Capacity Estimation and TCP Performance Enhancement over Mobile WiMAX Networks

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ABSTRACT

The mobile WiMAX system is based on IEEE 802.16e, which defines radio interface supporting several classes of Internet Protocol applications and services. While the mobile WiMAX system is being deployed, IEEE 802.16m TG is developing an amendment to the IEEE 802.16e to greatly improve the system performance, and it is focusing not only on the PHY and MAC performance but also on a level of end-to-end performance improvement that includes the scope of the network and application to embrace the strong market request and interest. To evaluate the mobile WiMAX system capacity and performance, all the aspects of performance evaluation — from air link to application — are required. For the network and application-level capacity and performance analysis, we first provide an overview of mobile WiMAX systems, especially of the OFDMA/TDD systems of IEEE 802.16e and then describe subscriber and application profiles that include traffic-mix ratio, data-session attempts for applications, diurnal-application traffic distribution, and the application-traffic model. Afterward, the simulation results of network-traffic characteristics and demand estimation are provided. Finally, in the last section, we provide simulation results of end-to-end application performance evaluation using the examples of VoIP and a TCP/IP performance-enhancement method that can be implemented in the mobile WiMAX MAC or MAC/IP cross layer.

INTRODUCTION

Mobile WiMAX, based on the IEEE 802.16e standard [1], is now a reality. Equipment is available from a number of vendors, and the WiMAX Forum has developed profiles for the interoperability testing of this equipment. A number of service providers have deployed mobile WiMAX systems all over the world. The mobile WiMAX system, based on IEEE 802.16e, definitely has a higher system capacity and a more sophisticated mechanism to provide a better quality of service (QoS) than previous wireless systems, such as code-division multiple-access (CDMA) or the universal mobile telecommunications system (UMTS). Also, the enhanced mobile WiMAX system currently under development in the IEEE 802.16m Task Group (TG) will have even higher capacity (> 2 × the IEEE 802.16e system). The IEEE 802.16m TG is focusing not only on the performance of the physical (PHY) and medium-access-control (MAC) layer but also on a level of end-to-end performance improvement that includes the scope of the network and application to embrace the strong market request and interest. The IEEE 802.16m evaluation methodology document emphasizes the importance of the performance beyond the PHY and MAC layer, and it includes the Transmission Control Protocol (TCP)-layer throughput metric as a mandatory performance measurement criterion in addition to the PHY- and MAC-layer throughput measurement [2].

In this article, we provide simulation results for the network-traffic demand analysis for the mixture of the various applications and also provide the voice-over IP (VoIP) capacity based on the analytic method and simulations over mobile WiMAX networks. Simulation results show that simple analytic estimation on channel capacity may not effectively reflect the dynamic behavior of the application traffic and protocol even for VoIP, which has semi-static or predictable application behavior. In addition to the capacity analysis, the performance of TCP, commonly used to carry best-effort (BE) traffic, is investigated. The effect of losing the acknowledgment (ACK) packet degrades the performance significantly. Therefore, the TCP ACK manager is introduced to mitigate this impact. To investigate TCP for unbalanced two-way traffic, we also developed an end-to-end WiMAX system and network-performance simulator, the wireless integrated-system emulator for WiMAX (WISE-W), on the OPNET Modeler. WISE-W complies with the IEEE 802.16e standard and WiMAX Forum Network Working Group specifications, and currently, it is used as a validation tool for the net-

This work was sponsored in part by a grant to Washington University in St. Louis from AWG of the WiMAX Forum.

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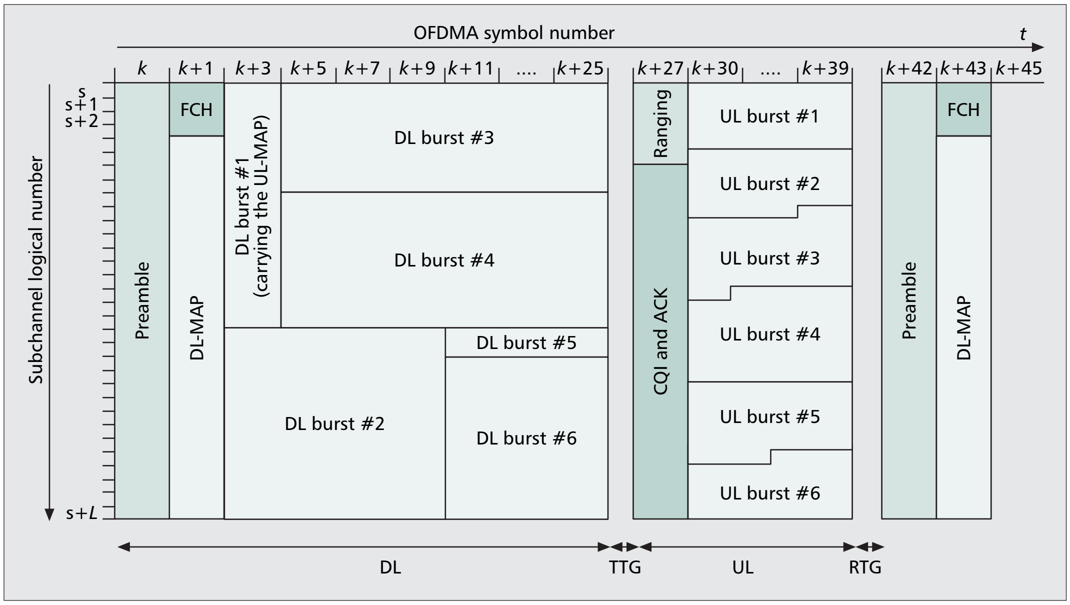

■ **Figure 1.** *A sample OFDMA TDD frame structure.*

The wireless metropolitan-area networks (MAN)-OFDMA PHY is based on OFDM modulation, and it is designed for NLOS operation in the frequency bands below 11 GHz. There are two different duplex modes for 802.16 systems: time-division duplex (TDD) and frequency-division duplex (FDD).

work simulator (NS)-2 WiMAX simulator being developed by the WiMAX Forum [3].

An Overview of Mobile WiMAX PHY

Mobile WiMAX uses scalable orthogonal frequency-division multiple access (OFDMA) to carry data — supporting channel bandwidths of between 3.5 MHz and 20 MHz, with up to 2048 subcarriers. The first release of the mobile WiMAX-certified system supports link adaptation using adaptive modulation and coding (AMC) and power control. Other PHY features include support for multiple-input multiple-output (MIMO) antennas to provide good non-line-of-sight (NLOS) characteristics and hybrid automatic repeat request (HARQ) for good error correction performance [4–7].

