Empirical Evaluation of Mobile WiMAX with MIMO

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***Abstract*—Mobile WiMAX is claimed to have the greatest potential of all wireless access technologies already in the markets with respect to network capacity, range, mobility, and quality of service support. Mobile WiMAX has also adopted MIMO as an essential element for increasing capacity and data propagation reliability. However, there are few publicly available studies demonstrating what is possible with Mobile WiMAX in practice and none that empirically evaluates the performance gains attained with MIMO. We fill this gap by comparing space-time coding based 2x2 MIMO with single antenna mode in our Mobile WiMAX testbed. We conduct thorough measurements that involve vehicular mobility with different types of traffic. We find that MIMO significantly increases the reliability of data propagation over the wireless link, which is particularly evident when we consider TCP traffic. Since 3GPP LTE, the main rival to Mobile WiMAX, equipment and publicly deployed networks are yet to become available, HSPA and the soon-to-be-deployed HSPA+ amendments to UMTS are the only wireless technologies challenging Mobile WiMAX. Thus, we also compare Mobile WiMAX with HSPA, providing the first publicly available side-by-side measurement study.**

I. Introduction

Adaptive antenna systems (AAS) and multiantenna systems are designed to combat interference and deal with multipath phenomena typical of wireless communication. In Multiple-input Multiple-output (MIMO), multiple antennas are used in both the transmitting and receiving sides to improve spectral efficiency by capitalizing on transmission and spatial diversities along with multipath propagation. Mobile WiMAX [1], based on the IEEE 802.16 air interface specifications [2], adopts MIMO as an important element in capacity increase. 3GPP has also specified MIMO in Release 7 (HSPA+) [3] and Release 8 (LTE, see www.3gpp.org/article/release-8). However, implementations of 3GPP MIMO specifications are reportedly late when compared with Mobile WiMAX. HSPA+ enhanced 3G networks are still not available. Long Term Evolution (LTE) is still in the offing. In fact, the first commercial HSPA+ networks are expected to be started up in late 2009. The first LTE-enabled equipment are expected to be introduced in the markets sometime in 2010. Notably, the IEEE 802.11 working group is also specifying an amendment standard for WLANs where MIMO is employed to increase throughput [4]. Although the standard is not complete, some companies have already developed pre-IEEE 802.11n implementations.

These developments clearly point to a future wireless networking environment where MIMO plays a key role in the effort to increase capacity and manage signal interference caused by, for example, multipath fading. It is widely anticipated that this environment will entail even more user mobility, which will only accentuate signal interference phenomena. Despite the increased interest, however, there are only a few empirical evaluations of MIMO performance gains in the open literature and none where Mobile WiMAX is employed. In this study, we evaluate 2x2 MIMO using Space-Time Block Coding (STBC), also called Space-Time Coding (STC), in practice using our Mobile WiMAX testbed. STC does not bring any gains with respect to maximum flow capacity but improves data transmission reliability and thus Bit Error Rate (BER) compared to single antenna mode. STC utilizes transmission diversity, that is, the same data are sent through different transmitting antennas using orthogonal coding, allowing individual fading channels for each data stream. The MIMO implementation in our base stations (BSs) is the first version released for customers, marking this study as the first of its kind in the peer-reviewed literature. This is the first step to quantify MIMO performance empirically and to demonstrate what is possible to be attained with STC MIMO in practice. This paper also empirically compares MIMO-enhanced Mobile WiMAX with HSPA in a vehicular mobility scenario with TCP traffic. This is an interesting comparison: network-deployed HSPA supports Hybrid-ARQ (HARQ) which compensates for the substantially smaller nominal capacity, while our MIMO Mobile WiMAX testbed does not have HARQ implemented, yet.

The rest of the paper is organized as follows. Section II presents and relates this paper to other Mobile WiMAX studies. Section III introduces our testbed, measurement tools, and MIMO, and briefly compares HSPA with Mobile WiMAX. Our measurement results are reported in Section IV. Section V concludes this paper and outlines future work items.

