Impact of WiMAX Network Asymmetry on TCP

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Abstract*—The IEEE 802.16 is the standard for broadband wireless access. One promise of this technology (also called WiMAX) is to provide high-speed access to the Internet where the transmission control protocol (TCP) is the core transport protocol. In this paper, we study the impact of network asymmetry in WiMAX on TCP performance. In particular, we investigate the dependence of the aggregate throughput and goodput of TCP on factors such as** *frame duration, direction of flow, DL:UL ratio, modulation and coding schemes, and offered loads. We find that these factors affect TCP performance by exacerbating the network asymmetry inherent to the MAC layer.**

I. INTRODUCTION

The emergence of broadband access enables users to tap the potential of high-performance backbone networks and high-speed Internet services. Broadband wireless access (BWA) is touted as the next logical step in broadband proliferation after a decade of digital subscribe line (DSL) and cable modem. BWA networks can more easily be deployed in difficult terrains where other wired infrastructures are not economically feasible. Worldwide Interoperability for Microwave Access (WiMAX) is the industry name for the standard(s) being developed for broadband wireless access by the IEEE 802.16 Working Group [1]. For WiMAX to be able to fulfill the promise of high speed Internet service, it must efficiently support the core transport protocol of the Internet Transmission Control Protocol (TCP).

In this work, we focus on the problems caused by WiMAX network asymmetry on TCP. Network asymmetry is when network characteristics in one direction greatly affect performance in the other [2]. Network asymmetry can greatly affect TCP performance. The disruption of smooth ACK-clocking mechanism of TCP is one of the causes, since TCP relies on the timely arrival of acknowledgments (ACKs) to increase its congestion window and data sending rate. Under normal network conditions, an ACK is duly received for (some) packets sent, and this helps the sender increase the data sending rate. In the face of congestion, typically indicated by packet loss, TCP abruptly decreases its congestion window, and retransmits the lost packets. The retransmission may aggravate the congestion. Normally, there are two indicators of packet loss or congestion: (1) expiry of retransmission timer (for severe congestion), or (2) receipt of 3 or more dupacks (for milder congestion). In the presence of an imperfect ACK channel, the ACK-clocking is disrupted, i.e., packets sent are not duly acknowledged. Consequently, at the sender, the timer expires which TCP interprets as congestion, the congestion window plummets and the packets are retransmitted, even though these packets may have correctly reached the receiver. This implies that the TCP throughput and goodput not only depend on the characteristics of the data sending channel, but also on the reverse channel used by ACKs.

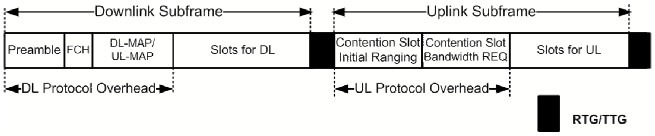

Fig. 1. IEEE 802.16 TDD frame and protocol overheads

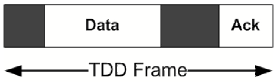

Fig. 2. Downloading frame.

Our study focuses on WiMAX networks using time division duplexing (TDD), and point to multi-point (PMP) network topology. In TDD, downlink (DL) and uplink (UL) transmissions use the same frequency, but occur at different times during the frame duration (see Fig. 1). The first portion of the frame is called downlink subframe and is used for transmission from the base station (BS) to subscriber stations (SSs). The ratio of the subframes, henceforth called DL:UL ratio, can be adaptive. In PMP, both downlink and uplink transmissions are controlled by the BS via downlink MAP (DL-MAP) and uplink MAP (UL-MAP) messages respectively (Fig. 1). The MAP messages define the allocation start times and profiles to be used by each burst and are sent at the beginning of each frame.

