(H(f)H(f)^H)$ [11] for switching between the STBC and the SM MIMO mode. However, the simulation is not WiMAX systems specific.

III. The Proposed Link Adaptation Algorithm

Based on the constructed simulation framework at the PHY layer in [4], a number of BER-SNR graphs at some of the different Demmel condition number values in a

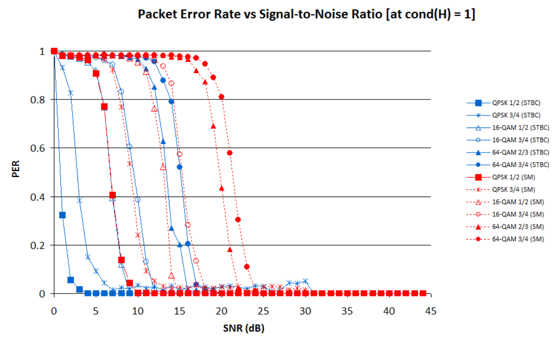

Figure 1. PER-SNR graph at the $\text{cond}_D(H)$=1

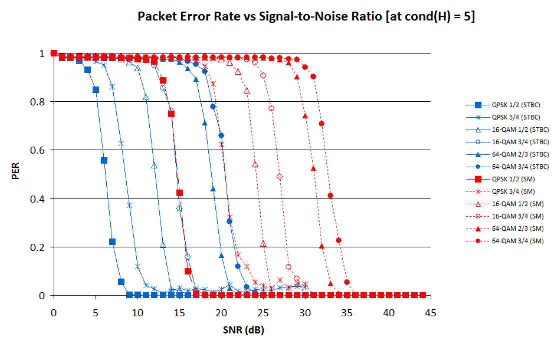

Figure 2. PER-SNR graph at the $\text{cond}_D(H)$=5

2x2 MIMO-based WiMAX systems were generated. The PER-SNR tables are obtained based on the BER to PER conversion process in [12]. Fig. 1 to Fig. 3 show the resulting PER-SNR graphs for the Demmel condition numbers 1, 5 and 15 respectively. Several observations are made from the simulation results:

1) For each of the figures, a higher MCS will shift the PER-SNR curve to the right under the same MIMO technique. This agrees to the fact that under a given target PER, a higher MCS would require higher SNR to achieve the same performance. Fig. 1 shows the simulation result where cond_D(H)=1. The condition number 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 PER. Therefore, spatial

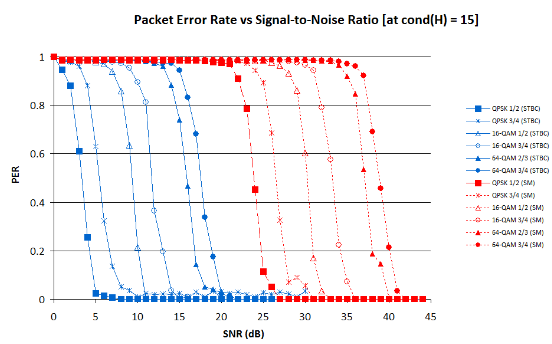

Figure 3. PER-SNR graph at the $\text{cond}_D(H)$=15

multiplexing shall be adopted to boost up the data rate.

2) Fig. 1 to Fig. 3 show the simulation results where the cond_D(H) values increase. The set of STBC curves and the set of SM curves start to separate from each other when the condition number increases. The set of STBC curves goes towards the left while the set of SM curves goes towards the right. This suggests an observation that when the SNR is high, SM with a higher MCS shall be adopted and when the SNR is low, it is better to be more conservative to stay with the STBC scheme. A general observation is to use SM scheme 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 worse, data transmission should be switched to exploit spatial diversity so that the transmission reliability can be increased at low SNR regions.

3) For a fixed MCS across different condition numbers, the set of SM PER-SNR curves moves towards the right as the condition value increases while the set of STBC PER-SNR curves does not show such obvious trend. This shows that SM scheme is more sensitive to SNR variation than the STBC scheme. It agrees to the fact that STBC scheme exploits spatial diversity by making use of the multipath property of signal propagation which results in the BER performance enhancement in multiple antenna systems. On the other hand, the BER performance of the SM scheme is easily affected by the channel condition and the correlation of the spatial streams. If the spatial streams are highly correlated, which is indicated by a high condition number, a much higher SNR is required to maintain a given BER performance for a particular MCS.