II. Related Work

As mentioned above, although there are several simulation-based studies of MIMO, empirical studies are not common. One of the few empirical Mobile WiMAX studies is [5]. Kim et al. conducted field trial measurements in a public commercial WiBRO network in Seoul, Korea, using UDP and TCP traffic in stationary and mobile use cases. The network employed operates in the 2.3 GHz frequency band using 10 MHz of bandwidth. Kim et al. also compared WiBRO performance with an HSDPA-enhanced 3G network. When downloading a 1 MB file, they measure TCP goodput in the order of 3 Mb/s and 800 kb/s for the WiBRO and HSDPA networks, respectively. In our measurements, we measured higher goodput with both technologies. Although Kim et al. do not use MIMO, the radio frequency is different, bandwidth is twice as large, and WiBRO technology has minor differences to our Mobile WiMAX, their measurements provide a good reference point to the results we report in this paper

With respect to simulation studies, there is a wealth of publicly available papers on Mobile WiMAX performance, some of which simulate MIMO performance as well. However, said simulations often are based on a number of assumptions and thus results reported can often be considered indicative, not conclusive. We also note that most MIMO simulation studies are conducted over wireless technologies other than Mobile WiMAX, such as WLAN. We sample from current literature the following studies which are carried out using Mobile WiMAX MAC and PHY. Tran et al. [6] compared the basic single antenna mode with various 2x2 MIMO extensions based on STBC, Space-Frequency Block Coding (SFBC), and spatial multiplexing. They attained up to 9dB SNR gain with STBC MIMO scheme. Alim and El Naggary [7] have also compared different MIMO and AAS techniques.

In addition to 2x2 MIMO, Marabissi et al. [8] have also conducted simulations with 4x2 MIMO and hybrid STBC. They show that because of interference, hybrid STBC suffers from BER degradation with different E_b/N_o values compared to basic STBC using two transmitting antennas. However, hybrid STBC scheme allows better MIMO multiplexing for multiple users. Jeffrey et al. present 2x2 and 4x2 MIMO mobility simulations with various MIMO schemes in [9]. At pedestrian speeds, the attained SNR gain at low BER values with 2x2 STBC, using the QPSK modulation scheme with FEC: 1/2 and the same Partial Usage of Subchannels (PUSC) permutation scheme as in our measurements, is nearly 5dB.

III. Methodology

Fig. 1 illustrates our Mobile WiMAX testbed which is located at the VTT Converging Networks Laboratory (www.cnl.fi) and comprises Alcatel-Lucent equipment operating on the 3.5 GHz frequency band. We use one 9710 C-WBS BS with a four-element array antenna. In single antenna mode, all antenna elements inject the same data into the radio link, while with MIMO the two middle elements were disabled. In the radio access network (RAN), Access Service Network Gateway (ASN-GW) is responsible for creating the data path between the mobile stations (MS) and the core network (CN). The radio-side Operation and Maintenance Center (OMC-R) provides full control over the RAN. We set bandwidth to 5 MHz, BS transmission power to 35 dBm, and disable ARQ and HARQ, as we want to focus this evaluation on the benefits obtained by employing MIMO alone. The maximum number of OFDM symbols per DL frame is 31 when single antenna mode is used, and 26 when MIMO is enabled. The lower symbol rate with MIMO was set by default. Hence, the frame header overhead is larger when MIMO transmissions are enabled.