There are several forms of asymmetry such as bandwidth asymmetry, access asymmetry, delay asymmetry and packet loss asymmetry [2]. In WiMAX, the DL:UL ratio plays an important role in the bandwidth asymmetry. In download-only situations, TCP packets are sent in the downlink subframe, and ACKs returned in the uplink subframe as shown in Fig. 2. While high DL:UL ratio values are good for large DL traffic, they may aggravate the bandwidth asymmetry and prohibit the smooth flow of ACKs. The protocol overheads also contribute to the asymmetry by consuming a significant portion of the bandwidth (see Fig. 1 and Fig. 2). In addition to bandwidth asymmetry, access asymmetry, delay asymmetry and packet loss asymmetry are also inherent in WiMAX. Particularly in

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WiMAX for best-effort class of service where TCP typically operates, the uplink access mechanism is mainly based on a request-grant process. Before an SS can send traffic, it must first contend with other SSs within the radio range for bandwidth requests. A collision may happen when two SSs request at the same time, in which case an algorithm is invoked based on truncated binary exponential backoff scheme.

Even if the bandwidth request succeeds, the SS still needs to receive the grant prior to sending any data. Therefore, there are bandwidth waste (to bandwidth request), delays (due to the request-grant process) and unpredictability (due to backoff) in uplink resource access. On the contrary, the bandwidth on the downlink is fully controlled by the BS which schedules transmissions without much overhead, loss and delay. The purpose of this paper is to investigate, via simulation, the dependence of TCP performance on several WiMAX design/operating parameters such as frame duration, direction of flow, DL:UL ratio, offered loads and modulation and coding schemes. Our results show that the above parameters impact the aggregate TCP throughput and goodput performance by exacerbating the network asymmetry at the MAC layer. The rest of the paper is structured as follows. The next section discusses related work in the literature. The system model for the investigation is introduced in Section III. In Section IV, simulation scenarios are presented and the results are discussed. Finally, we present our conclusions in Section V.

II. Related Work

Many researchers have presented various mechanisms with the objective of transporting data with different quality of service (QoS) requirements over WiMAX networks. Most of the work focus on defining the components such as scheduling which are intentionally left open in the standard for reasons of implementation flexibility [3]–[5]. Others focus on optimizing the bandwidth request-grant mechanism ratified by the standard but which need to be tuned for TCP-traffic because of bandwidth waste, delay, collision and backoff [6]–[9]. There are only few works studying the impact of network asymmetry on transport protocol performance. Chiang et al. [10] propose a DL:UL ratio that is dynamically adapted in response to actual number of FTP flows admitted within the system. Their simulative-analytic study focuses on the bandwidth asymmetry adaptation. They derive expressions for the asymmetry ratios for both uplink and downlink using long-lived TCP flows. They conclude that both ratios should be 1 to avoid asymmetries and maximize aggregated throughput at the WiMAX access network in simultaneous two-way transfers. Wu et al. [11] suggest the use of smart ACKing schemes originally proposed in [2] to improve TCP performance in bandwidth asymmetric networks. The main principle of these schemes is to reduce the frequency of ACKs in the reverse bottleneck link. In [12], the authors propose a spectrally efficient modulation and coding scheme together with Automatic Repeat reQuest (ARQ) for the data channel, and an expensive (robust) MCS in the reverse channel for ACKs. According to them, an ACK loss is highly undesirable. Their justification is that ACK losses contributes to the TCP-sender burstiness, an increased RTT (due to the cost induced by the bandwidth request mechanism), and an unfair augmentation of the packet loss rate (due to its relatively small size). Our work complements these works by investigating the dependence of TCP performance not only on bandwidth asymmetry but also on other WiMAX design/operating parameters that impact the network asymmetry. We believe our study is helpful in providing a better overall understanding of TCP performance in WiMAX networks.

III. System Model

In this section, we present the system model used in our investigation. The network setup is shown by Fig. 3 unless otherwise stated.

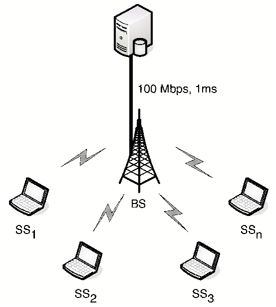

Fig. 3. The network setup.

A. Simulation Environment

The investigation was through simulation. The simulation platform is *ns-2* and the WiMAX module is from the National Institute of Standards and Technology (NIST) [13]. The simulation parameters are summarized in Table I. Ideal channel conditions are assumed[1]. In all cases, we have determined the 95% confidence interval. Since the confidence intervals are negligible, they are not reported in the results.

For the following scenarios we evaluate the performance of long-lived TCP flows. Each subscriber station holds a single downloading or uploading TCP flow.