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Inverse Fourier transforming creates the OFDM waveform; this time duration is called a useful symbol time. The remaining small portion of the useful symbol time is copied to the beginning of the time duration, called a cyclic prefix (CP), in order to collect multipath signals while maintaining the orthogonality of the subcarriers; as long as the delay spread is within the length of the CP, the inter-symbol interference can be eliminated completely.

The available subcarriers are grouped into a few subchannels, and the MS is allocated one or more subchannels for a specified number of symbols. The two types of subcarrier allocation are called distributed allocation and adjacent allocation.

In distributed-subcarrier allocation, multiple-data subcarriers are grouped into a subchannel, and usually, the subcarriers in a subchannel are non-adjacent but can be adjacent in some cases. Among various permutation schemes in IEEE 802.16e, partial usage of subcarrier (PUSC) is selected for DL and UL-PUSC for UL for the first release of mobile WiMAX systems.

Band AMC is an adjacent-subcarrier-allocation technique defined in IEEE 802.16e. Unlike distributed-subcarrier allocation, adjacent-subcarrier allocation has subchannels with adjacent subcarriers. Whereas distributed-subcarrier allocation can achieve frequency diversity gain in frequency selective fading channels, adjacent-subcarrier allocation can achieve multi-user diversity gain using frequency-selective, radio-resource scheduling.

The mobile WiMAX DL subframe, as shown in Fig. 1, starts with one symbol of preamble. Other than preamble, all other transmissions use slots as discussed above. The first field in the DL subframe after the preamble is a 24-bit frame-control header (FCH). For high reliability, the FCH is transmitted with the most robust modulation coding scheme (MCS) (quadrature-phase-shift keying [QPSK]1/2) and is repeated four times. The next field is the down-link–medium-access protocol (DL-MAP), which specifies the burst profile of all user bursts in the DL subframe. The DL-MAP also is transmitted with QPSK1/2 with a repetition of two, four, or six as indicated by the FCH. The DL-MAP has a fixed part that is always transmitted and a variable part that depends upon the number of bursts in

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the DL subframe. This is followed by the UL-MAP, which specifies the burst profile for all bursts in the UL subframe. It also consists of a fixed part and a variable part.

The first slot duration of the UL subframe usually is used for ranging and fast feedback channels for the channel quality indicator (CQI) report and the HARQ acknowledgment/ negative acknowledgment (ACK/NACK). Mobile WiMAX provides contention-based ranging channels with CDMA-like signaling.

In mobile WiMAX, there are four steps of channel coding: randomization, forward error correction (FEC), interleaving, and modulation. Randomization is performed by a pseudo-noise (PN) sequence generator per FEC block data. Randomized data is encoded by convolutional turbo coding (CTC). HARQ greatly increases the data rate when the signal-to-noise ratio (SNR) is very low, and hence it increases the coverage of mobile WiMAX systems. The first release of the mobile WiMAX system supports chase-combining HARQ only. For chase-combining HARQ, each retransmission is identical to the original transmission, and the receiver simply combines retransmitted bursts with the original burst.

MIMO systems bring higher spectral efficiency compared to single-input single-output (SISO) systems. MIMO systems have various advantages over SISO and multi-input single-output (MISO) systems: multiplexing gain, diversity gain, interference suppression, and array gain. In highly scattering channels, transmitting independent data from different antennas increases the capacity linearly. Also, there are receiver diversity gains with multiple-receiver antennas and space-time-coding gain with multiple-transmitter antennas.

As described earlier, the TDD system has an advantage over the FDD system due to its channel reciprocity for easy support of advanced antenna technologies such as beamforming (BF). Using the sounding zone in the uplink subframe, the base station (BS) can use beamforming efficiently without feedback delay, which is inevitable in FDD systems.

An Overview of Mobile WiMAX MAC

The mobile WiMAX MAC layer provides a medium-independent interface to the PHY layer. The basic mode of operation is the point-to-multipoint (PMP) mode. A central BS and multiple MSs establish a wireless link in the PMP mode that operates in the PMP mode, and all MSs receive the same transmission within a given frequency channel and antenna sector. The BS is the only transmitter operating in the downlink direction. The main functions governed by the MAC layer include the network-entry procedure, quality-of-service (QoS) support, handover, power-saving mode (sleep mode and idle mode), multicast and broadcast service (MBS), and the ARQ mechanism [1].

At the MAC layer, the smallest unit is the MAC protocol-data unit (MAC PDU). Each MAC PDU consists of six bytes of MAC header, followed by a variable-length payload consisting of a number of optional subheaders and data. An optional four-byte cyclic redundancy check (CRC) follows the payload. The optional two bytes of subheaders include fragmentation, packing, and grant management subheaders. To request bandwidth for the BE connection, the MSs rely on the contention-based ranging process followed by the minimal amount of grant for the mobile to transmit six bytes of bandwidth request header indicating the amount of bandwidth. The amount of bandwidth also can be piggybacked in a MAC PDU using a two-byte grant management subheader.

One of the critical features in the mobile WiMAX MAC is ARQ, and its parameters are determined during a connection-establishment step using MAC management messages. The basic unit acknowledged by the receiving station is an ARQ block assigned with a sequence number. Each ARQ block is managed as a distinct entity by the ARQ state machines. When ARQ is enabled for the connection, the transmitter divides each MAC service data unit (SDU) into ARQ blocks. The MAC PDU is formed using ARQ blocks transmitted for the first time or retransmitted. The receiving station provides ARQ feedback information using a standalone MAC management message, or it piggybacks the ACK/NACK information on an existing connection. Each ARQ block can be in one of the following states — *not sent*, *outstanding*, *discarded*, or *waiting for retransmission*. The state of the block becomes outstanding from its initial state of not sent after it is transmitted. The block in the outstanding state may be either acknowledged or discarded, or its state changes to waiting for retransmission after `ARQ_RETRY_TIMEOUT`. The state of the block also can become waiting for retransmission before the expiry of `ARQ_RETRY_TIMEOUT` if it is NACKed. Its state changes from *waiting for retransmission* to *discarded* when the transmitter station receives an ACK message for the block or after the expiry of `ARQ_BLOCK_LIFETIME`. Blocks are sent in *not sent* or *waiting for retransmission* state only. The blocks in *waiting for retransmission* are sent first.