With these observations, a dynamic threshold link adaptation (DTLA) algorithm is devised. The algorithm is designed for the SS DL. The UL is assumed to be error free where the most robust burst profile, BPSK 1/2 is adopted in the UL so that the MAC management messages can be transmitted to the base station (BS). Close-loop feedback with perfect CSI knowledge is not required at the SS and BS. However, partial channel knowledge on the channel matrix is required for the estimation of the Demmel condition number at the SS. The WiMAX specification does not mandate the implementation of ARQ at the MAC layer and it is optional in the WirelessMAN-OFDM air interface. Under such circumstance, the MAC layer will rely on the cyclic redundancy check (CRC) to determine if a packet is corrupted and let the upper layers to handle the retransmission of a packet.

The selection of a DL burst profile is basically based on the simulated SNR thresholds in the PHY layer with a dynamic probing mechanism to cope with different channel conditions. Since the PHY simulation results suggest the need to have an extra dimension other than the SNR to determine the switching between the STBC scheme and the SM scheme. The DTLA algorithm maintains five bins corresponding to the five Demmel condition numbers, 1, 5, 10, 15 and 20, for each MCS. The Demmel condition number is used to assist the estimation of the correlation of the spatial streams. If the Demmel condition number is large, the spatial streams are more correlated and a higher SNR is required for the SM scheme to work. The pseudo-code of the DTLA algorithm is provided in the Appendix of this paper. The DTLA algorithm consists of four main phases: update statistics, update thresholds, pick a MCS and adjust the choice according to the channel condition.

Phase 1 - update statistics The algorithm maintains statistics such as the number of corrupted packets, successive corrupted packets and successfully received packets for each condition number bin at each MCS. The estimated SNR and the measured Demmel condition number are also maintained over bursts. The SNR is updated by averaging the current SNR with previous values according to the equation:

$$SNR_{est} = (1-\alpha) * SNR_{est} + \alpha * SNR_{cur}, where \alpha = [0,1] \quad (1)$$

Phase 2 - update thresholds Two types of thresholds are introduced in the algorithm: the burst profile enter threshold (BPET) and the burst profile probe threshold (BPPT).

1) The burst profile enter threshold (BPET): Each MCS maintains a BPET which is the initial SNR at which the MCS is feasible to be used. A MCS which has a lower BPET value than the current estimated SNR of the system will become a candidate for rate selection. The selection rules is based on the collected statistics such as the packet error rate and the bit-rate of the MCS.

2) The burst profile probe threshold (BPPT): The BPPT is used in probing unused MCSs for possible improvement at channel steady state. The BPPT is always set not higher than the BPET since if the MCS works at a particular BPET, the MCS shall work under all SNRs higher than the BPET. The BPPT will initially be set at 3 dB lower than the BPET so that it will not overlap with the MCS at a less efficient FEC code-rate.

The BPET and the BPPT for each bin are dynamically updated according to various rules. Fig. 4 shows the state diagram for the BPET update at a Demmel condition number bin. The BPET of the currently using MCS is updated to the estimated SNR, SNR_{est}, only if SNR_{est} falls below SNR_{BPET} and the packet is successfully received because this shows that the MCS can be used at a lower SNR. The BPET is increased linearly by 2 dB if the received packet is corrupted and SNR_{est} is above the BPET of the currently using MCS because this shows that the MCS may not work well at the BPET.

Fig. 5 shows the state diagram for the update of the BPPT. The BPPT will be increased by 1 dB with a probability at the measured PER only if the packet is corrupted and the SNR_{est} is between the BPET and the BPPT of that burst profile. The BPPT is updated to (SNR_{est} - 3) dB if the SNR_{est} is smaller than the BPET and the packet is received successfully.

Phase 3 - pick a MCS A MCS where $\text{SNR}_{est} >$ SNR_{BPET} becomes a candidate. The order of MCSs is obtained from the simulation results in the PHY layer.

