INVITED PAPER

PHY/MAC CROSS-LAYER ISSUES IN MOBILE WiMAX

Issue Date: January 2006

Abstract—*After the IEEE 802.16-2004 standard was published, much attention was drawn to providing broadband access in rural and developing areas over fixed wireless channels. Now, the IEEE 802.16e standard for Mobile WiMAX is about to be published. It is known that Mobile WiMAX will incorporate error-correction capability and will be an enhanced version of the IEEE 802.16 standard with mobility support. Therefore, it is expected that Mobile WiMAX will not only compete with the broadband wireless market share in urban areas with DSL, cable, and optical fibers, but also threaten the hot-spot-based Wi-Fi™ and even the voice-oriented cellular wireless market. This paper first provides an overview of Mobile WiMAX, especially on OFDMA/TDD systems. Then, the paper addresses some PHY/MAC cross-layer issues that need to be resolved through radio resource management to increase throughput, cell coverage, and spectral efficiency.*

Jungnam Yun, PhD
POSDATA America
R&D Center
jnyun@posdata-usa.com

Professor Mohsen Kavehrad, PhD
The Pennsylvania
State University
(CITCTR)
mkavehrad@psu.edu

INTRODUCTION

IEEE 802.16e, the standard for Mobile WiMAX, is expected to be published by the end of 2005, and Mobile WiMAX service will launch in South Korea and possibly in North America in late 2006 or early 2007. Originally, the IEEE 802.16 standard was developed for fixed wireless in the search for a new tool to allow homes and businesses to link with the worldwide core networks. It was envisioned that the IEEE 802.16 standard would offer a better solution for last-mile connections, compared to fiber, cable, or digital subscriber line (DSL) links, because wireless systems are less costly to deploy over wide geographic areas. The publication in June 2004 of the IEEE 802.16d (IEEE 802.16-2004) standard provided assurance that the WiMAX market and its competitiveness for non-line-of-sight (NLOS) wireless broadband access are maturing [1–4].

Since the IEEE 802.16e standard (the mobile version of the IEEE 802.16-2004 standard) will be published soon, the focus of WiMAX is expected to shift from fixed subscribers to mobile subscribers with various form factors: personal digital assistant (PDA), phone, or laptop. The IEEE 802.16e standardization group promises to support mobility at speeds of up to approximately 40 to 50 mph; some vendors are already claiming success in testing prototype systems with mobility at speeds over 50 mph for data rates of 5 Mbps or better. Hence, Mobile WiMAX is not only expected to compete with other last-mile connections such as fiber, cable, and DSL; it also threatens Wi-Fi™ and code division multiple access (CDMA) voice communications with voice-over-Internet-Protocol (VoIP) services.

Unlike wired networks, wireless networks are highly dependent on communications channels; radio channels are dynamic, correlated, unreliable, and very expensive. This is why performance will be highly dependent on how well radio resource management supports quality-of-service (QoS) requirements, even if QoS might be a luxury in the early stages of the Mobile WiMAX market. Therefore, several cross-layer issues between the medium access control (MAC) layer and the physical (PHY) layer need to be optimally resolved on the radio resource management side of Mobile WiMAX systems.

In multiuser environments, especially on wireless fading channels, multiuser diversity is a key radio resource management element for maximizing throughput. Multiuser diversity is a form of selection diversity. Since different users experience independent time-varying fading channels in wireless networks, resources are allocated to the user with the best channel quality to maximize system throughput. Multiuser diversity has drawn attention since tracking user channel fluctuations is becoming more accurate

ABBREVIATIONS, ACRONYMS, AND TERMS

AAS	adaptive antenna system
AMC	adaptive modulation and coding
ARQ	automatic repeat request
ASCA	adjacent subcarrier allocation
ATM	asynchronous transfer mode
BE	best effort
BS	base station
CC	convolutional coding
CDMA	code division multiple access
CP	cyclic prefix
CQI	channel quality indicator
CRC	cyclic redundancy code
CS	convergence sublayer
CTC	convolutional turbo coding
DC	direct current
DCD	downlink coding descriptor
DHCP	dynamic host configuration protocol
DL	downlink
DLFP	DL frame prefix
DSCA	distributed subcarrier allocation
DSL	digital subscriber line
D-TDD	dynamic TDD
ertPS	extended real-time polling service
FEC	forward error correction
FBSS	fast BS switching
FCH	frame control header
FDD	frequency division duplex
FRF	frequency reuse factor
FUSC	full usage of subchannels
HARQ	hybrid ARQ
H-FDD	half-duplex FDD
HO	handover
HT	header type
IR	incremental redundancy
LDPC	low density parity check
LSB	least significant bit
MAC	medium access control
MAN	metropolitan area network
MAP	mobile application part
MIMO	multiple input, multiple output
MISO	multiple input, single output
MPEG	Moving Picture Experts Group
MS	mobile station
MSB	most significant bit
NLOS	non-line of sight
nrtPS	non-real-time polling service
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OFUSC	optional full usage of subchannels
OPUSC	optional partial usage of subchannels
PDA	personal digital assistant
PDU	protocol data unit
PHY	physical
PMP	point to multipoint
PN	pseudorandom noise
PUSC	partial usage of subchannels
QoS	quality of service
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RTG	receive/transmit transition gap
rtPS	real-time polling service
SDU	service data unit
SINR	signal-to-interference+noise ratio
SISO	single input, single output
SNR	signal-to-noise ratio
STC	space-time coding
TDD	time division duplex
TSA	time slot allocation
TTG	transmit/receive transition gap
TUSC	tile usage of subchannels
UBC	uplink coding descriptor
UGS	unsolicited grant service
UL	uplink
VoIP	voice over Internet Protocol
Wi-Fi™	wireless fidelity
WiMAX	worldwide interoperability for microwave access

and faster. Hence, diversity gain increases when the dynamic range of the fluctuation increases, but the gain is limited in environments with slow fading [5]. In slow fading, multiuser diversity hardly satisfies all QoS parameters at the same time, especially fairness among users. Ultimately, radio resource management needs to implement a combined form of multiuser diversity and fairness scheduling [6].