Subscriber and Application Profile

An application usage profile was studied for the purpose of consistent input for a system evaluation such as WiMAX network dimensioning, system capacitating, and end-to-end, application-performance simulation with additional information and an application-traffic model [3] across the WiMAX Forum working groups, especially the Application Working Group (AWG), Service Provider Working Group (SPWG), and Network Working Group (NWG) [8]. The usage profile inicludes the following items:
- Number of subscribers per cell
- Type of applications used by subscribers
- Type of subscribers
- Application-usage mix ratio
- Number of sessions used per day per application
- Diurnal traffic distribution per application

Class #	WiMAX AWG class	Packet data applications	% of Subscribers actively uising applications			Consumer (% of total subscribers)		Enterprise (% of total subscribers)		% of total machines
						64%		36%		100%
						Laptop PC	Smaller device	Laptop PC	Smaller device	
						30%	70%	70%	30%	
			Con-sumer	Enter-prise	Machine	No. ses-sions/day/subscriber	No. ses-sions/day/subscriber	No. ses-sions/day/subscriber	No. ses-sions/day/subscriber	No. ses-sions/day/subscriber
1	Internet gaming	Quake II	25.0%	5.0%	0.0%	0.15	0.15	0.05	0.05	0
		World of Warcraft	25.0%	5.0%	0.0%	0.15	0.15	0.05	0.05	0
		Xbox TimeSplitter2	25.0%	5.0%	0.0%	0.15	0.15	0.05	0.05	0
		ToonTown	25.0%	5.0%	0.0%	0.15	0.15	0.05	0.05	0
2	VoIP/Video Conference	VoIP	100.0%	100.0%	0.0%	5.71	5.71	4.44	4.44	0
		Video Conference	50.0%	100.0%	0.0%	0.30	0.30	0.27	0.27	0
		PTT	20.0%	20.0%	0.0%	0.10	5.00	0.10	5.00	0
3	Streaming media	Music/speech	100.0%	100.0%	0.0%	0.08	0.08	0.12	0.12	0
		Video clip	50.0%	100.0%	0.0%	1.10	1.10	1.50	1.50	0
		Movie streaming	100.0%	100.0%	0.0%	0.20	0.20	0.12	0.12	0
		MBS	100.0%	0.0%	0.0%	1.00	1.00	0.10	0.10	0
4	Information technology	IM	100.0%	100.0%	0.0%	7.26	7.26	7.26	7.26	0
		Web browsing	100.0%	100.0%	0.0%	5.00	2.00	5.00	2.00	0
		Email (POP3)	50.0%	50.0%	0.0%	0.65	0.65	1.50	1.50	0
		Email (IMAP)	50.0%	50.0%	0.0%	0.65	0.65	1.50	1.50	0
		Telemetry	0.0%	0.0%	100.0%	0.00	0.00	0.00	0.00	24
5	Media content download/ backup	FTP	50.0%	100.0%	0.0%	2.00	0.10	2.00	0.10	0
		P2P	30.0%	0.0%	0.0%	0.30	0.30	0.00	0.00	0

■ **Table 1.** *Application mix ratio and subscriber distribution.*

Number of Subscribers and Machines

South Korea predicts that 9.5 million users will sign up for WiBro (wireless broadband) services by 2012, and the estimated number of total WiBro subscribers, which is the main parameter affecting the system/network load, was submitted to the government of South Korea on the assumption that the service is rolled out in 84 cities, focusing on WiMAX users only [9]. South Korea estimates 320 subscribers and 670 machines per cell in 2011. The assumption may not hold for other regions or operators; however, the assumption is used as an example because it is essential for the end-to-end system performance study.

Traffic-Mix Ratio and Data-Session Attempt for Applications

Table 1 shows the types of subscribers, application-session attempts per application per day, and application-mix ratio among 18 applications categorized in five application classes as defined in the WiMAX Forum AWG. The application-mix ratio represents the distribution of applications that most likely users will use [8]. Table 1 shows three types of subscribers: consumer, enterprise, and machine. It assumes that 64 percent of the total human subscribers are consumers, and the rest of the human subscribers are enterprise subscribers. The table considers two different categories of mobile terminals that influence traffic and symmetry. Professionals tend to use terminals with high-resolution screens (*high-complexity* terminals) such as laptops and high-end PDAs for multimedia, where the accuracy and detail of the information is crucial. On the other hand, consumer subscribers have more interest in small, lightweight terminals, for which a high-resolution screen is not relevant. However, some exceptions are likely, for example, when a consumer (with a small device) sends a photo to someone in the fixed network (e.g., as

