Mobile WiMAX Systems: Performance and Evolution

Fan Wang, Amitava Ghosh, Chandy Sankaran, Philip J. Fleming, Frank Hsieh, and Stanley J. Benes,
Networks Advanced Technologies, Motorola Inc.

Abstract

Mobile WiMAX was successfully adopted by ITU as one of the IMT-2000 technologies in November 2007. Since then mobile WiMAX (a.k.a. IP-OFDMA) has officially become a major global cellular wireless standard along with 3GPP UMTS/HSPA and 3GPP2 CDMA/EVDO. Mobile WiMAX is an OFDM-based technology available for deployment today, and new WIMAX devices come to market at much reduced cost than that of current 3G solutions. Currently over 260 service providers are deploying fixed, portable and mobile WiMAX networks in 110 countries. This article provides an overview of the mobile WiMAX system and its performance under various configurations, channel conditions, and types of data traffic. Furthermore, the article provides an overview of mobile WiMAX evolution.

Mobile WiMAX and IEEE 802.16 Standards

The WiMAX Forum is an industry consortium promoting the IEEE 802.16 family of standards for broadband wireless access systems. Historically, the first IEEE 802.16 standard (and associated 802.16c profile definitions) addressed primarily line-of-sight (LOS) environments at high frequency bands (10–66 GHz) via conventional quadrature amplitude modulation (QAM) single-carrier techniques. The limited market potential for millimeter-wave LOS systems resulted in the development of the IEEE 802.16a amendment to support non-LOS (NLOS) modes in radio bands between 2–11 GHz. The 802.16-2004 standard [1] (also known as 802.16d) made further, more radical changes to 802.16 physical (PHY) layer operation for low frequency (2–11 GHz) bands by adding two additional PHY modes:
- A 256-point fast Fourier transform (FFT) orthogonal frequency-division multiplexing (OFDM) PHY mode
- A 2048-point FFT orthogonal frequency-division multiple access (OFDMA) PHY mode

The well understood goal of these developments was to use OFDM for both downlink (DL) and uplink (UL) to enable relatively simple high-performance receiver structures in the presence of frequency-selective fading channels.

This new PHY capability was augmented by addition of several features:
- Frequency-diverse and frequency-specific subchannelization schemes where respective groups of physically distributed and physically adjacent subcarriers are used to construct subchannels. These schemes enable both frequency-diverse and frequency-selective scheduling and resource allocation methods.
- Adaptive modulation and coding based on hybrid automatic repeat request (HARQ) techniques (previously used in Third Generation Partnership Project [3GPP]/3GPP2 systems such as Enhanced Data Rates for GSM Evolution [EDGE], High-Speed Downlink/Uplink Packet Access [HSDPA/HSUPA], Evolution Data Optimized [EVDO], etc.) along with support for chase combining (CC) and incremental redundancy (IR).
- Fast scheduling based on flexible channel quality indication (CQI)
- New forward error correction schemes including convolution turbo code (CTC) and low density parity check (LDPC) codes
- Support for multi-antenna operation including optional advanced antenna subsystem (AAS) modes, open-loop space time coding (STC) modes (supporting two–four transmit antennas), closed-loop multiple-input multiple output (MIMO) modes, and uplink coordinated space-division multiple access (SDMA).
- Efficient multicast-broadcast transmission schemes using single frequency network (SFN) concepts
- Variable frame sizes (e.g., 2 ms, 2.5 ms, 5 ms)

The mobility enhancements provided by the later 802.16e amendment [2] further enhanced operation of nomadic, portable, and mobile wireless access, and was published by IEEE at the beginning of 2006. The 802.16e specification (aka 802.16-2005) provides improved support for intercell handoff, directed adjacent-cell measurement, and sleep modes to support low-power

System bandwidth (MHz)	1.25	2.5	5	10	20
Sampling frequency (MHz)	1.4	2.8	5.6	11.2	22.4
FFT size	128	256	512	1024	2048
Subcarrier spacing (kHz)	10.94				
OFDM symbol duration (µs)	102.86				
Useful symbol time[1] (µs)	91.43				
Cyclic perfix[1] (µs)	11.43				

[1] Cyclic prefix is 1/8 of useful symbol time according to the mobile WiMAX profile.

■ **Table 1.** *IEEE 802.16e scalable OFDMA parameters.*

mobile station operation. Another important addition is the introduction into the 802.16e OFDMA PHY of FFT sizes of 128, 256, 512, and 1024 in addition to the original length, 2048. This permits so-called scalable deployment, wherein the OFDM symbol duration and inter-subcarrier separation is constant regardless of carrier bandwidth. Table 1 shows an example of such a carrier bandwidth-scaling process for a 5ms frame duration, where the cyclic prefix (CP) duration is 1/8 of the useful symbol duration.

The IEEE 802.16 family of standards contains many optional features that may not be implemented by the vendors and operators. One task of the WiMAX Forum is to decide on a commonly agreed system profile by reducing the number of options in the 802.16 specifications, and promote interoperability among equipment vendors and system operators.

The first release of mobile WiMAX system profile [3] supports time-division duplex (TDD) downlink and uplink transmissions. Besides scalable OFDMA, this profile also supports various frequency permutation schemes and multiple antenna technologies. In the following section we introduce the mobile WiMAX frame structure followed by a discussion of WiMAX control channel coverage in the next section. We later describe the fractional frequency reuse configuration of mobile WiMAX. We then describe multiple-antenna technologies supported in mobile WiMAX. We then present the mobile WiMAX system performance under various configurations and channel conditions, and for different data traffic. Finally, the last section provides an overview of mobile WiMAX evolution.