In the CN, AAA server provides MS authentication and Mobile IP (MIP) Home Agent (HA) mobility between different access points. MOSET server, IPTV streaming server, and

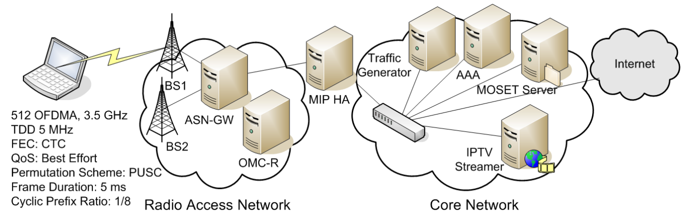

Fig. 1. Schematic of the Mobile WiMAX testbed

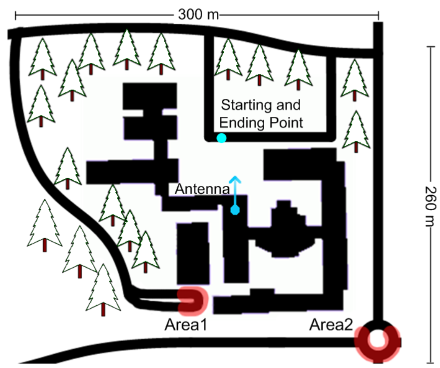

Fig. 2. Schematic of the measurement area

our custom-made traffic generator provide the selected traffic mix for our experiments. In the WiMAX wireless network side, we used Alcatel-Lucent 9799 MIMO PCMCIA card on a Windows XP laptop. It is a dual-frequency card suitable for the 2.5 GHz and 3.5 GHz frequencies, and possessing two antennas and a Beceem chipset.

Fig. 2 is a schematic of our measurement environment. The measurement route begins at the Starting point and first goes to Area 1. From Area 1, the route continues to Area 2, after which the route ends at the Ending point in front of the BS antenna. The route does not include long distances from the BS (200 m at maximum), however, includes challenging areas where signal strength is very low, marked around Area 1 and Area 2. Only a short part of the route includes line-of-sight conditions. In most of the areas, either buildings or foliage, i.e. tall trees and bushes, or a combination of both lie between the MS and the BS. The BS, at the center of Fig 2, is installed on the roof of the highest building in the measurement area. The MS is placed inside a car during all measurements. Vehicular speed is in the range of 25 - 40 km/h during most of each run, but, because part of the measurement route includes public roads, short stops do occur.

A. Multiple-Input Multiple-Output

The IEEE 802.16-2009 standard [2] offers a variety of tools for MIMO processing including STC, spatial multiplexing, and beamforming. The support for MIMO techniques is provided in IEEE 802.16-2009 by dividing the transmission frame into several parts, referred to as zones. The first zone is used for single antenna transmission while the latter zones can be used for spatially processed signaling. The latter zones can also be used for some other transmission schemes, such as optional PUSC, optional Full Usage of Subchannels (FUSC), or Adaptive Modulation and Coding (AMC), and some of them also have the possibility for processing in spatial domain. The standard supports the use of two, three, or four antennas at the BS, and two antennas at the MS. Also, for the UL, two single antenna MSs can perform collaborative spatial multiplexing onto the same subcarrier.

The very basic DL STC transmission scheme for two transmitter antennas is based on the Alamouti coding [10], which uses the transmission matrix

$$\begin{vmatrix} s_1 & -s_2* \\ s_2 & s_1* \end{vmatrix}$$

where s_1 and s_2 depict symbols, and can be used both in PUSC and FUSC permutations. The decoding algorithm is also presented in [10], and it is based on maximal ratio combining. Besides coding the symbols in time and space, [2] supports a technique referred to as frequency hopping diversity coding (FHDC) for DL. Basically, this technique is similar to Alamouti coding, but the OFDMA symbol index is replaced by the subcarrier index, leading to diversity coding in frequency and space. For the optional zones in the DL, spatial multiplexing is supported as well.

In PUSC mode, the number of pilot subcarriers is doubled in a cluster compared to the single antenna mode, in a way that half of the pilots are dedicated to antenna 0 and the other half is dedicated to antenna 1. In FUSC mode, pilots are divided between transmitter antennas. The MIMO midamble can be switched on by BS in the DL_MAP in STC_DL_Zone information element. Basically, the MIMO midamble is an OFDMA symbol filled with pilot symbols from different transmitter antennas that can be used for estimation purposes at the MS. The MIMO midamble can be boosted by 3 dB using midamble boosting if the STC_DL_Zone information element in DL_MAP is switched on.