TABLE I
Simulation Parameters

WiMAX and OFDM Parameters	
Channel bandwidth	7 MHz
Frame duration	5ms
Modulation & Coding	64QAM 3/4
Cyclic prefix	1/16
Contention size	5
Traffic Source and Other Parameters	
TCP version	New Reno
TCP segment size	960 Bytes
Delayed ACK factor	2
TCP start time	$t \subset [0, 35]$
Simulation duration	1000s

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[1] Error condition may be taken into consideration, but it would not bring radical change on the observations in this paper.

B. Performance Metrics

We study performance by means of three metrics:

- *Throughput* that measures the amount of raw bytes sent by a source.
- *Goodput* that measures bytes that are sent and successfully acknowledged.
- *Fairness* that measures fairness among multiple connections. We use the Jain's fairness index [14] which is defined for n simultaneous connections with throughputs x_i as:

$$f = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2} \qquad (1)$$

C. Pre-simulation Study: Data Rates and Protocol Overheads

Given the WiMAX primitive parameters (nominal channel bandwidth BW, number of used carriers N_{USED} , sampling factor n, cyclic prefix G), the frame size and the modulation and coding scheme, it is possible to derive the following parameters: (OFDM) slot duration, slot size, slots per frame, and data rate which is computed as the ratio $slot\_size/slot\_duration$. Specifically, they are respectively $34\mu s$, 108 bytes, 146 and 25.4 Mbps based on our simulation settings summarized in Table I.

TABLE II
SIZES OF PROTOCOL MESSAGES

Type	Size(B)	Type	Size(Slot)
DL-MAP	60	BW-REQ-Preamble	1
UL-MAP	180	INIT-RNG-Preamble	2
DCD	115	DL-Preamble	2
UCD	77	FCH	1

We can also calculate the overhead in the TDD frame due to control messages. See Fig. 1 and Table II. Since WiMAX signaling is in-band, the control messages share the bandwidth with data. To compute the MAP sizes, we assume 10 Information Elements in each of the MAP messages. IEs carry the profile information for each data burst and their number, thus the sizes of the MAP messages increase with the number of SSs. The MAP messages use the 16QAM 1/2. We summarize the overheads per frame in Table III, which shows that the protocol messages consume a considerable amount of bandwidth in both subframes.

TABLE III
SUMMARY OF MINIMUM OVERHEADS PER FRAME (IN OFDM SLOTS)

Downlink	Size	Uplink	Size
Preamble+FCH	3	Init RNG	11
MAP messages	6	BR	6
Padding	1	Padding	1
Total	10		18

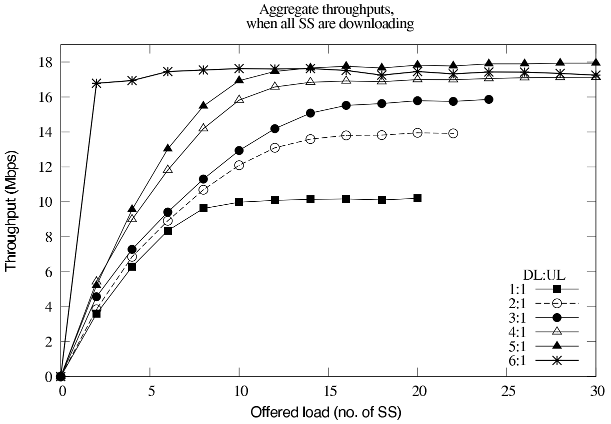
From Table III, it is possible to calculate the maximum allowed DL:UL ratio, for which we show simulation results (i.e., see Fig. 7). For instance, the maximum DL:UL ratio for one-way transfer is 6:1 which provides the minimum number of slots for transporting ACKs on the uplink.