MOBILE WIMAX FRAME STRUCTURE

Figure 1 shows the mobile WiMAX TDD frame structure. Each frame is configured to be 5 ms long and is time-division duplexed into downlink and uplink subframes. There are time gaps between downlink and uplink subframes, including mobile transceiver radio turn around time and a guard time avoiding interference between downlink and uplink signals. The time gap for the transition from downlink subframe to uplink subframe is called the transmit time gap (or TTG). The time gap for the transition from uplink subframe to downlink subframe is called Receive Time Gap (or RTG). The time gaps in the mobile WiMAX profile [3] support a maximum cell size of approximately 20.7 km for 3.5 or 7 MHz bandwidth, and 8.4 km for 5 or 10 MHz bandwidth mobile WiMAX systems. The 802.16e standard also specifies several options for mapping OFDM subcarriers to data subchannels so that both frequency-diverse and frequency-selective scheduling can be supported. For frequency-diverse subchannelization, IEEE 802.16e supports full usage subchannelization (FUSC) and partial usage subchannelization (PUSC). Other options include tile usage subchannelization (TUSC) and optional full usage subchannelization (O-FUSC)
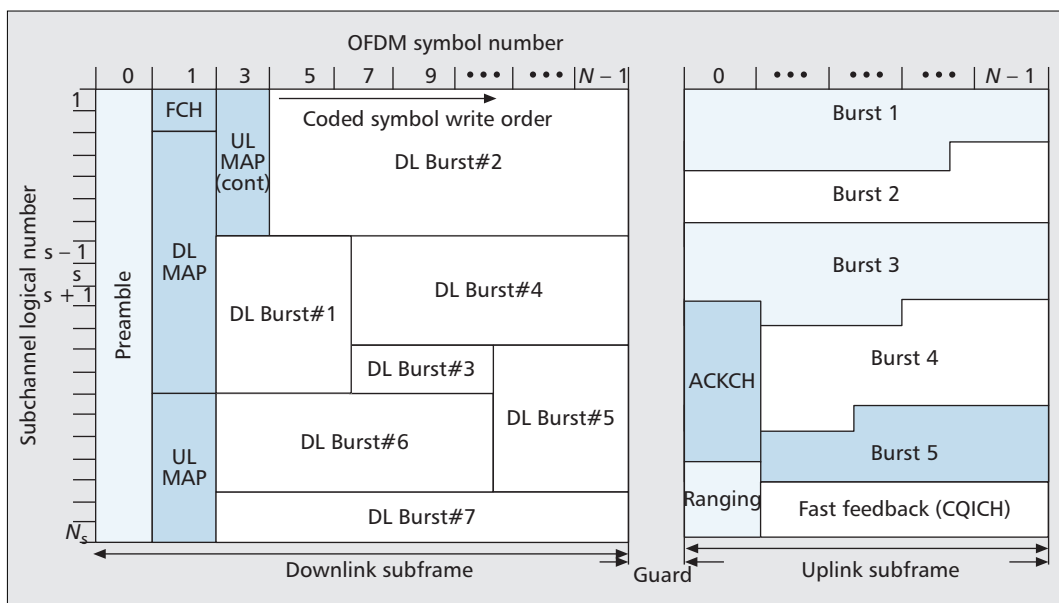
■ **Figure 1.** *Mobile WiMAX TDD frame structure.*

(a)	
MAP IEs	**Size (bits)**
Fixed compressed MAP (DL+UL+CRC)	152
Ranging region allocation IE (3 IEs: initial, periodic and bandwidth request IEs)	168
Fast feedback allocation IE	32
HARQ ACK region allocation IE	56
UL interference and noise level IE	28
Fixed overhead in HARQ DL MAP IE	72
Fixed overhead in HARQ UL MAP IE	64
UL HARQ per scheduled user	40
DL HARQ per scheduled user	44

(b)		
	5 users scheduled per frame	**10 users scheduled per frame**
MAP overhead symbols with Rep = 6	10	12
Other overhead symbols including guard time	5	5
Symbols for (DL + UL) bearer for Rep = 6	33	31
MAP overhead symbols with Rep = 4	6	8
Symbols for (DL + UL) bearer for Rep = 4	37	35