As broadband wireless networks encompass various services such as World-Wide Web (www), voice, video, and data, network traffic becomes very dynamic and unbalanced between the uplink (UL) and downlink (DL) stream volumes. To provide the highest transport efficiency in broadband networks, time division duplex (TDD) is preferred over frequency division duplex (FDD) because it offers more flexibility in changing the UL and DL bandwidth ratio according to the dynamic traffic pattern [7]. It has been assumed that the switching points for the UL and DL of TDD schemes are determined by network operators and are not changeable. Moreover, switching points in adjacent cells have been synchronized to avoid severe inter-cell interference. Having the same switching points in adjacent cells, a centralized controller could set switching points for all cells by observing the traffic characteristics [8]. For the duplex scheme, FDD, TDD, and half-duplex FDD (H-FDD) are all available options in Mobile WiMAX. This paper addresses only the TDD mode for the orthogonal frequency division multiple access (OFDMA) PHY layer. Even though it seems too early to adopt dynamic changes in the DL/UL ratio for Mobile WiMAX systems, several investigations show that appropriate time slot allocation (TSA) and beam forming can bring higher spectral efficiency in dynamic TDD (D-TDD) systems compared to conventional TDD systems [9, 10, 11].

This paper first describes the general PHY and MAC layers and then provides views on several cross-layer issues related to Mobile WiMAX, specifically focusing on the point-to-multipoint (PMP) mode of OFDMA/TDD systems, multiuser diversity, zone adaptation for interference cancellation, hybrid automatic repeat request (HARQ), and variable DL/UL ratio or D-TDD.

PHY LAYER IN OFDMA/ TDD MOBILE WiMAX

The three different PHY layers in Mobile WiMAX are single carrier, orthogonal frequency division multiplexing (OFDM), and OFDMA. The WiMAX Forum's Mobile Task Group is developing a Mobile WiMAX profile based on the OFDMA PHY layer only [1–4]. At the same time, the WiMAX Forum's Evolution Task Group is developing technical specifications for the evolution of OFDM-based networks from fixed to nomadic connections. Hence, the OFDMA PHY layer will be the baseline for Mobile WiMAX.

OFDMA

The wireless metropolitan area network (MAN)-OFDMA PHY layer based on OFDM modulation is designed for NLOS operation in the frequency bands below 11 GHz. OFDMA inherits OFDM's immunity to intersymbol interference and frequency selective fading.

An inverse Fourier transform may be used to synthesize the OFDMA waveform during a symbol time. A small end-portion of the symbol time, called a cyclic prefix (CP), is copied at the beginning of the symbol time duration to collect multipath while maintaining orthogonality among the subcarriers.

Within the OFDMA symbol time frame, the active subcarriers are split into subsets of subcarriers; each subset is termed a subchannel. On the DL, a subchannel may be intended for different (groups of) receivers. On the UL, a transmitter may be assigned one or more subchannels and several transmitters may transmit simultaneously. The subcarriers forming one subchannel may, but need not, be neighbors. A slot—the minimum possible OFDMA data allocation unit—consists of one or more symbols in the time domain by one subchannel in the frequency domain. Hence, OFDMA can fully use multiple user channel variations via two-dimensional resource allocation.

OFDMA can fully use multiple user channel variations via two-dimensional resource allocation.

TDD

The three different duplex modes for OFDMA Mobile WiMAX systems are TDD, FDD, and H-FDD (see **Figure 1**). TDD systems use the same frequency band for DL and UL, and the frame is divided into DL subframes and UL subframes in the time domain. FDD systems use different frequency bands, and DL and UL subframes are overlapped in the time domain. H-FDD systems have two different frequency bands for DL and UL, and DL and UL subframes do not overlap in the time domain.

Mobile WiMAX has an optional channel-sounding feature for TDD systems. Channel

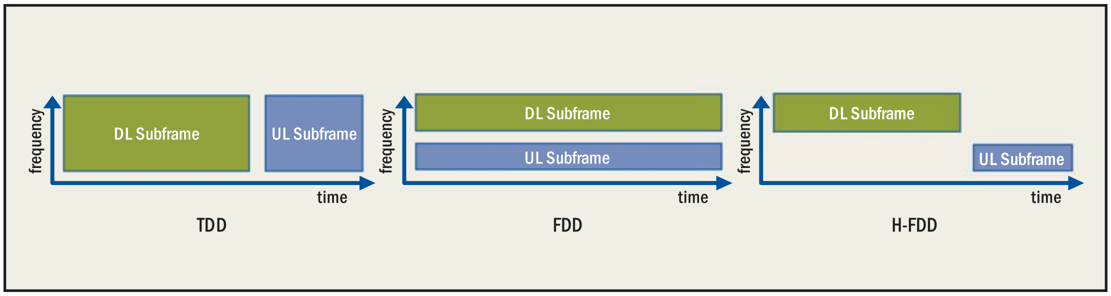

Figure 1. Duplex Modes TDD, FDD, and H-FDD

There are two main types of subcarrier allocation techniques: distributed and adjacent.

sounding is a signaling mechanism that enables the base station (BS) to estimate BS-to-mobile station (MS) channel response based on the UL signals transmitted by the MS. Channel sounding works only under the assumption of TDD reciprocity.

Due to channel reciprocity and DL/UL ratio adaptability, TDD is the most favored duplex mode in Mobile WiMAX [7]. It is the only mode addressed in this paper.

OFDMA/TDD Frame Structure

Figure 2 shows an example of the OFDMA frame structure for the TDD mode. Each frame is divided into DL and UL subframes by transmit/receive transition gaps (TTGs) and receive/transmit transition gaps (RTGs). Each DL subframe has a preamble in the first OFDMA symbol and then starts with the frame control header (FCH) in the second symbol. The FCH specifies the subchannel groups used for the segment, the burst profile, and the length of the DL-mobile application part (MAP) message, which directly follows the FCH. The UL-MAP message is carried by the first burst allocated in the DL-MAP. Each UL subframe may have one or more ranging slots, which are used for the network entry procedure. UL subframes may have fast feedback channels for fast channel quality indicator (CQI) reports or other fast operational requests or responses. (Fast feedback channels are not shown in Figure 2.)

Subcarrier Allocation

There are three types of subcarriers: data, pilot, and null. Data subcarriers are used for data transmissions, pilot subcarriers are used for channel estimation and various synchronization purposes, and null subcarriers are used for the direct current (DC) carrier and guard bands transmitting no signals. Multiple data sub-carriers are grouped into a subchannel, and a subchannel forms a slot with one or more OFDMA symbols. A slot is a channel and MAP allocation unit; it contains 48 data subcarriers.