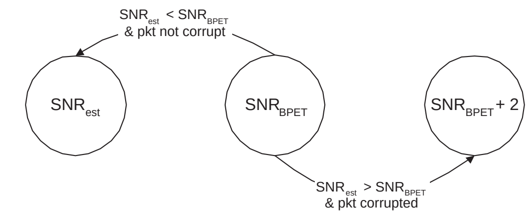

Figure 4. State diagram of BPET update

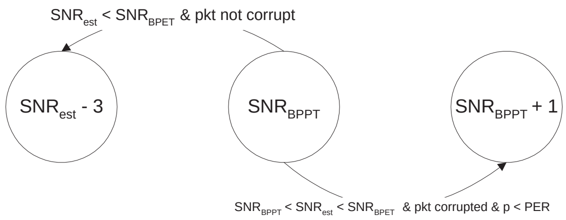

Figure 5. State diagram of BPPT update

Table I shows the rates order adopted in the algorithm. The algorithm first starts with one rate higher than the current rate and goes through all rates where SNR$_{est}$ > SNR$_{BPET}$ at the measured condH$_{est}$ bin. If the MCS has been failing to receive 5 consecutive packets or the Demmel condition number is increasing over the past few samples with decreasing SNR, the MCS is not selected. If a MCS has satisfied the criteria, the number of condition number bins which satisfied SNR$_{est}$ > SNR$_{BPET}$ will be counted and the MCS which has the most number of satisfied bins will be chosen as the best MCS. If there is no suitable MCS above the current rate, the rate which is one Rate ID lower until the slowest rate will be considered.

Phase 4 - adjustment If the choice of the MCS is lower than the current receive rate, the choice may further be adjusted. If the Demmel condition number is increasing across the condition number bins with a decreasing SNR$_{est}$, the MCS which is one rate ID lower will be

TABLE I.
RATES ORDER

Rate ID	*MCS*	*FEC code rate*	*MIMO mode*
0	$QPSK$	1/2	$STBC$
1	$QPSK$	2/3	$STBC$
2	$QPSK$	1/2	SM
3	16QAM	1/2	$STBC$
4	$QPSK$	3/4	SM
5	16QAM	3/4	$STBC$
6	16QAM	1/2	SM
7	64QAM	2/3	$STBC$
8	64QAM	3/4	$STBC$
9	16QAM	3/4	SM
10	64QAM	2/3	SM
11	64QAM	3/4	SM

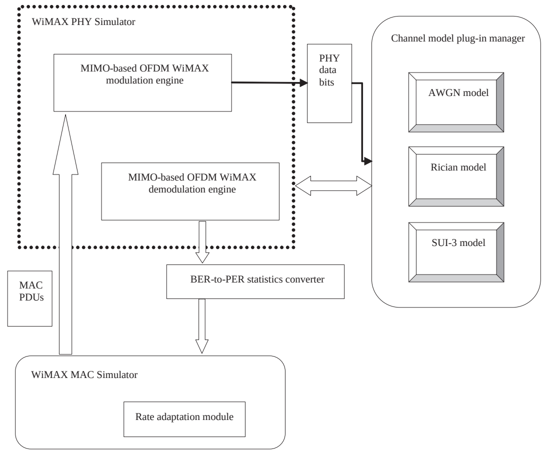

Figure 6. Structure of the simulation framework

selected instead. Otherwise, the chosen MCS will be sent to the BS via DBPC-REQ if it is not the same as the current rate.

IV. Simulation model design

Since the introduction of MIMO technology to the WiMAX systems, it raises an issue on how to select the best combination of antennas which could maximize the data transmission rates. This leads to the research topics in cross layer optimization where the MAC layer design has to take the PHY layer parameters into account. The evaluation methodology would be a combination of the signaling level simulation in the PHY layer and the protocol level simulation in the MAC layer. However, the absence of a suitable WiMAX simulator leads to little evaluation of the research in this area. Some researchers used OPNET to carry out WiMAX simulation, but the simulation model does not take MIMO techniques into account. In our previous work [4], a WiMAX link adaptation simulation framework was constructed. Fig. 6 shows the structure of the simulation framework. The PHY model adopted the WirelessMAN-OFDM air interface specification. It was based on OFDM-256 modulation designed for NLOS application. The MIMO model was constructed based on the work of [13] which used the Demmel condition number to characterize the channel matrix. A group of channel matrix H which captured the essence of different channel conditions were simulated using the MCSs defined by the IEEE 802.16e standard with the MIMO technology incorporated into the simulation. Alamouti STBC was used for spatial diversity while V-BLAST was used at the receiver for spatial multiplexing as the MIMO technique.