The Alamouti STC used in our Mobile WiMAX measurements is a rate one transmit diversity code. That is, it does not increase or decrease data throughput as spatial multiplexing or conventional error-correction codes would do, but it increases the reliability of the received signal by transmitting via two independently fading spatial subchannels and allows a simple but optimal combination of the signals at the receiver.

B. Mobile WiMAX vs. HSPA

3GPP introduced new downlink and uplink transport channels for high-performance packet-data applications in Release 5 and Release 6, respectively [11]. Compared to Release 99, HSDPA and HSUPA provide significant link capacity increases. We employed a commercial live HSPA-enhanced 3G network and compared its performance to our MIMO-enabled Mobile WiMAX. Of course, we have no control over the HSPA commercial network, and we do not know the used parameters and the amount of background traffic while conducting our measurements. We did repeat the measurements, however, several times, and they are inline with previous empirical studies. We used the GlobeTrotter GT-MAX HSUPA adapter on the MS. In addition, the HSPA link was monitored during all measurements using Nemo Outdoor (www.anite.com).

The main physical layer differences between Mobile WiMAX and HSPA relate to different signal formats. Mobile WiMAX is based on OFDM, more specifically on its multi-user version OFDMA, HSPA employs direct-sequence spread-spectrum based on Wideband Code Division Multiple Access (WCDMA). OFDM is advantageous with respect to multipath interference, which is further improved by MIMO. HSPA uses Frequency-division Duplex (FDD) mode in contrast to Time-division Duplex (TDD) used by current Mobile WiMAX equipment. In HSPA FDD, 5 MHz channels are reserved for UL and DL separately. In other words, our Mobile WiMAX testbed uses only half the bandwidth of the HSPA commercial network. Further, the HSPA network employs HARQ, which is yet to be fully implemented in our Mobile WiMAX testbed.

C. Traffic Generation and Analysis

We measured TCP goodput, defined as the ratio of application payload over time to complete the transfer, using MOSET [12], [13]. MOSET uses HTTP for downloading various size files from the MOSET server (see Fig. 1) in the CN. After each file retrieval is successfully completed, the next one is initiated. UDP performance is evaluated in two separate cases: first constant bitrate (CBR) UDP traffic is injected into the Mobile WiMAX link at various bitrates and, in addition, the quality of live IPTV streams with 1 Mb/s and 2 Mb/s bitrates are subjectively assessed. CBR UDP traffic is generated and analyzed using a custom-made traffic generator. The traffic generator logs losses, throughput, goodput, and inter-packet delay variation (jitter). The IPTV streams are encoded using MPEG-4 Part 14 codec for video and MPEG-1 Layer 3 for audio, and includes dynamic changes in the bitrate. The packet size remains constant at 1358 bytes for both of bitrates, thus, the two IPTV streams have different inter-packet arrival characteristics. Video quality is evaluated by taking notes from the disturbances in video and audio. In all measurements, QoSMET [14] is employed to calculate the L3 throughput and show traffic characteristics.

IV. Results

For every measurement run, the measurement route remained the same, as illustrated in Fig. 2. Each measurement run required approximately four minutes, on average. Due to occasional traffic on the public road segments, test durations varied slightly, in the order of ± 10 s. However, there was virtually no effect on the results since no long stop periods occurred. During the measurement runs, we logged current link conditions in terms of mean Received Signal Strength Indicator (RSSI) and mean Carrier-to-Interference-plus-Noise Ratio (CINR) on per-second basis using the information provided by the PCMCIA card. Unfortunately, we could not log BER, from which the gain of STC could also be clearly seen. RSSI and CINR varied between -85 and -25 dBm (avg. median -59 dBm) and 13 and 34 dB (avg. median 30 dB), respectively.