There are two main types of subcarrier allocation techniques: distributed and adjacent. In general, the distributed allocations perform very well in mobile applications, while adjacent subcarrier permutations can be properly used for fixed, portable, or low mobility environments. These options enable the system designers to trade mobility for throughput.

Distributed Subcarrier Allocation

In a distributed subcarrier allocation (DSCA), multiple data subcarriers are grouped into a subchannel. Although subcarriers in a subchannel are not usually adjacent to each other, they may be in some cases. DSCAs for the DL are DL-partial usage of subchannels (PUSC), full usage of subchannels (FUSC), optional FUSC (OFUSC), and tile usage of subchannels (TUSC) 1 and 2. DSCAs for the UL are UL-PUSC and UL-optional PUSC (OPUSC).

- DL-PUSC: The default DL subcarrier allocation method. All DL subframes start in the DL-PUSC zone. Subchannels are grouped into six major groups and assigned to three segments (three sectors) of a cell. Assigning two major groups to each segment, the cell can be viewed as frequency reused by a factor of three. By switching to a DL-PUSC zone that assigns all subchannel groups to each segment, the cell can realize a frequency reuse factor of one. DL-PUSC is designed to minimize the probability of using the same subcarrier in adjacent sectors or cells.
- FUSC: Uses all subchannels and minimizes the performance degradation of fading channels by frequency diversity. FUSC is also designed to minimize the probability of using the same subcarrier in adjacent sectors or cells. FUSC pilots are in both variable and fixed positions.
- OFUSC: Also designed to fully use frequency diversity. One difference from FUSC is that OFUSC uses a bin structure like band adaptive modulating and coding (AMC).

- TUSC: For use in the adaptive antenna system (AAS) zone; similar in structure to UL-PUSC.
- UL-PUSC: The default UL subcarrier allocation method. It is not necessary to start the UL subframe in the UL-PUSC zone. UL-PUSC has a tile structure, with each tile comprising four subcarriers by three symbols. The four corner subcarriers are used as pilots, and the remaining eight subcarriers are used as data subcarriers.
- OPUSC: Also has a tile structure, with each tile comprising three subcarriers by three symbols. The center subcarrier is used as a pilot, and the remaining eight subcarriers are used as data subcarriers.

On the DL side, DL-PUSC with all subchannel groups performs similarly to FUSC and to DL-PUSC with partial subchannel groups, which can avoid co-channel interference by deploying a frequency reuse factor of three. On the UL side, UL-PUSC, with its four pilot subcarriers, has a better channel estimation performance than OPUSC. However, OPUSC has more data slots than UL-PUSC because it has a smaller tile size with the same number of data subcarriers.

Adjacent Subcarrier Allocation

Band AMC and PUSC-adjacent subcarrier allocation (ASCA) are ASCA techniques. While DSCAs can gain frequency diversity in frequency selective slow fading channels, ASCAs can gain multiuser diversity in frequency non-selective fading channels. In the adjacent subcarrier permutation, symbol data within a subchannel is assigned to adjacent subcarriers, and the pilot and data subcarriers are assigned fixed positions in the frequency domain within an OFDMA symbol. This permutation is the same for both the UL and DL.

- Band AMC: In defining a band AMC allocation, a bin—the set of nine contiguous subcarriers within an OFDMA symbol—is the basic allocation unit on both the DL and UL. A group of four rows of bins is called a physical band. An AMC slot consists of six contiguous bins in the same band, and four types of AMC slots are defined in the IEEE 802.16-2004 standard. But in Mobile WiMAX, only one type of slot, defined as two bins by three symbols, is used.
- PUSC-ASCA: PUSC-ASCA uses distributed clusters for the PUSC mode. The symbol structure uses the same parameters as those of the regular PUSC, and the same cluster structure is maintained; only the subcarrier allocation per cluster is different from that of the regular PUSC.

Adjacent subcarrier allocations are preferred in the AAS zone.

While DSCAs can gain frequency diversity in frequency selective slow fading channels, ASCAs can gain multiuser diversity in frequency non-selective fading channels.

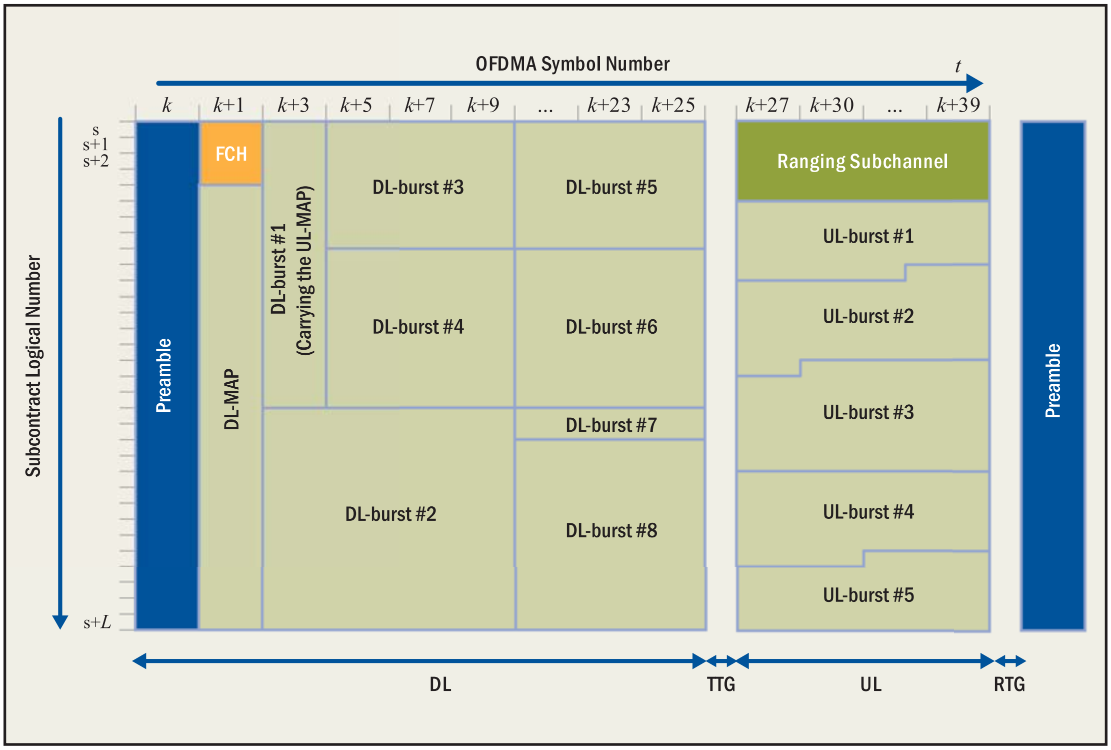

Figure 2. Example of the OFDMA Frame Structure for the TDD Mode

Ranging

For the purposes of network entry, connection maintenance, bandwidth request, and efficient handover (HO), Mobile WiMAX provides ranging channels with CDMA-like signaling. A maximum of 256 sets of 144-bit pseudo-noise ranging codes are generated and divided into four groups: initial, periodic, bandwidth request, and HO ranging.