■ **Table 2.** *a) MAP IEs and sizes; b) number of OFDM symbols available for bearer data (10 MHz).*
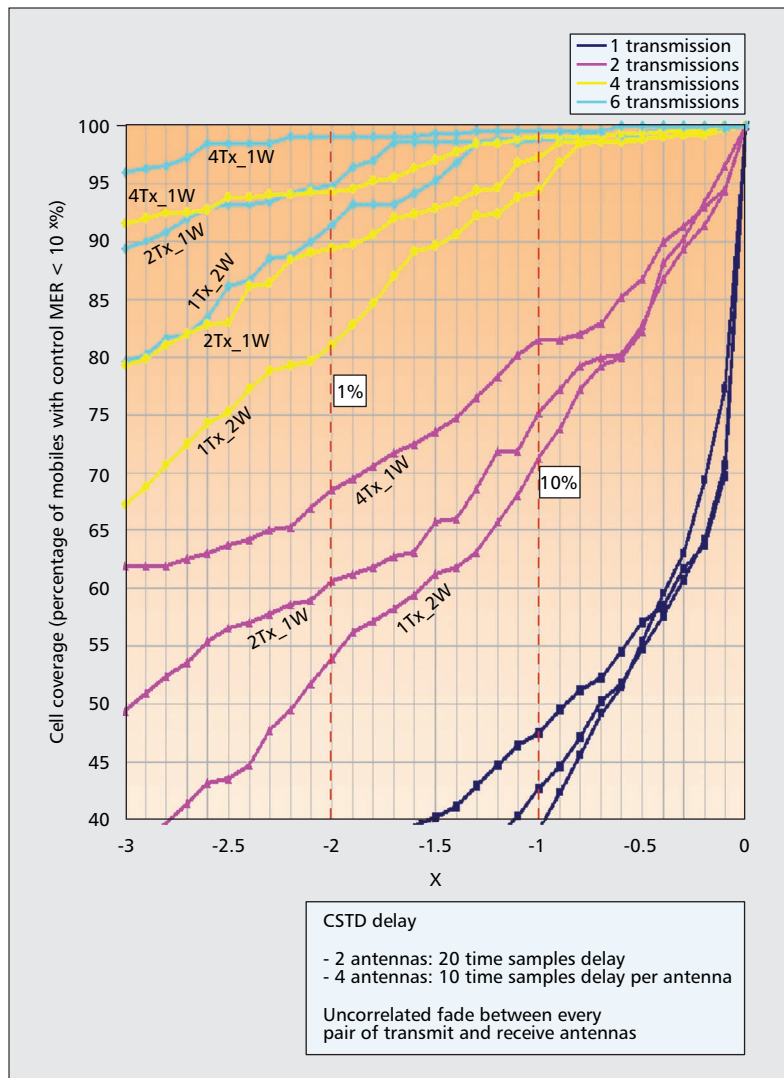
for downlink, and optional partial usage subchannelization (O-PUSC) for uplink. For frequency-specific subchannelization, IEEE 802.16e supports downlink and uplink band AMC (B-AMC). The minimum resource allocation unit in mobile WiMAX is a time-frequency slot containing 48 modulated data symbols.

At the beginning of each frame, downlink control information is transmitted consisting of a preamble, a frame control header (FCH), and a MAP message. The first symbol of every downlink subframe is the preamble, which can be used for synchronization, downlink channel estimation, and so on. The subcarriers allocated to the preamble are uniformly distributed throughout the spectrum and occupy every third subcarrier.

The first message at the beginning of the second downlink OFDM symbol is the FCH, which provides the information required to decode the subsequent DL-MAP message. The FCH carries information like the subchannels being used by the sector in the current frame, coding, and size of the DL-MAP.

The MAP message indicates the resource allocation for downlink and uplink data and control signal transmission. Each MAP message includes several information elements (IEs), and has a fixed part and a variable part. The size of the variable part is proportional to the number of downlink and uplink users scheduled in that frame. The number of OFDM symbols required for transmitting MAP messages depends on system bandwidth, number of users scheduled in the frame, frame size, IEs included in the MAP, and so on. Table 2a lists several essential IEs that are included in a compressed MAP message. It should be noted that the sizes of control messages in Table 2a might be different for different implementations. The compressed MAP messages in Table 2a are broadcast to all mobiles in the sector and thus need to be coded properly so that the mobiles at the edge of cells can decode them correctly. The total MAP overhead in OFDM symbols and the number of OFDM symbols available for transmitting bearer data with 5 or 10 users scheduled/frame for each downlink and uplink transmission is shown in Table 2b for a system with 10 MHz bandwidth allocation. With 5 scheduled users/frame (optimal for delay-insensitive data traffic, e.g., FTP and HTTP), the number of symbols available for both downlink and uplink bearer is 37 if 95 percent cell coverage is required for downlink MAP (achieved using 4 Tx CSTD and a repetition rate of 4, see the next section for control channel coverage details). This translates

Figure 2. *Cell coverage of a mobile WiMAX MAP control channel.*

uplink CQI or fast-feedback channel is used by a mobile station to report the measured carrier-to-interference-and-noise ratio (CINR) back to the access point. This information is used for functions such as selecting the downlink modulation and coding rates. The CQI information is quantized into a 6-bit format and carried over on one uplink slot consisting of 24 subcarriers by 3 OFDM symbols. Another uplink control channel, the uplink ACK channel, transports ACK/NACK feedback for the downlink hybrid ARQ data transmission and occupies half an uplink slot.

WiMAX Control Channel Coverage

WiMAX system coverage is limited by the control channel in the downlink and data channels in the uplink. The downlink control MAP message is coded with rate 1/2 convolution turbo code (CTC) and modulated using quaternary phase shift keying (QPSK). Since this message is broadcast to all mobile stations in the system, the CTC coded symbols are repeated one, two, four, or six times so that it can cover the mobile stations at the cell edge.

The MAP control channel system coverage is shown in Fig. 2 with and without cyclic shift transmit diversity (CSTD). CSTD is a space-time coding scheme used to achieve spatial diversity without explicit signaling to the mobiles. For the coverage performance shown in Fig. 2, every mobile station has a maximum ratio combining (MRC) receiver with two diversity receive antennas. Details of the simulation configurations are listed in [5].