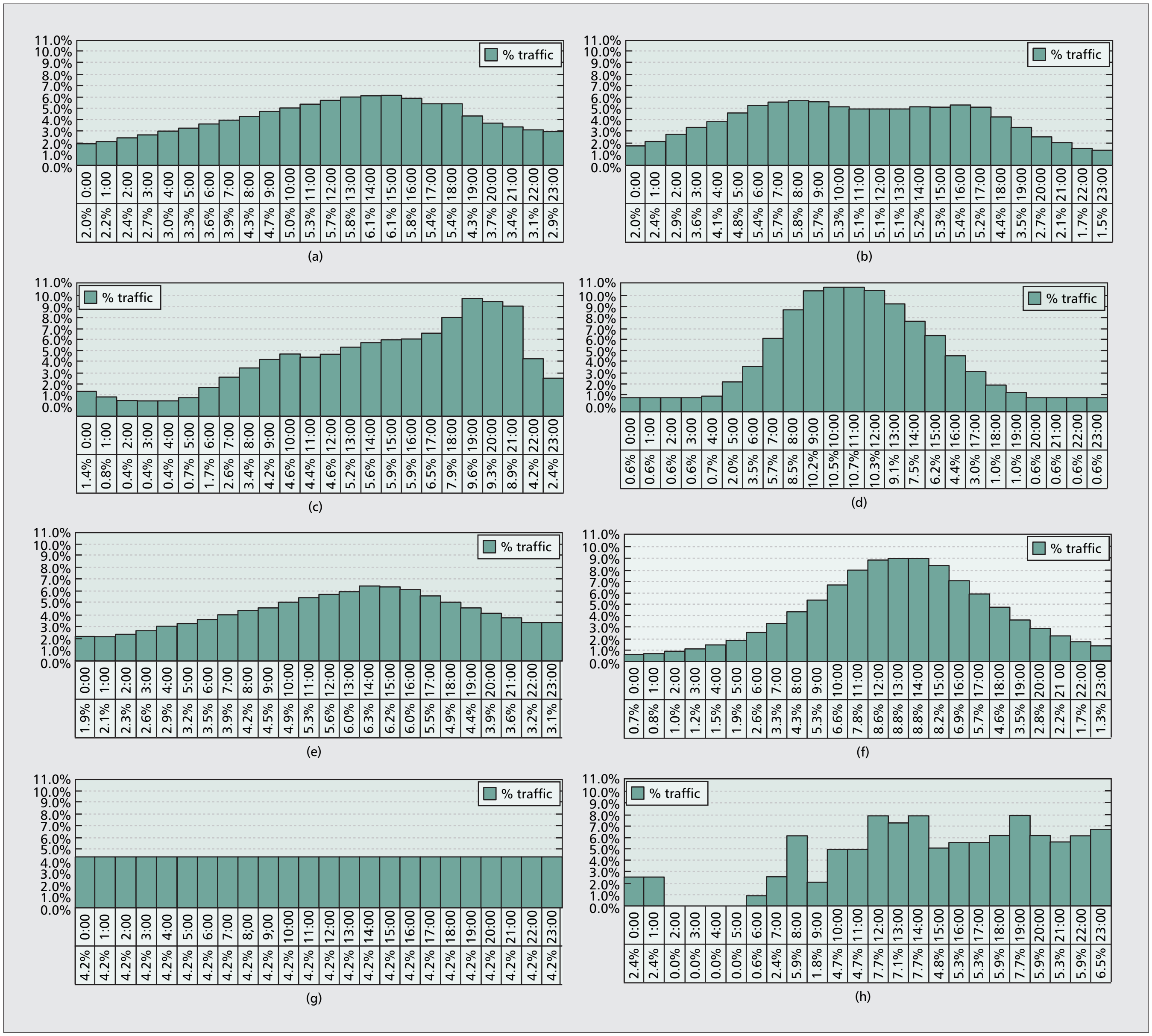


Figure 2. *Diurnal application traffic distribution: a) VoIP, PTT — consumer subscriber; b) VoIP, PTT — enterprise subscriber; c) IM, video clip — consumer subscriber; d) IM, video clip — enterprise subscriber; e) Web browsing, email, Internet game, streaming video, music, FTP, P2P — consumer subscriber; f) Web browsing, email, Internet game, streaming video, videoconference, music, FTP — enterprise subscriber; g) machine to machine — telemetry; h) MBS — consumer subscriber.*

an e-mail attachment). Here, the recipient has a high-resolution screen and printer and so wants the picture at high resolution. The size and resolution of the screen significantly affect the data volume of the picture or video media intended for it.

Diurnal-Application Traffic Distribution

The diurnal-application traffic distribution is important because daily traffic from certain applications can be concentrated during commuting hours, during working hours (e.g., 8:00 a.m. to 6:00 p.m.), in the evening, or can occur equally all day [10]. The number of sessions per active user during a day can be converted into the number of application sessions during a specific time of day with diurnal-application traffic distribution (Fig. 2).

Application-Traffic Model

With the advent of true wireless broadband access for the fixed and mobile workforce, new applications are emerging with their own challenges and requirements. WiMAX enables last-mile, point-to-point, and PMP elastic pipes that serve emerging *IP-based end devices*. The WiMAX Forum AWG characterized the applications in five classes and provided a consistent traffic model and a modeling framework across the WiMAX community so that each working group (e.g., SPWG and NWG) can use it as a reference when performing network dimensioning, system configuration or optimization, scheduling algorithm development, network sizing, simulating end-to-end application performance, and so on. The detailed application-traffic models can be found in [3].