One or more groups of six subchannels (for PUSC) or eight subchannels (for OPUSC) constitute a ranging channel. For initial and HO ranging, two OFDMA symbols are used, and the same ranging code is transmitted on the ranging channel during each symbol, with no phase discontinuity between the two symbols. Hence, initial and HO ranging have a wide range for the purpose of timing adjustments. Meanwhile, periodic and bandwidth request ranging are transmitted over one OFDMA symbol because active MSs are aligned mostly via frame time and the timing deviations are very small.

MIMO and AAS are seriously being considered for implementation in the early stage to boost spectral efficiency and to promote success in the broadband wireless market.

HARQ

HARQ greatly increases the data rate when the signal-to-noise ratio (SNR) is very low; hence, it increases the coverage of Mobile WiMAX systems. The major difference between conventional ARQ and HARQ is that a conventional ARQ discards erroneous packets when retransmitting lost and/or subsequent packets, whereas an HARQ does not discard the erroneous packets, but combines them with retransmitted packets to gain time diversity. For every MS, each packet transmission over a radio channel faces different channel characteristics. Therefore, HARQ can also be used to maximize the throughput from the time diversity gain.

There are two types of HARQ: chase and incremental redundancy (IR). For chase HARQ, each retransmission is identical to the original transmission; hence, implementation complexity is lower than for IR HARQ. Meanwhile, an IR HARQ transmits a different redundancy version for different subpackets. An IR HARQ is flexible in adapting the subpacket transmission rate according to the most recent channel quality feedback; this obviously has the potential of achieving better performance than that of a chase HARQ. However, chase HARQ using CTC is the preferred HARQ option because it is less complex than IR HARQ using CTC.

Channel Coding

Mobile WiMAX has four channel coding steps: randomization, forward error correction (FEC), interleaving, and modulation. A pseudorandom noise (PN) sequence generator is used to randomize each FEC data block. Multiple FEC types are available for encoding randomized data: tail-biting convolutional coding (CC), zero-tailed CC, convolutional turbo coding (CTC), and low density parity check (LDPC). Among these channel coding schemes, tail-biting CC and CTC are mandatory; the others are optional. CC is used for the FCH DL frame prefix (DLFP) and is mandatory. Except for the FCH, it is highly likely that CTC will be used for all control information and data bursts. FEC encoded data is interleaved in two steps: the scattering step and the least-significant-bit (LSB)/most-significant-bit (MSB) switching step. For modulation in OFDMA systems, quadrature phase shift keying (QPSK) and 16 and 64 quadrature amplitude modulation (QAM) are available.

Multiple Input, Multiple Output/Adaptive Antenna System

Since single input, single output (SISO) systems cannot achieve high spectral efficiency, multiple input, multiple output (MIMO) systems draw much attention, and they are included in the WiMAX profile as optional features. MIMO systems have various advantages over SISO and multiple input, single output (MISO) systems; these include multiplexing gain, diversity gain, interference suppression, and array gain. In a highly scattering channel, transmitting independent data from different antennas increases capacity linearly. Also, there are receiver diversity gains with multiple receiver antennas and space-time coding (STC) gains with multiple transmitter antennas. As is true of smart antenna systems, beam forming is also an advantage in MIMO systems when channel information is available.

Even though MIMO and AAS are optional Mobile WiMAX features, they are seriously being considered for implementation in the early stage to boost spectral efficiency and to promote success in the broadband wireless market.

MAC LAYER IN OFDMA/ TDD MOBILE WiMAX

The MAC layer of Mobile WiMAX provides a medium-independent interface to the PHY layer and is designed to support the wireless PHY layer by focusing on efficient radio resource management. The MAC layer supports both PMP and mesh network modes; this paper focuses only on the PMP mode.

The MAC layer schedules data transmission based on connections. Each MS creates one or more connections having various service classes: unsolicited grant service (UGS), real-time polling service (rtPS), extended real-time PS (ertPS), non-real-time PS (nrtPS), and best effort (BE) service. The MAC layer is intended to manage radio resources efficiently to support QoS for each connection; to maintain link performance using AMC, ARQ, and other methods; and to maximize throughput. The MAC layer handles network entry for the MS and creates the MAC protocol data unit (PDU). Finally, the MAC layer provides two convergence sublayer (CS) specifications: asynchronous transfer mode (ATM) CS and packet CS.

Service Classes

When created, each connection is assigned to a certain service class based on the type of QoS guarantees required by the application. The IEEE 802.16e standard provides the following service classes:

- UGS: Designed to support real-time service flows that periodically generate fixed-size data packets, such as T1/E1 and VoIP without silence suppression.
- rtPS: Designed to support real-time service flows that periodically generate variable-size data packets, such as Moving Picture Experts Group (MPEG) video.
- ertPS: A scheduling mechanism that builds on the efficiency of both UGS and rtPS. The BS provides unsolicited unicast grants as in UGS, thus saving the latency of a bandwidth request. However, UGS allocations are fixed in size, whereas ertPS allocations are dynamic.
- nrtPS: Offers regular unicast polls, which ensures that the service flow receives request opportunities even during network congestion.
- BE: Intended to provide efficient service for BE traffic. Typical BE service is Web surfing.

Network Entry

When an MS wants to enter the network, it follows the network entry process: (1) downlink channel synchronization, (2) initial ranging, (3) capabilities negotiation, (4) authentication message exchange, (5) registration, (6) IP connectivity, and (7) periodic ranging afterwards. The following paragraph amplifies this process.