This led, according to BS settings, to employing modulation schemes ranging between QPSK FEC: 3/4 and 64 QAM FEC: 5/6 in the DL. The signal quality values and behavior were quite similar most of the time during the measurement runs, regardless of whether MIMO was in use or not. Nevertheless, in low signal level areas and with MIMO enabled, CINR was often 2-3 dB better, but, at the same time, RSSI approximately 2 dBm worse than without MIMO.

We quantified the maximum capacity of the Mobile WiMAX link in stationary, line-of-sight conditions with and without MIMO using the maximum MTU of 1400 B. With single antenna mode we measured 9.3 Mb/s and 1.75 Mb/s for the DL and UL, respectively. With MIMO, the UL capacity remained the same, but the downlink capacity dropped to 7.1 Mb/s. Most likely, this is due to the overhead introduced to the transmitted data in the form of pilots and not by STC per se. Firstly, the use of STC doubles the number of pilot tones in the PUSC allocation. Secondly, the optional midamble is likely used to support multi-antenna transmission. The third reason for the performance degradation is that the use of STC zone increases the overhead in the from of additional MAPs inserted in the beginning of each zone. Finally, the vendor has chosen to limit the DL frame size in the case of STC compared to the single antenna transmission, which naturally increases the overhead of the Frame Control Header (FCH) and MAPs compared to the amount of payload data within each frame.

A. *TCP Performance*

We use MOSET to measure TCP goodput while considering the vehicular mobility use case described in the previous section. We configure MOSET to download three different file sizes; 64 B, 256 B and 1 MB. The total number of successful file downloads during each measurement run varied depending on the downloaded file size and whether MIMO was enabled or not. For 64 B file size, we were able to measure 1000 downloads in single antenna mode; MIMO allows us to download 20 % more files. For file sizes of 256 B, in single antenna mode we were able to complete 1000 downloads, while with MIMO we recorded 10 % more successful downloads. When we consider large transfers of 1 MB, as would be the case of email attachments, in single antenna mode we can repeat the download 19 times. With MIMO, we were able to repeat the back-to-back download 27 times, registering an impressive increase of 42 % over the single antenna measurement run. Since each measurement run was approximately of the same duration, we observe that MIMO has a clear advantage in terms of goodput in vehicular mobility use cases. This is unlike the stationary use case we presented above. The results reported next are average values from three measurement runs.

Fig. 3 presents boxplots of measured TCP goodput for the single antenna and MIMO runs when 64 B files were downloaded. With MIMO, the difference between the lower and upper quartiles is considerably smaller and points to lower number of TCP retransmissions. Mean goodput values are the same for both cases, approximately 3.2 kb/s. However, the

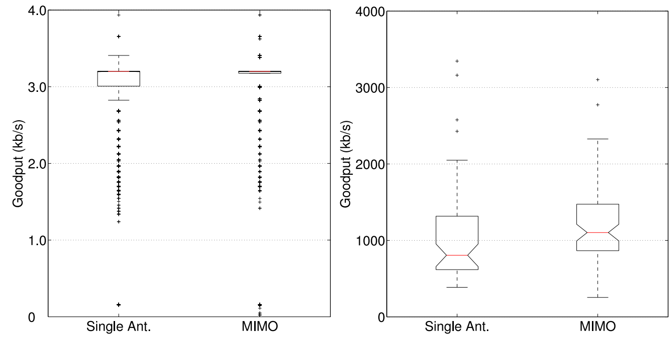

Fig. 3. TCP goodput values for 64 B (left) and 1 MB (right) file sizes

TABLE I
MOBILE WIMAX WITH MIMO (M): BETTER AND MORE CONSISTENT TCP PERFORMANCE COMPARED TO SINGLE ANTENNA (S) TRANSMISSION

