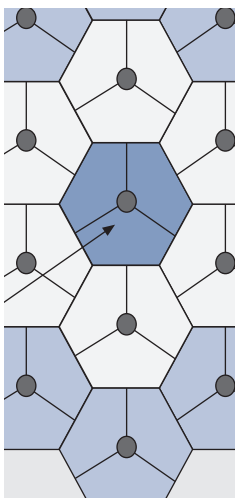


SYSTEM-LEVEL MODELING OF IEEE 802.16E MOBILE WiMAX NETWORKS: KEY ISSUES

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This article presents a summary of the simulation methodology and discusses the key issues and common mistakes in simulating various features of network configuration, physical layer, media access control layer, and application layer.

ABSTRACT

WiMAX¹ has attracted a lot of attention recently in the telecommunication community including researchers, product developers, and service providers. Numerous papers have been published on various design issues of WiMAX networks. Since the issues being discussed are usually ahead of product availability, most of these studies require simulation. It is important to have some common features among these models so that their results can be compared. Therefore, the Application Working Group of the WiMAX Forum has developed a standard simulation methodology that describes the key features to be simulated, the method of simulating these features, and various parameter values to be used. This system-level methodology has been used in several public and commercial WiMAX simulation models. This article presents a summary of the simulation methodology, and discusses the key issues and common mistakes in simulating various features of network configuration, and the physical, MAC, and application layers.

INTRODUCTION

The WiMAX Forum is a consortium of over 400 organizations interested in IEEE 802.16 based broadband wireless access. The members include service providers, equipment vendors, chip vendors, researchers, and users. The Forum develops interoperability specifications for equipment using IEEE 802.16 standards. IEEE standards have many options and allow a wide range of parameters. While this generality is good, it also makes it difficult for equipment from two vendors to interoperate unless they both choose the same set of optional features and similar values of various parameters. WiMAX Forum members

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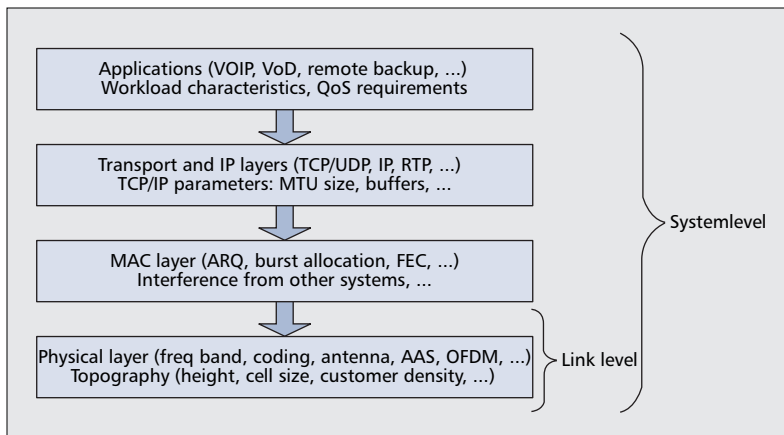
¹ WiMAX, Mobile WiMAX, Fixed WiMAX, "WiMAX Forum, WiMAX Certified, WiMAX Forum Certified, the WiMAX Forum logo, and the WiMAX Forum Certified logo are trademarks of the WiMAX Forum.

limit the standard options to a set of profiles that can be implemented in products [1]. The products are then tested for interoperability in WiMAX Forum certification laboratories. WiMAX Forum certification ensures that the equipment purchased from different vendors will interoperate. Most networking and telecommunications technologies have similar interoperability organizations; for example, the WiFi Alliance for IEEE 802.11 wireless LAN standards.

It is important to understand the difference between IEEE 802.16 standards and WiMAX, in the sense that WiMAX networks implement only a subset of the features and parameter values allowed by the IEEE standard. For example, IEEE 802.16 allows orthogonal frequency-division multiple access (OFDMA) frame duration to be 0.5 ms, 1 ms, 2 ms, and more. The WiMAX Forum has selected just one value: 5 ms. IEEE 802.16 allows mesh mode and license exempt mode operations. The WiMAX Forum does not yet have a profile for these modes, so they are more of theoretical interest at this point in time. OFDMA frame duration has a significant impact on the throughput and delay performance of applications and so researchers analyzing WiMAX networks may get very different results just by using an incorrect value.