(1) The MS first scans for a channel in the defined carrier frequency list and detects its frame synchronization, using the preamble at the PHY layer. (2) Once the PHY level is synchronized, the MS can obtain the DL-MAP, downlink coding descriptor (DCD), and uplink coding descriptor (UCD) for the DL and UL parameters. When the MS has all parameters and information regarding the UL ranging allocation, it starts sending a CDMA ranging code, followed by several MAC messages, and then adjusts timing and power according to the BS command. (3) After initial ranging is completed, the MS negotiates with the BS regarding its modulation level, coding scheme, MAP support, and other capabilities, so that the BS knows exactly what the MS is capable of and can allocate resources efficiently. (4) Once capabilities are negotiated, the BS authenticates the MS and sends important key material for data ciphering. (5) After the MS is authenticated, it finally registers onto the networks and starts the dynamic host configuration protocol (DHCP) to obtain the IP address and other parameters needed to establish IP connectivity. (6) After that, transport connections are made. The BS initiates the establishment of pre-provisioned connections while the MS initiates the establishment of non-pre-provisioned connections. (7) Finally, the MS conducts periodic ranging as needed.

There are five service classes in Mobile WiMAX: UGS, rtPS, ertPS, nrtPS, and BE.

MAC PDU Construction and Transmission

The MAC layer of Mobile WiMAX supports both fragmentation and packing of MAC service data units (SDUs) for ARQ-enabled and non-ARQ-enabled connections. Also, multiple MAC PDUs can be concatenated into a single transmission of either DL or UL connections. For ARQ-enabled connections, fragments are formed for each transmission by concatenating sets of ARQ blocks with consecutive sequence numbers. Even though ARQ implementation is mandatory, ARQ may be enabled on a per-connection basis. Furthermore, a connection cannot have both ARQ and non-ARQ traffic. A service flow may require that a cyclic redundancy code (CRC) be added to each MAC PDU carrying data for that service flow. In this case, for each MAC PDU with header type (HT) = 0, a CRC32 is appended to the payload of the MAC PDU; i.e., request MAC PDUs are unprotected. The CRC covers the generic MAC header and the payload of the MAC PDU. The CRC32 calculation methods for the OFDM mode and the OFDMA mode are different, which makes fixed wireless OFDM systems using the IEEE 802.16d standard and Mobile WiMAX (mobile OFDMA systems) using the IEEE 802.16e standard incompatible.

Packet Scheduling and Radio Resource Management

The main goal of packet scheduling and radio resource management is to maximize throughput while satisfying QoS requirements.

The BS packet scheduler works closely with the radio resource management entity to guarantee QoS while maximizing throughput by efficiently using the opportunistic characteristics of wireless channels. Meanwhile, the MS packet scheduler only schedules packets from the connection queues into the transmission buffer so that the MS can transmit packets when the BS allocates bandwidth in certain frames.

The addition of an HO scheme makes Mobile WiMAX much different from fixed broadband wireless systems.

Radio resource management is the main task of the scheduler, whose functions are to allocate DL and UL bandwidth, construct MAPs in the DL and UL subframes, and decide on the best burst profile for each connection. Bandwidth allocation and MAP construction should be done jointly, and the burst profile should be determined per connection beforehand, based on the signal-to-interference+noise ratio (SINR) report from each MS. For MAP construction, DL and UL subframes can be divided by multiple zones, i.e., a normal zone with multiple choices of subcarrier allocation, STC, AAS, and MIMO, based on how the optional features may be implemented and used.

Handover

The addition of an HO scheme makes Mobile WiMAX much different from fixed broadband wireless systems. Seamless HO is a must when the connection is for real-time service such as VoIP. There are three types of HO: hard HO, fast BS switching (FBSS), and macro-diversity HO. Also, either the MS or the BS can initiate HO. The first type of HO, hard HO, disconnects the MS from the previous serving BS before the MS connects with the target BS. The second type of HO, FBSS, uses a fast switching mechanism to improve HO quality. The MS can only transmit/receive data to/from one active BS at any given frame, and all active BSs should be ready for downlink data for the specific MS at any frame. For FBSS, all BSs should be synchronized based on a common time source and use the same frequency channel. The BSs are also required to share or transfer MAC context through networks. The third type of HO, macro-diversity HO, allows one or more BSs to transmit the same MAC/PHY PDUs to the MS so that the MS can perform diversity combining. This macro-diversity HO is also called a soft HO. Due to the complexity of the macro-diversity HO, it is not likely to be implemented in the early stage of Mobile WiMAX service.

To prepare and expedite a potential HO in the near future, the MS should be able to scan nearby BS signals and associate with possible target BSs to acquire and record ranging parameters and service availability information.

PHY/MAC CROSS-LAYER ISSUES IN MOBILE WiMAX

The challenges inherent in implementing Mobile WiMAX arise from its deployment of a frequency reuse of one and its adoption of many state-of-the-art technologies such as HARQ, MIMO, and AAS. This section describes some cross-layer issues that need to be addressed in the radio resource allocation management of Mobile WiMAX.

Zone Switch and Frequency Reuse

Since the OFDMA PHY layer has many choices of subcarrier allocation methods, multiple zones can use different subcarrier allocation methods to divide each subframe. One benefit of using zone switching is that different frequency reuse factors (FRFs) can be deployed in a cell (or sector), dynamically.

Figure 3 shows an example of deploying different FRFs in one frame. For the first half of each frame, the entire frequency band is divided by three and allocated in each sector. For the second half of each frame, the whole same frequency band is used in each sector. The benefits of deploying different FRFs in one frame are: (1) the FCH and DL-MAP are highly protected from severe co-channel interference; (2) edge users, who are receiving co-channel interference from other sectors in other cells, also have suppressed co-channel interference; and (3) users around the cell center have the full frequency band because they are relatively less subject to co-channel interference.

