Uplink Throughput Improvement at Cell Edge using Multipath TCP in Overlaid Mobile WiMAX/WiFi Networks

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***Abstract*—Recently, many laptops, smartphones and tablets are equipped with several broadband wireless interfaces, such as WiFi and Mobile WiMAX. However, the current Transport Control Protocol (TCP) only allows a single interface to be active at any moment, while the remaining ones are not used. Multipath TCP (MPTCP) is a proposed extension to standard TCP, which aims to exploit the availability of such multiple interfaces. This multipath capability is of great importance for current and future communication systems. In this work, we study the potential of MPTCP for improving uplink throughput at the WiMAX cell edge by dynamic data offloading to WiFi. To this end, we conducted measurements on real Mobile WiMAX/WiFi networks. The results show that MPTCP can significantly improve the uplink throughput of Mobile WiMAX users and also reduce the round-trip time (RTT).**

***Keywords*-Mobile WiMAX; cell edge; MPTCP.**

I. Introduction

The Internet is becoming mobile, as traditional voice-oriented cellular networks introduce enormous advances in data transmission capabilities. Mobile data traffic is growing very fast, with an 18-fold increase forecast between 2011-2016 [1]. Thus, Mobile Service Operators need to solve the critical problem of the throughput performance in their mobile networks. As more users connect to the network, the congestion levels increase accordingly. Furthermore, the popularity of devices with multiple interfaces introduces a new end-to-end communication paradigm. The conventional TCP/IP protocol stack assumes that end-systems communicate with each other by using a single connection point, i.e.,one IP address. However, the availability of multiple interfaces (and multiple IP addresses) within a single device enables it to transmit and receive through diverse paths over the Internet. Therefore, it is desirable to have the capability of using more than one interface at any time.

WiMAX has emerged as an important technology for Wireless Broadband communications [2]. Many telecom operators around the world have adopted it as an alternative to wired technologies. This technology belongs to the IEEE 802.16 family and has two main variants: 802.16d (Fixed Access WiMAX), and 802.16e (Mobile WiMAX). At the Physical Layer, Mobile WiMAX employs Orthogonal Frequency Division Multiplexing (OFDM), while the available modulation schemes are BPSK, QPSK, 16-QAM and 64-QAM. It also implements an Adaptive Modulation and Coding (AMC) functionality, which enables dynamic adjustment of the transmission profile depending upon the current radio signal condition. According to [6], the average throughput per sector ranges between 4-15 Mbps for uplink, and 9-28 Mbps for downlink, using TDD with several frequency bandwidth between 10-20 MHz.

Additionally, it is a very common practice to assign more transmission channels to the downlink than the uplink, with typical ratios of 2:1 and 3:2. Thus, in most cases the uplink has lower capacity than the downlink. This is an important fact to consider, because nowadays a growing number of users are generating traffic (uploading) from their mobile devices to the Internet, instead of receiving traffic (downloading) from it. These applications range from interactive video conferencing, remote video surveillance, and regular uploading of large files. Therefore, it is important to explore new alternatives for improving the uplink throughput.

In this paper, we explore the Multipath Transmission approach. The fundamental idea is to transmit over more than one path towards the final destination. As mentioned previously, mobile devices with more than one interface are already available nowadays, thus enabling the implementation of such Multipath scheme. A promising new protocol suitable for this purpose is Multipath TCP (MPTCP) [3], and it is the choice for our study.

The rest of the paper is organized as follows. In Section II, we describe related work. Next, in Section III we introduce the basics of MPTCP. In Section IV we present the experimental setup. Then, in Section V we analyze the measurement results. Section VI presents a brief discussion of the results. Finally, Section VII concludes the article.

II. Related work

Several works on multipath transmission have been presented. Iyengar *et al* [9] presented a scheme called Concurrent Multipath Transfer (CMT), based on the Stream Control Transmission Protocol (SCTP), which added the capability of transmitting over multiple interfaces. Later, Koh *et al* [10], extended SCTP to support traffic handover

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among interfaces, best suited for mobile environments where new IP addresses are possibly assigned while moving around an area. Although these studies showed interesting results, SCTP is not widely adopted in the current Internet.

Multimedia streaming via Transmission Control Protocol (TCP) has been deployed successfully over recent years. Thus, an extended multipath capability for TCP streaming has also been proposed by Wang *et al* [11]. The authors proved the feasibility of this approach for practical scenarios.

