Mobile WiMAX – Part II: A Comparative Analysis

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This paper has been prepared on behalf of the WiMAX Forum and the material presented represents the combined efforts of many people from several WiMAX Forum organizations with long-standing experience in wireless technologies. Additionally, a broader range of WiMAX Forum members have had the opportunity to technically review and critique the material and every attempt has been made to ensure its accuracy. Numerous references are cited in the document for the reader interested in a more in-depth discussion of the material. The overall preparation and editing was done by Doug Gray, a Telecommunications Consultant under contract to the WiMAX Forum.

Acronyms

3GPP	3G Partnership Project
3GPP2	3G Partnership Project 2
AAS	Adaptive Antenna System also Advanced Antenna System
ACK	Acknowledge
AES	Advanced Encryption Standard
AG	Absolute Grant
AMC	Adaptive Modulation and Coding
A-MIMO	Adaptive Multiple Input Multiple Output (Antenna)
AMS	Adaptive MIMO Switching
ARQ	Automatic Repeat reQuest
ASN	Access Service Network
ASP	Application Service Provider
BE	Best Effort
CC	Chase Combining (also Convolutional Code)
CCI	Co-Channel Interference
CCM	Counter with Cipher-block chaining Message authentication code
CDF	Cumulative Distribution Function
CDM	Code Division Multiplex
CDMA	Code Division Multiple Access
CINR	Carrier to Interference + Noise Ratio
CMAC	block Cipher-based Message Authentication Code
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CSN	Connectivity Service Network
CSTD	Cyclic Shift Transmit Diversity
CTC	Convolutional Turbo Code
CWTS	China Wireless Telecommunications Standards group
DL	Downlink
DOCSIS	Data Over Cable Service Interface Specification
DPCCH	Downlink Physical Control Channel
DRC	Data Rate Control
DSC	Data Source Control
DSL	Digital Subscriber Line
DVB	Digital Video Broadcast
E-AGCH	E-DCH Absolute Grant Channel
EAP	Extensible Authentication Protocol
EESM	Exponential Effective SIR Mapping
E-DCH	Enhanced Data Channel
E-DPCCH	E-DCH Dedicated Physical Control Channel

E-DPDCH	E-DCH Dedicated Physical Data Control Channel
E-HICH	E DCH HARQ Acknowledgement Indicator Channel
EIRP	Effective Isotropic Radiated Power
E-RGCH	E-DCH Relative Grant Channel
ErtPS	Extended Real-Time Polling Service
EVDO	Evolution Data Optimized or Evolution Data Only
E-UTRA	Evolved-UMTS Terrestrial Radio Access
EVDV	Evolution Data-Voice
FBSS	Fast Base Station Switching
FCH	Frame Control Header
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FTP	File Transfer Protocol
FUSC	Fully Used Sub-Carrier
GPRS	General Packet Radio Service
HARQ	Hybrid Automatic Repeat reQuest
HHO	Hard Hand-Off
HMAC	keyed Hash Message Authentication Code
HO	Hand-Off or Hand Over
HRPD	High Rate Packet Data
HSPA	High Speed Packet Access
HSDPA	High Speed Downlink Data Packet Access
HS-DPCCH	High-Speed Dedicated Physical Control Channel
HS-DSCH	High-Speed Downlink Shared Channel
HS-SCCH	High-Speed Shared Control Channel
HSUPA	High-Speed Uplink Data Packet Access
HTTP	Hyper Text Transfer Protocol
IE	Information Element
IEFT	Internet Engineering Task Force
IFFT	Inverse Fast Fourier Transform
IR	Incremental Redundancy
ISI	Inter-Symbol Interference
LDPC	Low-Density-Parity-Check
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Media Access Control
MAI	Multiple Access Interference
MAN	Metropolitan Area Network
MAP	Media Access Protocol
MBS	Multicast and Broadcast Service

MDHO	Macro Diversity Hand Over
MIMO	Multiple Input Multiple Output (Antenna)
MLD	Maximum Likely-hood symbol Detection
MMS	Multimedia Message Service
MMSE	Minimum Mean Squared Error
MPLS	Multi-Protocol Label Switching
MS	Mobile Station
MSO	Multi-Services Operator
NACK	Not Acknowledge
NAP	Network Access Provider
NLOS	Non Line-of-Sight
NRM	Network Reference Model
nrtPS	Non-Real-Time Polling Service
NSP	Network Service Provider
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
PER	Packet Error Rate
PF	Proportional Fair (Scheduler)
PKM	Public Key Management
PSK	Phase Shift Keying
PUSC	Partially Used Sub-Carrier
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Reverse Activity
RAB	Reverse-Link Activity Bit
RG	Relative Grant
RNC	Radio Network Controller
RPC	Reverse Power Control
RR	Round Robin (Scheduler)
RRI	Reverse Rate Indicator
RTG	Receive/transmit Transition Gap
rtPS	Real-Time Polling Service
RUIM	Removable User Identity Module
SDMA	Space (or Spatial) Division (or Diversity) Multiple Access
SF	Spreading Factor
SFN	Single Frequency Network
SGSN	Serving GPRS Support Node
SHO	Soft Hand-Off
SIM	Subscriber Identity Module

SIMO	Single Input Multiple Output (Antenna)
SINR	Signal to Interference + Noise Ratio
SISO	Single Input Single Output (Antenna)
SLA	Service Level Agreement
SM	Spatial Multiplexing
SMS	Short Message Service
SNIR	Signal to Noise + Interference Ratio
SNR	Signal to Noise Ratio
S-OFDMA	Scalable Orthogonal Frequency Division Multiple Access
SS	Subscriber Station
STBC	Space Time Block Code
STC	Space Time Coding
TD-CDMA	Time Division Code Division Multiple Access
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TDD	Time Division Duplex
TDM	Time Division Multiplex
TEK	Traffic Encryption Key
TFRI	Transport Format Related Information
TTG	Transmit/receive Transition Gap
TTI	Transmission Time Interval
TU	Typical Urban (as in channel model)
UE	User Equipment
UGS	Unsolicited Grant Service
UL	Uplink
UMTS	Universal Mobile Telecommunications System
USIM	Universal Subscriber Identity Module
UTRAN LTE	UMTS Terrestrial Radio Access Network Long Term Evolution
V-MIMO	Virtual Multiple Input Multiple Output (Antenna)
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
VSF	Variable Spreading Factor
VSM	Vertical Spatial Multiplexing
WAP	Wireless Application Protocol
WCDMA	Wideband Code Division Multiple Access
WiBro	Wireless Broadband (Service)
WiMAX	Worldwide Interoperability for Microwave Access

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EXECUTIVE SUMMARY

This paper is a companion paper to **Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation.** In part I the salient features of the 802.16e-2005 based Mobile WiMAX technology and details of how its distinct capabilities can be applied in enabling broadband mobile services were discussed. Part I also provided a Mobile WiMAX performance evaluation. In this companion paper a comparison of Mobile WiMAX performance characteristics with contemporary and evolving 3G technologies is provided. This discussion and performance comparison provides a more complete picture of the role that Mobile WiMAX can play in the evolution of broadband mobile networks.

Two 3G CDMA variants are widely used today, WCDMA, an FDD solution based on 5 MHz channels and CDMA2000, an FDD solution based on 1.25 MHz channels. To improve downlink capacity in 3G systems 3GPP has developed the HSDPA enhancement for WCDMA. A further enhancement, HSUPA, provides enhancements to the uplink. Similar changes have been developed by 3GPP2 for CDMA2000 where 1xEVDO-Rev 0 and 1xEVDO-Rev A provide throughput enhancements for data traffic. A further CDMA2000 enhancement, EVDO-Rev B adds multicarrier capability. 3GPP is also considering longer term enhancements for WCDMA such as MIMO support with HSPA. UTRAN Long Term Evolution (UTRAN-LTE) also referred to as 3.99G is also on the evolutionary roadmap for both WCDMA and CDMA2000.

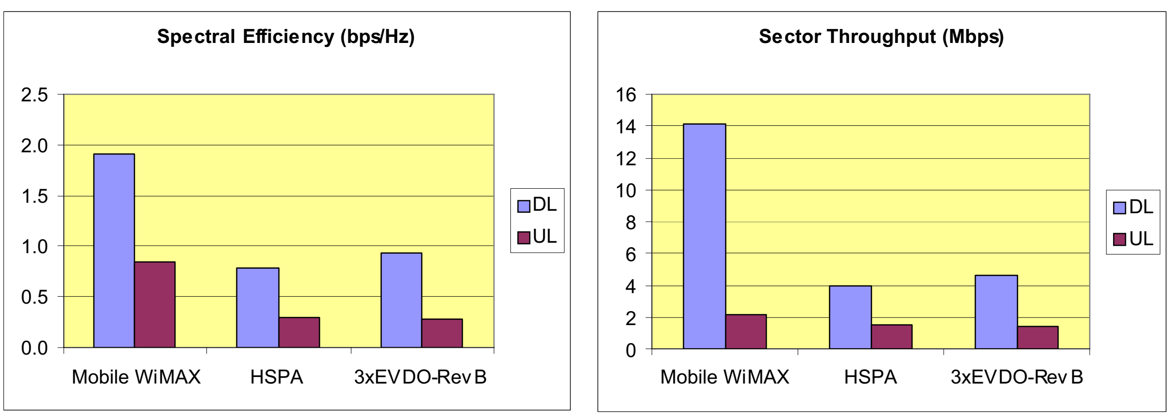
Mobile WiMAX is based on OFDM/OFDMA technology. Mobile WiMAX systems offer scalability in both radio access technology and network architecture, thus providing a great deal of flexibility in network deployment options and service offerings. This approach has several key advantages over the traditional CDMA-based 3G systems:

- **High Data Rates:** MIMO antenna techniques with flexible sub-channelization schemes and Advanced Coding and Modulation enable the Mobile WiMAX technology to support peak DL sector data rates up to 46 Mbps, assuming a DL/UL ratio of 3:1, and peak UL sector data rates up to 14 Mbps, assuming a DL/UL ratio of 1:1, in a 10 MHz channel.
- **Quality of Service (QoS):** The fundamental premise of the IEEE 802.16 MAC architecture is QoS. It defines Service Flows which can map to DiffServ code points or MPLS flow labels that enable end-to-end IP-based QoS. Additionally, sub-channelization and MAP-based signaling schemes provide a flexible mechanism for optimal scheduling of space, frequency, and time resources over the air interface on a frame-by-frame basis. With high data rate and flexible scheduling, the QoS can be

better enforced. As opposed to priority-based QoS schemes, this approach enables support for guaranteed service levels including committed and peak information rates, latency, and jitter for varied types of traffic on a customer-by-customer basis.

- **Scalability**: Despite an increasingly globalized economy, spectrum resources for wireless broadband worldwide are still quite disparate in its allocations. Mobile WiMAX technology therefore, is designed to be able to scale to work in different channelizations from 1.25 to 20 MHz to comply with varied worldwide requirements as efforts proceed to achieve spectrum harmonization in the longer term. This also allows diverse economies to realize the multi-faceted benefits of the Mobile WiMAX technology for their specific geographic needs such as providing affordable internet access in rural settings versus enhancing the capacity of mobile broadband access in metro and suburban areas.

To quantify the technology differences, a throughput and spectral efficiency performance comparison is provided based on simulations using a common set of parameters for the three systems: Mobile WiMAX, 1xEVDO Rev A and Rev B, and HSDPA/HSUPA (HSPA). The simulations show that Mobile WiMAX has a distinct advantage over the 3G enhancements in both spectral efficiency and channel/sector throughput in both the DL and UL directions. The spectral efficiency for Mobile WiMAX with MIMO is more than 2 times better than EVDO Rev B and HSPA in both downlink and uplink and, in the same bandwidth, the sector throughput is more than 2 times higher in the DL and about 2 times higher in the UL.