To evaluate the performance of our proposed algorithm, we continued our previous work on the simulation framework and the WiMAX MAC layer module is extended based on the "IEEE 802.16 module for NS-2" [14]. The module is released by the Information Technology Laboratory, Advance Network Technologies Division of the National Institute of Standards and Technology. We

TABLE II.
SIMULATION SETTINGS

Simulation Parameters	Settings
$System\ configuration$	2x2 $MIMO$
$Channel\ model$	$SUI-3\ (NLOS)$
$BS\ Tx\ Power$	45 dBm
$Carrier\ frequencies$	3.486 GHz
$Sampling\ frequency$	12500 Hz
$Shadow\ fading$	$Enabled$
$Initial\ distance$	200 m
$Final\ distance$	900 m
$Simulation\ start\ time$	5 s
$Simulation\ duration$	70 s
$PDU\ size$	1400 $bytes$
$Data\ sub-carriers$	192 $per\ symbol$
$Cyclic\ prefix$	0.0625
α	0.8

have extended the MAC module to support adaptive burst profiling. MAC layer management messages such as the Downlink Burst Profile Change Request (DBPC-REQ) and the Downlink Burst Profile Change Response (DBPC-RSP) messages are added into the WiMAX module. The transition of downlink burst profiles can be performed by specifying the downlink interval usage code (DIUC) number. Focus will be given to the link adaptation algorithm in this paper and only the key component which interfaces the PHY model with the MAC module is discussed below. The details of the simulation framework can be found in [15].

A module named PERManager is developed to give the WiMAX MAC module intelligence to determine whether a packet is corrupted according to the simulated PHY parameters such as the packet error rate (PER), the Demmel condition number of the channel matrix, SNR and MIMO mode obtained in the PHY layer simulation. The PERManager imports the PER-SNR tables for various MCSs and MIMO modes under different Demmel condition numbers. The PERManager is capable of synchronizing with the emulated clock in ns-2 and emulating a varying channel condition according to the channel variation generator. Channel variation generator is a sub-module of the PERManager module which provides a series of SNR and the Demmel condition numbers over time for the PERManager module to determine whether a packet should have been dropped as a result of high PER. Fig. 7 shows the flow diagram when a packet is received at an subscriber station (SS).

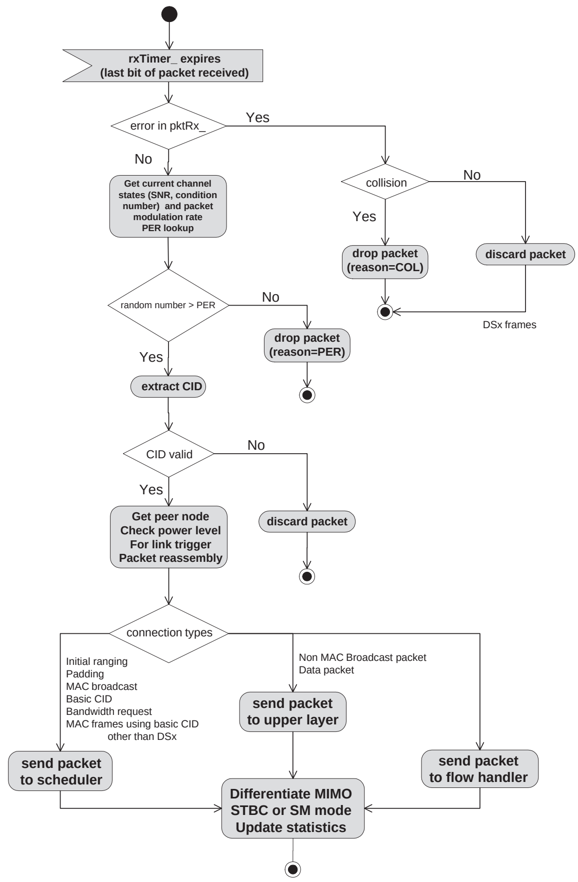

Figure 7. Received packet processing

V. SIMULATION RESULTS AND DISCUSSION

The simulation is based on the setting where the cell has 1 SS connecting to a BS. The DL performance from the BS to the SS is simulated. Table II shows the parameters of the simulation.