For performance results from two research studies or two vendors to be comparable, it is important that both be based on a similar set of features and parameter values, and be representative of the real-world equipment, which in the case of IEEE 802.16 equipment means parameters and features specified in WiMAX Forum profiles. In addition, new technologies often have features that are not well understood and may be modeled incorrectly. Therefore, experts need to discuss various modeling alternatives and select the best, if there is one.

The Application Working Group of the WiMAX Forum is chartered to study the performance of various applications on WiMAX networks and recommend best practices for optimizing the applications' performance. The tasks include developing standard application workload models. For the last three years, the Working Group has been developing a system-



■ **Figure 1.** *Component layers of a model.*

level simulation methodology [2] that can be used by anyone interested in simulating WiMAX networks. The document is a result of three years of deliberations by numerous simulation and technology experts. This article presents a summary of the issues presented in that document.

Other wireless standard groups, such as the Third Generation Partnership Project (3GPP) and 3GPP2, also have similar simulation methodology documents [3–6]. IEEE 802.16m, the group developing the next generation of IEEE 802.16 networks, is also beginning its work with a standard modeling methodology [7]. This will facilitate comparison of various proposed alternatives to be based on a common set of assumptions.

The simulation methodology described in the WiMAX Forum document and summarized here is general, so it can be used with any modeling platform such as Network Simulator 2 (NS2) (www.isi.edu/nsname/ns), CoWare (www.coware.com), OPNET (www.opnet.com), OMNET++ (www.omnetpp.org), and Qualnet (www.qualnet.com).

The organization of this article is as follows. The next section provides an overview of a mobile WiMAX system and its key technology (OFDMA). We then highlight the system-level and link-level approaches of modeling, and provide a list of recommended values for important network configuration parameters. The following section addresses physical layer (PHY) modem abstraction for system simulation. We then cover the medium access control (MAC) layer modeling issues, and discuss scheduler design and modeling, which are key to the performance of a WiMAX system. The final section captures the issues in application traffic modeling.

OVERVIEW OF MOBILE WIMAX AND OFDMA

IEEE 802.16 supports a variety of PHY layers. Each has its own distinct characteristics. First, WirelessMAN-SC (single carrier) PHY is designed for 10–60 GHz spectrum. While IEEE has standardized this PHY, not many products are implementing it because this PHY requires line-of-sight (LOS) communication. Also, rain

attenuation and multipath affect reliability of the network at these frequencies. To allow non-LOS (NLOS) communication, the IEEE 802.16 working group designed the orthogonal frequency-division multiplexing (OFDM) PHY using spectrum below 11 GHz [8]. This PHY is designed for fixed subscriber stations. The WiMAX Forum has approved several profiles using this PHY. Most of the current WiMAX products implement this PHY. In this PHY, multiple subscribers use time-division multiple access (TDMA) to share the media. OFDM is multicarrier transmission in which thousands of subcarriers are transmitted, and each user is given complete control of all subcarriers. For mobile users, it is better to reduce the number of subcarriers so that the subscriber station can use higher transmission power per subcarrier and increase their signal-to-noise ratio. This combination of time- and frequency-division multiple access in conjunction with OFDM is called OFDMA. The details of these interfaces can be found in [8].

The IEEE 802.16 standard is designed to use any available spectrum width, which can range from 1.25 to 20 MHz. Rather than designing a new circuit for each spectrum width, considerable cost savings can be obtained if the subcarrier spacing is kept fixed for all systems, and the number of subcarriers is set proportional to the width of the available spectrum. This is called scalable OFDMA or SOFDMA. Unless specified otherwise, 10 MHz spectrum width and a 5 ms OFDMA frame time are used. The 5 ms frame time gives low-latency jitter to delay-sensitive applications while keeping the framing overhead low. The default downlink to uplink subframe time ratio is 2:1. This is a compromise between data traffic, which is highly asymmetric, and voice traffic, which is symmetric. For a voice-only network, a downlink to uplink ratio of 1:1 will support more users. For data traffic, higher values of this ratio support more users.