Spectral efficiency and sector throughput comparison of HSPA, EVDO-Rev B, and Mobile WiMAX under the same user traffic conditions

The high data throughput results in better data multiplexing and low data latency, which is essential to enable broadband data services and VoIP with high quality of service. The performance will enable transparency of quality of service between Mobile WiMAX and broadband wired services such as Cable and DSL, an important requirement for the successful delivery of broadband mobile services ranging from real-time interactive gaming and streaming media to non-real-time web browsing and simple file transfers.

Additional WiMAX benefits include its open standard approach and healthy ecosystem. Hundreds of companies have contributed to the development of the technology and many companies have announced product plans for this technology. The broad industry participation and worldwide adoption will ensure economies of scale that will help drive low cost of subscription and enable the deployment of a wide range of broadband mobile services in both developed and emerging markets. With its architecture and performance advantages and wide industry support, Mobile WiMAX is well-positioned to play a key role in the evolution of future broadband wireless networks on a global scale.

Mobile WiMAX: A Comparative Analysis

1. Introduction

This paper is a companion paper to "**Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation" [**1]. Part I provided a detailed description the Mobile WiMAX technology and a performance evaluation based on a set of simulation parameters. This paper provides a detailed discussion of how Mobile WiMAX compares to the evolution of 3G technologies.

To improve downlink capacity in 3G systems 3GPP has developed the HSDPA [2] enhancement for WCDMA. This enhancement changes the downlink from CDM to TDM-CDM so as to enable adaptive modulation and coding and other spectral efficiency improvements. A further enhancement, HSUPA [3,4], provides enhancements to the uplink as well but the uplink is still limited to lower order modulation. Similar changes have been developed by 3GPP2 for CDMA2000. 1xEVDO-Rev 0 [5] changes the downlink from CDM to TDM. 1xEVDO-Rev A provides additional DL improvements along with throughput enhancements to the uplink and 1xEVDO Rev B adds multi-carrier capability. Further evolution for WCDMA such as 3GPP/3GPP2 Long Term Evolution (LTE) is expected to adopt OFDM-based technology to further improve data throughput.

Mobile WiMAX is based on OFDM/OFDMA technology [6,7,8]. Mobile WiMAX systems offer scalability in both radio access technology and network architecture, thus providing a great deal of flexibility in network deployment options and service offerings. It has several key advantages over the traditional CDMA-based 3G systems:

- **High Data Rates:** MIMO antenna techniques with flexible sub-channelization schemes, Advanced Coding and Modulation enable the Mobile WiMAX technology to support peak DL sector data rates up to 46 Mbps, assuming a DL/UL ratio of 3:1, and peak UL sector data rates up to 14 Mbps, assuming a DL/UL ratio of 1:1, in a 10 MHz channel.
- **Quality of Service (QoS):** The fundamental premise of the IEEE 802.16 MAC architecture is QoS. It defines Service Flows which can map to DiffServ code points or MPLS flow labels that enable end-to-end IP based QoS. Additionally, sub-channelization and MAP-based signaling schemes provide a flexible mechanism for optimal scheduling of space, frequency and time resources over the air interface on a frame-by-frame basis. With high data rate and flexible scheduling, the QoS can be better enforced. As opposed to priority-based QoS schemes, this approach enables support for guaranteed service levels including committed and peak information rates, latency, and jitter for varied types of traffic on a customer-by-customer basis.
- **Scalability***:* Despite an increasingly globalized economy, spectrum resources for wireless broadband worldwide are still quite disparate in its allocations. Mobile

WiMAX technology therefore, is designed to be able to scale to work in different channelizations from 1.25 to 20 MHz to comply with varied worldwide requirements as efforts proceed to achieve spectrum harmonization in the longer term. This also allows diverse economies to realize the multi-faceted benefits of the Mobile WiMAX technology for their specific geographic needs such as providing affordable internet access in rural settings versus enhancing the capacity of mobile broadband access in metro and suburban areas.

All of these technologies will become available in a phased fashion. 1xEVDO Rev 0 was initially launched in Korea and Japan in 2003 followed by extensive deployments in the in 2004 and 2005 [9,10]. The 1xEVDO-Rev A standard was approved in March 2004 and the commercial launch of services based on this standard took place in 2005 with more extensive deployments expected in 2006 [11,12]. The first commercial HSDPA deployment was announced in December 2005 [13] and operators in Europe [14] and Japan [15] have announced plans for HSDPA deployments in 2006. Mobile WiMAX is expected to begin rolling out in late 2006 and early 2007.

System	Enhancements	First Commercial Availability
1xEVDO, CDMA2000		
Rev 0	DL Enhancements	2003
Rev A	Add UL Enhancements	2005
Rev B	Add Multi-Carrier	2008
HSPA, WCDMA		
HSDPA	DL Enhancements	2005/2006
HSUPA	Add UL Enhancements	2007/8
WiMAX		
Mobile WiMAX	Mobility	2006/7

Table 1: WiMAX/3G Technology Availability

In this paper, a high level comparison of commonalities and differences of these different technologies is discussed. Section 2 provides a discussion of the enhancements for 3G systems, 1xEVDO and HSDPA/HSPA. These enhancements, based on the work of 3GPP and 3GPP2 are designed to add capacity to existing WCDMA and CDMA2000 3G FDD-based networks, thus providing an upgrade path to enable operators to offer data services over their existing networks.

In Section 3 a qualitative comparison of the Mobile WiMAX technology with the 3G enhancements is provided by describing and comparing key attributes and identifying the advantages that OFDMA-based Mobile WiMAX has over the 3G enhancements. The technology comparison continues in Section 4 with a quantitative comparison of the two key metrics, data throughput and spectral efficiency for all three technologies based on a common set of parameters and assumptions.

2. Evolution of 3G Systems

The 3G Partnership Project (3GPP) and 3G Partnership Project 2 (3GPP2) have been defining standards for enhancements to today's 3G systems. Extensions to both WCDMA and CDMA2000 have been defined with the objective of adding network capacity and features to enable operators to offer new data-oriented services over their existing networks. These extensions are:

- Evolution Data-Optimized[1] (1xEVDO) [5], also known as High Rate Packet Data (HRPD) is a data optimized evolution of CDMA2000 developed by the 3GPP2. In a 1.25 MHz channel, 1xEVDO offers, over the air peak data rates of 2.4 Mbps (Rev 0) and 3.1 Mbps (Rev A) in the downlink (DL) and 153.6 kbps (Rev 0) and 1.8 Mbps (Rev A) in the uplink (UL). EVDO-Rev B, which is still in the process of standardization, adds further DL capacity enhancements and is expected to increase the DL peak data rate to 4.9 Mbps in a 1.25 MHz channel. 1xEVDO-Rev 0 has had initial success in South Korea and is now being widely deployed.
- High-Speed Downlink Packet Access (HSDPA) [2]. HSDPA as defined by 3GPP provides downlink enhancements to WCDMA R'99. This enhancement offers over the air downlink peak data rate of up to 14 Mbps in a 5 MHz channel, and with a further release known as, High-Speed Uplink Packet Access (HSUPA), provides capacity enhancements to the uplink as well.

2.1 Brief Overview of 1xEVDO

1xEV-DO is a high-speed data only system for 1.25 MHz FDD channels. The original 1xEV-DO specifications can achieve 2.4 Mbps peak DL data rate and average DL throughput that is significantly higher than the baseline CDMA2000-1x system. Compared with CDMA2000-1x, significant changes have been made in 1xEV-DO Rev 0 to achieve this data throughput performance. Features that have been introduced or changed include:

- Downlink channel is changed from Code Division Multiplex (CDM) to Time Division Multiplex (TDM) to allow full transmission power to a single user.
- Downlink power control is replaced by closed loop downlink rate adaptation.
- Adaptive coding (Turbo Code)/modulation
- Hybrid Automatic Repeat Request (HARQ)
- Fast downlink scheduling
- Soft handoff is replaced by a more bandwidth efficient "virtual" soft handoff

[1] Originally referred to as Evolution-Data Only and more recently as Evolution-Data Optimized

1xEV-DO-Rev 0 however, was designed to support only packet data services and not conversational services. In a later release, called 1xEVDO-Rev A, additional enhancements were added to the 1xEV-DO specification. In the forward link, these enhancements include smaller packet sizes, higher DL peak data rate (up to 3.1 Mbps), and multiplexing packets from multiple users in the MAC layer. In the reverse (or up) link, they include support of H-ARQ, AMC, higher peak rates of 1.8 Mbps, and smaller frame size (6.67 milliseconds). With these enhancements in both forward and reverse links, conversational services (e.g. VoIP and gaming) can be supported in the newly enhanced 1xEVDO-Rev A systems.

The channel structure of the 1xEVDO-Rev A forward and reverse link is shown in Figures 1 and 2 respectively. The forward link contains time-multiplexed user channels for transport of traffic, pilot, MAC, and control information. The reverse link includes the following channels:

- Reverse Rate Indicator (RRI) channel to indicate whether the data channel is being transmitted or not transmitted and its corresponding rate,
- Data Rate Control (DRC) channel to indicate the supportable forward traffic channel data rate and the best serving sector on the HDR forward channel, and
- Acknowledgement (ACK) channel to inform the access network whether or not the forward link data packet was received successfully.

In 1xEVDO-Rev A, a new reverse link Data Source Control (DSC) channel is defined to specify the cell from which forward link packets are requested (serving cell selection), and an Auxiliary Pilot Channel is added to the reverse link to facilitate demodulation at high data rates. On the forward link, a Reverse Activity (RA) channel is added to provide an indication to the access terminal of loading on each sector's reverse link. A Reverse Power Control (RPC) channel is also added. The access terminal adjusts the mean output power level of the Pilot Channel in response to each power control bit received on this channel.