Fig. 8 shows the peak data rates of all the MCSs in the simulation. It can be observed that the throughputs of all the MCSs agree with the theoretical spectral efficiency of the MCSs (Fig. 9). The ratios between the maximum throughput of the MCSs match with the ratios of the theoretical spectral efficiency across the MCSs. In SISO system, a less robust MCS will have a higher spectral efficiency. However, in a 2x2 MIMO system, SM scheme will achieve double the efficiency for a given MCS. When forward error correction (FEC) code is combined with the modulation, the spectral efficiency will further be multiplied by the FEC code rate. From the figure, the throughput of some MCSs are the same. This provides clues to the design of the link adaptation algorithm. For example, QPSK 1/2 in SM mode and 16QAM 1/2 in STBC mode have the same spectral efficiency. It implies that 16QAM 1/2 in STBC mode should be chosen instead of the QPSK 1/2 in SM mode since the STBC scheme can work at a lower SNR than the SM scheme.

Fig. 10 shows the trace profile of UDP throughput over time with several LA algorithms. Initially, the SS and the BS are 200 m apart and the station is moved 100 m away from the BS every 10 s. The DTLA algorithm is compared with the static table lookup algorithms 1 and 2 with thresholds set according to our PHY simulation results and Table III which is from the WiMAX specification respectively. From the figure, it can be observed that algorithm 2 achieves the lowest throughput. This shows the limitation of the static table lookup algorithm design.

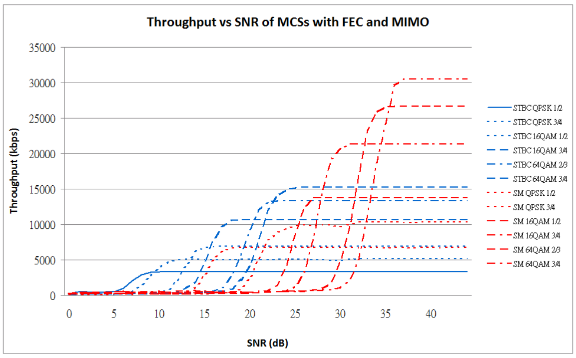

Figure 8. Peak data rates of MCSs

MCS	Efficiency (bit/s/Hz)	FEC code rate	MIMO mode	Resultant Spectral Efficiency (bit/s/Hz)
QPSK	2	1/2	STBC	1
QPSK	2	1/2	SM	2
QPSK	2	3/4	STBC	1.5
QPSK	2	3/4	SM	3
16QAM	4	1/2	STBC	2
16QAM	4	1/2	SM	4
16QAM	4	3/4	STBC	3
16QAM	4	3/4	SM	6
64QAM	6	2/3	STBC	4
64QAM	6	2/3	SM	8
64QAM	6	3/4	STBC	4.5
64QAM	6	3/4	SM	9

Figure 9. Spectral efficiency of MCSs

If the thresholds are set incorrectly, an unsuitable MCS may be selected which results in lower overall throughput or fluctuating throughput due to the high packets lost rate. Static table lookup algorithms may incorporate a number of simulated thresholds in different channel models and adapt to different models during operation. However, it is still an open research issue on how to switch between those models. At the start of the simulation, all algorithms are able to switch to an efficient MCS which provides high throughput at high SNR. At the 15^{th} second, SNR drops significantly. The DTLA algorithm and the static algorithm 1 can still respond to the change in the channel condition accordingly. The DTLA algorithm achieves higher throughput than the static algorithm 1 in low SNR region. The increase in throughput is achieved by selecting the most suitable MCS based on the statistical data to predict the channel condition dynamically.

TABLE III.
SNR ASSUMPTION OF THE STATIC TABLE LOOKUP ALGORITHM 2

MCS	$SNR\ Assumption\ (dB)$
$QPSK1/2$	9.4
$QPSK3/4$	11.2
$16QAM1/2$	16.4
$16QAM3/4$	18.2
$64QAM2/3$	22.7
$64QAM3/4$	24.4