The use of WiFi for offloading traffic from cellular networks has also been proposed in earlier works. Balasubramanian *et al* [13] studied the feasibility of augmenting Mobile 3G using WiFi. They analyzed measurements made in three cities from a moving vehicle. Positions of the WiFi access points were recorded and used by an algorithm for determining their proximity at a given moment. After implementing their solution called Waffler, they determined a reduction of 45% in 3G usage. However, they did not consider simultaneous interface usage, since their approach is based on a single interface opportunistic scheme.

An experimental study on the throughput gains when using a new protocol called Multipath TCP (MPTCP) was presented by Raiciu *et al* [12]. The authors proved the functionality of MPTCP while moving inside a building with 3G and WiFi coverage. They moved from floor to floor while measuring the corresponding variability in the signal levels from 3G and WiFi. After comparing the measurements against an optimal TCP scheme, the gains obtained with MPTCP were at least 12%. They also simulated walking and driving scenarios, reporting gains ranging between 50-100%. However, the results showed only downlink performance, and details about radio signal conditions were not specified.

In our work, we have chosen MPTCP, due to its compatibility with current Internet. We study the uplink performance, which was not considered in previous studies. Also, we focus on the most challenging area of any wireless system, the cell edge, which was also not considered.

III. Multipath TCP (MPTCP)

In current Internet technology, Transmission Control Protocol (TCP) is one of the most important transmission protocols. It has reached maturity over the years and most of the available services use it. However, it was originally designed for managing communications over a single path between two end-hosts. At any time, TCP uses only one interface, regardless of the total available interfaces. This fact limits the potential of the increasingly popular multi-interface mobile devices, resulting in their under-utilization. Thus, it is desirable to have more flexibility in the selection of transmission resources.

Multipath TCP (MPTCP) is an extension to conventional TCP, which aims to leverage the concurrent use of multiple interfaces within a single device. Currently, it is being standardized by an active working group at IETF [7]. The most important features of MPTCP when compared to conventional TCP are:

- Connection Reliability: enables connection recovery when one or more links become unavailable, by dynamically selecting an appropriate interface.
- Throughput Improvement: enables bandwidth aggregation by simultaneous use of multiple interfaces.

Moreover, a very important advantage of MPTCP is its compatibility with current Internet architecture and services. It does not require changes either to existing infrastructure or applications. Therefore, it can be used transparently from both the user and network point of view.

The MPTCP working group also pays considerable attention to wireless scenarios similar to the one described in our work, as they envisage the necessity of wireless networks converging [8].

IV. Experimental setup

In this study, we conducted field measurements on real networks within a university campus. Specifically, we used a commercial Mobile WiMAX network and the campus WiFi. Our objective was to investigate the effects of MPTCP use on WiMAX uplink throughput in a overlaid WiMAX/WiFi scenario. In particular, we focused on cases with poor radio signal conditions, with power levels equivalent to those at a cell edge. The reason for choosing this particular case was that it represents the most challenging environment for a mobile device.

Figure 1 shows the tested scenario. The Mobile WiMAX Base Station was located on the rooftop of a five-story building, and it is referred to as BS. The WiFi network is based on 802.11g (2.4 GHz), providing good coverage within the university campus. Measurement locations are indicated by points A and B. The distances BS-A and BS-B are approximately 370 and 280 meters, respectively. The Mobile WiMAX antenna was located at 30 meters high, transmitting at 20 Watts. The frequency band was 2.62 GHz, with channel bandwidth of 10 MHz. The system was operating in TDD mode.

Location A has better WiMAX RSSI and higher CINR. When checking the relative positions of A and B in Figure 1, it is important to clarify that location A has a better radio condition for WiMAX because it has more favorable Line-Of-Sight (LOS) to BS, even though it is farther away. On the other hand, location B is closer to the BS, but its LOS is obstructed by a building, which introduce additional degradation to the link quality. On the other hand, WiFi RSSI values show the opposite behavior, being worse at A than B. Location A is outside the campus and far away from the WiFi Access Point (AP), while location B is within the campus, close to the AP.

The measuring equipment was a laptop equipped with a WiFi interface and a Mobile WiMAX Router connected to it through an USB port. In the experiments, we measured

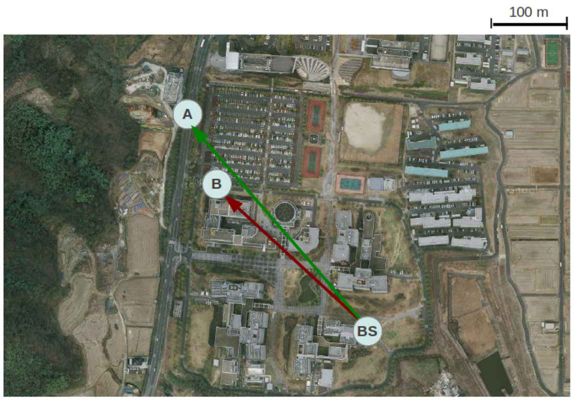


Figure 1. Base Station and Measurement Locations

Table I
RADIO SIGNAL CONDITIONS

Location	WiMAX RSSI (dBm)	WiMAX CINR (dB)	WiFi RSSI (dBm)
A	-75	16	-90
B	-81	10	-65

the uplink throughput at locations A and B. In both cases, WiMAX had low signal strength, while WiFi radio condition was poor at one location and good at the other. The average values are shown in Table I.