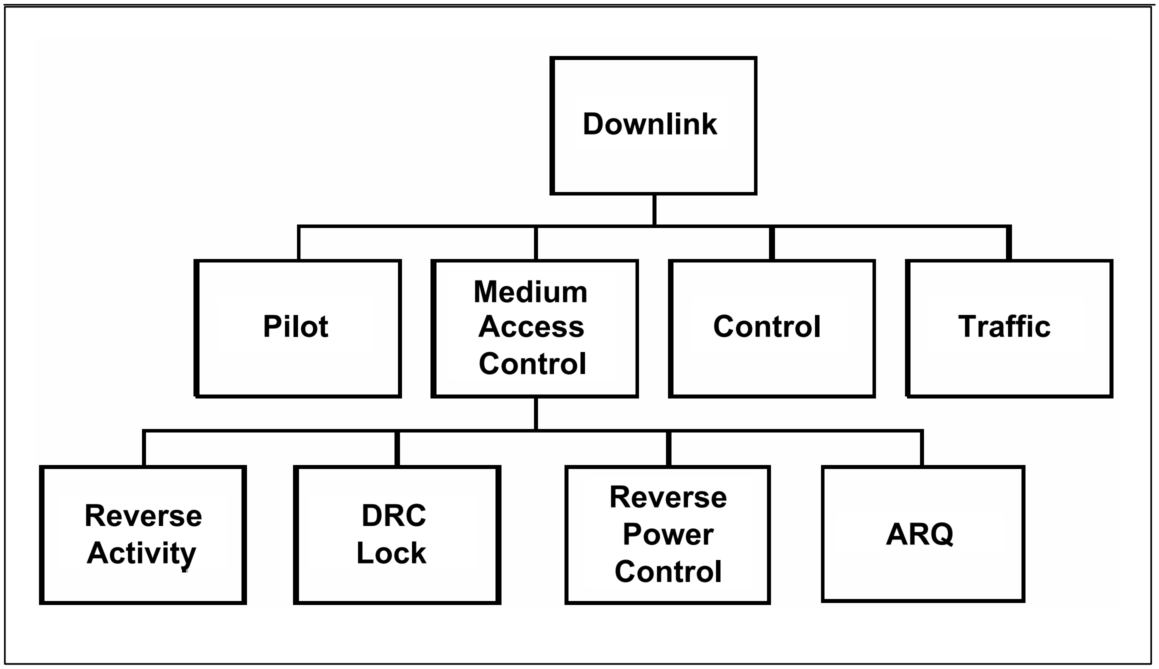


Figure 1: 1xEV-DO-Rev A DL Channel Structure

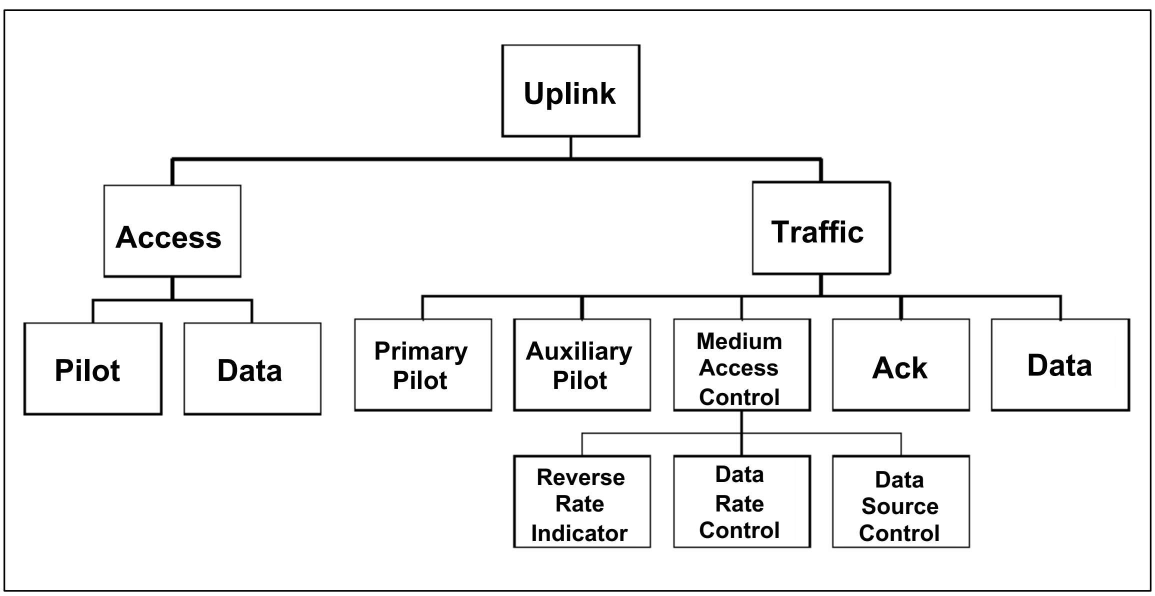


Figure 2: 1xEV-DO-Rev A UL Channel Structure

In the forward link, each user's data transmission is time-division multiplexed on the data time slot using a fixed spreading factor of 16, while the user's MAC layer transmissions are code-division multiplexed on the MAC time slot. The supported DL modulation formats include QPSK, 8-PSK, and 16-QAM. Synchronous H-ARQ and incremental redundancy are also supported. In each time slot on the DL, four information fields are present - preamble, MAC information, pilot, and data. The pilot bits are allocated 192 chips; the MAC bits occupy 256 chips, while the remaining 1600 chips are allocated to the preamble and data bits. Figure 3 provides an example of the coding structure and packet assembly for a data rate of 307.2 kbps.

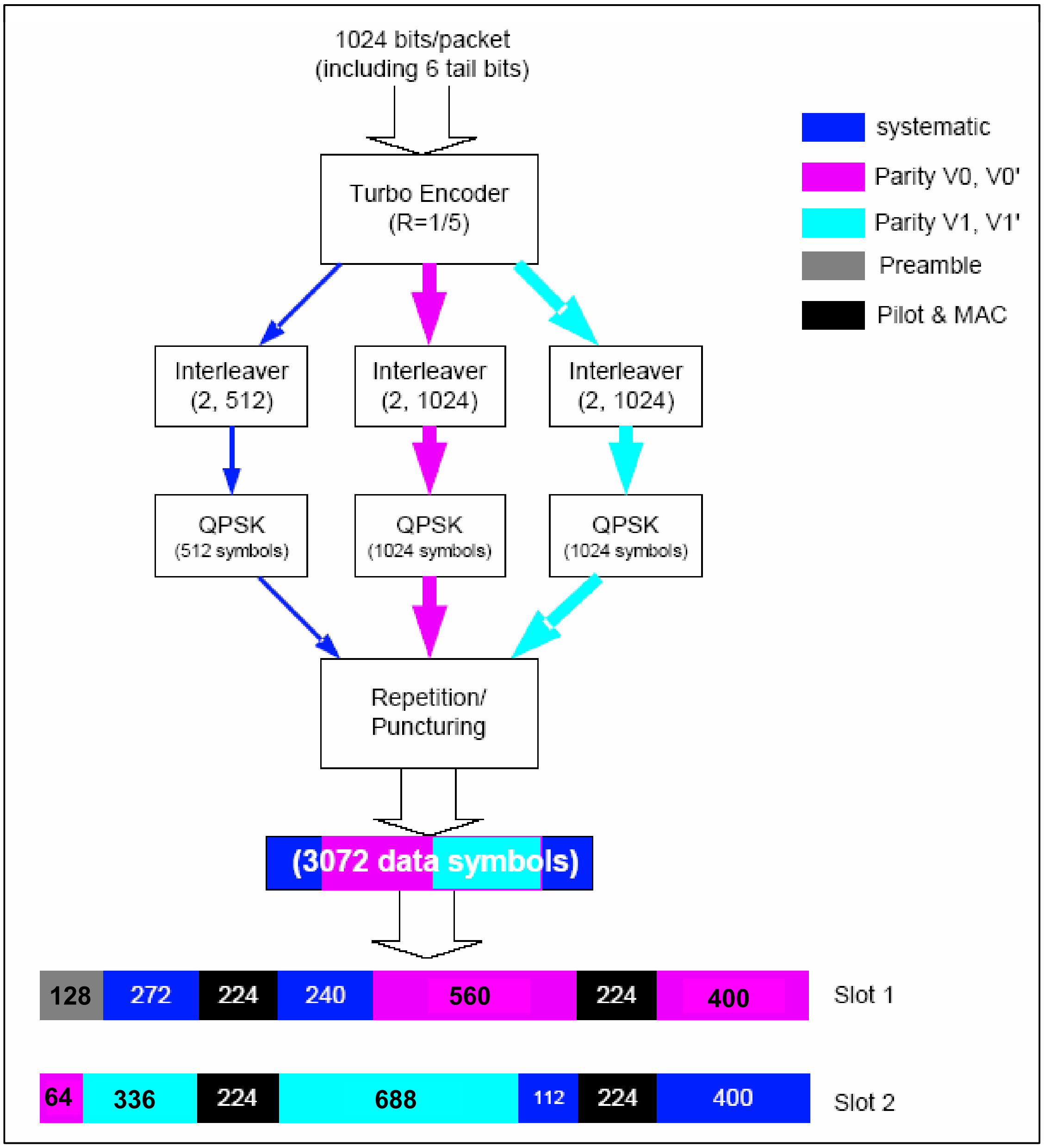


Figure 3: Example of 1xEVDO-Rev A Forward Traffic Channel

Transmission Format (1024, 2, 128), Nominal Data Rate = 307.2 kbps

Table 2 provides a summary of the data rates supported by 1xEVDO-Rev A in the forward link. The DL data rate for 1xEVDO-Rev A ranges from 4.8 kbps to 3.072 Mbps. For QPSK modulation, the possible packet sizes range from 128 to 2048 bits. With 8-PSK, the only packet size supported is 3072 bits. Similarly, for 16-QAM, packet sizes of 4096 and 5120 bits are supported. Each data rate has a different preamble length, error control coding rate, and modulation rate. The access terminal (AT) may request one of the data rates based on the measured forward link signal strength and the AT buffer size. For each forward link transmission, there is an ACK/NACK feedback from the AT. If the transmission is successfully received before using up the assigned time slots (*early termination*), the achieved data rate is higher than the nominal data rate. For example, for the transmission format (1024, 16, 1024) in the table, if the packet is received successfully after one time slot, the achieved data rate will be 614.4 kbps as opposed to the nominal data rate of 38.4 kbps.

Transmission Format: Physical Layer Packet Size (bits), Nominal Transmit Duration (slots), Preamble Length (chips)	Code Rate	Modulation Type	Nominal Data Rate (kbps)
(128, 16, 1024)	1/5	QPSK	4.8
(128, 8, 512)	1/5	QPSK	9.6
(128, 4, 1024)	1/5	QPSK	19.2
(128, 4, 256)	1/5	QPSK	19.2
(128, 2, 128)	1/5	QPSK	38.4
(128, 1, 64)	1/5	QPSK	76.8
(256, 16, 1024)	1/5	QPSK	9.6
(256, 8, 512)	1/5	QPSK	19.2
(256, 4, 1024)	1/5	QPSK	38.4
(256, 4, 256)	1/5	QPSK	38.4
(256, 2, 128)	1/5	QPSK	76.8
(256, 1, 64)	1/5	QPSK	153.6
(512, 16, 1024)	1/5	QPSK	19.2
(512, 8, 512)	1/5	QPSK	38.4
(512, 4, 1024)	1/5	QPSK	76.8
(512, 4, 256)	1/5	QPSK	76.8

Transmission Format: Physical Layer Packet Size (bits), Nominal Transmit Duration (slots), Preamble Length (chips)	Code Rate	Modulation Type	Nominal Data Rate (kbps)
(512, 4, 128)	1/5	QPSK	76.8
(512, 2, 128)	1/5	QPSK	153.6
(512, 2, 64)	1/5	QPSK	153.6
(512, 1, 64)	1/5	QPSK	307.2
(1024, 16, 1024)	**1/5**	**QPSK**	**38.4**
(1024, 8, 512)	1/5	QPSK	76.8
(1024, 4, 256)	1/5	QPSK	153.6
(1024, 4, 128)	1/5	QPSK	153.6
(1024, 2, 128)	1/5	QPSK	307.2
(1024, 2, 64)	1/5	QPSK	307.2
(1024, 1, 64)	**1/3**	**QPSK**	**614.4**
(2048, 4, 128)	1/3	QPSK	307.2
(2048, 2, 64)	1/3	QPSK	614.4
(2048, 1, 64)	1/3	QPSK	1,228.8
(3072, 2, 64)	1/3	8-PSK	921.6
(3072, 1, 64)	1/3	8-PSK	1,843.2
(4096, 2, 64)	1/3	16-QAM	1,228.8
(4096, 1, 64)	1/3	16-QAM	2,457.6
(5120, 2, 64)	1/3	16-QAM	1,536.0
(5120, 1, 64)	1/3	16-QAM	3,072.0

Table 2: 1xEVDO-Rev A Supported DL Data Rates[2]

2.2 Brief Overview of HSDPA/HSUPA

3GPP Release 5 extends the WCDMA specification with High Speed Downlink Packet Access (HSDPA). HSDPA includes the following advanced features:

- Adaptive modulation and coding (AMC)

[2] The actual supportable data rate depends on the link SINR.

- Multi-code operation
- Hybrid Automatic Repeat Request (HARQ)
- Higher DL peak rates (up to 14 Mbps)
- De-centralized architecture where scheduling functions are moved from the Radio Network Controller (RNC) to Node-B thus reducing latency and enabling fast scheduling.

These features replace two fundamental WCDMA features, namely Variable Spreading Factor (VSF) and fast power control. A significant reduction in overall delay was enabled by moving the scheduling and HARQ functionality from the Radio Network Controller (RNC) to the base transceiver station (or Node-B) and using a smaller frame size (also known as Transmission Time Interval (TTI)) of 2 milliseconds. The smaller frame size improves fat pipe multiplexing, multi-user diversity, and H-ARQ.