SYSTEM-LEVEL VS. LINK-LEVEL MODEL

A link-level model is used to study the transmission between a base station (BS) and one or more users. The key is to study the point-to-point link and the effect of various link-level design decisions on the performance. Link-level models generally concentrate on the PHY layer. Higher layers, such as IP routing, TCP sessions, or applications, may or may not be modeled. The performance is measured in terms of bit per second throughput. A system-level model, on the other hand, consists of a network of BSs, and the emphasis is on the application layer performance as expressed by user-perceived quality of service parameters such as voice or video quality. The PHY layer is abstracted as much as possible. Figure 1 shows important issues in various layers. A link-level model concentrates on the PHY layer, while a system-level model concentrates on the other layers.

CENTER CELL CONFIGURATION

It is well known that the performance of a wireless transmission is determined by the signal-to-noise ratio (SNR). The noise usually arises from

stray transmissions and thermal causes. However, in WiMAX as well as other cellular networks, “interference” from nearby BSs may affect the signal much more than noise; therefore, it is important to model the signal-to-interference-plus-noise ratio (SINR). To determine the interference, we need an accurate representation of various sectors of a cell and the surrounding cells. System-level models traditionally use a center cell configuration consisting of 19 cells, as shown in Fig. 2.

Basically the network consists of 19 hexagonal cells with six cells surrounding the center cell in the first tier. There are 12 cells surrounding the center cell in the second tier. Each cell has three sectors by default; thus, there are 57 total sectors. A number of mobile subscriber stations (SSs) are randomly dropped over these 57 sectors. Each SS corresponds to an active user session that runs for the duration of a drop. A *drop* is defined as a simulation run for a given set of subscribers over a specified number of OFDMA frame times. At the beginning of each drop, the subscribers are associated with a specific BS and sector, henceforth referred to as the serving BS. The association is based on both path loss and shadow fading, which are fixed for the duration of the drop.

INTERFERENCE MODELING

One of the key benefits of the OFDMA air interface is its possibility of enabling frequency reuse of one; that is, the same frequency is used in all neighboring cells and sectors. This eases deployment since no frequency planning is required. This attribute is already available in code-division multiple access (CDMA) networks, and is highly desirable in mobile WiMAX based on IEEE 802.16e. High frequency reuse patterns, however, cause the system to become interference limited. The interference seen by an SS in downlink and a BS in uplink is typically frequency- and time-selective. Therefore, it is not accurate to model interference as a white noise process with flat spectrum. Network simulators should model interference using a realistic channel model, which includes both slow fading and fast time-/frequency-selective fading components. As an optional simplification, the time-frequency channel of only the strongest interferers may be modeled to reduce simulation complexity. The remaining interferers are then modeled as (spatially) white and non-frequency-selective additive white Gaussian noise (AWGN) processes whose variances change in time based on a Rayleigh fading process.

FREQUENCY REUSE MODEL

The network topology is basically divided into clusters of N cells. Each cell in the cluster has a different frequency allocation, S sectors per cell, and K different frequency allocations per cell. Thus, the frequency reuse pattern can be represented as $N \times S \times K$. Figure 3 shows a network topology with reuse pattern $1 \times 3 \times 3$. The colored markings in the center of each cell indicate the sectors and point in the boresight direction. The red markings correspond to sector deployment in the same frequency allocation. The blue and green markings indicate the other two fre-