To test the MPTCP functionality, we installed the publicly available MPTCP Implementation developed by Barré et al [15]. Our testing laptop runs the Linux Kernel version 3.2.0 along with the mentioned patch.

We used the networking tool *iperf* to conduct the measurements [4]. Then, we tested the connection quality to the Kernel implementers website located in Belgium, which is also running MPTCP [5]. This was deliberate, to confirm the functionality when sending traffic across the Internet.

The measurements were conducted over two weeks, twice a day, at 11 AM and 16 PM. Both sessions lasted 1 hour, where five-minute long flows were transmitted.

V. EVALUATION

In this section we introduce our measurement results. Our objective is to investigate how MPTCP affects uplink performance in an overlaid WiMAX/WiFi scenario. We analyze not only the absolute values of the throughput, but also use the Coefficient of Variation (CV) parameter to get a normalized comparison value. Thus, we analyze the throughput variability by using Eq. 1:

$$CV = \frac{StdevThp}{AvgThp} \tag{1}$$

where $StdevThp$ is the Standard Deviation and $AvgThp$ is the Average of measured Throughput. Low CV indicates that most values lie close to the average, whereas high CV suggests values that are distant from the average, i.e., more dispersed values.

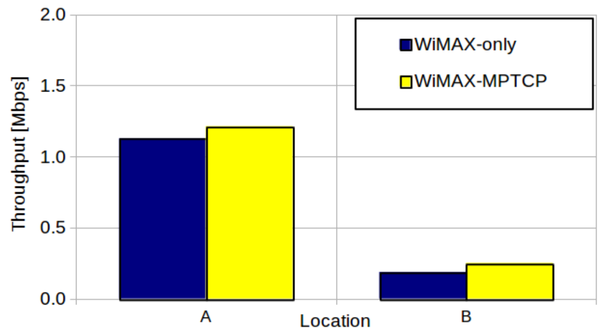


Figure 2. Mobile WiMAX Uplink Throughput

A. WiMAX-only uplink throughput

Initially, we measured the WiMAX-only uplink behavior at locations A and B. We wanted to compare the difference in the throughput at both locations, to determine the initial reference values. The results are shown in Figure 2. While at location A, the average throughput was 1.1 Mbps, at location B it was only 0.18 Mbps. The difference between the throughput values at A and B is due to the good LOS in BS-A path, as well as the shadowing effect by the building in the BS-B path, which introduces about 6 dB of attenuation.

Next, we enabled MPTCP transmission and used WiMAX and WiFi simultaneously. The WiMAX component of the total traffic over MPTCP was 1.2 Mbps at A and 0.25 Mbps at B. In practical terms, these values can be considered nearly equal to the previous WiMAX-only values. Thus, MPTCP was able to fully use the WiMAX link capacity at both locations.

Another interesting characteristic to investigate is the Throughput Variability. To this end, we used the Coefficient of Variation (CV) defined in Eq. 1. The results are shown in Figure 3. The WiMAX-only case showed a CV increase of 0.13, from 0.29 to 0.42 at locations A and B, which indicates that the throughput fluctuation around the average increased slightly. However, when MPTCP was enabled, the CV increased about 1.27, from 0.36 to 1.63 at A and B, much more than the previous value. This means that there are relatively high values, which are distant from the average and appear in a sporadic way during the observation time. In other words, this behavior shows that the WiMAX interface increased its traffic only occasionally. If we take this to the limit, WiMAX will not transmit any traffic at all, and WiFi will carry the total traffic, practically resulting in a vertical handover. However, this is not allowed under normal operation, because MPTCP needs to keep some traffic on each interface, to probe the links and make appropriate traffic distribution decisions.