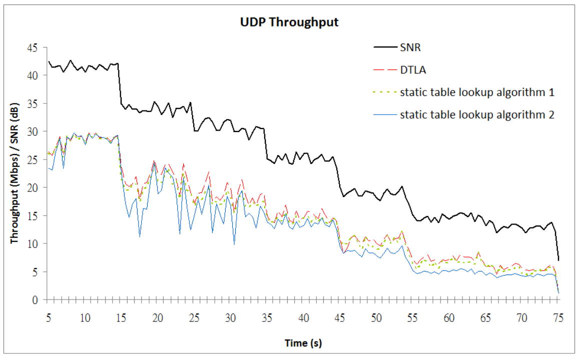

Figure 10. UDP Throughput Performance

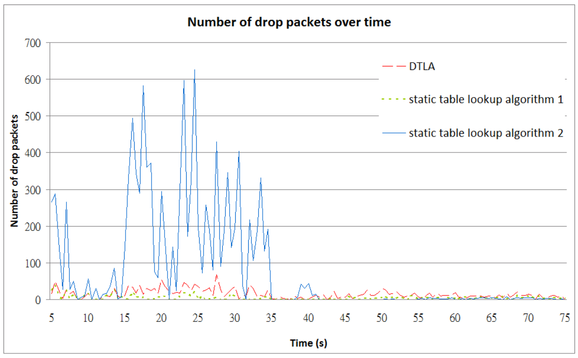

Figure 11. Number of drop packets over time

Fig. 11 shows the number of drop packets over time for the algorithms. From the figure, the static table lookup algorithm 2 has the highest packets drop rate. It is because of its static threshold nature which cannot responds to the correct channel condition. A high data rate MCS which is not suitable for the channel condition may be selected and results in the high packets drop rate. The static table lookup algorithm 1 drops the fewest packets on average. The DTLA algorithm achieves higher throughput than the algorithm 1 at an expense of slightly increasing the packets drop rate. The packets drop rate remains low in the two algorithms which are both below 5%.

Since the introduction of the MIMO technology, there is a research issue on how to characterize the channel and determine the switching between the STBC and SM schemes. Fig. 12 and Fig. 13 show the effect of different Demmel condition numbers on throughput. The algorithm 2 shows a more diverse throughput in different condition numbers at a particular SNR than the DTLA algorithm. It shows that the algorithm 2 does not take the condition number into account and only switches to SM mode in high SNR region. However, if the channel condition goes worse for the SM scheme, throughput drops sharply and hence results in the scattered distribution of throughput in the figure. The data points in Fig. 12 are more uniformly distributed as the DTLA algorithm takes the changes of condition numbers into account and select the best MIMO mode and MCS.

Fig. 14 to Fig. 16 are the probability mass function (pmf) of the MCSs. They show the distribution of rate

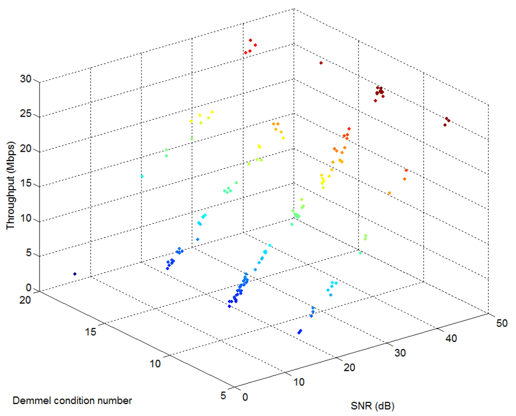

Figure 12. Effect of the condition number on throughput using the DTLA algorithm

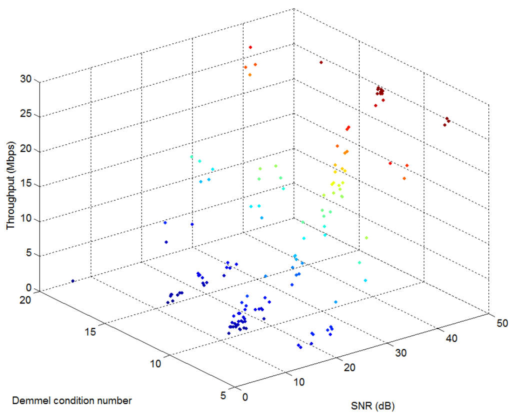

Figure 13. Effect of the condition number using the static table lookup algorithm 2

selection under different SNRs and condition numbers. In general, when the SNR is high, a higher order MCS will be selected because higher SNR makes high order MCSs, with higher throughput, feasible. The figures also reveal the effect of condition number on rate selection. At small condition numbers, there are more chances to adopt SM schemes which can bring additional throughput enhancement to the system. The DTLA algorithm has higher probability of selecting SM schemes such as Rate ID 9, 10 and 11, verifying its effectiveness to take advantage of that. At large condition numbers, which favour STBC, the probability of selecting those MCSs drops significantly. This is to be more conservative for the transient changes in the channel condition. Under such channel condition, the DTLA algorithm will at most select Rate ID 8, the highest order MCSs in STBC instead when the SNR is high.