Application payload	64 B		256 B		1 MB	
Antenna mode	S	M	S	M	S	M
Download time (ms)						
—Mean	231	190	241	190	9590	7369
—Median	160	160	160	160	8337	7178
—Std deviation	406	262	455	260	4935	2358

amount of non-outlier observations is not significantly smaller with MIMO. Actually, we noticed that on relatively low signal strength areas, no data is carried over the link when MIMO is enabled. In the runs with single antenna mode, traffic is propagated over the link until the link breaks down when the measured mean CINR value drops below 5 dB and mean RSSI value is less than -90 dBm. When MIMO is in use, the link stays up similarly to single antenna mode, but traffic propagation stops when mean CINR goes below 20 dB and mean RSSI below -76 dBm. On the BS side, CINR threshold of 20 dB is set to change the used modulation scheme from 64 QAM FEC: 1/2 to 16 QAM FEC: 3/4 in DL. Unfortunately, the employed PCMCIA card does not allow us to monitor dynamic changes in the modulation scheme. Thus, we cannot verify whether it changes to 16 QAM or not. However, this is a clear indication that the MIMO implementation is still work in progress.

Fig. 3 also illustrates TCP goodput values for 1 MB file sizes. The median goodputs were 1.1 Mb/s and 825 kb/s for MIMO and single antenna mode, respectively, which translates into a performance gain of 33 %. Goodput deviation in the MIMO case is remarkably larger (35 %), however, and is caused by the same phenomenon of the interrupted data transfer at low CINR and RSSI values as with 64 B file size. This affects all results of the MIMO case.

Table I summarizes the download times for each file size in terms of mean, median, and standard deviation. The impact of the previously introduced phenomenon in low signal level areas when using MIMO is taken into consideration as we exclude the results from those areas from all the measurement runs. Thus, the comparison is fairer because of equal link conditions. As can be seen from the mean values, goodput performance improvement with MIMO is notable already with very small payloads, clearly exceeding 20% with the 64 B and 256 B file sizes. For large downloads the benefits from STC become even more significant. The mean time for a 1 MB download with MIMO is 30% less than in the case of single antenna mode. Moreover, MIMO reduces the spread of the measurement observations quite dramatically. For small file sizes the standard deviation is reduced by 35-43%. For large transfers, standard deviation is reduced to less than half of that observed without MIMO. In short, Mobile WiMAX with MIMO registers better and more consistent TCP performance in our vehicular mobility use case.

B. UDP Performance

We measured CBR UDP performance by employing packet streams at four bitrates: 1 Mb/s, 2 Mb/s, 3Mb/s, and 4 Mb/s. Without MIMO, the packet loss rate was 1.3% for the 1 Mb/s and 2 Mb/s streams, and 1.6% for the 3 Mb/s stream. With the 4 Mb/s stream, the packet loss increased to 2.7%. This is quite impressive as the driving route includes areas where QPSK FEC: 3/4 modulation is shortly used. Note that 16 QAM FEC: 1/2 is barely sufficient for delivering the 4 Mb/s stream in the DL while QPSK cannot provide capacity for a 4 Mb/s stream in the Mobile WiMAX DL.

In the measurements with MIMO, the above-mentioned low signal reception in Area 1 and Area 2 (Fig. 2) led to significant packet losses in the range of 8-11%. We compare CBR UDP performance only on the route area where MIMO works without stagnation, i.e. between Area 1 and Area 2. Fig. 4 illustrates the throughput (including UDP/IPv4 headers) for all tested bitrates. The difference between MIMO and single antenna mode are minor compared to the performance difference observed for TCP transfers. In the case of 1 Mb/s CBR traffic, there is no significant difference in mean throughput and its standard deviation. In the case of the 2 Mb/s stream, MIMO improves average throughput by 21 kb/s and decreases deviation by 14.5 kb/s. For the case of the 3 Mb/s stream, there is no difference in mean throughput; MIMO slightly improves standard deviation by 10 kb/s. It is only in the case of the 4 Mb/s stream where we start observing a clear improvement in performance. Standard deviation decreases by 50% and average sustained throughput increases by 64 kb/s. Fig. 4 shows that the throughput with MIMO oscillates less and we observe no major degradation. With respect to delay jitter, we observe no major differences. Even for the 3 and 4 Mb/s streams, the average jitter is slightly over 1 ms lower with MIMO. Jitter values with MIMO are 1.8 ms and 2.4 ms for 3 Mb/s and 4 Mb/s streams, respectively.