A High Speed Downlink Shared Channel (HS-DSCH) transmission uses channelization codes at a fixed spreading factor of 16. The TTI of an HS-DSCH sub-frame is 2 milliseconds compared to 10 milliseconds for R99 WCDMA. The HS-DSCH supports both QPSK and 16-QAM modulation. Multi-code transmission is allowed, which translates to mobiles being assigned multiple channelization codes (CCs) in the same HS-DSCH sub-frame, depending on its capability. The same scrambling code sequence is applied to all the CCs. Furthermore, multiple UEs may be assigned CCs in the same TTI, i.e. multiplexing of multiple mobiles in the code-domain is allowed which is illustrated in Figure 4.

In HSDPA AMC, HARQ and scheduling are handled by the Node-B, which allows for fast link adaptation based on instantaneous channel conditions. Multi-channel stop-and-wait ARQ is the underlying form of ARQ, rather than selective repeat with a large window size. Multi-channel stop-and-wait ARQ with a small number of channels (e.g., 6) is an efficient, simple protocol that minimizes the memory required for HARQ and stalling. Signaling is provided to allow fully asynchronous operation.

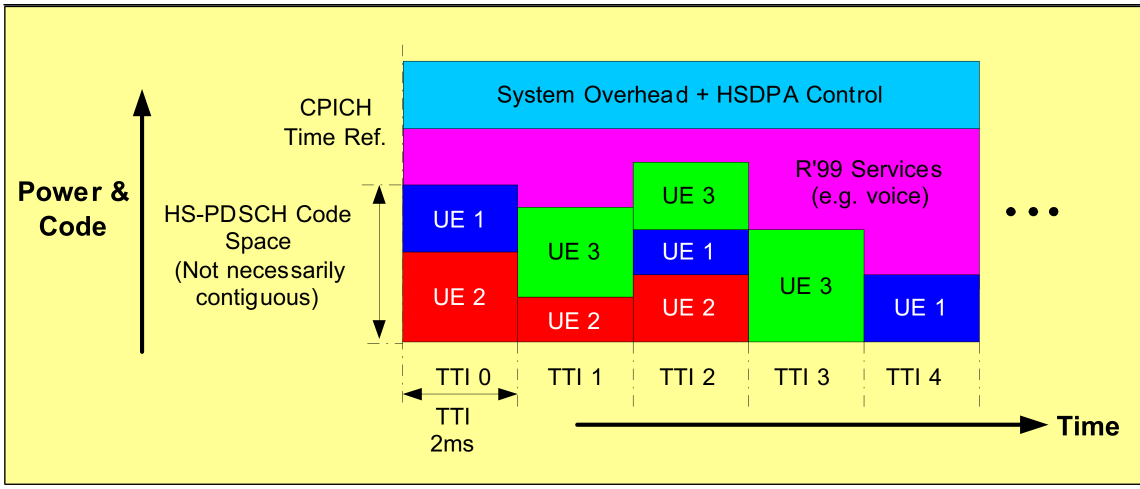


Figure 4: Multiplexing of UE's in the Code Domain

Design of the associated control channel is very important to maximize the throughput of HS-DSCH. The overall control channel structure of the HS-DSCH is shown in Figure 5. On the downlink, high-speed data is transmitted on the HS-DSCH while the associated signaling information is transmitted by the High Speed Shared Control Channel (HS-SCCH). The signaling information includes Transport Format and Resource Information and HARQ related information. On the uplink, the new High Speed Dedicated Physical Control Channel (HS-DPCCH) is used to signal HARQ acknowledgement and the Channel Quality Indicator (CQI) to the Node B. The HS-DPCCH is a separate code multiplexed uplink channel. Concurrent to high-speed data, regular data and control information may also be transmitted on the Dedicated Physical Data and Control Channels (DPDCH and DPCCH).

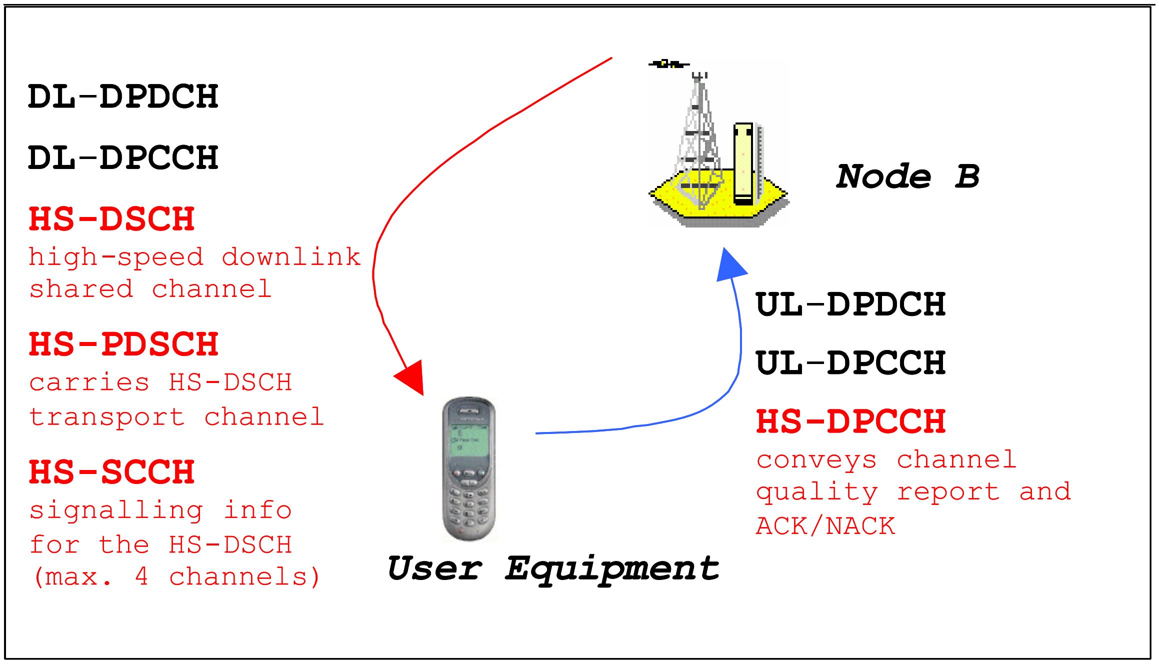


Figure 5: Control Channel Structure for HSDPA

For each HS-DSCH TTI, downlink signaling for the mobile station is carried on the HS-SCCH. The number of HS-SCCHs can range from one to a maximum of four per mobile station. There is a one to one mapping between the HS-DSCH data sub-frame and the HS-SCCH control sub-frame with a 2-slot delay between the two as shown in Figure 6. This allows time for the mobile to set up for HS-DSCH demodulation.

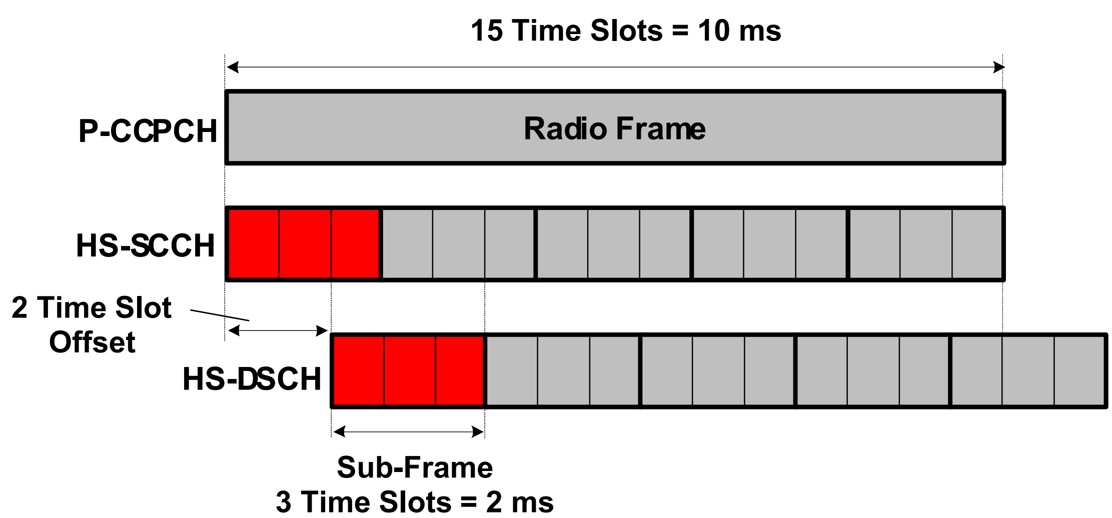


Figure 6: HS-DSCH to HS-SCCH Association

HARQ acknowledgements on the HS-DPCCH are positive (ACK) or negative (NACK). The ACK/NACK message is signaled via different transmitted power levels relative to the R99 uplink DPCCH. The CQI contains measurement feedback information used by the Node-B to select transport format (also called MCS) and resource.

The 3GPP has also defined WCDMA enhancements for the uplink path [16]. This enhancement is known as High Speed Uplink Packet Access (HSUPA) and the combination of HSDPA and HSUPA is known simply as HSPA (High Speed Packet Access).

In the Enhanced Uplink, several new physical channels are introduced to provide and support high-speed data transmission for the Enhanced Data Channel (E-DCH) as shown in Figure 7. On the uplink, two new code-multiplexed channels are added – E-DCH Dedicated Physical Data Channel (E-DPDCH) and E-DCH Dedicated Physical Control Channel (E-DPCCH). Similarly, three new channels are added in the downlink, namely, E-DCH HARQ Acknowledgement Indicator Channel (E-HICH), E-DCH Absolute Grant Channel (E-AGCH) and E-DCH Relative Grant Channel (E-RGCH).

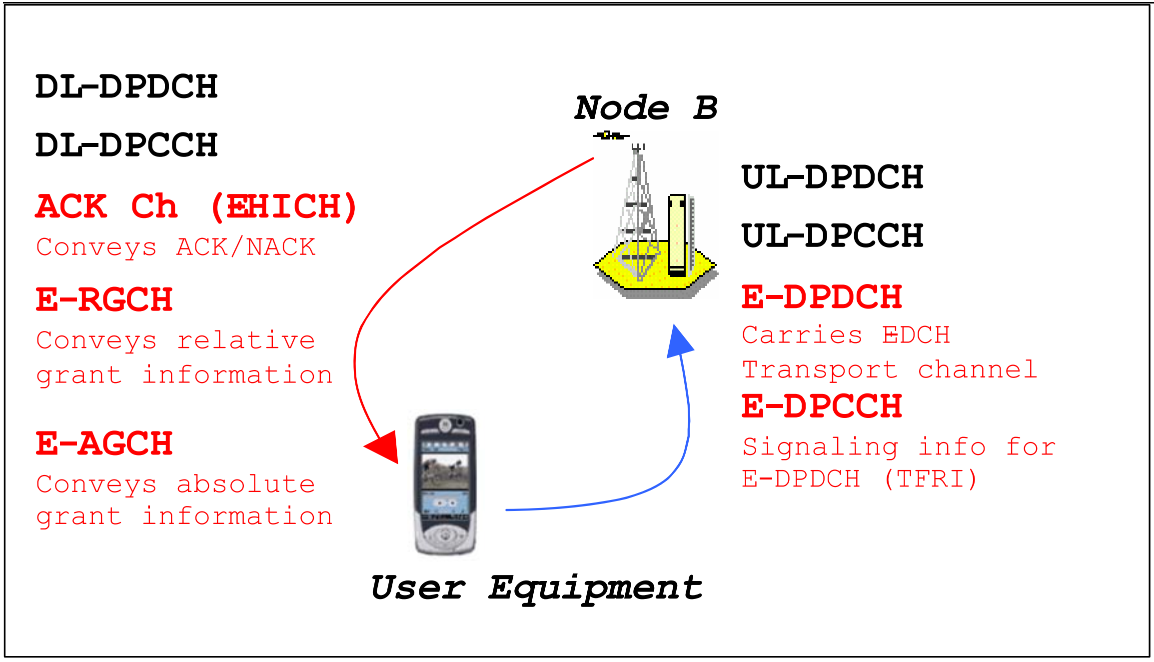


Figure 7: E-DCH Physical Channel Structure

The E-DPDCH carries the data payload and supports AMC with fully synchronous HARQ. The length of the E-DCH sub-frames is either 2 milliseconds or 10 milliseconds. An 8-channel and 4-channel stop-and-wait HARQ protocol is used for the 2 ms and 10 ms frames respectively. The scheduling and Transport Format Related Information (TFRI) are sent on the corresponding E-DPCCH. Two fundamental approaches exist in scheduling UE transmissions – (1) Node B controlled rate scheduling, where all uplink transmissions can randomly occur in parallel with the selected rates restricted to keep the total noise rise at the Node B at an acceptable level, and (2) Node B controlled time and rate scheduling, where only a subset of UEs with pending data are selected to transmit over a given time interval with selected rates restricted. Both schemes can be viewed as a management of Transport Format Combination selection at the UE with different scheduling-related signaling rules.

