Dziyauddin, R., Doufexi, A., Kaleshi, D., & Tran, T. (2010). Performance of MIMO downlink WiMAX at application layer. In *IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications 2010 (PIMRC 2010), Istanbul, Turkey* (pp. 1281 - 1286). Institute of Electrical and Electronics Engineers (IEEE).
<https://doi.org/10.1109/PIMRC.2010.5672024>

Peer reviewed version

Link to published version (if available):
[10.1109/PIMRC.2010.5672024](https://doi.org/10.1109/PIMRC.2010.5672024)

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Performance of MIMO Downlink WiMAX at Application Layer

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Abstract—WiMAX, based on the IEEE 802.16 standard, is designed to support a variety of applications, including voice and multimedia services, through scalable OFDMA, advanced antenna techniques supporting MIMO, and well-defined quality of service classes. This paper presents WiMAX downlink achievable user goodput and operating range for different modulation and coding schemes for SISO and MIMO (both Space Time Block Code (STBC) and Spatial Multiplexing (SM)) connections. The achievable maximum goodput is shown to be between 94.5% and 97.0% of the theoretical data rates. The analysis is then expanded to multiple Subscriber Stations (SSs) and different packet sizes for a specific transmission mode, and also to multiple connections considering an additional real-time polling service (rtPS). The maximum goodput of Unsolicited Grant Service (UGS) is dropped to 51% and 58% when an rtPS is used for multiple connections due to the scheduling type.

Keywords—WiMAX, SM, STBC, goodput, overheads, network

I. INTRODUCTION

WiMAX has accommodated the diverse needs of industry by considering the latest technologies. Two primary standards, IEEE 802.16-2004[1] and IEEE 802.16 e-2005 [2] are established to define PHY and MAC interoperability and are promoted by the WiMAX forum. The key technologies in the standards are scalable OFDMA and advanced antenna technologies, namely beamforming, STBC (Space Time Block Code) and SM (Spatial Multiplexing). Furthermore, mobile WiMAX [2] provides time division duplexing (TDD), and enhances quality of service (QoS) and mobility. According to [3], the next major release of mobile WiMAX, Release 2.0, is being considered by the 16m technical group (TGm) of 802.16.

SM [4] and STBC [5] MIMO techniques are defined in the standard to achieve higher data rates and improved link reliability. Our WiMAX simulator implements the STBC Alamouti scheme to provide transmit and receive diversity. SM can double the goodput compared to SISO for a 2x2 configuration in suitable channel conditions by transmitting separate data streams from each antenna. For SM, our PHY simulator uses an MMSE receiver to remove the inter-stream interference on a per sub-carrier basis. WiMAX performance studies for SISO, STBC and SM have been presented in [6, 7].

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Most WiMAX capacity studies focus on PHY and MAC performance [6-8]. To date, only limited analysis has been presented on WiMAX goodput at higher layers [9]. Nonetheless, [9] only considers the WiMAX goodput for the SISO case without exploring spatial diversity. The implication of MAC overhead on the WiMAX capacity is analysed in [8, 10, 11].

The primary objective of this paper is to investigate the downlink user goodput of UGS and its achievable maximum goodput and operating range when employing SISO, STBC and SM in a 2x2 MIMO configuration. SISO and MIMO PHY link level simulations are initially performed in MATLAB models using the Spatial Channel Model [13] and then incorporated in the Qualnet simulator to evaluate realistic user performance. The MAC header overheads including UDP and TCP/IP headers are computed to support the simulation analysis. A straightforward downlink scenario consisting of a BS and a stationary SS is initially assumed. The scenario is then extended to two scenarios where multiple SSs and multiple connections are analysed. For the case of multiple SSs, all users are evaluated at the range supporting 64QAM $\frac{3}{4}$ STBC. The aim is to study the aggregate goodputs trends as well as its limitation at specific ranges and also to investigate the significance of overheads against packet sizes. An additional rtPs connection is then considered to observe the UGS goodput performance when having dual connections. In addition, the maximum achievable UGS goodput of a single SS is compared with that of multiple SSs and multiple connections.