IV. SIMULATION RESULTS

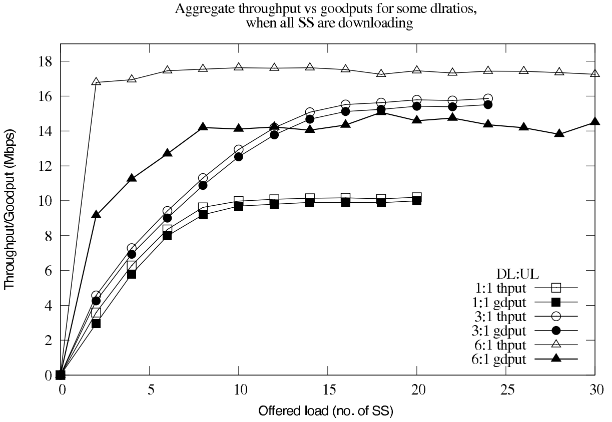
In this section, we present our simulation scenarios and discuss the results obtained. Several scenarios are considered to highlight the effects of offered load, modulation and coding schemes, frame duration, and two-way transfers on aggregate TCP performance.

A. Scenario 1: Effect of Load

In the first scenario, all SSs download FTP traffic from the server. We study the impact of offered load (i.e., number of SSs) on aggregate throughputs and goodputs of the system for each DL:UL ratio. The results are presented in Fig. 7.



(a) Aggregate Throughputs.



(b) Aggregate Throughput vs Aggregate Goodput.

Fig. 4. Aggregate Thrughputs and Goodputs – One way.

As can be seen, aggregate throughput increases with offered loads and DL:UL ratios. The system is more utilized with more downloading SSs (loads). However, the system resources are only finite, and when its capacity is reached new connections cannot be admitted. For 1:1 ratio, for instance, maximum throughput is around 10Mbps and this DL:UL ratio cannot serve more than 20 downloading SSs. Since all SSs are downloading, increasing the DL:UL ratio increases performance and admission capacity. The only exception is the DL:UL ratio 6:1 which, unlike others, also has big gaps between throughput and goodput (see Fig. 4(b)).

Note that the overhead in the uplink subframe is 18 slots (see Table III). Using 6:1, we have a total of 21 slots in uplink subframe which leaves only 3 slots that can be used by uplink data. Therefore the uplink bandwidth is too small to accommodate the ACKs returning from many SSs. ACKs may pile up in the receiver's buffer, and be lost disrupting TCP's ACK-clocking mechanism. Packets transmitted are not duly acknowledged, resulting in timeouts and retransmissions. As we can see from Fig. 4b, the useful throughput (goodput) is much smaller and most of the throughput in 6:1 is due to retransmitted packets. The gap is much higher for fewer connections. This is because fewer connections attain congestion windows much larger than many TCP connections sharing the same resources. Upon impending timeouts, a very large number of packets in flight get discarded.

A question arises as to why the 6:1 throughput is significantly larger for few, say 2, connections. 6:1 offers the maximum possible slots for data in DL, and 3 slots for ACKs in the UL. The 3 slots are initially enough for 2 connections. With abundant slots in DL, TCP can continuously increase its window to make use of the available space. As the congestion window increases, the ACK flow increases in the reverse channel. However, this is not possible after some time because of the limited space in UL. ACKs are lost and become infrequent at the sender. ACK losses are usually followed by TCP sender data bursts, which in turn results in further loss of packets, and retransmissions. Table IV shows retransmissions as much as 49% when there are two downloading TCP connections in 6:1. The percentage of retransmitted packets is less when there are several TCP connections, or when the DL:UL ratio allows far more space in uplink (e.g., 4:1).

TABLE IV
RETRANSMISSIONS AND TIMEOUTS FOR DIFFERENT DL:UL RATIOS.

Offered load	Data	DL:UL=4:1	DL:UL=6:1
2	Timeouts	23	8
	Retx packets(%)	12.98	49.1
30	Timeouts	163	91
	Retx packets(%)	1.8	14.39

Since we consider aggregate values for performance, it is of interest to see how the individual connections perform. In Fig. 5, we plot the fairness among TCP connections against various DL:UL ratios, for offered loads of 5, 10, and 20 downloading SSs. We also include standard deviations in percent of their respective mean throughputs shown as dotted lines, and calibrated on the right *y-axis*. Higher fairness corresponds to lower standard deviation. In all cases, fairness scores are extremely high due to the Round Robin scheduling principle that has been adopted in the simulation. Note that the scheduling scales well, i.e., increasing offered load makes the fairness better. While higher DL:UL ratios produce fairness indexes very close to 1, that is not the case with 6:1 (0.8571) due to strong asymmetry.