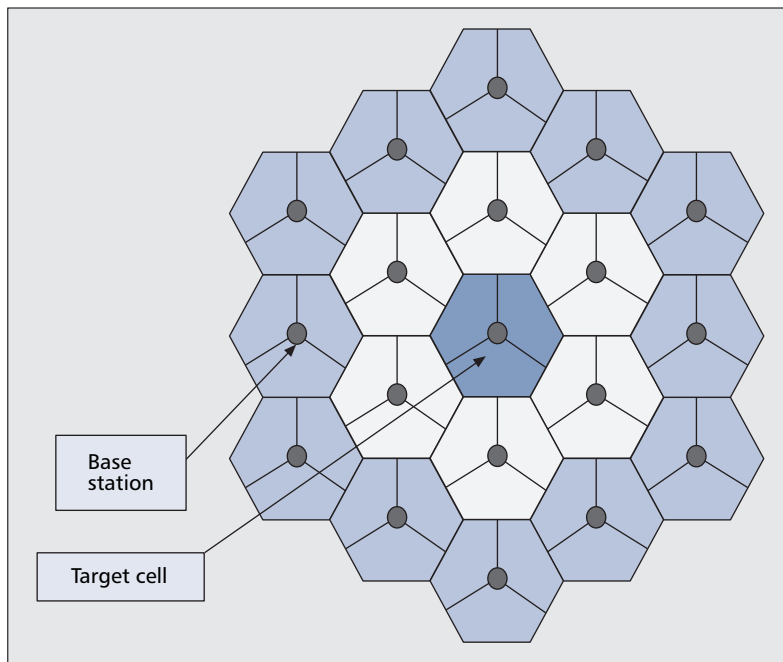


Figure 2. 19-cell configuration used in system-level models.

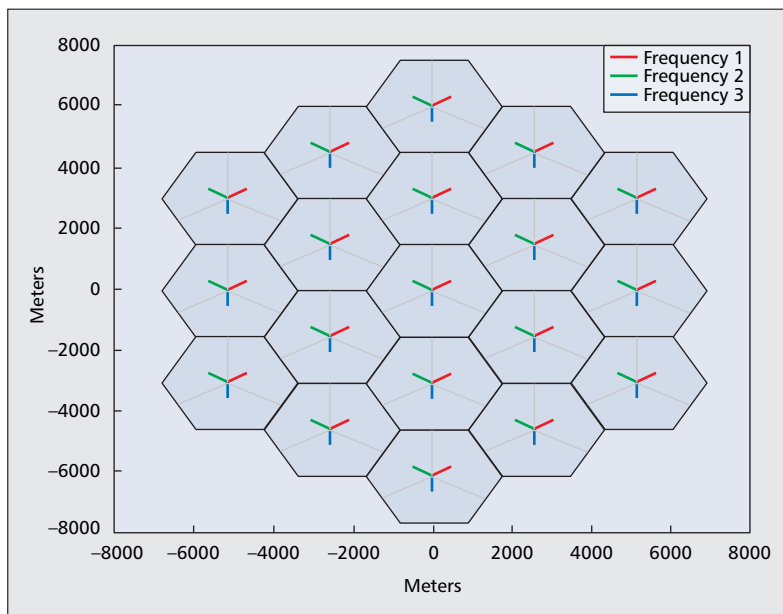


Figure 3. Network topology for trisector (19-cell) configuration with $1 \times 3 \times 3$ reuse.

quency allocations for a reuse three network. Networks with universal frequency reuse $1 \times 3 \times 1$ have the same network topology, except the same frequency allocation is deployed in all sectors throughout the network. Thus, an operator using, say, 10 MHz channelization would require a total of 10 MHz of spectrum to support a time-division duplexing (TDD) system with $1 \times 3 \times 1$ reuse. To reduce interference, a frequency reuse pattern of $1 \times 3 \times 3$ can be implemented by either sharing the available subchannels (say 1/3) in a 10 MHz channel or using 30 MHz of spectrum with 10 MHz in each sector.

Table 1 shows a key subset of network config-

Parameter	Description	Value Range
N_c	Number of cells	19
S	Number of sectors/cell	1, 3, 4, 6
$N_s = S \times N_c$	Total number of sectors	19, 57, 76, 114
R	Base station to base station distance	0.5 to 30 km (1 km)
S	Number of sectors per cell	3, 6
K	Number of frequency allocations in the network.	1, 2, 3, 4, 6
F_{BS}	Frequency allocation (integer index) used in each base station sector	1, 2, 3, 4, 5, 6
	Operating frequency	2.0 — 3.5 GHz (2.5 GHz)
	Duplexing scheme	TDD

■ **Table 1.** Network configuration parameters.

uration parameters that have been discussed in this article. There are three sources for these recommended values. First, the values specified in the profile documents were used to set ranges. Second, the values used in recent requests for proposals by leading service providers were discussed to be used as default. Third, the members decided that the parameter ranges should be such that the models can easily be adopted for upcoming waves and the next generation of WiMAX based on IEEE 802.16m. This third requirement leads us to not limit the options to strictly follow the current profiles, but to be a superset of the current WiMAX profile. The default values are shown in bold and are compliant with current WiMAX profiles.