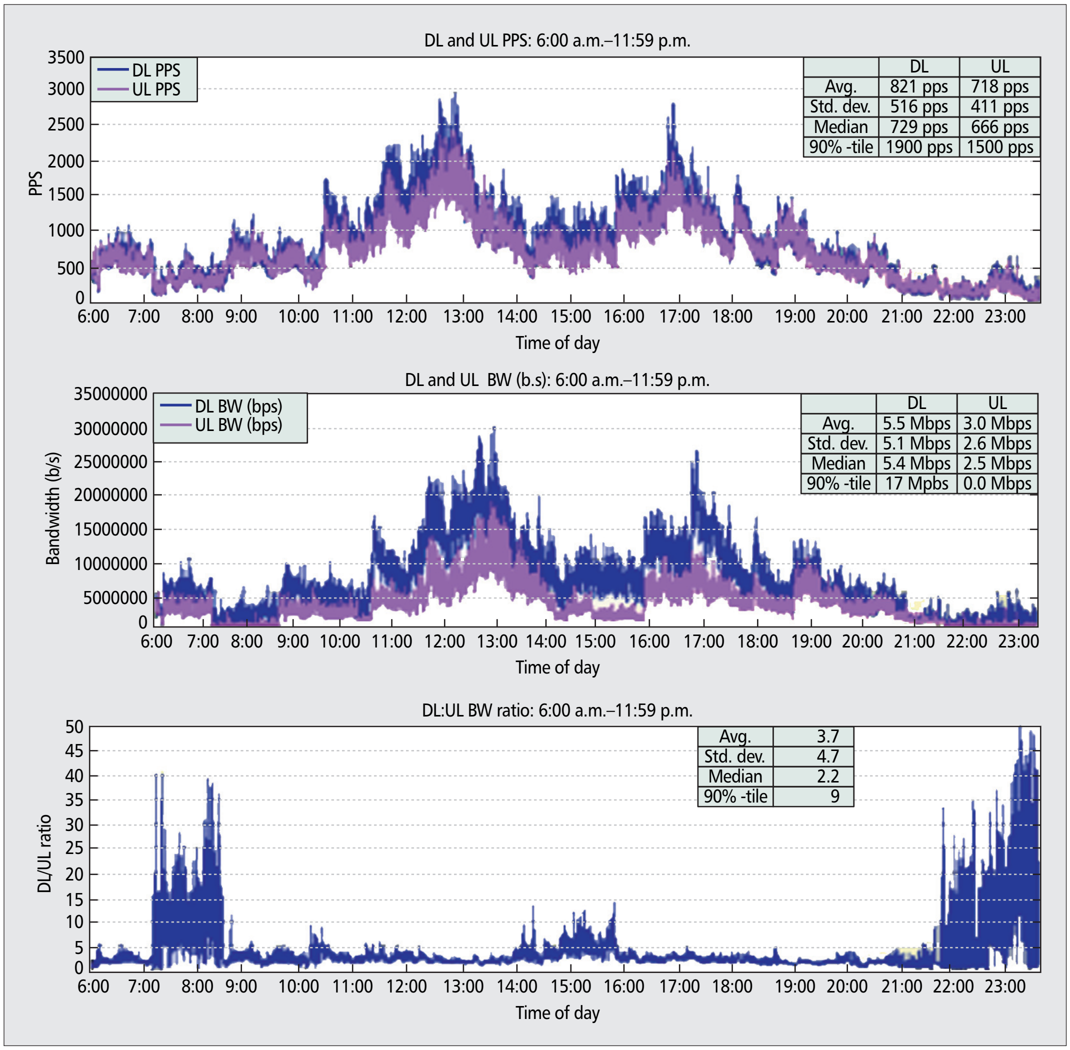


Figure 3. *Network traffic demand expectation.*

With the advent of true wireless broadband access for the fixed and mobile workforce, new applications are emerging with their own challenges and requirements. WiMAX enables last-mile, point-to-point, and PMP elastic pipes that serve emerging IP-based end devices.

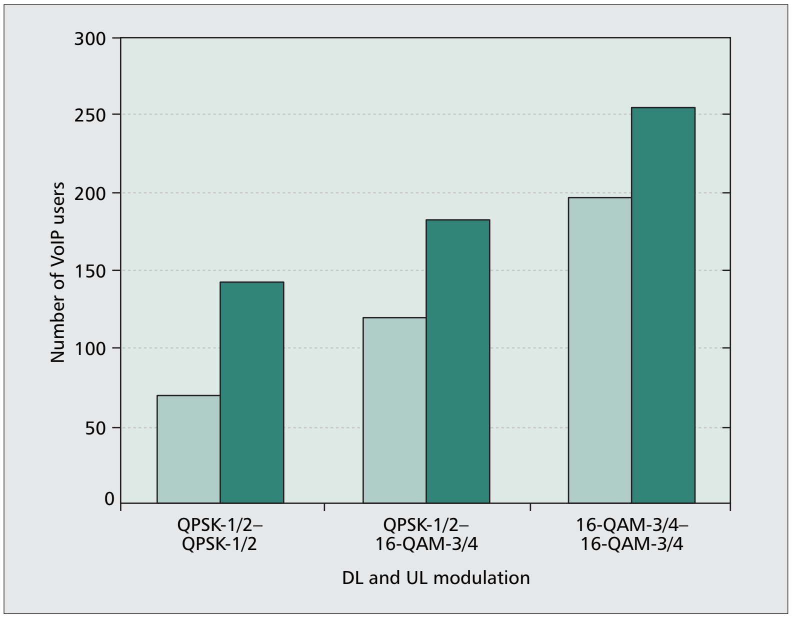
Network Traffic Characteristics and Demand Estimation

The IP-layer traffic characteristics and demand, in terms of bandwidth (bps and pps) in the R6 interface (between the BS and the access service network gateway [ASN-GW]), are estimated by the number of subscribers per cell for the year 2011 and an application usage profile as described in the previous section, using WISE-W, except for MBS, instant messaging (IM), push-to-talk (PTT), and peer-to-peer (P2P). For the sake of simplicity, packet loss is not considered in the network, and 70 msec of round-trip time (RTT) is statically configured.

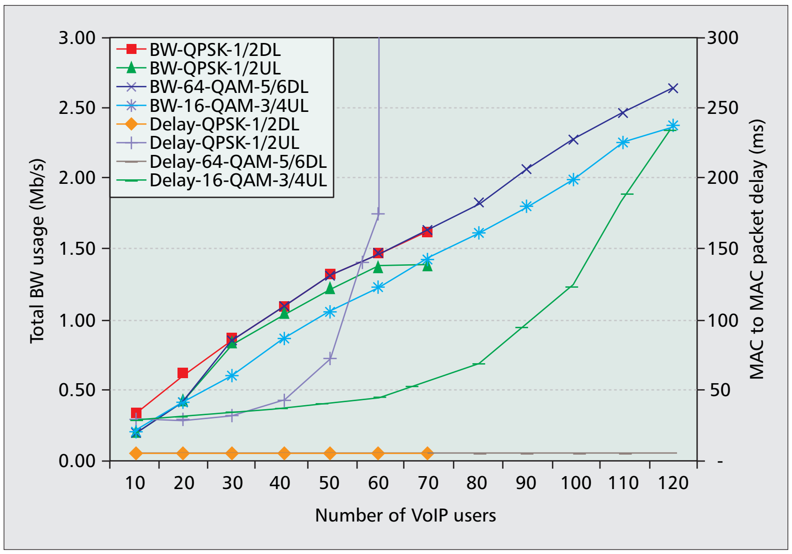
Figure 3 shows that the average DL and UL bandwidth is 6.5 Mb/s and 3.0 Mb/s, respectively, and the number of packets is 821 pps and 718 pps, respectively. The average DL to UL bandwidth ratio is 3.7, but the median is 2.2. The higher average is caused by the larger DL and UL ratio in the morning and evening. The higher ratio during these times of day is less significant for allocating the DL and UL radio resource, known as the DL and UL symbol ratio because the total amount of traffic during the time is low compared to the system capacity. The default symbol ratio for the system profile 1.A is 27:15 [11], and this is equivalent to approximately a 2:1 bandwidth ratio that matches the bandwidth ratio shown in Fig. 3.

System Capacity and Performance for VoIP

We have performed analyses to estimate the upper bound of the total number of simultaneous VoIP users, which is limited by the system bandwidth and performance simulation to identify the number of simultaneous VoIP users that satisfy the VoIP packet-delay guideline with same assumptions and the VoIP traffic model in [3]. The assumptions include the 27:15 symbol ratio for DL/UL, PUSC for both DL and UL, four repetitions for `DL_MAP`, and three UL symbol reservations for the control messages. Figure 4 shows the upper bound of the total number of VoIP users when header compression is disabled or enabled while (DL, UL) MCS levels are (QPSK1/2, QPSK1/2), (QPSK1/2,16QAM3/4), and (16QAM3/4, 16QAM3/4). The range of the number of users is from 70 to 250 users. This result may not be meaningful when QoS is considered in addition to the bandwidth require-



■ **Figure 4.** *Number of VoIP users: BW usage perspective (without and with header compression).*