In Fig. 2 the cumulative distribution function (CDF) of the control channel coverage for various repetition rates using 1, 2, or 4 transmit antennas is shown under a typical urban (TU) channel with 50 percent of the users at 3 km/h and 50 percent at 30 km/h. It may be observed that more than 95 percent cell coverage is achieved at an MAP error rate (MER) operating point of 1 percent using CSTD with 4 transmit and 2 receive antennas, R = 1/2 CTC code with a repetition of 4. Using more advanced mobile receivers, such as a receiver with interference rejection, the coverage of the MAP control channel can be significantly improved, especially for mobiles whose interference is from one or two dominant interfering signals.

Fractional Frequency Reuse

Under the full frequency reuse system configuration, mobiles in different sectors use the same frequency and result in low cell edge throughput due to interference from all their neighboring sectors. By taking advantage of flexible resource allocation on frequencies utilizing OFDMA, mobile WiMAX supports full frequency reuse, partial frequency reuse, and even a mixture of full and partial frequency reuse within one TDD frame. This feature of mobile WiMAX is known as fractional frequency reuse and can provide high cell edge throughput.

In partial frequency reuse, each neighboring sector takes a disjoint part of the frequency

into an overhead of approximately 23 percent without accounting for cyclic prefix and the pilot overhead for bearer data. It may be noted that for voice-over-IP (VoIP) traffic, the number of users scheduled per TDD frame will be higher (e.g., 15 to 20 users/frame for each downlink and uplink transmission).

Besides the control messages in the compressed MAP shown in Table 2a that are broadcast as one packet, mobile WiMAX also supports another MAP control message transmission mode known as SUB-DL-UL-MAP. Using SUB-DL-UL-MAP, different modulation and coding schemes can be applied for user-specific control information within the MAP message. For users scheduled within the frame that have good channel conditions, user-specific control messages can be transmitted using a more efficient modulation and coding scheme, and thus the MAP overhead can be reduced [4].

Uplink control channels support ranging, CQICH, and acknowledge (ACK)/negative ACK (NACK) transmissions. Ranging channel provides the random access capability for initial entry, timing adjustment, periodic synchronization, bandwidth request, and handover entry. The

band. A typical example is a system with three sectors per cell, with each sector taking one third of the frequency band. There is no cross-sector interference between the three neighboring sectors with the partial frequency reuse configuration. The disadvantage of partial frequency reuse, however, is a reduction in effective bandwidth for each sector.

Fractional frequency reuse takes advantage of the partial frequency reuse benefit of reduction in cross-sector interference for users at the cell edge while avoiding its disadvantage of reduced effective bandwidth. In fractional frequency reuse, mobiles close to cell sites are configured to operate with full frequency reuse for part of the time (known as a *zone*), while mobiles at the cell edge are configured to operate with partial frequency reuse in another zone for the remaining portion of the subframe.

As a comparison, 3G code-division multiple access (CDMA)-based systems typically only operate in a full frequency reuse configuration.

MULTIPLE ANTENNA TECHNOLOGIES IN MOBILE WiMAX

Mobile WiMAX supports various multiple-antenna system (MAS) technologies. The MAS technologies can generally be classified into two categories:
• Open loop MIMO
• Closed loop MIMO

Open loop MIMO includes space-time block coding (STBC or MIMO-A), open loop spatial multiplexing (SM-MIMO or MIMO-B), and adaptive mode selection between the two. Transmitters using open loop MIMO do not require explicit knowledge of the fading channels.

For closed loop MIMO, a transmitter forms antenna beams adaptively based on channel side information. These technologies are commonly referred to as transmitter adaptive antenna array (Tx-AA) techniques.

OPEN LOOP MULTIPLE ANTENNA TECHNOLOGIES

Space Time Block Coding — In mobile WiMAX systems, STBC encoding (known as Matrix-A, or the Alamouti scheme) is performed on pairs of encoded modulated symbols and occurs immediately after constellation mapping. Each symbol is transmitted twice, once per antenna, so that the overall space-time coding rate is one. Subcarrier mapping is performed independently for each transmit antenna signal. In addition, the signal from each transmit antenna has orthogonal dedicated pilots.

Cyclic Shift Transmit Diversity — Cyclic shift transmit diversity (CSTD) takes advantage of the OFDM receiver by adding spatial diversity from each transmit antenna. With CSTD, each antenna element in a transmit array sends a circularly shifted version of the same OFDM time domain symbol. For example, if antenna 1 sends an unshifted version of the OFDM symbol, antenna m transmits the same OFDM symbol, but circularly shifted by $(m - 1)D$ time domain

samples. An equivalent operation can be done in the frequency domain by multiplying a phase shifting sequence. Note that each antenna adds a cyclic prefix after circularly shifting the OFDM symbol; thus, the interblock interference protection offered by the cyclic prefix is unaffected by CSTD.

Compared to STBC, a receiver for CSTD with short circular delay does not need knowledge of the transmission scheme. Thus, dedicated pilots corresponding to each individual transmit antenna are not required. Since the WiMAX system is based on OFDM, the added multipath interference due to cyclic shift delay from different transmit antennas does not increase the complexity of the mobile receiver, but provides additional spatial diversity. However, the spatial diversity gain of CSTD is usually smaller than that of STBC.