In the downlink, the Absolute Grant (AG) provides an absolute limitation of the maximum amount of uplink resources the UE may use. For each UE, there is only one Absolute Grant transmitted by the serving E-DCH cell. The Relative Grant (RG) is sent by both the Serving and non-Serving Node-Bs as a complement to Absolute Grant. Relative Grant increases or decreases the resource limitation with respect to the previous value.

Relative grant from a serving cell has three values - up, down and hold, while relative grant from a non-serving cell has only two values - down and hold. The scheduler could be operated in per-UE or per-HARQ process mode for 2 ms TTI depending on whether the resource grants are associated with each UE or with each HARQ process. For a 10-ms TTI, only per-UE process scheduling is used. Furthermore, the scheduler can be operated only in dedicated mode. In dedicated mode, the serving cell sends RGs to update the maximum resource the UE may use. Note that autonomous scheduling where the UE simply ramps up its rate until it reaches the maximum set or receives a down RG command was not included in the final specification

2.3 Roadmap for 3G Enhancements

1xEVDO Rev 0 had initial success in Korea and Japan beginning in 2003 with additional major deployments following in 2004 and 2005 [9,10]. The initial launch for EV-DO Rev A with CDMA2000 UL enhancements took place in Korea and Japan in 2005. Extensive US deployments have been announced for 2006 [12]. A further enhancement to the CDMA2000 standard is 1xEVDO-Rev B (also known as DO Multi-Carrier). This revision to the standard [17], increases DL spectral efficiency and data throughput by adding 64QAM to the DL modulation scheme. It also provides for dynamic allocation of up to fifteen 1.25 MHz carriers in a 20 MHz bandwidth. As a result, the 1xEVDO-Rev B enhancement will increase the DL peak over the air data rate for a 1.25 MHz carrier to 4.9 Mbps and, by aggregating 3 carriers in a nominal 5 MHz channel bandwidth, will provide a peak DL rate of 14.7 Mbps and a peak UL data rate of 5.4 Mbps. Commercial deployments for 1xEVDO-Rev B are not anticipated until 2008 [17].

The first commercial launch of HSDPA-based services was announced in December 2005 [13] and operators in Europe [14] and Japan [15] have announced plans to launch services based on HSDPA in 2006. HSUPA/HSPA availability is not expected until the 2007 or 2008 timeframe. The 3GPP envisions additional long term WCDMA enhancements leading to UMTS Terrestrial Radio Access Node Long Term Evolution (UTRAN LTE) [18] also referred to as 3.99G or Evolved UMTS. 3GPP2 is on a similar path with LTE for CDMA2000. Since approved standards for LTE are not expected until 2007, it is not likely that products will be available until 2009 or later. These additional 3G enhancements therefore, are not considered in the following section which compares WiMAX attributes and performance to 3G. The 3G evolution roadmap excluding LTE is summarized in Figure 8.

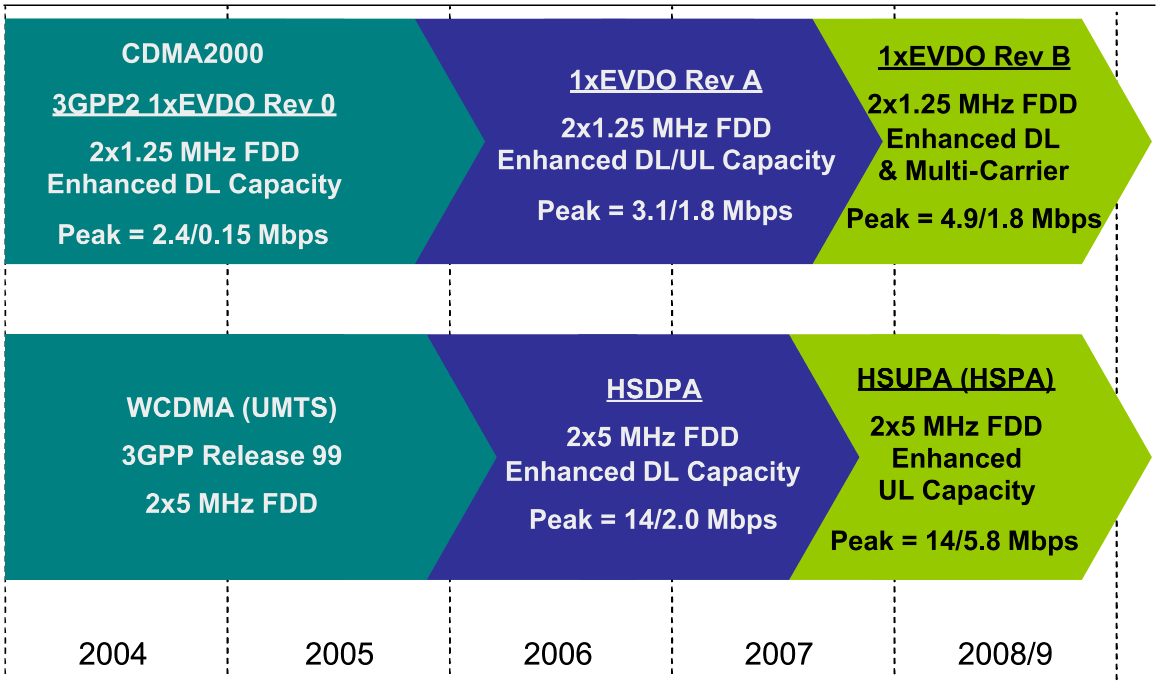


Figure 8: Evolution for 3G CDMA Systems

3. Comparing Mobile WiMAX to 1xEVDO and HSPA

1xEVDO and HSDPA/HSPA have evolved from 3G CDMA standards to provide data services over a network originally conceived for mobile voice services. These 3G enhancements have evolved from the 3G experiences and as a result, inherit both the advantages and limitations of legacy 3G systems. WiMAX on the other hand was initially developed for fixed broadband wireless access and is optimized for broadband data services. Since Mobile WiMAX has evolved from system concepts initially designed for fixed wireless access, WiMAX faces the challenge of meeting the additional requirements necessary to support mobility. A point by point comparison of the attributes of Mobile WiMAX with 3G-based 1xEVDO and HSDPA/HSPA systems is useful in addressing how these technologies can meet future network requirements for mobile broadband data services. In the following sections, we look at what these technologies have in common and how they differ. The following table provides a summary of the attributes that have been discussed in more detail in the previous sections and the companion paper, Mobile WiMAX – Part 1 [1].

Attribute		1xEVDO Rev A	HSDPA/HSUPA (HSPA)	Mobile WiMAX
Base Standard		CDMA2000/IS-95	WCDMA	IEEE 802.16e-2005
Duplex Method		FDD	FDD	TDD[3]
Downlink		TDM	CDM-TDM	OFDMA
Uplink Multiple Access		CDMA	CDMA	
Channel BW		1.25 MHz	5.0 MHz	Scalable: 5, 7, 8.75, 10 MHz
Frame Size	DL	1.67 milliseconds	2 milliseconds	5 milliseconds TDD
	UL	6.67 milliseconds	2, 10 milliseconds	
Modulation DL		QPSK/8PSK/ 16QAM	QPSK/16QAM	QPSK/16QAM/ 64QAM
Modulation UL		BPSK,QPSK/8PSK	BPSK/QPSK	QPSK/16QAM
Coding		Turbo	CC, Turbo	CC, Turbo
DL Peak Over the Air Data Rate		3.1 Mbps	14 Mbps	46 Mbps, DL/UL=3[4] 32 Mbps, DL/UL=1 (10 MHz BW)
UL Peak Over the Air Data Rate		1.8 Mbps	5.8 Mbps	7 Mbps, DL/UL=1[5] 4 Mbps, DL/UL=3 (10 MHz BW)
H-ARQ		Fast 4-Channel Synchronous IR	Fast 6-Channel Asynchronous CC	Multi-Channel Asynchronous CC
Scheduling		Fast Scheduling in the DL	Fast Scheduling in the DL	Fast Scheduling in DL and UL
Handoff		Virtual Soft Handoff	Network Initiated Hard Handoff	Network Optimized Hard Handoff
Tx Diversity and MIMO		Simple Open Loop Diversity	Simple Open & Closed Loop Diversity	STBC, SM
Beamforming		No	Yes (Dedicated Pilots)	Yes

Table 3: Summary of Comparative Features

[3] FDD will be considered for future WiMAX profiles based on specific market opportunities and regulatory requirements.

[4] Assumes MIMO (2x2) mode in DL and 4 OFDM symbols for overhead and 44 data OFDM symbols (out of 48 total) in each frame. The peak throughput performance for TDD is related to the DL/UL range supported by the Release-1 Mobile WiMAX profiles. The user peak rate may also be limited by its service capabilities.

[5] The user UL peak data rate assumes 4 OFDM symbols overhead. With UL collaborative MIMO, the aggregated UL sector peak throughput can be doubled to 14 Mbps for DL/UL=1 and 8 Mbps for DL/UL=3.

3.1 Common Features

Several features, designed to enhance data throughput, are common to EVDO, HSPDA/HSPA and Mobile WiMAX including:

- Adaptive Modulation and Coding (AMC)
- Hybrid ARQ (HARQ)
- Fast Scheduling
- Bandwidth Efficient Handoff

3.1.1 Adaptive Modulation and Coding (AMC)

Downlink power control is replaced with Adaptive Modulation and Coding in both 1xEVDO and HSDPA/HSPA. 1xEVDO-Rev B introduces 64QAM to further increase the peak downlink data rate. 1xEVDO-Rev A and HSUPA introduce adaptive coding and modulation in the uplink to enhance uplink data rate. In 1xEVDO and HSPA, there is a finite number of transmission formats with each mapping to a specific packet size, code rate and modulation order combination. An incoming packet has to be fragmented to fit to the correct transmission format. With a limited number of transmission formats, the scheduling overhead can be reduced. However, fragmenting or padding to the predetermined packet size causes overhead in packet convergence.

Mobile WiMAX supports AMC in both downlink and uplink with variable packet size. The uplink can support 16QAM modulation (64QAM optional) due to OFDMA orthogonal uplink subchannels. Although the scheduling overhead is higher to support variable packet size, the overhead for fragmentation and padding is reduced. The AMC capabilities for each of the systems are summarized in the following table.