During our subjective IPTV stream evaluation, MIMO gains became more evident, however. We evaluated the quality of live IPTV streams with the average bitrates of 1 Mb/s and 2 Mb/s. With single antenna mode, we observed a large amount of small errors in the video or audio quality of the IPTV streams. When the 1 Mb/s stream was injected into the WiMAX link, we perceived 67 small or moderate errors in the quality during the drive through the same measurement route used in the earlier measurements. With the 2 Mb/s stream, the number of experienced errors effectively doubled to 133. At this streaming rate, significant errors do occur leading the IPTV client to failures in frame decoding, even for a few seconds. Overall, however, IPTV streaming at 2 Mb/s was rather flawless in most of the runs in both cases.

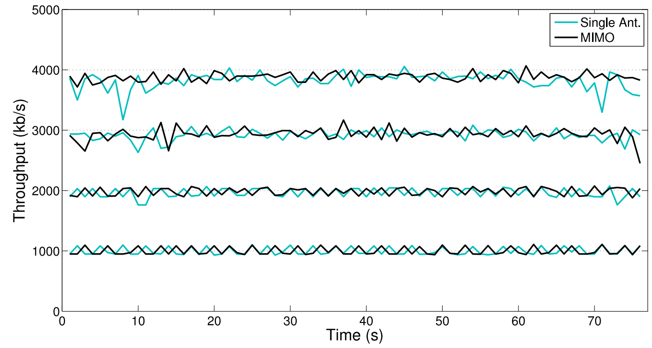

Fig. 4. UDP throughputs for various bitrate CBR traffic

With respect to IPTV streaming performance around Areas 1 and 2 in the measurement route, the problematic reception of data packets with MIMO had a negative effect on the user's perception of the IPTV quality. In these areas, the IPTV stream was undecodable for few seconds or caused major disturbance to the stream at both bitrates. Overall, in the case of the 1 Mb/s IPTV stream we detected only six small errors in addition to the errors encountered in Areas 1 and 2. With the 2 Mb/s IPTV data rate, the number of the visible small or moderate errors increased to ten. Even if we would not factor in the error findings in Areas 1 and 2, when MIMO was not in use, the MIMO gain is observed significant with respect to small errors caused by, for example, a loss of one packet. As mentioned above, the packet loss rates without MIMO and with the 1 Mb/s and 2 Mb/s CBR UDP streams were only in the order of 1.3%. At this level of packet loss rate, the use of ARQ or HARQ would bring significant performance improvement. We plan to extend our study in the near future and compare the video qualities with and without MIMO with more subjective measurements and use of Mean Opinion Scores (MOS) [15].

C. HSPA vs. Mobile WiMAX

Given that the theoretical capacity of HSPA is 3.6 Mb/s in the DL and 1.46 Mb/s in the UL, one would assume that HSPA should clearly underperform in the DL compared to Mobile WiMAX. In a recent empirical study in the same area, the maximum DL UDP throughput in this HSPA network was measured to be 2.7 Mb/s [16]; recall that in a similar stationary setting we measured a UDP throughput of 9.3 Mb/s in our Mobile WiMAX testbed. Of course, the modulation schemes in the measurements are different as HSPA does not support 64 QAM. Recall also that HSPA uses twice as much bandwidth as our Mobile WiMAX testbed. All measurements reported next were repeated three times. HSPA RSSI stayed on a good level, ranging between -43 and -74 dBm, and no cell reselections occurred during the measurement runs