Open Loop Spatial Multiplexing MIMO — The Mobile WiMAX system profile supports allocating two downlink data streams on the same time-frequency resource to one mobile receiver. This scheme (known as SM-MIMO or Matrix B) consists of encoding a single stream of data and then splitting each pair of modulation symbols between the two antennas. SM-MIMO doubles the peak data rate and improves the system performance when the system is bandwidth limited. However, the achievable system performance improvement of SM-MIMO over single-stream STBC depends on system configuration issues such as frequency reuse factor, mobile geometry, and traffic type.

A similar spatial multiplexing scheme is supported in mobile WiMAX on uplink. In this uplink coordinated space-division multiple access (SDMA) scheme, an access point scheduler allocates two uplink data streams on the same time-frequency resource from two mobile transmitters. The access point receiver separates the two data streams utilizing the receiver antenna array. Similar to downlink SM-MIMO, uplink SDMA doubles the peak sector data rate and improves the system performance when the system is bandwidth limited.

Adaptive Mode Selecon between STBC and Open Loop MIMO — Both STBC and SM-MIMO are downlink open loop MIMO schemes. The criterion to switch between Matrix-A (STBC) and Matrix-B (SM-MIMO) should be based on picking the scheme that gives the highest spectral efficiency.

CLOSED LOOP MULTIPLE ANTENNA TECHNOLOGIES

A TDD mobile WiMAX system supports closed loop transmission by taking advantage of the reciprocity of the downlink and uplink transmissions. In this article two types of closed loop MIMO schemes are described. In the first scheme, known as maximum ratio transmission (MRT), an antenna beam is formed on each OFDM subcarrier. The second scheme is known as statistical Eigen beamforming (EBF) where only one antenna beam is formed across multiple allocated subcarriers.

Transmitters using open loop MIMO do not require explicit knowledge of the fading channels. For closed loop MIMO, a transmitter forms antenna beams adaptively based on channel side information.

Parameter	Value
Number of sectors	19 cells, 3 sectors/cell
Carrier freq., bandwidth	2.5 GHz, 10 MHz
Frequency reuse	PUSC 1/1, PUSC 1/3, and FFR
Propagation model	Path loss (dB): $L = 126.2 + 36 \log (d)$, d in km
Lognormal shadowing	8 dB standard, 50 m correlation distance
Number of AP transmit antennas	1/2/4
Number of AP receive antennas	2/8
Number of MS TX/RX antennas	1/2
MS antenna gain	–2 dBi
Traffic models	Full buffer, Web browsing (HTTP), and VoIP

■ **Table 3.** *System simulation parameters.*

Maximum Ratio Transmission — MRT is similar to adaptive beamsteering. While adaptive beamsteering phases the transmit array to point the main beam toward the subscriber using knowledge of the subscriber's location, MRT attempts to track the channel response between the transmit and receive arrays on each subcarrier in frequency. MRT tries to maximize the received signal-to-noise ratio (SNR) on each subcarrier at the receiver's antenna array, and generally provides better performance than adaptive beamsteering because it is robust to high angular spread channels. Its difficulty lies in obtaining accurate channel knowledge of the transmit array. A benefit in this technique is that it poses no strict constraints on the characteristics of the TX antenna array. It makes no assumption about antenna placement, polarization, orientation, or even antenna patterns. Although some of these factors can limit ultimate performance, the algorithm attempts to take full advantage of the given physical hardware.

Statistical Eigen Beamforming — In EBF a single set of transmit weights are computed and applied to each subcarrier within a desired band, instead of calculating a separate set of weights for each subcarrier as in MRT. A covariance matrix of the channel is first computed in EBF over the band of interest, and the transmit antenna weights are computed by taking the largest eigenvector of this covariance matrix and applying it to all the subcarriers within the band.

MRT requires accurate knowledge of the channel and is better for high signal-to-interference-plus-noise ratio (SINR) and low velocity. Statistical EBF is more robust and outperforms MRT for low SINR, and for high-velocity mobiles with large delay between channel measurement and beamforming. Additionally, statis-

tical EBF simplifies downlink channel estimation since the same beamforming weights are applied for all subcarriers within the band of interest.

MOBILE WiMAX SYSTEM PERFORMANCE

A system simulator based on the mobile WiMAX system profile [3] and system evaluation methodology [6] is used to study the mobile WiMAX system performance with different MIMO technologies. This simulator uses 19 hexagonal three-sector cells. The number of mobile stations in the simulator is adjusted to meet the target outage probability requirement. The cell layout, path loss model, antenna configurations at access points and mobile stations and traffic models are listed in Table 3. More detailed assumptions for system simulations can be found in [7–9]. The link performance curves used in system simulations are included in [10].

MOBILE WiMAX DOWNLINK SYSTEM PERFORMANCE SUMMARY

The spectral efficiency improvement using open loop MIMO and closed loop beamforming over single-input multiple-output (SIMO) configuration depends on factors such as traffic model (full buffer or HTTP), frequency reuse pattern, and so forth. Figures 3a and 3b show the comparison of sector spectral efficiency for various multiple-antenna technologies including SIMO, STBC, adaptively switching between STBC and MIMO (denoted MIMO in Figs. 3a and 3b), and closed loop beamforming (denoted Tx-AA in Figs. 3a and 3b).