PHYSICAL LAYER MODELING

In a system simulation it is important to define a model that accurately predicts the link-layer performance in a computationally simple way. The requirement for such a model stems from the fact that simulating the physical layer links between multiple BSs and SSs in a network/system simulator can be computationally prohibitive. This model is referred to as the PHY abstraction. The role of abstraction is to predict the decoded packet data unit (PDU) error rate (PER) given a set of SINR values for each subcarrier k in the PDU and the modulation coding scheme (MCS).

EQUIVALENT SINR COMPUTATION

WiMAX uses OFDMA which is a multicarrier modulation. Each subcarrier has a different SINR. We need a method to combine these SINRs to a single equivalent SINR for an AWGN channel. Many wireless technologies use a simple method based on averages of SINRs. This is not adequate for an OFDMA system for four reasons. First, forward error correction

(FEC) block bits are spread between subcarriers. Second, due to frequency selectivity of a desired signal, each subcarrier observes a different SINR. Third, decoder behavior depends on the SINR fluctuations between FEC block bits, not only on the average SINR. Fourth, bursts that observe different channel and interference characteristics will display different bit error rate (BER) or block error rate (BLER) results even though they may have the same average SINR. For OFDMA systems, the mapping from a vector of the code word's per-subcarrier SINR values to an AWGN-equivalent SINR metric is required.

Several mapping functions have been proposed over the years: the quasi-static, convex, and Shannon methods, and exponential effective SINR mapping (EESM). After significant discussions, the WiMAX Forum AWG group has decided to recommend EESM as a default recommended method. EESM mapping is defined as follows:

$$SINR_{eff} = -\beta \cdot \ln \left(\frac{1}{N} \sum_{i=1}^N e^{-\frac{SINR_i}{\beta}} \right)$$

where $SINR_i$ is the SINR of the i th subcarrier in the code word, β is an adjustment factor that depends on the FEC type and MCS, and is modem-implementation-specific. The WiMAX Forum commissioned a simulation study to determine appropriate values of β . The recommended values are shown in Table 2. These values are to be used for single-input single-output (SISO), PUSC mode, spatial channel model with velocities of 3 km/h (Ped-B) and 60 km/h (Veh-A), and 100 independent channel realizations. Ideal channel estimation is assumed.

MAC LAYER MODELING

The main functions at the MAC layer that have significant impact on the performance of WiMAX systems are: scheduling, automatic repeat request (ARQ) and hybrid ARQ (HARQ), fragmentation and packing, and packet header suppression (PHS). Among these, the scheduler is possibly the most significant and complex. If an inefficient scheduler is used, it is possible to get meaningless results from simulation models. Also, the IEEE 802.16 standard does not specify any scheduling mechanism. In this section we discuss the simulation issues related to scheduling and refer the reader to the WiMAX simulation methodology document for discussion of other MAC features.

The MAC scheduler must efficiently allocate the available radio resources in response to bursty data traffic, time-varying channel conditions, and specified scheduler criteria, if any. The data packets are associated with service flows with well defined QoS parameters in the MAC layer so that the scheduler can correctly determine the packet transmission ordering over the air interface. The CQICH provides fast channel information feedback to enable the scheduler to choose the appropriate coding and modulation for each allocation. The adaptive