<table>
<tr><th>Technology</th><th>DL Modulation</th><th>DL Code Rate</th><th>UL Modulation</th><th>UL Code Rate</th></tr>
<tr><td>1xEVDO-Rev 0</td><td rowspan="2">16QAM, 8PSK, QPSK</td><td rowspan="3">Turbo: 1/3, 1/5</td><td>Fixed (BPSK)</td><td>Fixed</td></tr>
<tr><td>1xEVDO-Rev A</td><td rowspan="2">BPSK, QPSK, 8PSK</td><td rowspan="2">Turbo: 1/2, 1/4</td></tr>
<tr><td>1xEVDO-Rev B</td><td>64QAM[6], 16QAM, 8PSK, QPSK</td></tr>
</table>

6 Rev B with 64QAM is a hardware upgrade from Rev A; Rev B software upgrade is limited to 16QAM.

Technology	DL Modulation	DL Code Rate	UL Modulation	UL Code Rate
HSDPA	16QAM, QPSK	Turbo, CC: 1/4, 2/4, 3/4, 4/4	Fixed (BPSK)	Fixed
HSPA (HSDPA+HSUPA)			BPSK, QPSK	Turbo, CC: 2/3, 3/4, 4/4
Mobile WiMAX	64QAM, 16QAM, QPSK	Turbo, CC, Repetition: 1/12, 1/8, 1/4, 1/2, 2/3, 3/4, 5/6	16QAM, QPSK, *64QAM Optional*	Turbo, CC, Repetition: 1/12, 1/8, 1/4, 1/2, 2/3, 3/4, 5/6 *Optional*

Table 4: Summary of AMC Capability

3.1.2 Hybrid ARQ

All systems support HARQ as an important means to improve the robustness of data transmission over the wireless channel [19,20]. HARQ is a physical layer stop and wait ARQ protocol. A dedicated ACK channel is allocated to provide feedback for fast retransmission in case the packet is in error. The packets in error are kept at the receiver. Chase Combining (CC) or Incremental Redundancy (IR) can be implemented at the receiver to jointly process the packets in error and new retransmission to improve the packet reception. HARQ CC is supported by Mobile WiMAX and HSPA. Since in HARQ CC, the retransmissions are identical, it is easy to extend to different transmission techniques such as MIMO. HARQ IR is supported by 1xEVDO. In IR, the packet is coded across all the sub-packets for retransmission. IR decoding is more complex than CC.

Multi-channel HARQ operation is supported by all systems. Multi-channel stop-and-wait ARQ with a small number of channels (e.g., 6) is an efficient, simple protocol that minimizes the memory required for HARQ and stalling. Mobile WiMAX and HSPA provide signaling to allow fully asynchronous operation. In asynchronous operation, the packet retransmission after receiving a NACK is determined by the base station scheduler. The asynchronous operation allows variable delay between retransmissions which provides more flexibility to the scheduler at the cost of additional overhead for each retransmission allocation. 1xEVDO supports synchronous operation where all the retransmissions occur in fixed intervals that are scheduled at the first transmission. If a transmission is successfully received, the remaining pre-assigned time slots are given up (*early termination*) for reuse. The synchronous operation avoids scheduling overhead for retransmissions. However, some large packets span over multiple slots. Since the retransmission slots are predetermined, these large packets do not get the same level of protection from HARQ as small packets even though they require better protection.

3.1.3 Fast Scheduling

Fast schedulers located in the base station are specified for all three technologies, in order to enable rapid response to traffic and channel condition variations. The scheduling is constrained by traffic QoS requirements and CQI channel feedback.

Mobile WiMAX, HSPA and 1xEVDO all apply fast scheduling in the downlink. HSPA uplink supports (1) Autonomous scheduling - all uplink transmissions can randomly occur in parallel with controlled rates; and (2) Dedicated scheduling [21]- controlled time and rate scheduling, where only a subset of UEs with pending data are selected to transmit over a given time interval with selected rates restricted. However, due to non-orthogonal uplink, the quality of an individual link cannot be easily controlled even with dedicated scheduling.

Mobile WiMAX applies fast scheduling in both downlink and uplink. Furthermore, WiMAX performs scheduling on a per-frame basis and broadcasts the downlink/uplink scheduling in the MAP messages at the beginning of each frame. With Mobile WiMAX, therefore, the scheduling can change very quickly and the amount of resources allocated ranging from the smallest unit to the entire frame. This is especially well suited for bursty data traffic and rapidly changing channel conditions. Particularly since uplink sub-channels are orthogonal, with uplink scheduling - the uplink resource is more efficiently allocated, performance is more predictable, and QoS is better enforced.

3.1.4 Bandwidth Efficient Handoff

With soft handoff, typically employed in voice-centric mobile networks, multiple base stations in a mobile active set of base stations transmit the same data simultaneously, in order to minimize the handoff delay. Soft handoff however, is not the preferred approach since it is neither spectrally-efficient nor is it necessary for delay-tolerant data traffic. 1xEVDO depends on the DSC signal for feedback on link conditions to accomplish "Virtual" Soft Handoff. HSPA does not support soft handoff but uses a more bandwidth efficient "Network Initiated Hard Handoff" that can be optimized for reduced delay. Mobile WiMAX supports "Network Optimized Hard Handoff" for bandwidth-efficient handoff with reduced delay achieving a handoff delay less than 50 ms. Mobile WiMAX also supports Fast Base Station Switch (FBSS) and Marco Diversity Handover (MDHO) as options to further reduce the handoff delay.

3.2 Key Advantages of Mobile WiMAX

Unlike the CDMA-based 3G systems, which have evolved from voice-centric systems, WiMAX was designed to meet the requirements necessary for the delivery of broadband data services as well as voice. The Mobile WiMAX physical layer is based on Scalable OFDMA technology. The new technologies employed for Mobile WiMAX result in lower equipment complexity and simpler mobility management due to the all-IP core network and provide Mobile WiMAX systems with many other advantages over CDMA-based 3G systems including:

- Tolerance to Multipath and Self-Interference
- Scalable Channel Bandwidth
- Orthogonal Uplink Multiple Access
- Support for Spectrally-Efficient TDD
- Frequency-Selective Scheduling
- Fractional Frequency Reuse
- Fine Quality of Service (QoS)
- Advanced Antenna Technology

3.2.1 Tolerance to Multipath and Self-Interference

With OFDMA systems, the sub-channels maintain their orthogonality in a multipath channel. The number of multipath components does not limit the performance of the system as long as the multipaths are within the cyclic prefix window. OFDMA systems therefore are robust to multipath effects. The sub-channel orthogonality within the cyclic prefix window also relaxes the time synchronization requirement.

In CDMA systems, RAKE receivers are usually employed to combat multipath fading. However, in addition to multipath, other impairments such as frequency offset, Doppler effect and lack of time synchronization can cause CDMA systems to suffer from intra-cell interference between users in the same cell and even self-interference in the absence of other users. This interference can be mitigated by employing a time domain equalizer. The equalizer however, cannot completely remove interference as in OFDMA and does not scale well with channel bandwidth since the complexity increases with channel bandwidth and increased delay spread. Therefore, in broadband wireless systems where multipath effect is prevalent, OFDMA systems are more robust and the equipment less complex than CDMA systems.

3.2.2 Scalable Channel Bandwidth

Scalability is one of the most important advantages of OFDMA [8]. With the OFDMA sub-carrier structure, it can support a wide range of bandwidths. The scalability is achieved by adjusting the FFT size[7] to the channel bandwidth while fixing the sub-carrier frequency spacing. By fixing the sub-carrier spacing and symbol duration, the basic unit

[7] Channel bandwidths of 7 MHz and 8.75 MHz are exceptions. The sampling factor, rather than FFT size, is changed in these two cases resulting in a different sub-carrier spacing.

of physical (time and frequency) resource is fixed. Therefore, the impact to higher layers is minimal when scaling the bandwidth.

One immediate advantage stemming from scalability is the flexibility of deployment. With little modification to air interface, OFDMA systems can be deployed in various frequency band intervals to flexibly address the need for various spectrum allocation and usage model requirements. Mobile WiMAX supports channel bandwidths of 5 MHz, 7 MHz, 8.75 MHz, and 10 MHz and can optionally support channel bandwidths ranging from 1.25 MHz to 20 MHz.

With the flexibility to support a wider bandwidth, Mobile WiMAX also enjoys high aggregate sector throughput, which allows more efficient multiplexing of data traffic, lower latency and better QoS.

The CDMA-based systems such as 1xEVDO and HSPA on the other hand, are optimized for a specific channel plan (1.25 MHz for 1xEVDO and 5 MHz for HSPA). These systems are very sensitive to bandwidth change, because the signals occupy the entire bandwidth and do not have the same modular property as the OFDMA signals in the frequency domain. Both the CDMA code and frame structure may have to be re-optimized for the new channel bandwidth. Therefore, 1xEVDO and HSPA and do not provide scalability in a natural manner.

3.2.3 Orthogonal Uplink Multiple Access

When considering multiple access benefits, sub-channel orthogonality provides OFDMA with a distinct advantage over CDMA. Since with OFDMA, users are allocated different portions of the channel, there is no (or little) multiple access interference (MAI) between multiple users. OFDMA therefore, can support higher order uplink modulations and achieve higher uplink spectral efficiency. With CDMA, on the other hand, each user transmits over the entire channel. Even though it is possible to construct orthogonal spreading codes, due to the uplink synchronization issues, asynchronous CDMA is used in the uplink in most practical CDMA systems. With asynchronous CDMA, the users interfere with each other during uplink multiple access and MAI significantly reduces uplink spectral efficiency. Uplink capacity, in fact, is the bottleneck in most CDMA systems. WiMAX with OFDMA on the other hand, is capable of providing balanced downlink/uplink throughput. Orthogonal uplink sub-channels also enables the uplink scheduler to provide better control of the uplink quality and uplink resource allocation. Therefore the uplink performance is more predictable and QoS is better enforced.

3.2.4 Support for Spectral-Efficient TDD

Both HSDPA and 1xEVDO are FDD-based, whereas Mobile WiMAX supports TDD and optionally, Full and Half-Duplex FDD. To counter interference issues, TDD does require system-wide frame synchronization; nevertheless, TDD is the preferred duplexing mode for broadband services for the following reasons:

- TDD enables adjustment of the downlink/uplink ratio on a per cluster basis to efficiently support asymmetric downlink/uplink traffic while maintaining frame synchronization. With traffic becoming more and more dominated by data, downlink traffic will generally be dominant. With FDD, downlink and uplink always have fixed and generally, equal DL and UL bandwidths. Either the downlink channel or the uplink channel will be underutilized when the traffic is asymmetric resulting in a net decrease in overall spectral efficiency.
- TDD assures channel reciprocity for better support of link adaptation, MIMO and other closed loop advanced antenna technologies.
- Unlike FDD, which requires a pair of channels, TDD only requires a single channel for both downlink and uplink providing greater flexibility for adaptation to varied global spectrum allocations.
- Transceiver design for TDD implementations is less complex and therefore less expensive.

It should be noted that there are TDD solutions for 3G as well. UMTS-TDD or TD-CDMA uses a combined time division code division access scheme based on a radio access approach defined by the ETSI Delta group. TD-CDMA is designed for operation at a 3.84 Mcps chip rate in a 5 MHz channel. TD-CDMA can also use AMC features developed for HSDPA to further enhance channel capacity. Specifications for TD-CDMA were approved by 3GPP in 1999 and continue to evolve. TD-SCDMA was proposed by the China Wireless Telecommunications Standards group (CWTS) and approved by the ITU in 1999. TD-SCDMA adds a synchronization mechanism and is designed to operate at a 1.28 Mcps chip rate in a 1.6 MHz channel. Both TD-CDMA and TD-SCDMA were adopted by 3GPP as part of UMTS Release 4 in 2001. To date, worldwide adoption of these systems has been limited and therefore, are not discussed in greater detail in this paper. Nevertheless, given the favorable attributes of TDD for data-centric services these systems can also be expected to play an important part in the ongoing evolution of 3G networks.

3.2.5 Frequency Selective Scheduling

Both 1xEVDO and HSPA signals occupy the entire bandwidth. Mobile WiMAX signals on the other hand only occupy a portion of the bandwidth. In broadband wireless channels, propagation conditions can vary over different portions of the spectrum in different ways for different users. Mobile WiMAX supports frequency selective scheduling to take full advantage of multi-user frequency diversity and improve QoS. WiMAX with adjacent sub-carrier permutation makes it possible to allocate a subset of sub-carriers to mobile users based on relative signal strength. By allocating a subset of sub-carriers to each MS for which the MS enjoys the strongest path gains, this multi-user diversity technique can achieve significant capacity gains over TDMA/CDMA [22].