As shown in Figs. 3a and 3b, STBC does not improve the system throughput. Although STBC improves the link performance and system coverage, the system throughput does not improve with the additional spatial diversity due to other diversities in mobile WiMAX systems (e.g., receive diversity, multi-user diversity).

By adaptively switching between single-data-stream STBC and two-data-stream SM-MIMO, WiMAX system performance can be improved over SIMO by about 50 percent for $1 \times 3 \times 3$ frequency reuse and 10 percent for $1 \times 3 \times 1$ frequency reuse using minimum mean square error (MMSE) receivers. With more complex pseudo MLD receivers, the MIMO-MMSE system performance can be further improved by an additional 15~20 percent.

For $1 \times 3 \times 1$ frequency reuse, the system performance can be further improved using closed loop beamforming. For $1 \times 3 \times 3$ frequency reuse, however, open loop MIMO outperforms closed loop beamforming for full buffer data traffic.

Figure 3b shows the performance comparison for HTTP data traffic. It may be observed that the relative performance of various multiple-antenna technologies for HTTP is different from that for full buffer. Closed loop beamforming provides higher system performance improvement for equal data rate types of traffic such as HTTP than with full buffer. Open loop MIMO is more effective for data traffic with large pay-

loads such as full buffer since the scheduler gives preference to users with good channel conditions. These full buffer users are bandwidth limited and can use the extra bandwidth through spatial multiplexing.

MOBILE WiMAX UPLINK SYSTEM PERFORMANCE WITH MULTIPLE RECEIVE ANTENNAS

In this section the performance of MU-MIMO and SU-MIMO are analyzed for two types of access points with two and eight receive antennas, respectively. For the first type of access points, the two receive antennas at the access point are four wavelengths apart. For the second type of access points, each one has a linear array that contains eight antenna elements and half of a wavelength between two adjacent antenna elements. In the case of SDMA, the scheduler assigns one or two mobiles to transmit on each time-frequency resource at each scheduling instance. Similar to downlink MIMO, the peak sector data rate of uplink transmission can be doubled using SDMA.

Uplink sector spectral efficiencies using MRC and SDMA with MMSE receivers are shown in Fig. 3c. We note that for $1 \times 3 \times 3$ frequency reuse, the system is bandwidth limited but not power limited. In this case, even though the combined signal power from multiple receive antennas is increased by increasing the number of receive antennas, the uplink system performance is only slightly improved in the SIMO mode. However, by allocating two users to transmit simultaneously using SDMA, the system performance can be improved by more than 80 percent using the second type of access point with eight receive antennas. In the case of $1 \times 3 \times 1$ frequency reuse, the system performance improvement of SDMA over MRC using the second type of access point is around 20 percent.

MOBILE WiMAX WITH FRACTIONAL FRACTIONAL REUSE

Figure 3d shows the relative improvement with fractional frequency reuse compared to full frequency reuse (PUSC 1/1) configuration and partial frequency reuse (PUSC 1/3) configuration. The result is for mobile WiMAX systems with 10 MHz bandwidth, a load of 150 users/sector, and HTTP traffic. Cell edge throughput is defined as the minimum data rate achieved by 95 percent of users in the sector. The results show that fractional frequency reuse outperforms the full and partial frequency reuse configurations, especially for cell edge throughput.

In order to get good cell edge reliability, it is preferable to send the MAP message in a PUSC 1/3 zone. The fractional frequency reuse configuration would be a good choice in this kind of deployment since it can combine both the PUSC 1/3 zone and a PUSC 1/1 zone in the same downlink subframe to provide good cell edge coverage and cell edge throughput performance, while at the same time not compromising on overall sector throughput and average user throughput.

VoIP OVER MOBILE WiMAX

The VoIP capacity of mobile WiMAX is studied using the system simulator, and is shown in Fig. 3e. Since the system capacity for VoIP-only service is uplink limited, the simulation results in Fig. 3e are for uplink system performance with an MRC receiver and two diversity receive antennas at each access point. The VoIP model in Fig. 3e is 12.2 kb/s AMR with 50 percent voice activity factor [6]. A VoIP user is in outage if less than 98 percent of its packets are delivered successfully within a given delay bound. System VoIP capacity is defined as the number of users that can be supported in each sector such that the percentage of users in outage is less than a certain criterion. From Fig. 3e, it can be observed that with a load of 105 active VoIP users in one sector and an over-the-air delay request of 50 ms, the system outage is less than 5 percent. With a higher system load of 110 active VoIP users in one sector, the system outage increases to 8 percent. With an even higher system load of 120 active VoIP users in one sector, the system outage increases to almost 20 percent.

An alternative analytic methodology described in [11] is also used to study the packet queuing delay. The result from [11] substantiates the VoIP capacity from system simulations. Furthermore, the result from [11] shows that in order to meet the delay request of VoIP service, system utilization is around 80 percent. This observation implies that more delay-insensitive services (e.g., HTTP or FTP) can be added without affecting the VoIP capacity shown in Fig. 3e.

MOBILE WiMAX EVOLUTION

Since early 2007, the WiMAX Forum and the IEEE 802.16 Working Group have started separate evolution projects to improve the performance of the current release of mobile WiMAX and keep the momentum of evolving mobile WiMAX as a leading mobile broadband wireless communication solution.