VI. Conclusion

In this paper, we extend our previous work in constructing a simulation framework for the evaluation of link adaptation algorithms in MIMO-based WiMAX systems.

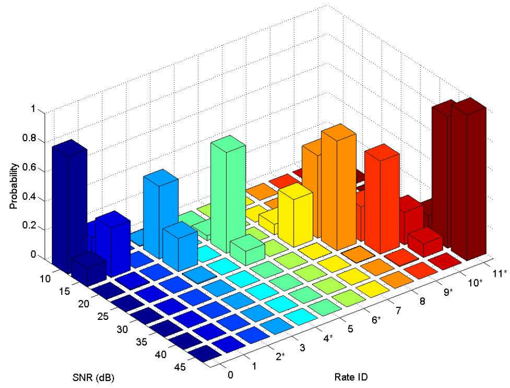

Figure 14. pmf of MCSs at $cond_D$(H)=5

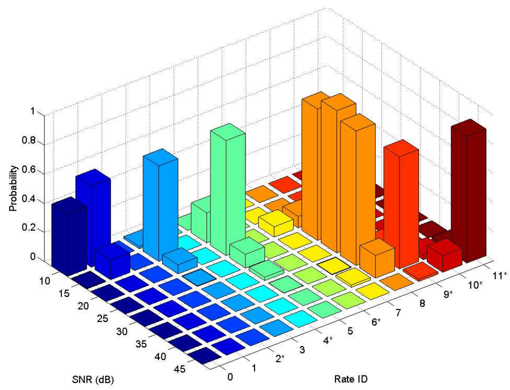

Figure 15. pmf of MCSs at $cond_D$(H)=15

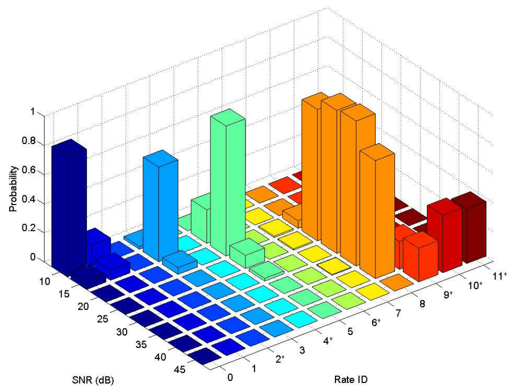

Figure 16. pmf of MCSs at $cond_D$(H)=20

The simulation framework is capable to simulate PHY signaling parameters with MIMO technology incorporated. It allows the PHY layer metrics to be passed into the MAC layer under practical simulation environment. The MAC layer module is extended using existing well-known simulation tools for facilitating research in the area. The PHY layer simulation results has shown the need of an extra dimension other than the SNR to consider the switching between the STBC scheme and the SM scheme.

In addition, cross layer design approach which combines both the signaling level simulation in the PHY layer and the protocol level simulation in the MAC layer are adopted to devise a link adaptation algorithm for the MIMO-based WiMAX systems. A number of SNR thresholds with different Demmel condition numbers are investigated. Compared with static table lookup link adaptation algorithms which study a particular channel condition, our dynamic threshold link adaptation (DTLA) algorithm is designed with a dynamic probing mechanism which adapts to different channel conditions. The simulation results has demonstrated the DTLA algorithm can achieve good performance. The algorithm has taken the correlation of the spatial streams in MIMO systems into consideration and it collects MAC layer statistics to assist burst profile selection at the downlink of the MIMO-based WiMAX stations. With the simulation framework and simulation results, it is expected that more work on the performance analysis in this research area could be carried out in the near future.

APPENDIX

The pseudo-code of the DTLA algorithm is provided in this section.