This paper is organised as follows: Section II presents the WiMAX PHY and MAC, including a discussion of MAC overheads. Section III shows the simulation model and scenario parameters. Section IV discusses the simulation results. Section V concludes the paper.

II. WiMAX PHY AND MAC OVERHEAD

A. WiMAX PHY Data Rates

The raw data rates of OFDMA rely on several parameters such as the bandwidth, FFT size, cyclic prefix, modulation scheme, and coding rate [1,2]. The raw data rates can be obtained from the following equation:

$$R = N * b * c / T \quad (1)$$

where N , b , c and T denote the number of used subcarriers, number of bits per modulation symbol, coding rate and

OFDM symbol duration accordingly. The computed symbol duration is 100.8 μ s. Table I presents the PHY data rates for uplink (UL) and downlink (DL) for SISO, STBC and SM MIMO 2x2 with a DL to UL ratio of 1:1 for a 10MHz bandwidth. SISO and STBC essentially achieve the same maximum PHY data rates, while SM can double the data rate.

B. IP and MAC Overhead Calculations for DL Subframe

The impact of MAC overheads in decreasing the WiMAX throughput has been published in [8, 10, and 12]. According to [8] and [12], MAC PDUs header consists of a generic MAC Header (6 bytes), a packing sub-header (2 or 3 bytes) and the optional CRC (4 bytes). [10] also discusses MAC overheads using the symbol and frame duration, whereby, the MAC overhead can be summarised as follows:

MAC and PHY overhead in downlink = 4 symbols

Total MAC Overhead = (4 * symbol duration) = 403.2 μ s

Overhead over frame size=(0.4032ms/20ms)*100 = 2.016 %

The UDP header and the IPv4 header convey an 8-byte [RFC 768] and a 20-byte [RFC 791] per packet respectively. They contribute to 2.734% overhead over the packet size used for simulations (1024 bytes). Thus, the total percentage of MAC, UDP and IPv4 overheads is close to 5%. Note that for smaller packet sizes, for example, 186 bytes, the total overheads percentage is around 17%.

TABLE I. PHY DATA RATES FOR SISO, STBC AND SM (PUSC, DL:UL[99:99])

Modulation and Encoding Rate	SISO and STBC (Mbps)		SM (Mbps)	
	Downlink	Uplink	Downlink	Uplink
QPSK 1/2	3.571	2.778	7.142	5.556
QPSK 3/4	5.357	4.167	10.714	8.334
16QAM 1/2	7.143	5.556	14.286	28.572
16QAM 3/4	10.714	8.333	21.428	16.666
64QAM 1/2	10.714	8.333	21.428	16.666
64QAM 2/3	14.286	11.111	28.572	22.222
64QAM 3/4	16.071	12.500	32.142	25.000

C. PHY DL Data Rates After Overhead

In order to measure the goodput (application level throughput excluding protocol overheads), the net data rates are calculated. Considering the protocol overheads as in Section II (B) with respect to the DL PHY data rates, the calculated data rates are presented in Table II. These maximum net data rates can be used as a benchmark to be compared with the achievable goodput shown in the analysis part.

III. SIMULATION MODEL

A. Link Level Simulation

Link level of BER performance simulations for SISO, SM and STBC are initially performed across all modes. The channel model used is the Spatial Channel Model (SCM) by 3GPP and an urban micro 3GPP tapped delay line (TDL) is

generated in the link level analysis[13]. Perfect channel estimation and synchronization is assumed. A correlation factor of 0.4 is assumed for the MIMO channels. In the SM-MIMO, an MMSE receiver is chosen due to its ability to remove the inter-stream interference while reducing the Gaussian noise that is presented in the channel.