B. MPTCP total uplink throughput

Here, we consider the Total uplink Throughput result when using WiMAX and WiFi simultaneously. Figure 4

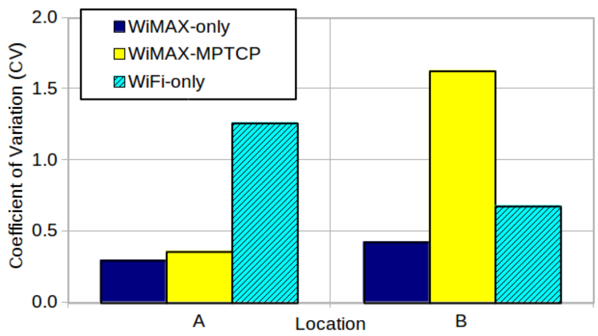


Figure 3. Coefficient of Variation

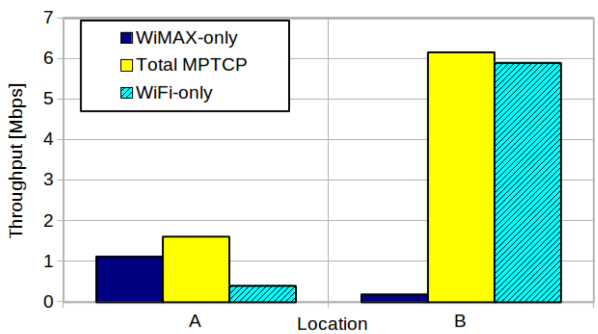
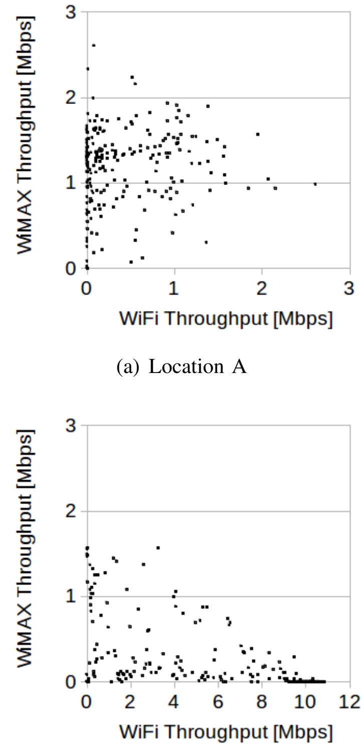


Figure 4. Total Throughput using MPTCP



(a) Location A

(b) Location B

Figure 5. Traffic Distribution over WiMAX and WiFi

shows the measured values. We compared this result to the WiMAX-only case from Figure 2. At location A, the throughput increased from 1.1 Mbps to 1.6 Mbps, or about +33%. Considering that, at this location, WiFi is operating at nearly its cutoff signal level, this increase indicates the advantage of using Multipath transmission. The throughput increase was much more abrupt at location B, from 0.2 Mbps to 6.1 Mbps. The reason for such a huge increase was the high-speed WiFi, which became prevalent. In this case, the resulting throughput aggregation had more similarity to a vertical handover from WiMAX to WiFi.

Overall, the aggregation capability of MPTCP showed important gains on the user's total throughput when compared to using only WiMAX. Moreover, the WiMAX cell capacity is indirectly increased because less WiMAX resources are used, since a portion of the traffic is sent over WiFi.

C. Traffic distribution among interfaces

One of the MPTCP design objectives is to distribute traffic fairly among available interfaces. In Figure 5 we show the measured traffic distribution over WiMAX and WiFi at locations A and B.

At location A, we verified that WiMAX gets more throughput than WiFi about 88% of the time. This was determined by observing the samples above the 45 degree line. The traffic distribution for location B was nearly the opposite, because WiFi gets more throughput than WiMAX about 86% of the time, which was an expected value due to the good signal strength of WiFi. These values are located below the 45 degree line.

The traffic distribution over real networks strongly depends on the current network congestion and wireless link quality. In our scenario, the traffic distribution should be ideally 50-50% among WiMAX and WiFi interfaces. However, due to asymmetries in terms of bandwidth capacity and wireless connection quality, the distribution was expected to be asymmetric too. On the one hand, the WiFi network has much more available bandwidth than WiMAX, and it was prevalent when it had good wireless link conditions. On the other hand, when WiFi quality degraded, it became more unstable.

D. Round-trip time

Another important parameter is the round-trip time (RTT) between end-hosts. This parameter is especially important for many real-time applications such as video-conferencing and Voice over IP (VoIP) running on TCP. The results are shown in Figure 6. The WiMAX-only transmission suffers from a large RTT at both locations. While the values at Location A reached about 843 ms, the values at Location B reached about 1500 ms.