In the WiMAX Forum the evolution project is known as mobile WiMAX release 1.5; the current mobile WiMAX release is 1.0. The focus of this project includes adding FDD configuration to the mobile WiMAX profile, enabling MIMO/BF under FDD mobile WiMAX, adding persistent allocation to improve efficiency for VoIP data traffic, reducing MAP control message overhead, and reducing handoff latency. The target of this project is to provide performance enhancement to current mobile WiMAX systems within a short time period (targeting deployment in late 2009) and without introducing significant changes to the IEEE 802.16-2005 specification.

The project that introduces more fundamental performance enhancements to mobile WiMAX is led by the IEEE 802.16 Working Group. This project and the associated future standard are known as 802.16m. The target for 802.16m is to meet the requirements of IMT-Advanced, the fourth generatioin (4G) successor of IMT-2000. In other words, 802.16m will be the 4G mobile WiMAX evolution. According to the system requirement document (SRD) of

Since early 2007, the WiMAX forum and the IEEE 802.16 working group have started separate evolution projects to improve the performance of the current release of mobile WiMAX and to keep the momentum of evolving mobile WiMAX as a leading mobile broadband wireless communication solution.
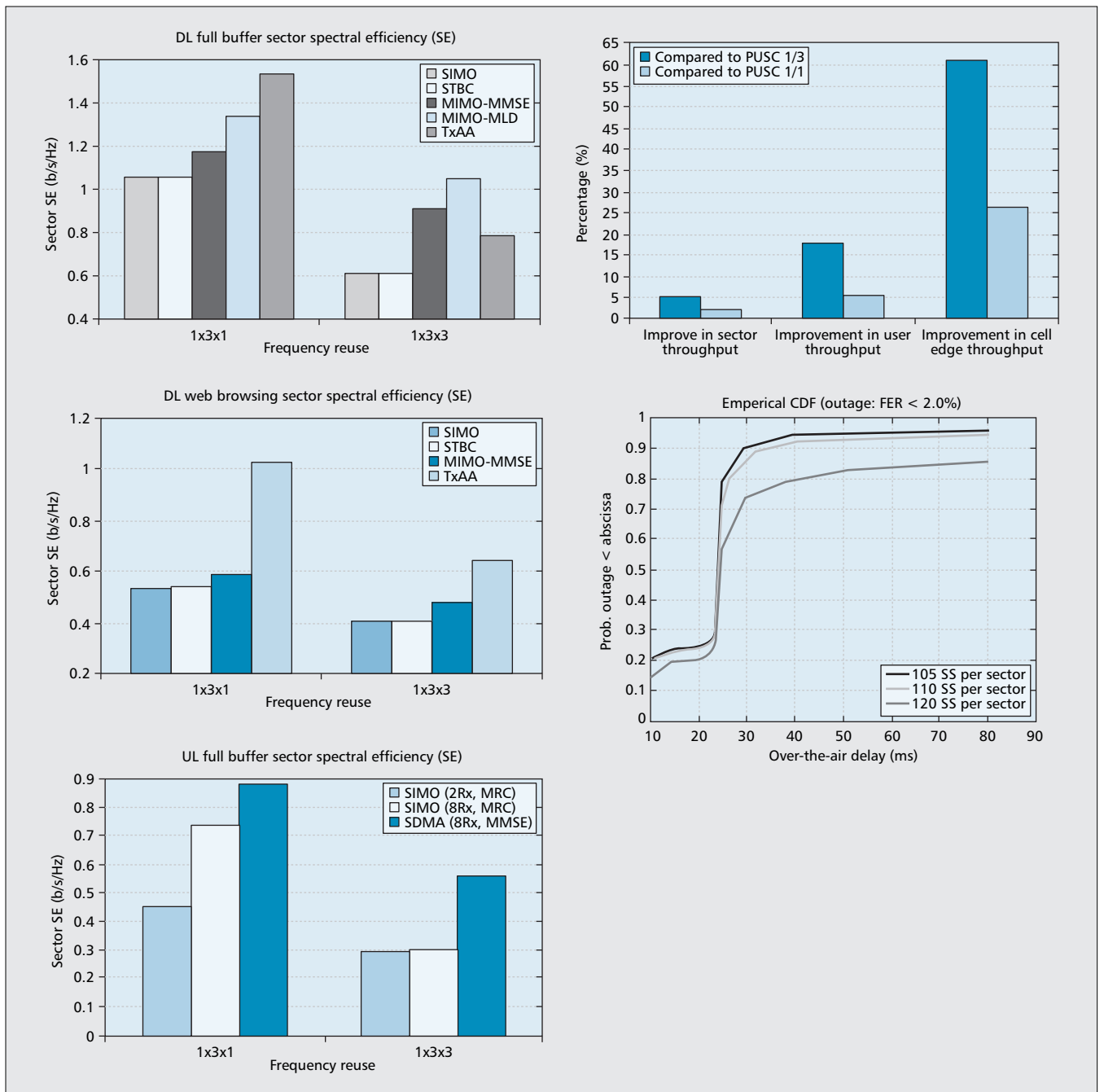
Figure 3. *a) Downlink sector spectral efficiency comparison with full buffer traffic; b) downlink sector spectral efficiency comparison with HTTP traffic; c) uplink sector spectral efficiency comparison with full buffer traffic; d) relative improvements of fractional frequency reuse over PUSC 1/3 and PUSC 1/1; e) VoIP performance of mobile WiMAX systems.*

802.16m [12], the key performance targets for 802.16m include:
- The 802.16m system should be backward compatible with current mobile WiMAX systems.
- The 802.16m system should provide more than twice the spectral efficiency of mobile WiMAX release 1.0 in both downlink and uplink for metrics like average sector throughput, average user throughput and cell edge user throughput.
- The 802.16m system should provide more than 1.5 times the VoIP capacity of mobile WiMAX release 1.0.