Figure 1 shows a block diagram of MIMO-enabled WiMAX architecture which has been used in our PHY simulator [7]. The channel coding block includes randomization, coding and puncturing. The encoded bits are then interleaved by mapping adjacent encoded bits onto separated subcarriers and followed by modulation. The data is mapped by segmenting the sequence of modulated symbols into a sequence of slots and followed by the slots mapping into a data region. A single input data stream is converted into multiple output data streams at the MIMO 2x2 block. All data symbols are assigned to their logical subcarriers and subsequently to the physical subcarriers using PUSC.

Figure 2 shows the BER performance of SM MIMO across all modulation schemes. All BER curves produced from the PHY simulator are then exploited to calculate exit and entry thresholds for the link adaptation algorithm (see Figure 2) in Qualnet. Both thresholds are set at a BER between 10^{-4} and 10^{-5} . The BS uses these thresholds when adopting a suitable transmission mode based on the instantaneous SNR.

TABLE II. WIMAX DOWNLINK DATA RATES AFTER CONSIDERING THE IP AND MAC OVERHEADS (PUSC, DL:UL [99:99])

Modulation and Encoding Rate	SISO and STBC (Mbps)	SM (Mbps)
QPSK 1/2	3.393	6.786
QPSK 3/4	5.089	10.178
16QAM 1/2	6.786	13.572
16QAM 3/4	10.179	20.358
64QAM 1/2	10.176	20.358
64QAM 2/3	13.571	27.142
64QAM 3/4	15.268	30.536

Figure 1. MIMO-Enabled WiMAX functional stages for link level simulation [7]

B. System Level Simulation

The generated BER performance results are incorporated in Qualnet as SNR-BER look-up tables to compute burst errors for the corresponding channel condition. New exit and entry thresholds referring to the generated BER curves are defined in both uplink and downlink for every modulation and coding scheme (MCS) for both a single antenna and multiple antenna techniques. The use of BER tables and threshold values for different MIMO 2x2 algorithms make the Qualnet link adaptation decisions more realistic in regard to the MIMO cases.

Figure 2. BER vs SNR for SM MIMO 2 x 2 (a correlation factor = 0.4)

C. Scenarios

In our downlink scenario, a BS initially communicates to a stationary SS with fixed-size data packets of 1024 bytes at a Constant Bit Rate (CBR). No ARQ at the MAC protocol is employed in this study. The main system parameters of the simulation model are summarised in Table III. Our key objective is to observe the goodput performance including packet loss and average delay across MCS for the MIMO techniques and also to determine their maximum achievable goodputs relative to the theoretical data rates. The maximum achievable goodput is then analysed as a function of operating range. The link load varies around the saturation load value; load is changed using the packet generation interval whilst the packet size is constant. The traffic load is calculated as below:

$$\text{Traffic Load (bps)} = \frac{\text{Packet Size (bytes)} \times 8 \text{ bits}}{\text{Packet Interval (s)}} \quad (2)$$

The single scenario is then expanded to two types of scenarios (i) multiple SSs and (ii) multiple connections. In our multiple SSs scenario, we consider 1, 3, 6 and 10 users at the range supporting 64QAM $\frac{3}{4}$ for STBC. We simulate with a saturation CBR traffic load and vary the packet size to 186 and 1024 bytes. Our aim is to study the limitation of achievable UGS goodput for multiple users and also to investigate the significance of overheads on distinctive packet sizes as well as number of users as discussed in [14].

We consider dual connections at the single SS by adding an rtPS connection to the existing UGS connection. The rtPS transmission of packet length of 512 bytes only begins after 15 s of UGS traffic. Our objective is to study the reduction of the achievable maximum goodput after considering an rtPS connection.