Multiuser Diversity

In the wireless multiuser environment, it is well known that multiuser diversity is a very important leveraging factor of resource allocation management [5, 6, 12]. Each MS faces a different fading channel; hence, radio resource management can use multiuser diversity to maximize system throughput. The difficulty lies in the fact that radio resource allocation also should satisfy fairness among subscribers. Moreover, in slow fading, multiuser diversity

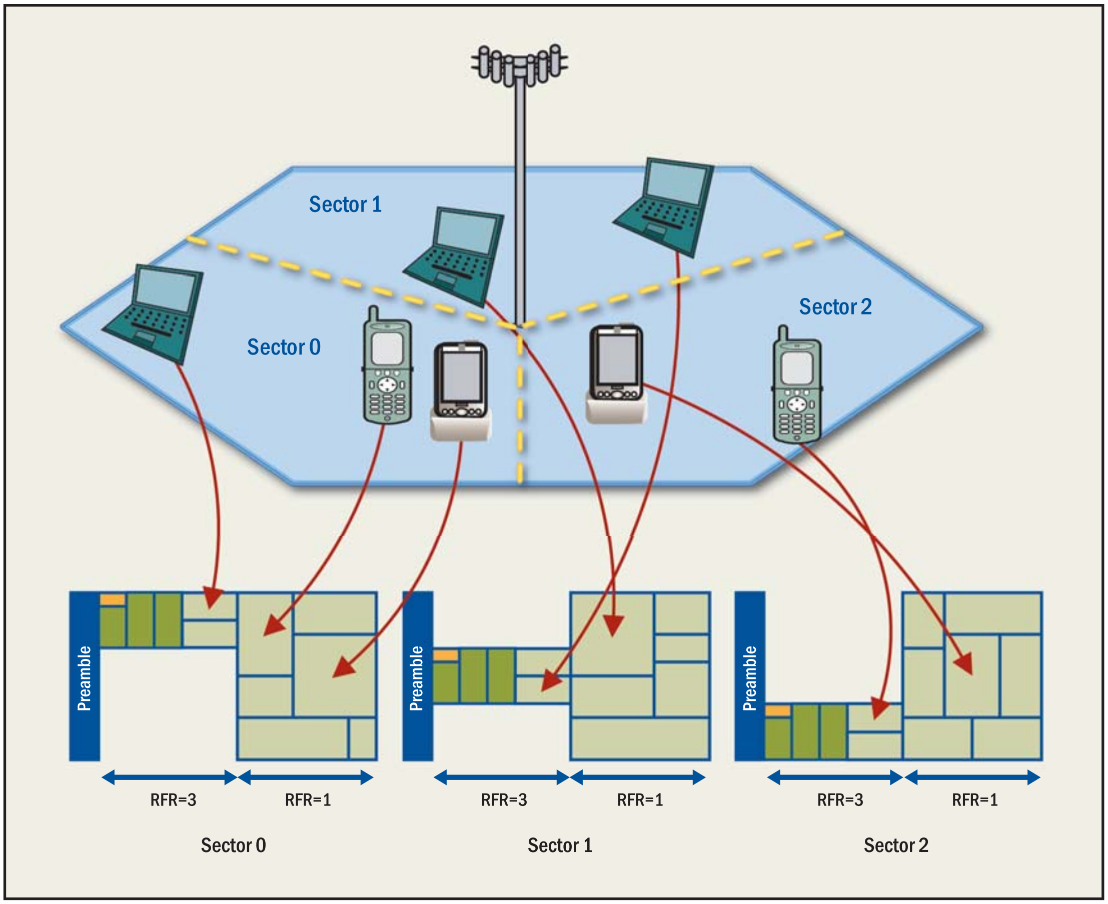

Figure 3. Zone Switch for FRF Change

Ultimately, radio resource management should follow a combined form of multiuser diversity and fairness scheduling.

hardly satisfies all QoS parameters at the same time, especially fairness among users. Ultimately, radio resource management should follow a combined form of multiuser diversity and fairness scheduling.

Figure 4 illustrates the deployment of multiuser diversity with a band AMC zone. Similarly, multiuser diversity can also be deployed with a DSCA zone such as PUSC, FUSC, optional FUSC, and TUSC. The only thing different from a band AMC zone is that the multiuser diversity gain can be obtained only from time domain allocations.

Dynamic TDD Usage

Each MS and BS experiences not only different channel characteristics, but also various data traffic. In other words, UL and DL stream volumes that have been considered symmetrical for conventional voice transmissions are unbalanced, and the ratio is time varying. To provide the highest transport efficiency in broadband networks, TDD is preferred to FDD because it enables real-time adaptation of UL and DL bandwidth according to the dynamic traffic pattern. Even though FDD can also be used for asymmetric traffic, DL and UL channel bands should be matched to the ratio of DL and UL traffic. Moreover, FDD channel bands cannot be adjusted dynamically in response to the varying ratio of DL and UL traffic, due to hardware limitations. The ratio of UL to DL streams is fixed for FDD.

It has been assumed that network operators determine the switching points for TDD UL and DL schemes and that once such systems are deployed, the DL/UL ratio is not changeable. Moreover, switching points in adjacent cells must be synchronized to avoid severe inter-cell interference.

Figure 5 shows various co-channel interference cases. In conventional TDD systems, only DL/DL and UL/UL cases can occur. However, if the DL/UL ratio is changed dynamically frame by frame and independently cell by cell, co-channel interference can exist in all four cases.

A cross-layer D-TDD scheme considering traffic and channel condition together may be adopted. Since each cell can have different offered loads for UL and DL, cell switching points are set independently. Although this may cause severe co-channel interference at time slots around the

Although D-TDD is complex, it has the potential of offering higher bits-per-hertz efficiency when needed.