■ **Figure 5.** *Number of VoIP Users: BW usage and packet delay perspective. DL/UL: (QPSK 1/2, QPSK1/2) and DL/UL: (64-QAM-5/6, 16-QAM-3/4).*

ment. Especially when VoIP service is provided through a BE service flow (SF), other than unsolicited grant service (UGS) or extended real-time polling service (ert-PS), the VoIP quality is more affected by the number of VoIP users as indicated in Fig. 5. The average VoIP packet delay from the MS to the BS when both DL and UL MCS is QPSK1/2 already exceeds 150 msec, which is the preferred end-to-end packet delay for VoIP service when the number of VoIP users is 60. When the DL and UL MCSs are 64QAM5/6 and 16QAM3/4, the average packet delay starts exceeding 150 msec with 100 VoIP users. The packet delay for DL is not a concern because the bandwidth and packet-delay constraint first appears in the UL when the BE SFs are used. The UL packet delay is primarily caused by the bandwidth request (BWR) procedure, and it is more serious when BWR collision occurs when many VoIP users transmit a BWR at the same time. The secondary cause is insufficient UL bandwidth (BW). When silence suppression is used, the packets are statistically multiplexed at the link level, and it may exceed the total link bandwidth for certain instances, which causes additional delay.

TCP IN IEEE 802.16E MOBILE WIMAX

In this section, we focus on the characteristics of TCP over mobile WiMAX. A common drawback, losing TCP ACK, is investigated. Because we developed a simulator, WISE-W, we also validate our results with a network simulator (NS)2 provided by the WiMAX Forum.

We prepare the PHY abstraction in two steps. First, the link-level simulator (LLS) generates effective signal-to-interference-plus-noise ratio (Eff_SINR) vs. block error rate (BLER) curves. Because each subcarrier of an OFDM system faces a different channel response, frequency selectivity is considered in calculating the post-processing SINR to predict the effective SINR. Then, a system-level simulator (SLS) runs simulations over a large number of frames to obtain the Eff_SINR trace for 19 cells, 57 sectors with various OFDMA, and link parameters. Based on the calculated effective SINR, the resulting BLER values can be obtained from the link abstract. Then, the OPNET simulator uses the Eff_SINR trace and the BLER curves as PHY abstractions for end-to-end simulations. Figure 6 shows an example of PHY abstraction and its usage in an OPNET simulation. Based on SINR traces generated by SLS, OPNET can directly map the BLER from link curves as in this figure.

Whereas the main focus of the LLS and SLS simulator is limited to PHY and MAC characteristics, the WISE-W focuses on the interaction between the MAC and the above-layer, network-layer, and application-layer characteristics with the PHY abstraction based on the LLS and SLS.

When TCP segments transmitted by the connections in one direction share the same physical path with the ACKs of connections in the opposite direction, the packets and ACKs can share a common buffer in the network elements. This sharing was shown to result in an effect called ACK compression, where ACKs of a connection arrive at a bottleneck link behind the data packets. The effect of ACK compression and the resulting dynamics of transport protocols under two-way traffic were studied previously by many researchers including Kalampoukas *et al.* [12]. The degradation in throughput due to bidirectional traffic can be dropped to 66.67 percent of that under one-way traffic and the separation of the flow of ACKs and data for the bidirectional TCP connection [13].

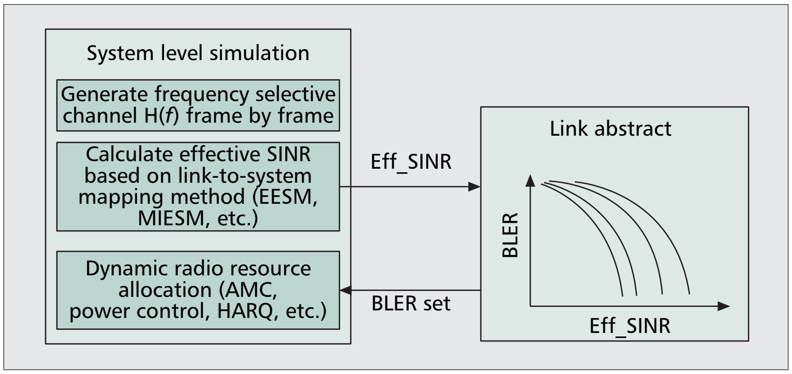
The mobile WiMAX MS and BS use SFs mapped to a specific connection identifier (CID) classified by certain classification rules in the WiMAX MAC; in the MAC layer, a dedicated traffic queue would be used per SF, which mixes the UL traffic belonging to the SF [14]. This would introduce the ACK compression effect; to separate the TCP ACK and upload traffic, independent SFs should be created. It is, however, impractical to create SFs for every application or service between the MS and the BS.

TCP ACK MANAGER: ACK UNIFIER AND ACK EXTRACTOR

We introduce the ACK manager, which consists of the ACK unifier and the ACK extractor in the WiMAX MAC, to reduce the probability of losing ACK packet information at the air link and the ACK compression effect. This also saves air-link bandwidth with a bidirectional TCP application sharing a single TCP connection that cannot be separated to separate SFs between the MS and BS without modifying the widely used TCP protocol at the transport layer. We evaluated the performance of the ACK manager with the end-to-end WiMAX system and the network performance simulator.

The TCP ACK manager consists of the ACK unifier and the ACK extractor to reduce the drop rate or delay of the TCP ACK packet between MS and the BS. The ACK unifier and ACK extractor are independent features but for higher performance improvement, both features can be implemented in the MS and the BS.

For a bidirectional traffic application, an MS can send and receive large packets through a single TCP connection simultaneously, and the TCP ACK packets can limit the UL/DL transmission throughput. For simplicity, we monitor download traffic only. If both end devices use a maximum transmission unit (MTU) size of 1500 bytes, a TCP ACK packet can be delivered as a separate packet or can be embedded in a 1500-byte packet from the mobile to the fixed terminal. When a TCP ACK packet is delivered separately, it could be delayed by the large packets waiting in a queue in the MS MAC by the UL traffic that belongs to the same SF and can degrade the download performance. The ACK unifier in Fig. 7 searches for a TCP/IP packet with a payload in the corresponding queue in the MS MAC; dedicated packet queues would be used per WiMAX SF. The TCP ACK information, such as the ACK sequence number and the ACK validation bit in the new ACK packet, is copied to, and TCP checksum must be recalculated in the TCP header in the selected packet. After unifying the ACK information, the TCP ACK packet is discarded. Because the TCP-ACK information is embedded in a large MAC SDU, the probability of losing the TCP ACK information is higher when the FEC BLER increases. A 1500 byte SDU consists of 42 36-bytes FEC blocks. The probability of losing a 1500-byte SDU between the MS and the BS with a 5 percent BLER and a maximum of two link-layer retransmissions is 10 percent over mobile WiMAX, and this is higher than losing a separate TCP-ACK packet (0.5 percent packet-loss probability). To eliminate the drawback, the SDU can be delivered into two MAC PDUs; one PDU includes the TCP/IP header, and the other PDU includes the rest of the fragment. The early recovering mechanism is described in the ACK extractor description.