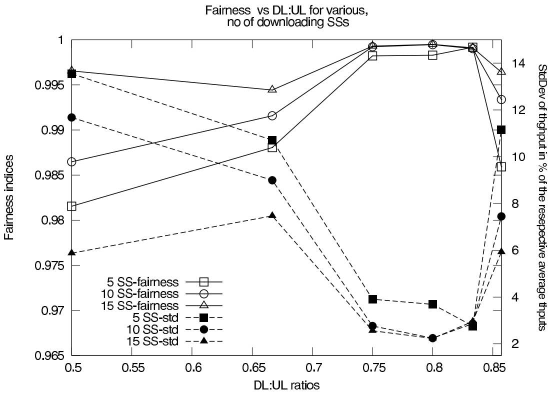


Fig. 5. Fairness of throughput for one-way flows.

B. Scenario 2: Effect of Modulation and Coding Scheme

Thus far, our study considers the same radio conditions and hence the same modulation and coding schemes (MCS) for all SSs. In this section, we change the MCS for all SSs. The offered load is constant with 15 downloading SSs. We plot the aggregate throughputs against MCS for several DL:UL ratios in Fig. 6.

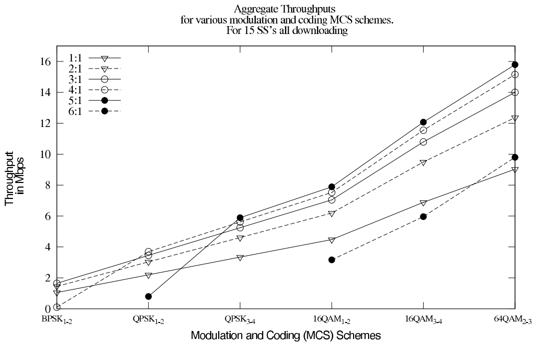


Fig. 6. Impact of MCS on aggregate throughput.

The aggregate throughputs decrease from the 64QAM $2/3$ to BPSK $1/2$. The number of OFDM slots is the same as in scenario 1, but the bit carrying efficiency of the slots is the reason behind this decrease and the increased asymmetry. The efficiency of a slot in units of bytes for each MCS mode is: BPSK $1/2$ (12), QPSK $1/2$ (24), QPSK $3/4$ (36), 16QAM $1/2$ (48), 16QAM $3/4$ (72), 64QAM $2/3$ (96), 64QAM $3/4$ (108). Except for BPSK $1/2$, slot efficiency doubles every other MCS. The throughputs shown in Fig. 6 are roughly in the same proportion as the slot efficiencies.

Because of the reduced efficiency, the uplink channel can become a bottleneck for DL:UL ratios that do not exhibit asymmetry before. The 5:1 produces the highest goodputs for the majority of MCS schemes (see also Fig. 4). When the MCS downgrades to QPSK $1/2$, the 7 free slots in the UL are no more efficient as before to provide enough bandwidth for ACKs returning from the 15 SSs. The slot efficiency has dropped to 22% compared to the 64QAM $3/4$. It thus experiences asymmetry and its throughput performance abruptly falls below that of 1:1. Similarly, 6:1's asymmetry increases significantly and ACKs do not arrive timely enough when the efficiency falls below that of 16 QAM $1/2$. Using BPSK $1/2$ for 6:1, for example, it is not even possible to transmit a single ACK in one 5ms-frame. The result in this subsection shows that asymmetry not only depends on DL:UL ratio, but also on the MCS mode. The less efficient MCS modes exacerbate the asymmetry and hence decrease TCP performance.

We have also performed simulations with three groups, each with 5 downloading SSs and using the following MCS: Group 1 (64QAM $2/3$), Group 2 (16QAM $1/2$), Group 3 (QPSK $1/2$). While aggregate throughputs are as expected with an SS in Group 1 having, on average, four times that of an SS in Group 3, and the fairness indexes of each group are close to 1, the system fairness is not 1. It varies between 0.75 and 0.80. The theoretical fairness score is $7/9$ (see Eq. (1)).

C. Scenario 3: Effect of Frame Duration

We double the frame size to 10ms. Every other simulation parameter is the same as in scenario 1. Simulation results are shown in Fig. 7.