TABLE III. MAIN SYSTEM PARAMETERS OF THE NETWORK SIMULATOR

Layer	Parameters	Value
PHY	Operating Frequency	2.5 GHz
	PHY Mode	OFDMA
	Duplexing Mode	TDD
	Channel Bandwidth	10 MHz
	FFT Size	1024
	No of Used Subcarriers	720
	Sampling Factor	8/7
	Guard Interval	1/8
	Channel Model	SCME
	Propagation model	Two Ray Ground
MAC	Propagation Limit	-111.0 dBm
	Shadowing Model	Constant
	Shadowing Mean	4.0
	Antenna Model	Omni directional
	Antenna height	1.5 m
	Number of symbols/frame	198
	DL: UL symbol ratio	99:99
	Scheduler	Strict Priority and Weighted Fair Queuing (WFQ)
	Link Adaptation and Fragmentation	Enabled
	ARQ	Disabled
Transport	Internet Protocol	IPv4
	Simulation Duration	100 s

IV. SIMULATION RESULTS

A. Goodput Performance

Figure 3-5 shows that the achievable user goodput of UGS increases gradually when increasing the traffic load. This is because the network manages thus far to serve the configured traffic load. It can be seen that the user goodput has a linear relationship with the traffic load at the initial stage which is also observed in [8]. The goodput, however, stops increasing at a certain traffic load. This is where the link reaches its maximum goodput as shown by the arrows (see Figures 3-5) with respect to the carried traffic. At this particular point, the maximum goodput is associated with low packet loss as well as low average delay, as shown in Table IV for the 64QAM $\frac{1}{2}$ SISO case as an example. The goodput starts falling slightly and then remains flat when traffic load is increased further (see Figures 3 -5), which agrees with the observations in [8]. Under this conditions the network is overloaded, which is indicated by significantly higher packet loss and worse average packet delay, albeit the system maintains constant goodput as shown in Table IV.

Both SISO and STBC reached similar maximum user goodput for similar traffic loads (see Table V) but, as

expected, at different SNRs. STBC certainly does not improve the maximum goodput, however, it improves the link reliability due to the enhanced BER performance. On the contrary, for SM 2x2, the achievable maximum throughput is double for all modes using minimum mean square error (MMSE) receivers at the link level simulation. Comparing to the theoretical data rates (see Table II), the achievable maximum goodput in Table V is found to be in the range of 94.5% to 97.0% of the theoretical data rates due to packet losses during the transmission. The BS does not adopt all MCSs for its link adaptation due to the fact that some modes never provide the highest throughput in these channel conditions. The table also shows that SM performs exceptionally well at higher SNRs, as expected, whilst the robustness of STBC in poor channel conditions is its primary advantage over SM.

Figure 3. UGS goodput vs. traffic load for SISO

Figure 4. UGS goodput vs. traffic load for STBC

TABLE IV. 64QAM 1/2 SISO FOR A SINGLE UGS USER SCENARIO

Traffic Load (kbps)	UGS Goodput (Mbps)	Packet Loss (%)	Average End-2-End Delay (ms)
9102.22	9.11	0.01	20.30
9637.65	9.64	0.01	20.60
9869.88	9.88	0.01	21.26
10240.00	9.58	6.59	81.85
11702.86	9.58	18.26	100.67
13653.33	9.58	29.24	103.92

Figure 5. UGS goodput vs traffic load for SM

TABLE V. MAXIMUM GOODPUTS OF UGS USER

Modulation Coding Scheme	Antenna Technology	SNR (dB)	Maximum Traffic Load (Mbps)	Maximum User Goodput (Mbps)
QPSK 1/2	SISO	19.40	3.3092	3.2934
	STBC	6.25	3.2768	3.2701
	SM	20.54	6.5536	6.5504
QPSK 3/4	SISO			
	STBC	8.41	4.8188	4.8138
	SM	23.93	9.6376	9.5591
16QAM 1/2	SISO	23.16	6.5536	6.5504
	STBC	12.49	6.5536	6.5504
	SM	24.93	13.107	13.101
16QAM 3/4	SISO			
	STBC	14.7	9.8698	9.8671
	SM			
64QAM 1/2	SISO	30.10	9.8698	9.8601
	STBC	16.07	9.8698	9.8601
	SM	32.15	19.739	19.730
64QAM 2/3	SISO	32.16	13.1281	13.1276
	STBC	17.22	13.1072	13.1038
	SM	34.75	26.2986	26.2752
64QAM 3/4	SISO	41.23	14.7603	14.7324
	STBC	30.12	14.8945	14.5392
	SM	42.75	29.4676	29.2873