Algorithm 1 DTLA Algorithm

```
DTLA(int current_rate, bool corrupted):
update_stats(current_rate, corrupted);
best_MCS = pick_MCS(SNR_est,condH_est,current_rate);
if best_MCS < current_rate then
    int feasible_rate = best_MCS;
    int condH = H2bin(condH_est);
    int condH_inc = H2bin(condH_est+1);
    int num_valid = count the number of bins where SNR_est > SNR_BPET at rate best_MCS;
    if condH_est is increasing and condH_inc > condH and SNR_est is decreasing then
        for the first rate i lower than the best_MCS with the same MIMO mode do
            int nv = count the number of bins where SNR_est > SNR_BPET at rate i;
        if nv > num_valid then
            feasible_rate = i; num_valid = nv;
    if feasible_rate != best_MCS then
        best_MCS = feasible_rate;
if best_MCS != current_rate then
    send_dbpc_request(best_MCS);
```

```
H2bin(double h_val):
if h_val <= 1 then
    h_idx = 0;
else if h_val <= 5 then
    h_idx = 1;
else if h_val <= 10 then
    h_idx = 2;
else if h_val <= 15 then
    h_idx = 3;
else if h_val <= 20 then
    h_idx = 4;
return h_idx;
```

```
update_stats(int current_rate, bool corrupted):
store SNR_est and condH_est as past samples every 10 ms
update SNR_est; update condH_est;
int h = H2bin(condH_est);
stats[current_rate].total_packets[h]++;
if corrupted then
    stats[current_rate].successive_failures[h]++;
    stats[current_rate].corrupted_packets[h]++;
    updateThresholds(current_rate,h,SNR_est,corrupted);
    for all rate i higher than the current_rate do
        if SNR_est >= SNR_BPET[h] then
            updateThresholds(i,h,SNR_est,corrupted);
else
    stats[current_rate].successive_failures[h] = 0;
    stats[current_rate].last_rx[h] = NOW;
    updateThresholds(current_rate,h,SNR_est,!corrupted);
    for each rate i lower than the current_rate do
        if SNR_est >= SNR_BPET[h] then
            updateThresholds(i,h,SNR_est,!corrupted);
for all rates i do
    for all condition number bins j do
        if stats[i].last_rx[j] + 3 < NOW then
            stats[i].last_rx[j] = 0;
            stats[i].successive_failures[j] = 0;
            stats[i].total_packets[j] = 0;
            stats[i].corrupted_packets[j] = 0;
```

```
updateThresholds(int mod_rate, int h, double SNR_est, bool corrupted):
if corrupted then
    double PER = stats[mod_rate].corrupted_packets[h] / stats[mod_rate].total_packets[h];
    if rand()/rand_MAX < PER and SNR_est >= SNR_BPPT[h] and SNR_est < SNR_BPET[h] then
        SNR_BPPT[h]++;
        if SNR_BPPT[h] > SNR_BPET[h] then
            SNR_BPET[h] = SNR_BPPT[h]; SNR_BPPT[h] = SNR_BPET[h] - 3;
            stats[mod_rate].successive_failures[h] = 0;
            stats[mod_rate].corrupted_packets[h] = 0;
            stats[mod_rate].total_packets[h] = 0;
    if SNR_est >= SNR_BPET[h] then
        SNR_BPET[h] = SNR_BPET[h] + 2;
        stats[mod_rate].successive_failures[h] = 0;
        stats[mod_rate].corrupted_packets[h] = 0;
        stats[mod_rate].total_packets[h] = 0;
        SNR_BPPT[h] = SNR_BPET[h] - 3;
else
    if SNR_est < SNR_BPET[h] then
        SNR_BPPT[h] = SNR_est - 3;
        stats[mod_rate].successive_failures[h] = 0;
        stats[mod_rate].corrupted_packets[h] = 0;
        stats[mod_rate].total_packets[h] = 0;
```

```
pick_MCS(double SNR_est, double condH_est, int current_rate):
int feasible_rate = -1; int num_valid = 0;
condH = condH2bin(condH_est);
condH_inc = condH2bin(condH_est + 1);
for each MCS, i, starting from current_rate+1 until the highest rate, followed by current_rate-1 until the slowest rate at the condH bin do
    if SNR_est > SNR_BPET[condH] then
        if i is rate ID 2, 4 or 6 then
            skip to next MCS;
        if successive_failures[condH] > 5 then
            skip to next MCS;
        if condH_est is increasing and condH_inc > condH and SNR_est is decreasing and SNR_est < SNR_BPPT[condH_inc] then
            skip to next MCS;
        if i <= current_rate then
            return i;
        int nv = count the number of bins where SNR_est > SNR_BPET[0 to 4] at rate i;
        if nv > num_valid then
            feasible_rate = i; num_valid = nv;
        if feasible_rate ! = -1 and i == highest rate then
            return feasible_rate;
return current_rate;
```

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