3.2.6 Fractional Frequency Reuse

Mobile WiMAX, 1xEVDO and HSPA all support frequency reuse one, i.e. all cells/sectors operate on one frequency channel to maximize spectrum utilization. However, due to heavy interference in frequency reuse one deployment, users at the cell edge may suffer low connection quality. 1xEVDO and HSPA address the interference issue by adjusting the loading of the network. However, the same loading factor is applied to all users within the coverage area, leading to capacity loss by "over-protecting" users that are closer to the base station.

Since in WiMAX, users operate on sub-channels, which only occupy a small fraction of the channel bandwidth, the cell edge interference problem can be easily addressed by reconfiguration of the sub-channel usage without resorting to traditional frequency planning. In Mobile WiMAX, the flexible sub-channel reuse is facilitated by sub-channel segmentation and permutation zone. A segment is a subdivision of the available OFDMA sub-channels (one segment may include all sub-channels). One segment is used for deploying a single instance of MAC. Permutation Zone is a number of contiguous OFDMA symbols in DL or UL that use the same permutation. The DL or UL sub-frame may contain more than one permutation zone.

The sub-channel reuse pattern can be configured so that users close to the base station operate on the zone with all sub-channels available. While for the edge users, each cell/sector operates on the zone with a fraction of all sub-channels available. In Figure 9, F1, F2 and F3 are different sets of sub-channels in the same frequency channel. In this configuration, the full load frequency reuse of one is maintained for center users to maximize spectral efficiency while fractional frequency reuse is achieved for edge users to improve edge user connection quality and throughput. The sub-channel reuse planning can be adaptively optimized across sectors or cells based on network load and interference conditions on a per frame basis. All the cells/sectors can operate on the same frequency channel and no frequency planning is required.

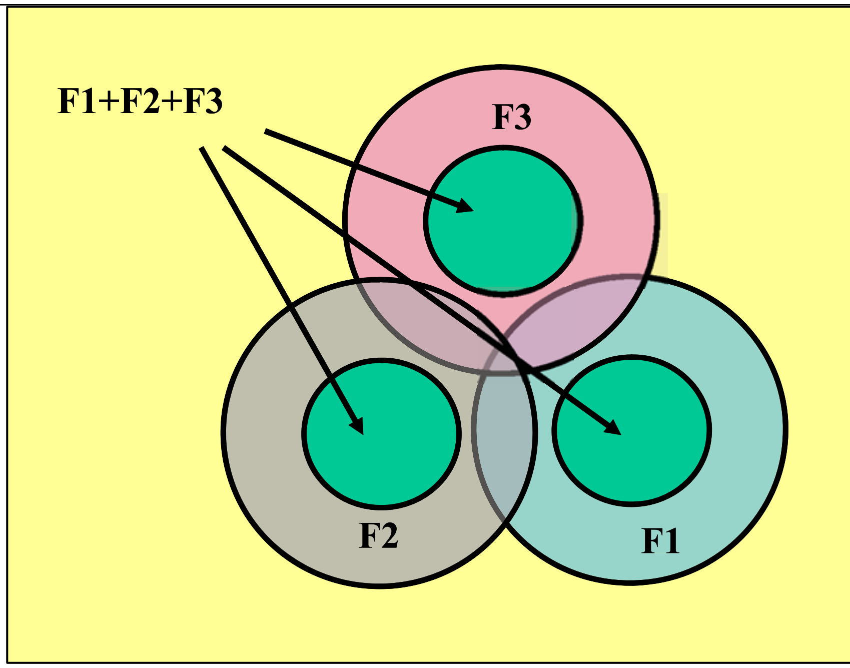


Figure 9: Fractional Frequency Reuse with Mobile WiMAX

3.2.7 Quality of Service

WiMAX was developed from the outset to meet the stringent requirements for the delivery of broadband services. The WiMAX QoS is specified for each service flow. The connection-oriented QoS therefore, can provide accurate control over the air interface. Since the air interface is usually the bottleneck, the connection-oriented QoS can effectively enable the end-to-end QoS control. The service flow parameters can be dynamically managed through MAC messages to accommodate the dynamic service demand. Service flows provide the same control mechanism in both the DL and UL to improve QoS in both directions. Furthermore, since the sub-channels are orthogonal, there is no intra-cell interference in either DL or UL. Therefore, the DL and UL link quality and QoS can be easily controlled by the base station scheduler. The high system throughput also allows efficient multiplexing and low data latency. Therefore, with fast air link, high system throughput, symmetric downlink/uplink capacity, fine resource granularity and flexible resource allocation Mobile WiMAX can support a wide range of data services and applications with varied QoS requirements as summarized in Table 5.

Support for QoS in 3G systems, on the other hand, is more limited. Using a priority-based technique to support Conversational Class, Streaming Class, Interactive Class, and Background Class services, higher priority traffic may completely starve lower priority traffic during periods of high usage.

QoS Category	Applications	QoS Specifications
UGS Unsolicited Grant Service	VoIP	• Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance
rtPS Real-Time Polling Service	Streaming Audio or Video	• Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Traffic Priority
ErtPS Extended Real-Time Polling Service	Voice with Activity Detection (VoIP)	• Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance • Traffic Priority
nrtPS Non-Real-Time Polling Service	File Transfer Protocol (FTP)	• Minimum Reserved Rate • Maximum Sustained Rate • Traffic Priority
BE Best-Effort Service	Data Transfer, Web Browsing, etc.	• Maximum Sustained Rate • Traffic Priority

Table 5: Mobile WiMAX Applications and Quality of Service

3.2.8 Advanced Antenna Technology

In CDMA-based systems, the signals occupy the entire bandwidth. Since the processing complexity for smart antenna technologies scales with the channel bandwidth, supporting advanced antenna technologies in broadband wireless channels poses a more significant challenge than it does with Mobile WiMAX [23]. Both 1xEVDO and HSPA support simple transmit diversity and the HSPA standard has an option to support Beamforming. In general however, the use of advanced antenna technologies in current 1xEVDO and HSPA solutions has been limited.

Mobile WiMAX on the other hand, is based on smart antenna friendly OFDM/OFDMA technology. OFDM/OFDMA converts a frequency selective wideband channel into multiple flat narrow band sub-carriers and allows smart antenna operations to be performed on vector flat sub-carriers. Complex equalizers are not required to compensate frequency selective fading. With OFDM/OFDMA systems therefore, it is far easier to support smart antenna technologies. Mobile WiMAX supports a full range of smart antenna technologies to enhance performance including Beamforming, STC and SM [24,25,26,27]. These technologies can improve both system coverage and capacity.

WiMAX also supports dynamic switching between the smart antenna technologies to maximize the benefit based on channel conditions. SM for example, improves peak throughput but, when channel conditions are poor, the Packet Error Rate (PER) can be high and thus the coverage area where target PER is met may be limited. STC on the other hand provides large coverage regardless of the channel condition but does not improve the peak throughput. Mobile WiMAX supports Adaptive MIMO Switching (AMS) between multiple MIMO modes to maximize spectral efficiency with no reduction in coverage area as illustrated in Figure 10.

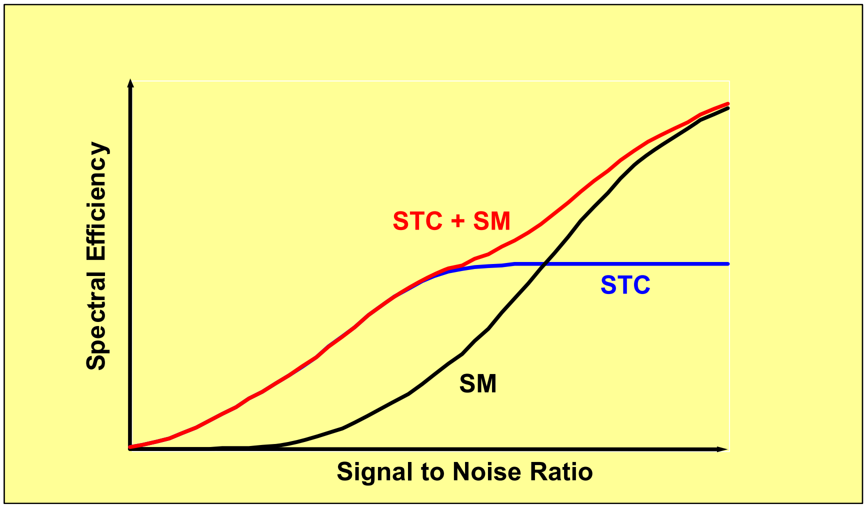


Figure 10: Performance of Adaptive MIMO Switch (AMS)

4. WiMAX-EVDO-HSPA Performance Comparison

In this section, the performance of Mobile WiMAX is compared with EVDO and HSPA. UTRAN-LTE is a further 3G evolution planned by the 3GPP but work is in its early stages and projected performance specifications are not yet well-defined. LTE therefore is not included in the comparative analysis. EVDO (Rev A & Rev B) and HSPA on the other hand are well defined and have a similar product time-line as Mobile WiMAX.

To provide a quantitative comparison of Mobile WiMAX, 1xEVDO and HSPA system performance, the commonly accepted 1xEV-DV evaluation methodology [28,29,30] is used. The Mobile WiMAX system configuration is based on the WiMAX Forum baseline minimum configuration and is summarized in Tables 6 and 7. Table 6 also includes the EVDO and HSPA system parameters used for the simulation. The performance simulation is based on the propagation and mixed user model summarized in Tables 8 and 9.

Parameters	Values		
	Mobile WiMAX	1xEVDO	HSPA
Number of 3-Sector Cells	19		
Operating Frequency	2500 MHz	2000 MHz	
Duplex	TDD	FDD	
Channel Bandwidth	10 MHz	2 x 1.25 MHz	2 x 5 MHz
BS-to-BS Distance	2.8 kilometers		
Minimum Mobile-to-BS Distance	36 meters		
Antenna Pattern	70° (-3 dB) with 20 dB front-to-back ratio		
BS Height	32 meters		
Mobile Terminal Height	1.5 meters		
BS Antenna Gain	15 dBi		
MS Antenna Gain	-1 dBi		
BS Maximum PA Power	43 dBm		
Mobile Terminal Maximum PA Power	23 dBm		
# of BS Tx/Rx Antenna	Tx: 2; Rx: 2	Tx: 1; Rx: 2	
# of MS Tx/Rx Antenna	Tx: 1; Rx: 2	Tx: 1; Rx: 2	
BS Noise Figure	4 dB		
MS Noise Figure	7 dB		

Table 6: Mobile WiMAX and 3G System Parameters

Parameters	Values
System Channel Bandwidth (MHz)	10
Sampling Frequency (F_p in MHz)	11.2
FFT Size (N_{FFT})	1024
Sub-Carrier Frequency Spacing	10.94 kHz
Useful Symbol Time ($T_b = 1/f$)	91.4 microsec
Guard Time ($T_g = T_b/8$)	11.4 microsec
OFDMA Symbol Duration ($T_s = T_b + T_g$)	102.9 microsec
Frame duration	5 millisec
Number of OFDMA Symbols	48

Parameters		Values
DL PUSC	Null Sub-carriers	184
	Pilot Sub-carriers	120
	Data Sub-carriers	720
	Sub-Channels	30
UL PUSC	Null Sub-carriers	184
	Pilot Sub-carriers	280
	Data Sub-carriers	560
	Sub-Channels	35

Table 7: Mobile WiMAX OFDMA Parameters

Parameters	Value
Propagation Model	COST 231 Suburban
Log-Normal Shadowing SD (σ_s)	8 dB
BS shadowing correlation	0.5
Penetration Loss	10 dB

Table 8: Propagation Model

Channel Model	Multi-path Model	# of Fingers	Speed	Fading	Assignment Probability
Model A	Pedestrian A	1	3 km/hr	Jakes	30%
Model B	Pedestrian B	3	10 km/hr	Jakes	30%
Model C	Vehicular A	2	30 km/hr	Jakes	20%
Model D	Pedestrian A	1	120 km/hr	Jakes	10%
Model E	Single Path	1	0, $f_{Doppler}$ = 1.5 Hz	Rician Factor K = 10 dB	10%

Table 9: Multipath Models for Performance Simulation

Each frame in the Mobile WiMAX configuration contains 48 OFDM symbols, 37 data symbols and 11 overhead symbols (7 for DL, 3 for UL and 1 for TTG). The 37 data symbols are partitioned to provide a DL to UL ratio of 28:9 (approximately 3:1). The configurations summarized in Table 5 are applied to 1xEVDO and HSPA for the quantitative performance comparison. The key differences in the simulation parameters between Mobile WiMAX and EVDO and HSPA are:

- EVDO and HSPA operate on a carrier frequency of 2.0 GHz as opposed to 2.5 GHz for Mobile WiMAX. This frequency difference puts Mobile WiMAX at a slight propagation disadvantage to the other two technologies for this analysis.
- HSPA operates on two 5 MHz FDD channels and 1xEVDO-Rev A operates on two 1.25 MHz FDD channels whereas Mobile WiMAX is TDD on a single 10 MHz channel.
- For multi-carrier EVDO-Rev B a 3-carrier 5 MHz FDD channel implementation is selected to provide a case comparable to a 10 MHz TDD channel for the Mobile WiMAX implementation. EVDO-Rev B also assumes optional 64QAM is used in the DL.
- For all the 3G cases, single antenna Tx and dual antenna Rx (1x2, SIMO) with RAKE receivers are assumed in both DL and UL. For Mobile WiMAX, 2x2 MIMO with Space Time Coding (STC) and Vertical Spatial Multiplexing (VSM) with Adaptive MIMO Switching (AMS) are assumed in the DL and two-user collaborative SM is assumed in the UL. Low complexity Maximum Likelihood Symbol Detection (MLD) is assumed at the receivers in both DL and UL. This configuration represents the baseline functionality as specified in the Release-1 system profile for Mobile WiMAX.