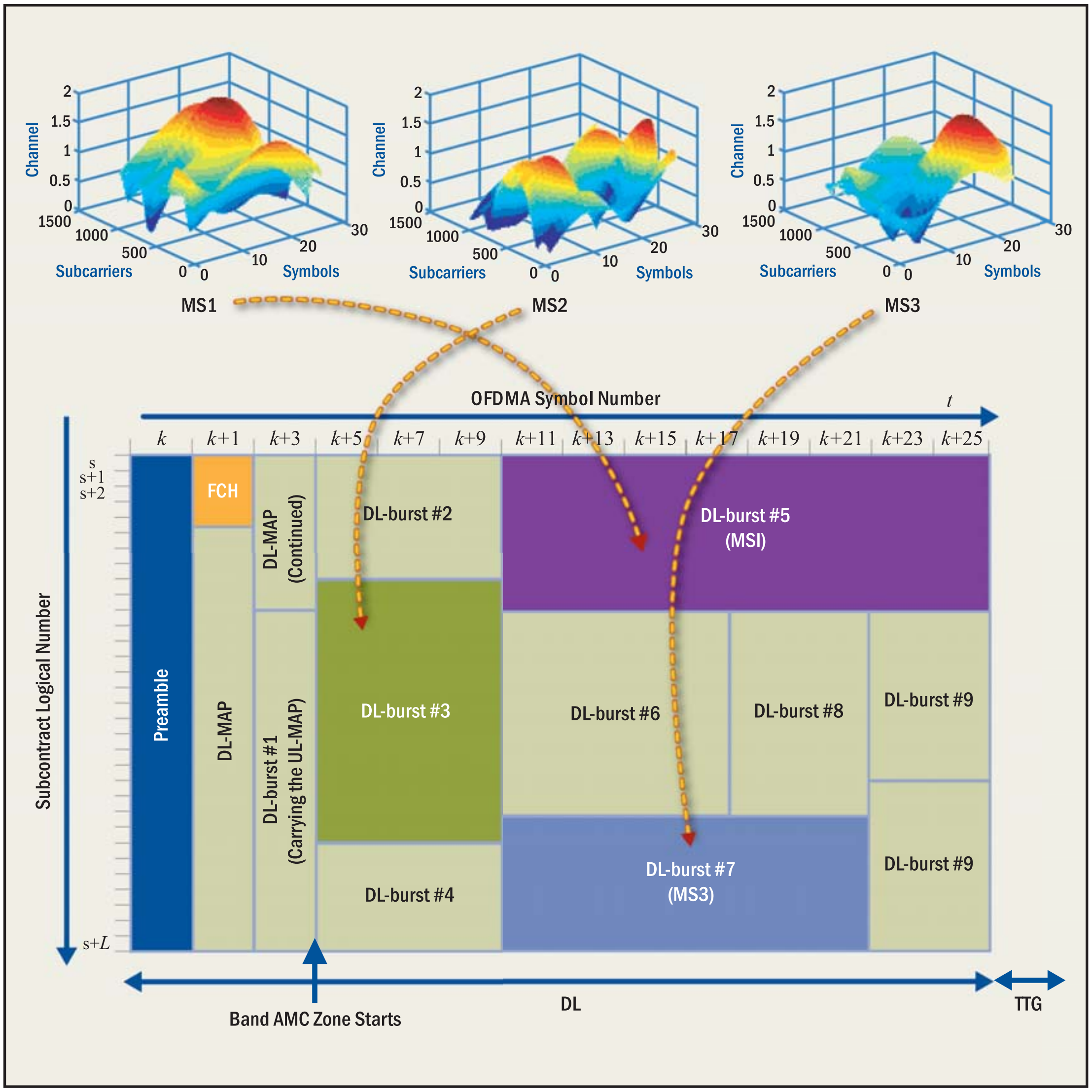

Figure 4. Usage of a Band AMC Zone Based on Multiuser Diversity

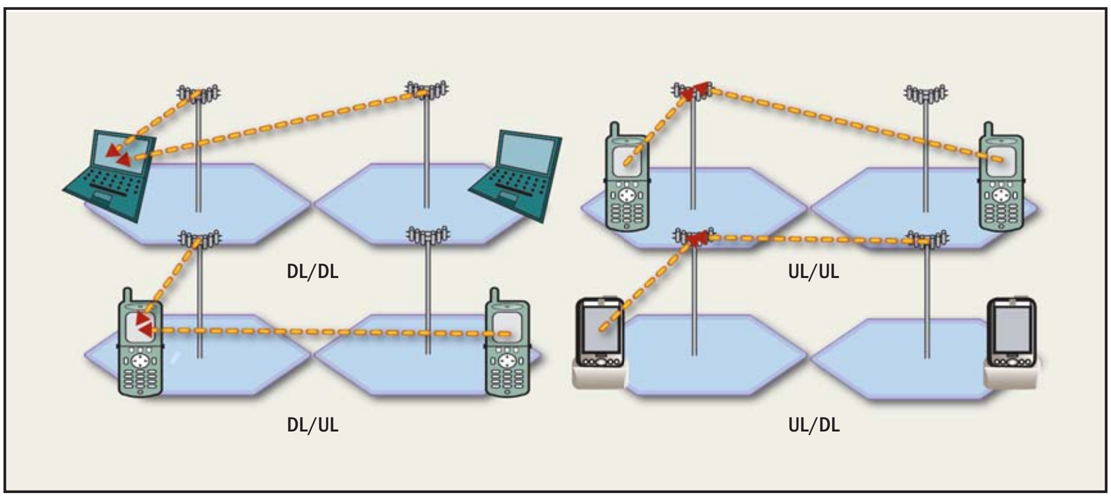

Figure 5. Various Co-channel Interference Cases

switching points, it still produces more throughput than the conventional TDD scheme with a fixed DL/UL ratio.

Switching points can be updated daily or by frame. In the daily approach, the network operator monitors for a certain amount of time, then updates the switching point to allocate resources based on switching point information. In the frame approach (used in this paper), the switching point is changed dynamically for each frame based on traffic characteristics and channel status. Based on the resource allocation algorithm, each user is given a number of time slots, with corresponding indices and a modulation format. Modulation is determined by the estimated channel state, and the time slot indices are determined by the TSA algorithm.

Figure 6 illustrates the deployment of different DL/UL ratios for different cells. In this example, for the early symbols of the UL subframe in Cell 2, the BS experiences severe co-channel interference coming from Cells 1 and 3 because they are all in the DL period and signals from their BSs interfere with the UL signals of users in Cell 2. To suppress interference in this case, a good TSA algorithm with beam forming is necessary. Several investigations of TSA algorithms show that D-TDD systems outperform conventional TDD systems when the dynamic traffic has unbalanced DL/UL characteristics [9, 11]. Although the complexity of D-TDD makes its adoption in the early stages of Mobile WiMAX unlikely, it has the potential of offering higher bits-per-hertz efficiency when needed.

CONCLUSIONS

This paper has provided an overview of the IEEE 802.16e standard and Mobile WiMAX and has provided some simple suggestions to address certain PHY/MAC cross-layer issues.