B. Operating Range Analysis

Figure 6 illustrates the maximum achievable user goodput from our Qualnet results versus calculated distance for the SISO, STBC 2x2 and SM MIMO 2x2. The envelope is generated using adaptive modulation and coding. The operating range d is obtained from the link budget equation as below:

$$SNR = (P_T G_T G_R / kTB\eta)(\lambda / 4\pi)^2 (1/d)^n \quad (3)$$

Thus,

$$d = [(P_T G_T G_R / kTB\eta)(\lambda / 4\pi)^2 (1/SNR)]^{1/n} \quad (4)$$

where the transmit power, $P_T = 30$ dBm, the transmit antenna gain, $G_T = 0$ dBi, the receive antenna gain, $G_R = 0$ dBi, the noise temperature, $T = 290$ K, the bandwidth, $B = 10$ MHz, the noise figure, $\eta = 10$, the carrier wavelength, $\lambda = 0.0528$ m and Boltzman's constant, $k = 1.379 \times 10^{-23}$ J/K/Hz. The path loss exponent, n is 4.0. SISO and STBC achieve similar maximum goodput, but STBC is able to operate at a greater range than SISO. STBC can considerably increase operating range due to the spatial diversity.

SM MIMO 2x2 achieves double the maximum throughput at short distances from the base station. For instance, SISO achieves 6.5 Mbps at a range of ~90m whilst SM MIMO 2x2 achieves 13 Mbps at a similar range. SM enables to improve the achievable maximum goodput at shorter ranges since it needs a higher SNR for enhanced performance. However, STBC has better performance after a range of 90m than SM as shown in Figure 6. At that distance, the network switches from SM MIMO 2x2 to STBC 2x2 in order to achieve better user goodput and also broader cell coverage.

Figure 6. Maximum User Goodput vs. Distance

C. Multiple Subscriber Stations

Figure 7 summarises the aggregate goodput performance for multiple SSs at a range of 83.6m from the BS in a single cell. At this range, a single SS is able to achieve ~14.6 Mbps, roughly the maximum achievable goodput for 64QAM $\frac{3}{4}$ STBC, with a traffic load of 14.89 Mbps. We observed that by simulating the same total traffic load for 3, 6 as well as 10 users, the expected maximum achievable goodput decreased gradually with the increased number of users. This is due to more users in the network generating more DL-MAP overheads after the Frame Control Header (FCH) in the DL subframe as discussed in [14]. Simulating higher total traffic load for 3, 6 and 10 users (6 Mbps/user) in the network for the same packet size of 1024 bytes, the achievable goodputs exhibit a similar trend due to the maximum link-speed capacity and also similar amount of DL-MAP and higher level layers overheads; that is, the IP and UDP headers. However, the single user able to achieve 5.9 Mbps goodput

because the traffic load, 6 Mbps, is below than the maximum capacity offered by 64QAM $\frac{3}{4}$ STBC.

While sustaining the same total traffic load, 14.89 Mbps, the smaller packet size of 186 bytes significantly generated more overheads in the network compared to the overheads generated by the packet size of 1024 bytes. The degree of performance degradation is higher when the network consists of more users with smaller packet sizes as can be seen in Figure 7. Three possible approaches to reduce the upper layer overheads which are Payload Header Suppression (PHS) as in the mobile WiMAX standard and Robust Header Compression (ROHC) specified by the Internet Engineering Task Force (IETF RFC 3095) and also Enhanced Compressed Real Time Protocol or Enhanced Compressed (EC RTP specified in IETF RFC 3545) can be employed [10][15]. The WiMAX standard typically allows recipients employing the same MCS to be grouped into a single data region to reduce some of the MAC overheads.