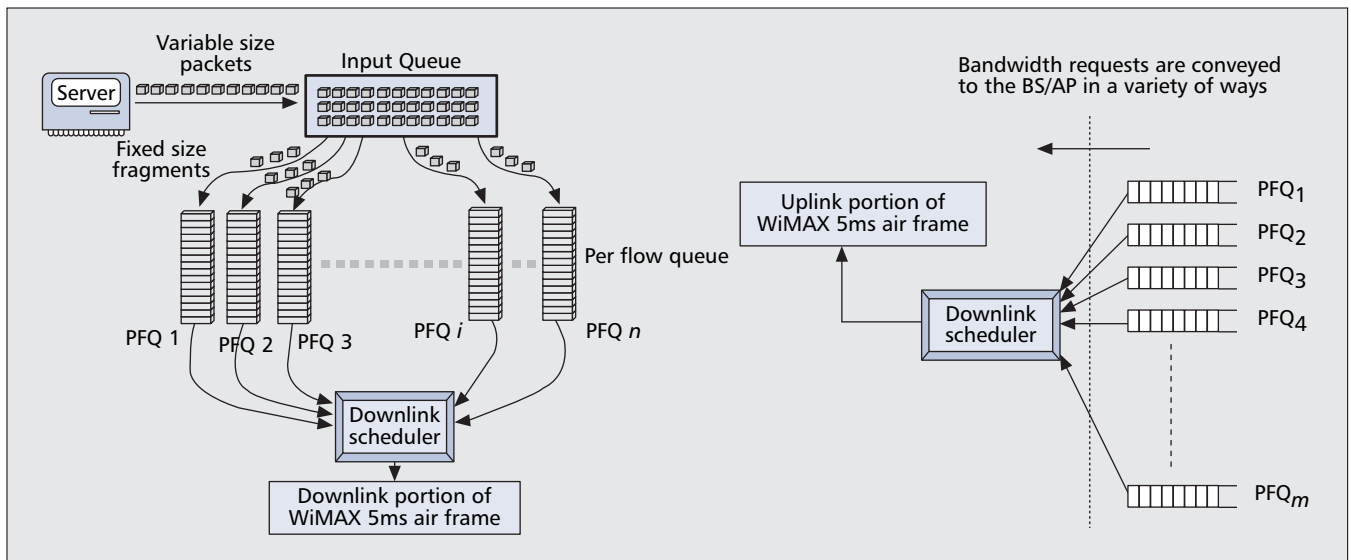
Index	Modulation	M (bits per symbol)	Rate	n (repetitions)	J	Data block size (bytes)	Encoded data block size (bytes) = $48 \times n \times M/8$	β Ped-B (dB)	β Veh-A (dB)
1	QPSK	2	1/2	1	10	6	12	2.46	2.54
2	QPSK	2	1/2	2	10	12	24	2.28	2.26
3	QPSK	2	1/2	3	10	18	36	2.27	2.26
4	QPSK	2	1/2	4	10	24	48	2.18	2.12
5	QPSK	2	1/2	5	10	30	60	2.05	2.07
6	QPSK	2	1/2	6	10	36	72	2.00	2.06
7	QPSK	2	1/2	8	10	48	96	2.03	2.02
8	QPSK	2	1/2	9	10	54	108	2.04	2.01
9	QPSK	2	1/2	10	10	60	120	1.98	2.01
10	QPSK	2	3/4	1	6	9	12	2.56	2.50
11	QPSK	2	3/4	2	6	18	24	2.43	2.43
12	QPSK	2	3/4	3	6	27	36	2.46	2.44
13	QPSK	2	3/4	4	6	36	48	2.41	2.39
14	QPSK	2	3/4	5	6	45	60	2.41	2.41
15	QPSK	2	3/4	6	6	54	72	2.38	2.37
16	16-QAM	4	1/2	1	5	12	24	7.45	7.48
17	16-QAM	4	1/2	2	5	24	48	7.14	7.14
18	16-QAM	4	1/2	3	5	36	72	7.00	6.92
19	16-QAM	4	1/2	4	5	48	96	7.34	7.53
20	16-QAM	4	1/2	5	5	60	120	6.89	6.82
21	16-QAM	4	3/4	1	3	18	24	8.93	8.93
22	16-QAM	4	3/4	2	3	36	48	8.87	8.87
23	16-QAM	4	3/4	3	3	54	72	8.85	8.90
24	64-QAM	6	1/2	1	3	18	36	11.31	11.43
25	64-QAM	6	1/2	2	3	36	72	11.11	11.16
26	64-QAM	6	1/2	3	3	54	108	11.09	11.01
27	64-QAM	6	2/3	1	2	24	36	13.80	13.74
28	64-QAM	6	2/3	2	2	48	72	13.69	13.70
29	64-QAM	6	3/4	1	2	27	36	14.71	14.68
30	64-QAM	6	3/4	2	2	54	72	14.59	14.55
31	64-QAM	6	5/6	1	2	30	36	15.32	15.17
32	64-QAM	6	5/6	2	2	60	72	15.29	15.27

■ **Table 2.** Reference EESM beta values.

modulation and coding combined with ARQ and HARQ provide robust transmission over the time varying channel.