Mobile WiMAX is expected to bring fast, broad, seamless data communications, not only for fixed home and small business subscribers, but also for mobile subscribers. Mobile WiMAX will begin competing in fixed broadband markets to link homes and businesses with worldwide core networks, before ultimately penetrating mobile communication market shares. To strengthen the market power of Mobile WiMAX, radio resource management that deals with PHY/MAC cross-layer issues needs to be developed accurately and close to optimally. ■

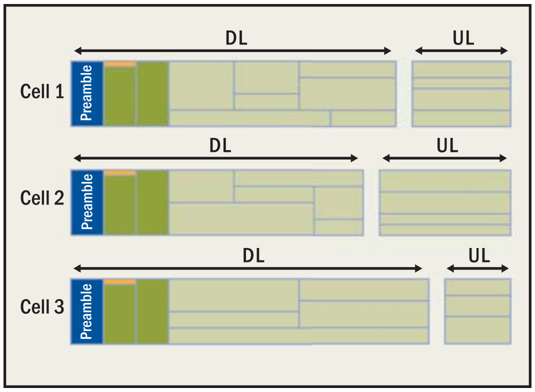

Figure 6. Various DL/UL Ratios for Different Cells

Mobile WiMAX is expected to bring fast, broad, seamless data communications, not only for fixed home and small business subscribers, but also for mobile subscribers.

TRADEMARKS

Wi-Fi is a registered trademark of the Wireless Ethernet Compatibility Alliance, Inc.

REFERENCES

[1] Wireless MAN Working Group (http://www.wirelessman.org/).

[2] IEEE Std 802.16-2004, "IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed Broadband Wireless Access Systems," October 2004.

[3] IEEE P802.16-Cor1/D5, "Draft Corrigendum to IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed Broadband Wireless Access Systems," September 2005.

[4] IEEE P802.16e/D11, "Draft Amendment to IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems — Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands," September 2005.

[5] P. Viswanath, D.N.C. Tse, and R. Laroia, "Opportunistic Beamforming Using Dumb Antennas," *IEEE Transactions on Information Theory*, Vol. 48, No. 6, pp. 1277–1294, June 2002.

[6] H. Fattah and C. Leung, "An Overview of Scheduling Algorithms in Wireless Multimedia Networks," *IEEE Wireless Communications*, pp. 76-83, October 2002.

[7] TDD Coalition white paper, "The Advantages and Benefits of TDD Broadband Wireless Access Systems," September 2001.

[8] D.G. Jeong and W.S. Jeon, "Time Slot Allocation in CDMA/TDD Systems for Mobile Multimedia Services," *IEEE Communications Letters*, Vol. 4, No. 2, February 2000.

[9] J. Li, S. Farahvash, M. Kavehrad, and R. Valenzuela, "Dynamic TDD and Fixed Cellular Networks," *IEEE Communications Letters*, Vol. 4, pp. 218–220, July 2000.

[10] W.C. Jeong and M. Kavehrad, "Co-channel Interference Reduction in Dynamic-TDD Fixed Wireless Applications, Using Time Slot Allocation Algorithms," *IEEE Transactions on Communications*, Vol. 50, No. 10, pp. 1627–1636, October 2002.

[11] J. Yun and M. Kavehrad, "Adaptive Resource Allocations for D-TDD Systems in Wireless Cellular Networks," *Proceedings of MILCOM*, Vol. 2, pp. 1047–1053, November 2004.

[12] M. Ergen, S. Coleri, and P. Varaiya, "QoS Aware Adaptive Resource Allocation Techniques for Fair Scheduling in OFDMA Based Broadband Wireless Access Systems," *IEEE Transactions on Broadcasting*, Vol. 49, No. 4, pp. 362–370, December 2003.

BIOGRAPHIES

Jungnam Yun is a member of the Technical Staff at the POSDATA America R&D Center, Santa Clara, California, where he works as a system engineer for the OFDMA PHY algorithm and MAC scheduler. His research interests are signal processing, communication theories, and cross-layer optimization for radio resource allocations in broadband wireless communication systems.

Dr. Yun received his BS and MS in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Taejun, South Korea, and his PhD in Electrical Engineering from The Pennsylvania State University, State College, Pennsylvania.

Mohsen Kavehrad was with the Space Communications Division, Fairchild Industries, and Satellite Corporation and Laboratories, GTE, from 1978 to 1981. In December 1981, he joined Bell Laboratories, and in March 1989, he joined the Department of Electrical Engineering, University of Ottawa, Ottawa, Ontario, Canada, as a full professor. At the same time, he also was director of the Broadband Communications Research Laboratory, director of Photonic Networks and Systems Thrust, project leader in Communications and Information Technology Ontario (CITO), and director of the Ottawa-Carleton Communications Center for Research (OCCCR). He was an academic visitor (senior consultant) at NTT Laboratories, Yokosuka, Japan, in the summer of 1991. He spent a 6-month sabbatical term as an academic visitor (senior consultant) with Nortel, Ottawa, Ontario, Canada, in 1996. In January 1997, he joined the Department of Electrical Engineering, The Pennsylvania State University, University Park, as the AMERITECH (W.L. Weiss) professor of Electrical Engineering and director of Communications Engineering. Later, in August 1997, he was appointed founding director of the Center for Information and Communications Technology Research (CICTR). From 1997 to 1998, he also was chief technology officer and vice president with Tele-Beam Inc., State College, Pennsylvania. He visited, as an academic visitor (senior consultant), Lucent Technologies (Bell Laboratories), Holmdel, New Jersey, in the summer of 1999. He spent a 6-month sabbatical term as an academic visitor (senior technical consultant) at the AT&T Shannon Research Laboratories, Florham Park, New Jersey, in 2004.

Dr. Kavehrad has been a consultant to a score of major corporations and government agencies. He has published over 300 refereed journal and conference papers, several book chapters, and books. His research interests are in the areas of technologies, systems, and network architectures that enable the vision of the information age, e.g., broadband wireless communications systems and networks and optical fiber communications systems and networks. He holds several key issued patents in these areas.

Dr. Kavehrad received three Exceptional Technical Contributions Awards for his work on wireless communications systems while he was with Bell Laboratories; the 1990 TRIO Feedback Award for his patent on a "Passive Optical Interconnect"; the 2001 IEEE Vehicular Technology Society Neal Shepherd Best Propagation Paper Award; three IEEE Lasers and Electro-Optics Society Best Paper Awards; and a Canada National Science and Engineering Research Council (NSERC) PhD dissertation Gold Medal award, jointly with his former graduate students, for work on wireless and optical systems. He is a fellow of the IEEE and has lectured worldwide as an IEEE distinguished lecturer and as a plenary and keynote speaker at leading conferences.

Dr. Kavehrad received his PhD in Electrical Engineering from Polytechnic University (Brooklyn Polytechnic), Brooklyn, New York.