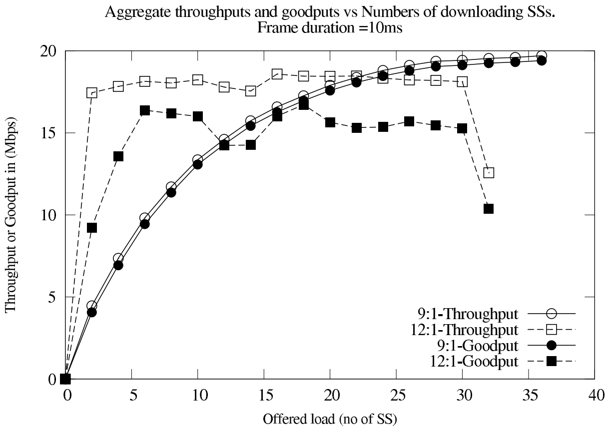
With 10ms frame size, the total number of slots in a frame doubles to 294. However, the peak data rate is still 25.4 Mbps. Now, 6:1 has 22 more OFDM slots available for ACKs in the uplink than when the frame is 5ms long. Hence, 6:1 does not exhibit asymmetry as before. One can compute the maximum asymmetry ratio, which is very close to 12:1. Similarly, the 4:1 DL:UL ratio provides many slots for data in its DL subframe without sacrificing the ACK channel in the uplink. A corresponding ratio with similar advantage in 10 ms is 9:1. A throughput comparison between the two DL:UL ratios is given in Fig. 7(b). Still the 9:1 of 10ms performs better. It guarantees all users a broadband wireless goodput of around 1Mbps when the number of SSs is less than 20.

In both 4:1 of 5ms and 9:1 of 10ms, there are 30 OFDM slots in the uplink subframe. However, the 9:1, by virtue of its higher DL:UL ratio and larger frame size, can provide more than twice as many slots for data in downlink. In addition, the protocol overheads (MAP messages, preambles, and contention regions) regularly take away a more significant percentage of the slots in the 5ms-frame than in the 10ms-frame.

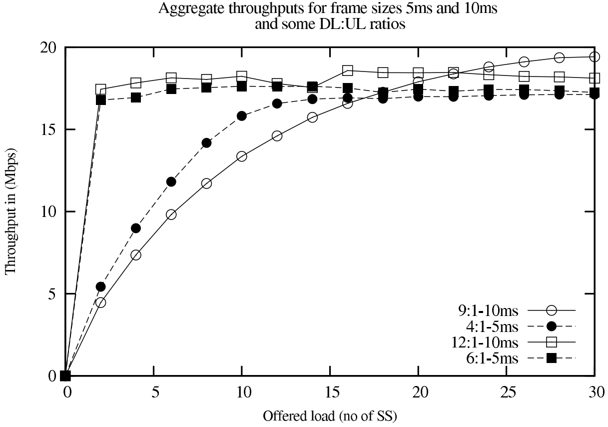
Similarly, the 12:1 ratio in a 10ms-frame is equivalent to the 6:1 ratio in a 5ms-frame. With 18 UL slots assigned to init ranging and contention bandwidth request, there are only 5 slots left available for ACKs. As discussed before, the lack of enough slots in UL means the ACK-clocking mechanism gets disrupted, and packets transmitted in downlink are not duly acknowledged. This results in reduced goodputs, and the throughput-goodput disparity shown in Fig. 7(a).

D. Scenario 4: Simultaneous Two-Way

In this section we analyze simultaneous two-way file transfers. We have a total of 15 SSs where some download, and the remaining upload. We consider two contrasting DL:UL ratios: 6:1 and 1:6.



(a) Aggregate Throughputs.



(b) Aggregate Throughput vs Aggregate Goodput.

Fig. 7. Aggregate performance for one-way flows, in 5 and 10ms-frames

The aggregated throughputs and goodputs versus the increasing uplink loads for both cases of DL:UL ratios are plotted in Fig. 8. Despite having the same number of SSs, the results vary wildly depending on the DL:UL ratio and direction of traffic flow. Intuitively, we found that performance and admission capacity is mainly determined by the shorter subframe. For instance, the uplink subframe is shorter for 6:1 DL:UL ratio, and its performance decreases with increasing uplink traffic. Because of its limited resources in uplink, it does not support more than 12 uploading SSs. Therefore, the 1:6 and 6:1 are more suitable for largely uploading and downloading situations respectively.