■ **Figure 6.** *System-level simulation procedure and effective SINR mapping.*

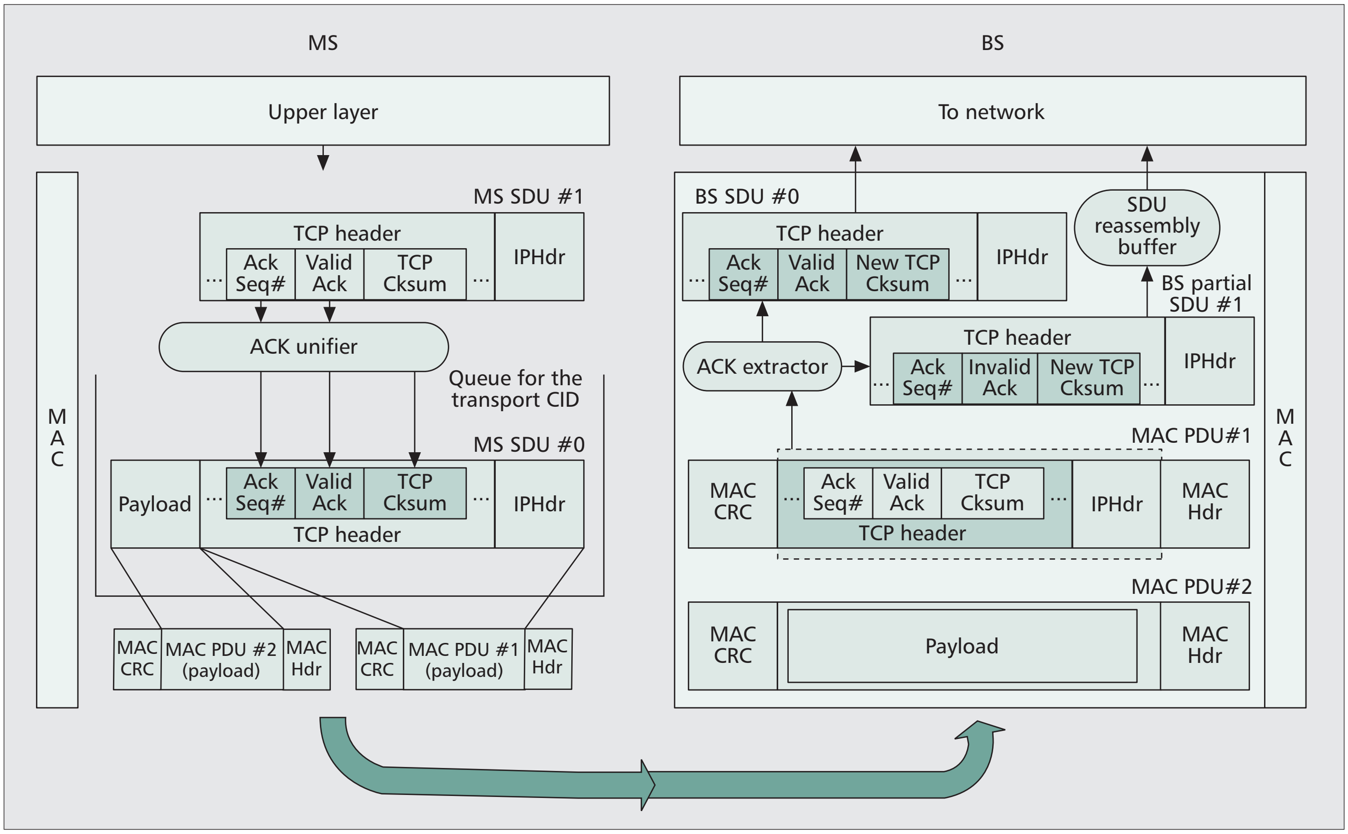
When TCP ACK information is embedded in a large SDU, either by the originating TCP or the ACK unifier, the ACK information should be recovered as soon as the TCP/IP header part is delivered without error, even before the entire SDU is delivered. The MAC PDU CRC is used for this purpose because the CRC in the IP and TCP header cannot be used. The ACK extractor in the BS in Fig. 7 monitors the first fragment of a MAC SDU to determine if it has the TCP/IP header, and if the valid ACK field of the TCP header was marked. If it satisfies this condition, then the TCP ACK extractor duplicates the TCP/IP header from MAC PDU #1 and updates the length and header checksum fields in the IP and TCP header checksum fields in the extracted packet so that the IP and TCP headers carry the correct information. Also, it must invalidate the valid ACK field of the TCP header in the original fragment received to prevent the TCP protocol from treating it as a duplicate TCP ACK. It immediately transmits the recovered ACK packet to the network and also puts the payload of MAC PDU#1 into the SDU reassembly buffer. The SDU is reassembled after receiving corresponding MAC PDUs. The TCP ACK extractor reduces the delay of the ACK packet because it is not required to wait for the entire packet to be successfully delivered from either the MS or the BS, whichever is delivering the packet.