The scheduling service is provided for both

downlink and uplink traffic. In order for the MAC scheduler to make an efficient resource allocation and provide the desired QoS in the uplink, the SS must feedback accurate and time-



■ **Figure 4.** Downlink packet scheduler (left) and uplink packet scheduler (right).

ly information as to the traffic conditions and QoS requirements.

The scheduler basically first chooses the appropriate coding and modulation for each allocation and then maps individual service flows to specific regions of the 2D TDD frame. The mapping problem is a generalized 2D bin packing problem (NP-hard); thus, heuristic schemes are used for practical systems, typically vendor-specific and proprietary implementations.

The downlink scheduler basically allocates the resource in each frame based on the traffic conditions and QoS requirements of service flows at SSs. As shown in Fig. 4, the scheduler needs to maintain per-flow queues so that the QoS of each flow can be met. The uplink scheduler is very similar to the downlink scheduler. The uplink scheduler maintains the request/grant status of various uplink service flows. Bandwidth requests arriving from various uplink service flows at the WiMAX BS will be granted in a similar fashion as the downlink traffic. One additional consideration is that of available SS power. This power is divided among allocated subchannels and therefore affects the number of subchannels the subscriber station can use. Another important consideration is that the leftover resources should be fairly allocated. A quantitative measure of fairness is defined in [9].

APPLICATION LAYER MODELING

There are two main types of traffic models: foreground traffic and background traffic. Foreground traffic represents a specific user behavior or interaction. On the other hand, background traffic is not directly related to a specific user interaction or activity.

Each model can be represented using two major traffic models: user-level and IP packet-level. An example of a user-level model is the distribution of video frame sizes. The performance metrics are also at the user level (e.g., the number of video frames with errors). IP packet models represent the packet arrival statistics at

the IP layer. These models can be generated from network traffic measurements.

A user-level model is more complicated than an IP-level model, but gives more information about users' quality of experience (QoE). The WiMAX Forum has identified the following application classes to cover several applications for 802.16e-based systems: multiplayer interactive gaming, voice over IP (VoIP) and videoconferencing, streaming media, and Web browsing and instant messaging. Three key issues in performance modeling are:

- The standard traffic models specified in older technologies such as 3GPP and 3GPP2 documents are now dated. The Web usage model is a clear example. 3GPP documents have a model of Web traffic [10]. However, with the advent of Web 2.0, the Web usage pattern has changed significantly. The older models no longer correctly represent current user behavior.
- No traffic models are available for many of the new applications (gaming, video streaming, instant messaging, etc.).
- Everyone uses a different model for the same application and comes up with very different conclusions.

To avoid such problems, the WiMAX Forum has selected a set of traffic models that are recommended for use in system-level studies. These models include Internet gaming, VoIP, videoconferencing, push-to-talk, music/speech, small video clips, movie streaming, multimedia broadcast services, instant messaging, Web browsing, email, telemetry, FTP, peer-to-peer networking, virtual private networking (VPN) service, and near-real-time video. These models are based on recent measurements and represent current user behavior, and are included in the System Evaluation Methodology [2].

CONCLUSIONS

System-level modeling of IEEE 802.16e-based mobile WiMAX networks requires a careful consideration at every layer including the physical, MAC, and application layers. It is possible to come up with misleading results unless careful

attention is paid to various key features at these layers. Even network configuration and user placement are important. For this reason, the WiMAX Forum has developed a system-level simulation methodology. Along with pointing out how to model some key features, the document also suggests default parameter values that should be used. Anyone involved in simulation modeling should use this methodology so that their results can be compared to those of others.

The summary guidelines presented in this article can be used by WiMAX service providers, equipment vendors, and users in their performance evaluation projects. These guidelines are general in that they can be used for any kind of simulation tool such as NS2, OPNET, OMNET, and Qualnet. In this article we discuss many of the WiMAX system modeling issues: physical layer modeling, MAC layer modeling, and application modeling. For more details on these and for advanced topics, such as modeling of multiple-input multiple-output, adaptive antenna systems, and beamforming, the reader is urged to refer to the detailed WiMAX Forum document.

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BIOGRAPHIES

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The guidelines presented in this article can be used by WiMAX service providers, equipment vendors, and users in their performance evaluation projects. These guidelines are general in that they can be used for any kinds of simulation tools such as NS2, OPNET, OMNET, and Qualnet.