An increasing disparity between throughput and goodput is noted in 6:1 when the traffic in downlink is increasing (i.e., when uploading SSs are fewer). Since this result is not intuitive, we have run further simulations and collected the results in Tables V and VI. Table V summarizes timeouts and packet retransmissions in both UL and DL for two extreme cases of uplink load: when uploading SSs are 3 and 12. Table VI shows the time-average of the congestion window for a sample TCP flow in UL and DL.

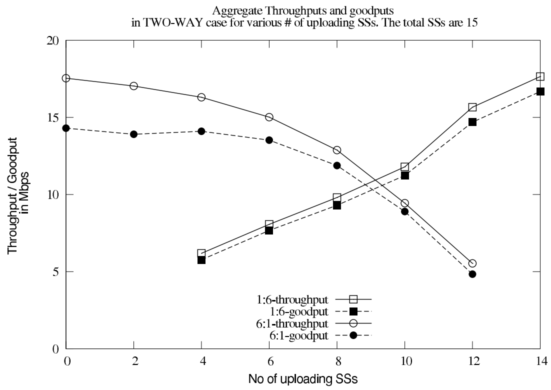


Fig. 8. Aggregate throughput and goodput for two-way transfers.

TABLE V
PACKET (RE)TRANSMISSIONS IN UL/DL FOR 6:1 TWO-WAY

Uploading SS	Timeouts in		Transmitted pkts		Retransmitted pkts	
	DL	UL	DL	UL	DL	UL
3	24	1840	2165180	8474	331104	2756
12	5	8782	698988	33100	82143	12094

There are excessive timeouts, and backoffs in uplink due to significant overhead for uplink transmission of data in 6:1 such as: limited uplink resources, contention for uplink access, bandwidth requests for 1006-byte TCP service data units and ACKs. Because of this, uploading connections have trouble in increasing their TCP windows and they rarely access the channel due to repetitive backoffs. Due to their smaller windows, the contribution of the uplink TCP connections to total retransmissions is therefore minimal. Because of backoffs, the competition between uplink connections for resource access is not severe. On the other hand, timeouts are fewer, but retransmitted packets are numerous in the downlink because of large congestion windows. With 12 downloading SSs, a larger number of returning ACKs compete in the reverse channel for access to the limited resource. This brings up the disruption of the ACK-clocking mechanism, and the system ends up with numerous retransmitted packets in the downlink. With 3 downloading SSs, however, the returning ACKs and their contention for bandwidth access are much less, resulting in reduced retransmissions. DL-timeouts increase from 5 to 24, and the retransmitted packets rise by 300% when we increase the downloading TCP connections from 3 to 12. The increased retransmissions explain the bigger gaps between throughput and goodput. From the discussion, it follows that TCP performance also depends on the direction of traffic flow.

TABLE VI
TIME-AVERAGE OF A TCP WINDOW, 6:1 TWO-WAY

Flow direction	WHEN THERE ARE	
	3 UL TCP connections	12 UL TCP connections
UL TCP	27.73	9.4
DL TCP	167.6	240

V. CONCLUSION

In this paper, we investigated the impact of network asymmetry inherent in WiMAX on TCP performance. Specifically, we have shown that TCP performance in terms of throughput and goodput depends on DL:UL ratio, frame duration, direction of flow, offered loads, and modulation and coding schemes. The performance is impaired because these parameters can exacerbate the network asymmetry. The results show that the DL:UL ratio is the main contributor to network asymmetry in WiMAX. In downloading-only transfers, for instance, increasing the ratio improves the performance and admission capacity of the system. Increasing it beyond a certain threshold value, however, backfires as asymmetry develops in the system. The threshold value depends on the frame duration. Protocol messages also impact performance especially when using smaller frames, since they consume a non-trivial portion of the useful bandwidth. In addition, modulation and coding schemes impact TCP performance by the changing the slot efficiency, and hence the useful bandwidth available for TCP packets and ACKs. Moreover, the flow direction can also affect TCP performance.

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