- The 802.16m system should provide lower latency than mobile WiMAX release 1.0.

The 802.16m evolved mobile WiMAX profile is targeted to finish at the fourth quarter of 2009 and be deployed in 2011. IEEE 802.16 Task Group m (TGm) is working actively to develop the new 802.16m standard. Several new techniques are under discussion for 802.16m, including:
- Improved and backward compatible frame structure and system protocol
- Smaller frame/sub-frame size to reduce latency
- New multi-antenna technologies

- Improved interference coordination and management schemes for both downlink and uplink
- New control channel design with better system coverage and reduced overhead
- Persistent scheduling for VoIP and real-time video services
- Optimized handover, more efficient paging and random access, and so on

These new techniques cover almost all areas of cellular system design, and will significantly improve the performance of the current WiMAX system while maintaining backward compatibility.

SUMMARY

Mobile WiMAX has spurred tremendous interest from operators seeking to deploy high-performance yet cost-effective broadband wireless networks. This article provides a detailed overview of the mobile WiMAX system, and summarized its coverage and performance capabilities for various features including different types of MIMO schemes, fractional frequency reuse schemes, and receiver structures under different workloads and channel conditions.

With the ongoing phased deployment of the first release of mobile WiMAX systems in the United States and globally, the wireless industry has already started the evolution process toward more advanced mobile WiMAX systems. The evolutions include a project in the WiMAX Forum with minor revisions to the 802.16e specification and a project at the IEEE 802.16 working group for developing a more advanced 802.16m standard. This article highlights several key requirements and techniques of the ongoing mobile WiMAX evolution.

ACKNOWLEDGMENT

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BIOGRAPHIES

FAN WANG [SM] (fanw@motorola.com) received B.S. and M.S. degrees from Shanghai Jiao Tong University, China, and a Ph.D. degree from the School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana, in 1992, 1995, and 1999, respectively. Since 2000 he has been with the Networks Advanced Technologies Department of Motorola Networks. His current research interests are in signal processing and wireless communications. He was an associate editor of the IEEE Control Systems Society Conference Editorial Board from 2001 to 2005. He was a finalist for the 1999 American Control Conference Best Student Paper Award.

AMITAVA GHOSH [SM] joined Motorola in 1990 after receiving his Ph.D. in electrical engineering from Southern Methodist University, Dallas, Texas. Since joining Motorola he has worked on eight different wireless technologies: IS-95, cdma-2000, 1xEV-DV/1XTREME, 1xEV-DO, UMTS, HSPA, 802.16e/WiMAX/802.16m, Enhanced EDGE, and 3GPP LTE. Recently, he led the effort from Motorola's side in defining 3GPP LTE physical layer standards from the concept phase to the adopted baseline. He has 37 issued patents and numerous external and internal technical papers. He is a reviewer for IEEE Communications Society and was a book reviewer for a popular WiMAX book. Currently, he is a fellow of technical staff in Network Advance Technology, Motorola Home and Networks Mobility, and works in the area of current and future air interface technologies for 802.16m, 3GPP LTE, and other broadband technologies. His research interests are in the area of digital communications, signal processing and wireless communications. He is an associate member of the Motorola Science Advisory Board.

CHANDY SANKARAN has been with Motorola since August 2000 and is currently in the Networks Advanced Technologies organization of the Wireless Broadband Division. His research interests are on problems related to wireless communications, and he has been working on advanced topics related to emerging broadband technologies like WiMaX and LTE. He holds a Ph.D. in electrical engineering from the University of Maryland, College Park.

PHILIP J. FLEMING is a fellow of technical staff in the Networks Advanced Technologies organization of the Wireless Broadband Division at Motorola, Inc. where he is also senior director of the Advanced Radio Technology and Performance group. His current research interests lie in the area of broadband wireless networking and communication theory, and he has done work in queuing theory and its applications to wireless and wireline networking and computer engineering. He has received both the Distinguished Innovator Award and the Dan Noble Fellow Award at Motorola, and has a Ph.D. in mathematics from the University of Michigan.

FRANK HSIEH is a senior staff engineer in Networks Advanced Technologies at Motorola. He has 10 years of experience in wireless communications and cellular network systems. His current work at Motorola is related to WiMAX (802.16e) and its evolution standard (802.16m), particularly in the areas of MIMO technologies and advanced receivers. He holds a Ph.D. in physics from the University of Michigan.

STANLEY J. BENES is a principal staff engineer in the Networks Advanced Technologies organization of the Wireless Broadband Division at Motorola, Inc. where he serves as a member of the Advanced Radio Technology and Performance group. His current research interests lie in broadband wireless networking and electromagnetic propagation. He has five U.S. patents, is a Lieutenant in the U.S Navy Engineering Duty Officer Corps, and has an M.S.E.E. from Marquette University and an M.S.TCOM. from DePaul University.

With the ongoing phased deployment of the first release of mobile WiMAX systems in the U.S. and globally, the wireless industry has already started the evolution process for more advanced mobile WiMAX systems.