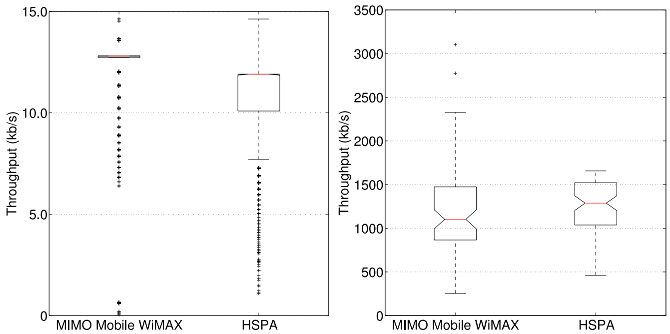

Fig. 5. TCP goodput comparison of MIMO enhanced Mobile WiMAX and HSPA with 256 B (left) and 1 MB (right) file sizes

in the exact same area and route shown in Fig. 2. That is, we repeated the measurements presented above following the same methodology and tools, but this time employ HSPA instead of MIMO enhanced Mobile WiMAX radio access. Overall, the signal level was slightly better with HSPA than with Mobile WiMAX. Fig. 5 illustrates the TCP goodput values for HSPA and Mobile WiMAX using 256 B and 1 MB file sizes. The HSPA mean goodput when downloading 256 B file is 10.7 kb/s, which is 1.6 kb/s lower than with Mobile WiMAX. Surprisingly, the goodput standard deviation is nearly 30% larger with HSPA, despite the use of HARQ in HSPA, and the fact that Areas 1 and 2 are not well-covered by our Mobile WiMAX testbed.

The benefits from employing HARQ are evident in the case of large downloads. Our measurements show that although Mobile WiMAX is capable of delivering the same mean TCP goodput as HSPA, HARQ allows HSPA to maintain a clearly better median goodput, by significantly reducing the number of TCP retransmissions. TCP retransmissions are followed by significantly smaller TCP sending window sizes, which clearly affects the application-perceived network access capacity. Mean TCP goodputs for HSPA and Mobile WiMAX are approximately 1.2 Mb/s. Even if we exclude the measurements performed around Areas 1 and 2, TCP mean goodput over Mobile WiMAX is only 30 kb/s greater than with HSPA, while the median goodput is still 100 kb/s smaller. Meanwhile, goodput standard deviation of HSPA is 35% lower than that of Mobile WiMAX. However, we point out that the maximum attained goodput during our route for HSPA is 1.66 Mb/s while for Mobile WiMAX it is nearly twice as much (3.1 Mb/s). In [16], the measured DL TCP goodput in the same network and with stationary conditions was 2.1 Mb/s. Thus, mobility affects TCP goodput over HSPA considerably as well.

V. Conclusion and Outlook

We empirically evaluated an Alamouti STC-based MIMO in a Mobile WiMAX testbed in both stationary and vehicular mobility scenarios. Although MIMO implementations have yet to reach maturity, our results clearly show that transmit diversity will bring large gains in next generation wireless networks. The MIMO gains will be observed more starkly when reliable transfers are required. In particular, under comparable signal conditions, and for a vehicular mobility scenario where the receiver maintains a velocity of 25-40 km/s, MIMO allows us to complete 42% more 1 MB file downloads over TCP. For traffic streams that do not require reliable delivery, MIMO appears to limit the number of sporadic packet losses. This had a significant effect on both CBR and real IPTV streams. The use of ARQ at the MAC layer or HARQ at the physical layer would alleviate the effect of sporadic losses, as we observed in our comparative HSPA measurements. Quantifying the performance gains of MIMO in combination with ARQ and HARQ in Mobile WiMAX is high in our future work agenda, as is the empirical evaluation of adaptive antenna systems. Static and dynamic beamforming schemes should provide a significant gain with respect to BS coverage area in scenarios similar to the ones explored in this paper.

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