Figure 7. Goodput performance for multiple subscriber stations for 64QAM $\frac{3}{4}$ of STBC

D. Combination of Traffic Classes

It can be seen from Figures 3-5 that the goodput of UGS reduces with an additional of rtPS connection. The previous achievable maximum UGS goodput inevitably decreases between 51% and 58% of the one achieved in a single connection for SISO, STBC and SM as shown in Figure 8 due to sharing the resources with the rtPS connection. Even though both classes have the same packet arrival interval, the rtPS queue will be served after the UGS queue has been emptied. There is a case when the UGS queue is emptied and the resources are allocated for rtPS packets. Prior to the scheduling and associated overheads, Figure 8 shows that for SM the UGS goodput drops nearly to the goodput of a UGS single connection of SISO and STBC, albeit having the benefit of double capacity due to SM. Furthermore, more than 10% packet losses and longer than 90 ms average delay are found for the UGS connection due to the resource sharing with the rtPS connection as can be seen in Table VI as an example. This table can be compared with Table IV to analyse the UGS performance degradation.

TABLE VI. 64QAM 1/2 SISO FOR A UGS CONNECTION IN MULTIPLE CONNECTIONS SCENARIO

Traffic Load (kbps)	UGS Goodput (Mbps)	Packet Loss (%)	Average End-2-End Delay (ms)
9102.22	6.77	14.8	110.27
9637.65	6.51	13.25	112.69
9869.88	6.79	16.57	92.52
10240.00	6.65	21.28	95.89
11702.86	6.60	31.6	122.59
13653.33	6.62	41.18	126.33

Figure 8. UGS Maximum Goodput for a single connection and UGS Goodput after considering an rtPS connection

V. CONCLUSIONS

In this paper, goodput results as well as operating range were presented for a number of MIMO modes and all standardised link-speeds for WiMAX. The MIMO channel was modeled using the 3GPP spatial channel model, and a fully compliant 802.16e-2006 physical layer simulator was employed. New exit and entry thresholds were configured in the Qualnet simulator based on the BER performances of link level simulation for all techniques so that the BS employs a realistic link adaptation and burst error computation for the WiMAX applications. The achievable maximum goodput for a single SS using a single class of CBR is found to be between 94.5% and 97.0% of the theoretical data rates; the drop matches the calculated MAC/IP overheads. We showed that STBC 2x2 operates at a greater range than SISO though they have similar maximum achievable goodput. It is found that SM MIMO 2x2 achieves maximally up to ~ 30 Mbps at ~ 79m from the base station. On the contrary, STBC 2x2 achieves a better goodput after ~90 m distance from the BS compares to SM MIMO 2x2 as seen in Figure 6. Our results show that to support broad area coverage and even better user performance, a system can sensibly switch from SM to STBC at a distance of ~90 m. For the multiple SSs case, users exhibit a gradual total goodput reduction due to overheads dependent on the packet sizes and number of users. When having dual connections, it is shown that the maximum goodput of UGS is dropped to 51% and 58% compared to that achieved in a single connection, depending on the traffic load and mode types,

when an rtPS connection is used. This behavior occurs due to the combination of Strict Priority and WFQ schedulers for DL scheduling and slot allocation. Future work will investigate the interplay between these schedulers, and overall system performance, under different channel conditions (spatial correlation, interference).

ACKNOWLEDGMENT

The first author would like to thank Qualnet Support for their supportive forums and also to Zamri Napiyah as well as Rosdiadee Nordin for their comments. The first author is also grateful to the Ministry of Higher Education (MoHE) of Malaysia and Universiti Teknologi Malaysia for her funding.

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