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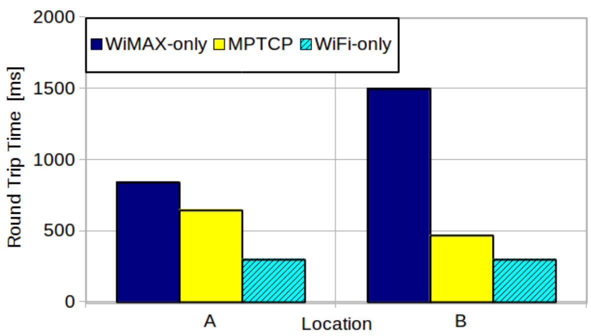

Figure 6. Round-trip Time (RTT)

On the other hand, the WiFi RTT values are much lower and they are consistently around 300 ms at both locations. As expected, for MPTCP we found values in between WiMAX and WiFi. At location A, an RTT of around 650 ms was observed, which represents a reduction of about 23% from WiMAX-only, thanks to the collaboration of WiFi. The RTT at location B was around 470 ms, a reduction of almost 70%, due to the high dominance of WiFi. Hence, these improvements also demonstrate the advantage of introducing MPTCP in this scenario, reducing the RTT values by considerable percentages.

VI. Discussion

Although using MPTCP is advantageous in overlaid networks, we should consider some factors affecting its performance. One of them is the IP configuration procedure. Before transmitting any useful data, the mobile device needs to first be associated with the access points and authenticated. Only then is the user granted access to the network. This procedure takes about 4 to 5 seconds to complete, which is relatively slow. Additionally, the routing configuration is lost whenever the device goes out of range from Mobile WiMAX or WiFi. Thus, whenever the connection is re-established, the routing information is not complete and the procedure needs to be performed again, introducing even more delay. We alleviated this issue by creating monitoring scripts, which reconfigured the routing tables in the events of connection/disconnection to the access point. However, fully automatic configuration will be necessary.

Another effect is caused by TCP itself, since it takes an additional 3 to 5 seconds to reach a steady throughput level after TCP flow initiation. This characteristic also prevents users from getting faster access to the network capacity, and could have a considerable impact especially in high-mobility environments, which we did not cover in this paper.

For more complex environments, where multiple radio bases and access points co-exist, it is important to identify and properly choose the most advantageous connections. Factors affecting this decision could be technical, e.g., signal levels, bandwidth, delay, and jitter, or financial, e.g., cost, or limited data transmission. MPTCP can already detect congested networks and move the traffic away from them [17], but an additional consideration of the current radio signal conditions could be interesting for evaluating the connection quality.

Interactive applications can also benefit from MPTCP. Although further evaluation is needed, we have conducted preliminary tests showing that it is possible to get packet losses below 0.5% when using Skype. MPTCP will be especially useful with weak radio signal conditions, where the connection is unreliable and subject to rather frequent disconnection events. By having an additional communication path, the impact of these disconnection events could be reduced.

We measured uplink-only throughput because previous works did not show it. It should be recalled that uplink resources are more scarce. Also, it may be affected by downlink traffic.

VII. Conclusion and Future Work

In this work, we conducted an experimental study of the uplink throughput when using Multipath TCP (MPTCP) in a overlaid Mobile WiMAX/WiFi scenario. Our interest was to verify the potential benefits of a multipath protocol such as MPTCP. In particular, we focused on cases of low WiMAX signal levels, with good WiFi at one location and poor at another. First, we observed a minimum of 33% increase in the achieved throughput, even when the WiFi was near its signal cutoff level. Second, we studied the variability of throughput by introducing the Coefficient of Variation parameter defined as the ratio between the Standard Deviation and the Average Throughput. The main finding was that the WiMAX interface achieved higher throughput only in a sporadic way when WiFi was prevalent. The WiMAX interface was not pushed to its maximum capacity all of the time. Thus, the system behaved as if WiFi had received some priority, effectively reducing the load on the WiMAX network. Third, we analyzed the relative traffic distribution over both interfaces. When the WiFi signal condition was better than WiMAX, it achieved higher throughput 86% of the time. However, when WiMAX was better than WiFi, it had higher throughput 88% of the time. Also, the RTT values showed a reduction of at least 23%, which is very important for real-time applications.

The results demonstrated that multipath protocols, such as MPTCP, are a very interesting option for improving uplink throughput near the cell edge of Mobile WiMAX.

As a future work, it is interesting to explore further considerations for the practical use of MPTCP in mobile networks. We are customizing a Mobile WiMAX/WiFi testbed for the study of MPTCP performance under different network parameters, such as backhaul and WiMAX channel bandwidth, WiFi AP load, among others.

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