TCP ACK MANAGER PERFORMANCE EVALUATION

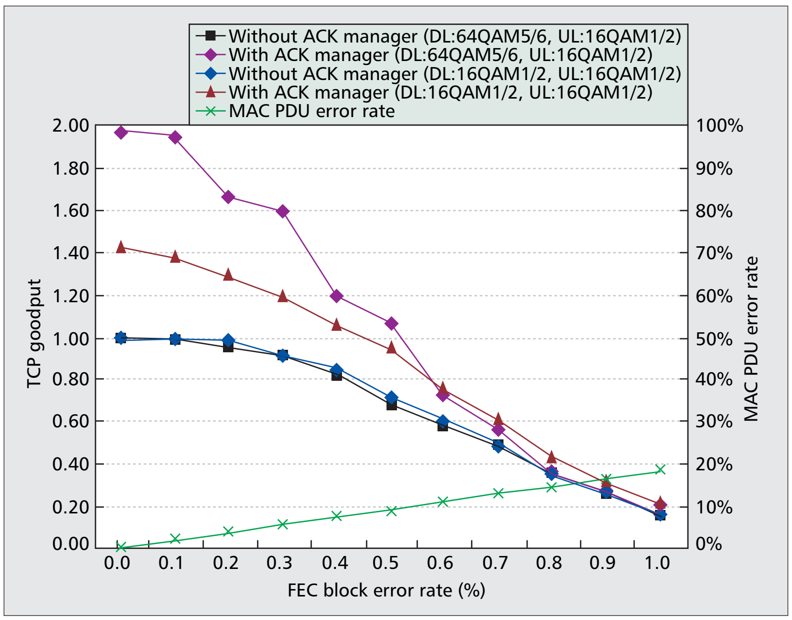
This section describes an enhancement of TCP ACK manager. For workload, a bidirectional File Transfer Protocol (FTP) application exchanging 5-Mbyte files was used on top of the WiMAX MAC ARQ scheme with and without TCP ACK manager, to analyze the performance improvement by the ACK manager.

For the MCSs, we use 16QAM 1/2 and 64QAM 5/6 modulation for the DL and 16QAM 1/2 modulation for the UL; and for the sake of simplicity, only DL air-link distortion was introduced.

Figure 8 shows a downloading TCP goodput improvement ratio vs. the FEC BLER, with and without the ACK manager; the MAC PDU error rate corresponds to the FEC BLER. While the FEC BLER is increasing, the TCP performance degradation ratio for both 64QAM DL and



■ **Figure 7.** *ACK manager: ACK unifier and ACK extractor.*



■ **Figure 8.** *TCP goodput vs. block error rate.*

16QAM DL scenarios is very similar without the ACK manager; and the performance dropped to about 20 percent when the FEC BLER reached 1 percent. This indicates that the FTP download could not take advantage of the higher DL bandwidth because the TCP performance was limited by the TCP ACK packet delay from the MS to the BS, incurred by the large packets by the FTP uploading.

In addition, in Fig. 8 the offered DL bandwidth was utilized significantly by adopting the ACK manager. When the FEC BLER is zero, the ACK manager increases the performance up to 40 percent with 16QAM 1/2 DL and more than 90 percent in a 64QAM 5/6 DL scenario. The performance improvement is reduced while the DL FEC BLER increases because the impact of the delayed ACK packet decreased due to the degraded DL quality. The TCP goodput performance improvement by the ACK manager diminishes when the FEC BLER reaches 1 percent, but the ACK manager still provides some of the air-link bandwidth saving by unifying a single TCP ACK packet with other TCP packets belonging to the same SF.

Conclusions

In this article we provide an overview of mobile WiMAX, subscriber and application profiles, and the simulation results for the network-traffic characteristics and the demand estimation and number of VoIP users; we introduced the TCP/IP performance enhancement method called TCP ACK manager.

One of the major objectives of developing the next-generation wireless communication technology is to provide a higher link capacity and to increase the application/service performance from the user perspective. Because the wireless application/service (from the user perspective) performance improvement efforts are emphasized more and more, we must consider more precise and dynamic environmental condition and system characteristics, including the type of application, application-traffic model, diurnal-usage scenario, and the behavior of various protocol-layers. This enables an operator to achieve successful cell and network-capacity planning while satisfying service performance from the user perspective. As indicated in the network-traffic demand estimation results, the amount of traffic into the system at different times of the day easily could be larger than a five-fold difference; and the estimation of the number of VoIP users could be very different with or without considering application performance guidelines. When 16QAM3/4 MCS is used for both DL and UL, the number of VoIP users is about 100 with a 150 msec packet-delay QoS guideline; whereas the number is about 200 users without considering the packet-delay QoS guideline.

This article also introduces the ACK manager, which reduces the probability of losing ACK packet information at the air link without modification to the widely used TCP protocol at the transport layer, and hence, greatly improves TCP performance. The ACK manager does not have the significant drawbacks that were often observed in the other mechanisms that are intended to solve the TCP problems over a wireless network.

REFERENCES

[1] IEEE P802.16Rev2/D9a, "Draft Standard for Local and Metropolitan Area Networks, Part 16: Air Interface for Broadband Wireless Access Systems," Mar. 2009.

[2] IEEE 802.16m, "Evaluation Methodology Document (EMD)," Jan. 2009; IEEE 802.16m-08/004r5.

[3] R. Jain, C. So-In, and A. Tamimi, "System Level Modeling of IEEE 802.16e Mobile WiMAX Networks: Key Issues," *IEEE Wireless Commun.*, vol. 15, no. 5, Oct. 2008.

[4] C. Eklund *et al.*, *WirelessMAN: Inside the IEEE 802.16 Standard for Wireless Metropolitan Networks*, IEEE Press, 2006.

[5] J. G. Andrews, A. Ghosh, and R. Muhamed, *Fundamentals of WiMAX: Understanding Broadband Wireless Networking*, Prentice Hall, 2007.

[6] L. Nuaymi, *WiMAX: Technology for Broadband Wireless Access*, Wiley, Mar. 2007.

[7] H. Yaghoobi, "Scalable OFDMA Physical Layer in IEEE 802.16 WirelessMAN," *Intel Tech. J.*, vol. 8, no. 3, Aug. 2004, pp. 201–12.

[8] WiMAX Forum AWG, "WiMAX Application Usage Profile," Apr. 28, 2006.

[9] WiMAX Forum MWG, "WiBro Briefing Document, WiMAX Forum Positioning, and Q&A," June 24, 2005.

[10] UMTS Forum, "3G Offered Traffic — All Services," June 2003.

[11] WiMAX Forum, "Mobile System Profile Release 1.0 Approved Specification," Rev. 1.7.0, Sept. 2008.

[12] L. Kalampoukas, A. Varma, and K. Ramakrishnan, "Two-Way TCP Traffic over Rate Controlled Channels: Effects and Analysis," *IEEE/ACM Trans. Net.*, vol. 6, no 6, Dec. 1998, pp. 729–43.

[13] L-E. Jonsson, G. Pelletier, and K. Sandlund, "Framework and Four Profiles: RTP, UDP, ESP, and Uncompressed," RFC 3095, July 2001.

[14] C. So-In, R. Jain, and A. Tamimi, "Scheduling in IEEE 802.16e Mobile WiMAX Networks: Key Issues and a Survey," *IEEE JSAC*, vol. 27, no. 2, Feb. 2009.

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