All systems assume a (1, 1, 3)[8] frequency reuse pattern, EESM PHY abstraction [31] and ideal channel estimation and all apply the same channel model and channel mix as shown in Tables 8 and 9. The spatial channel mode is based on the delay line MIMO channel model [32] with multiple path components defined in Table 9 and spatial correlation 0.2. The full buffer traffic performance is simulated with 10 active users in each sector (30 per cell). The HARQ, turbo coding, link adaptation and proportional fair scheduler of each system are optimized according to its specification. The simulation results are summarized in Table 10 assuming a DL/UL ratio of 3:1 for Mobile WiMAX. The results of the simulation clearly show the spectral efficiency and sector throughput advantages of Mobile WiMAX over both 1xEVDO [21,33,34] and HSDPA/ HSPA [35].

Since only three (3) 1.25 MHz carriers are supported in the 5 MHz bandwidth channel the UL spectral efficiency for EVDO-Rev B is about 25% less than that of 1xEVDO-Rev A. The EVDO-Rev B DL spectral efficiency however, improves slightly as a result of the optional 64QAM feature in the DL channel. The spectral efficiency for Mobile WiMAX with MIMO is 1.91 bps/Hz/sector in the DL and 0.84 bps/Hz/sector in the UL. The 3G systems on the other hand, range from 0.78 to 0.93 bps/Hz/sector in the DL and 0.14 to 0.36 bps/Hz/sector in the UL. The UL spectral efficiency gain for Mobile WiMAX is achieved with no additional complexity at the client due to orthogonal uplink access, UL scheduling and UL collaborative spatial multiplexing.

[8] Frequency reuse pattern is denoted as (c, n, s); where c is the number of BS sites per cluster, n is the number of unique frequency channels required for reuse, and s is the number of sectors per BS site.

Parameter		1x EVDO Rev A	3x EVDO Rev B	HSDPA	HSPA	Mobile WiMAX
Duplex		FDD	FDD	FDD	FDD	TDD
Occupied Spectrum (MHz)		2.5	10	10	10	10
Channel BW (MHz)	DL	1.25	5	5	5	DL/UL= 3
	UL	1.25	5	5	5	
Spectral Efficiency (bps/Hz)	DL	0.85	0.93	0.78	0.78	1.91
	UL	0.36	0.28	0.14	0.30	0.84
Net Information Through-put per Channel/ Sector (Mbps)	DL	1.06	4.65	3.91	3.91	14.1
	UL	0.45	1.39	0.70	1.50	2.2

Table 10: Performance Comparison

Table 10, summarizes the Mobile WiMAX performance with a 2x2 MIMO configuration and a specific DL/UL ratio of 3:1. Mobile WiMAX however, supports flexible configurations and DL/UL ratios ranging from 3:1 to 1:1. Furthermore, although a 2x2 MIMO configuration is required in the Release-1 system profile, 1x2 SIMO configurations may be adopted in early product releases. Therefore, it is of interest to understand the performance differences with a SIMO configuration for Mobile WiMAX. The assumptions for a SIMO configuration are the same as 2x2 MIMO except that STC and SM are disabled in the DL and collaborative MIMO is disabled in the UL. The Mobile WiMAX SIMO and MIMO performance results for DL/UL ratios of 1:1 and 3:1 are shown in Table 11. To provide a more complete comparison of the simulation results the bar charts in Figures 11 and 12 summarize the data throughput and spectral efficiency performance for all of the analyzed cases.

Parameter		SIMO		MIMO	
		DL/UL = 1	DL/UL=3	DL/UL= 1	DL/UL=3
Spectral Efficiency (bps/Hz)	DL	1.10	1.23	1.71	1.91
	UL	0.69	0.61	0.94	0.84

Parameter		SIMO		MIMO	
		DL/UL = 1	DL/UL=3	DL/UL= 1	DL/UL=3
Net Information Through-put per Channel/ Sector (Mbps)	DL	5.9	9.1	9.2	14.1
	UL	3.1	1.6	4.2	2.2

Table 11: Mobile WiMAX SIMO/MIMO Comparison

As can be seen in Figure 11 and Figure 12, even early Mobile WiMAX deployments with SIMO will outperform EVDO and HSPA. In the same occupied spectrum. Mobile WiMAX with SIMO provides a DL throughput advantage of 28 to 96 % compared to 3xEVDO Rev B and 52 to 133% compared to HSPA depending on the DL/UL partition.

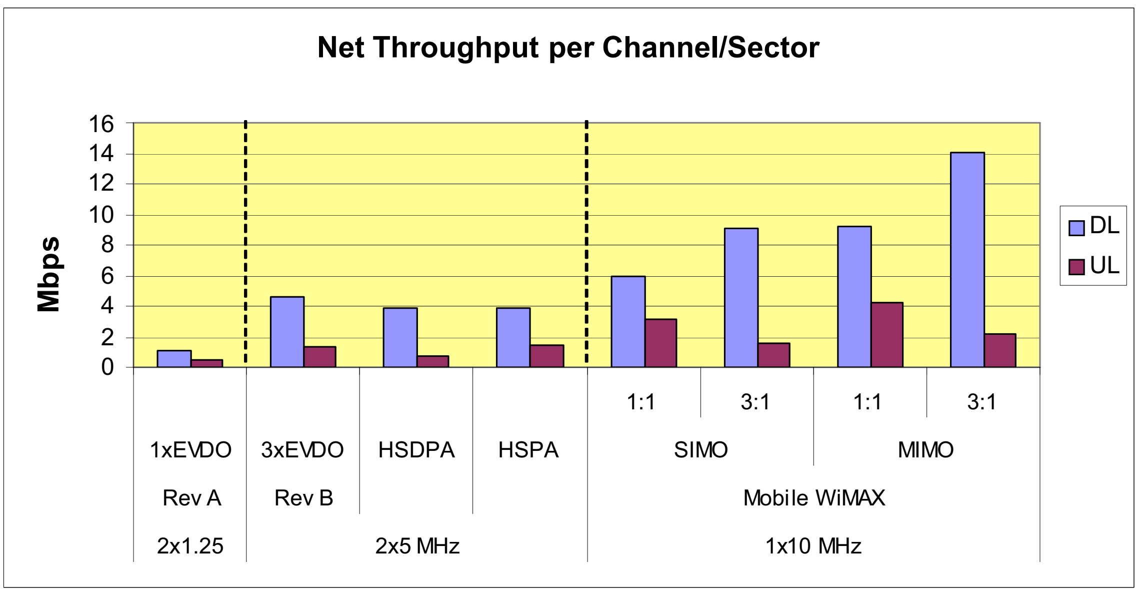


Figure 11: Channel/Sector Throughput Comparison

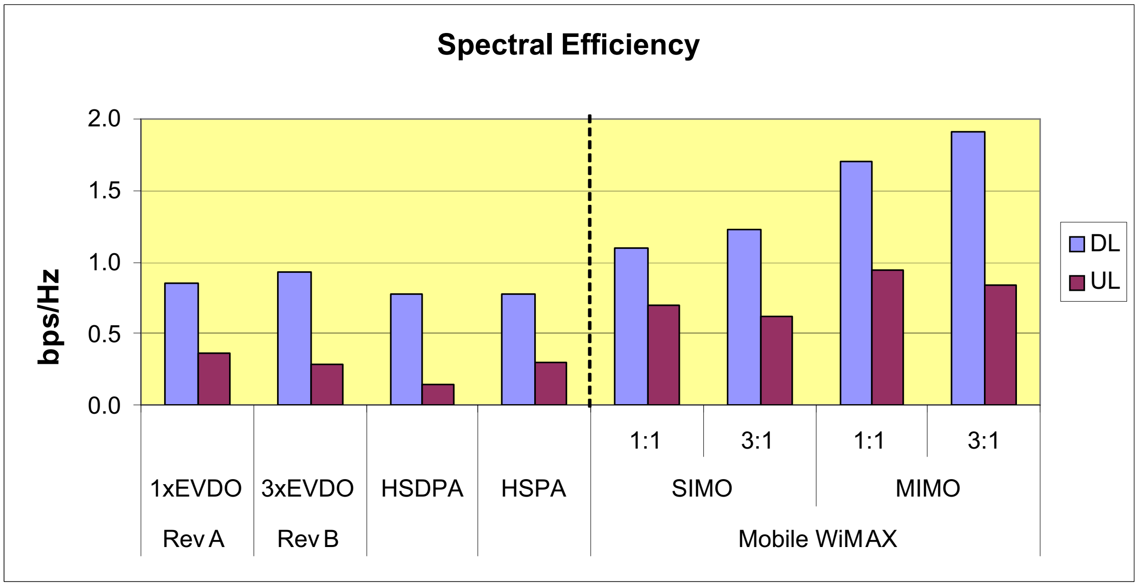


Figure 12: Spectral Efficiency Comparison

It should be noted that the 11 symbols for control channel overhead assumed in the previous analysis is a conservative estimate for the traffic models used for the comparative analysis. For most data applications, the traffic is bursty and Mobile WiMAX, under those conditions, can typically operate with less overhead and therefore, achieve higher spectral efficiency than the values indicated in Tables 10 and 11. In addition, the sub-channel considered for this case is PUSC diversity sub-channelization and frequency selective scheduling gain is not taken into account in the simulation. With frequency selective AMC sub-channelization, the spectral efficiency for Mobile WiMAX can be further increased by 15 to 25%. Therefore, with an optimized Mobile WiMAX system and bursty data traffic, the spectral efficiency and throughput can be further improved by 20 to 30%. The typical range for improvement in channel/sector throughput and spectral efficiency for a Mobile WiMAX system under these conditions as compared to the simulation results is illustrated in Figure 13 for the (2x2) MIMO configuration. With this added performance the spectral efficiency for Mobile WiMAX will be 2 to 3 times better than the 3G systems and, with a 3:1 DL to UL ratio, the DL sector throughput will be greater than 18 Mbps and the UL sector throughput more than 2.8 Mbps. This high spectral efficiency combined with channel bandwidths up to 20 MHz provides a very high sector throughput capability for Mobile WiMAX systems compared to the 3G systems. This throughput performance enables efficient data multiplexing and low data latency. These are key attributes essential for enabling broadband mobile services such as data, video, and VoIP.

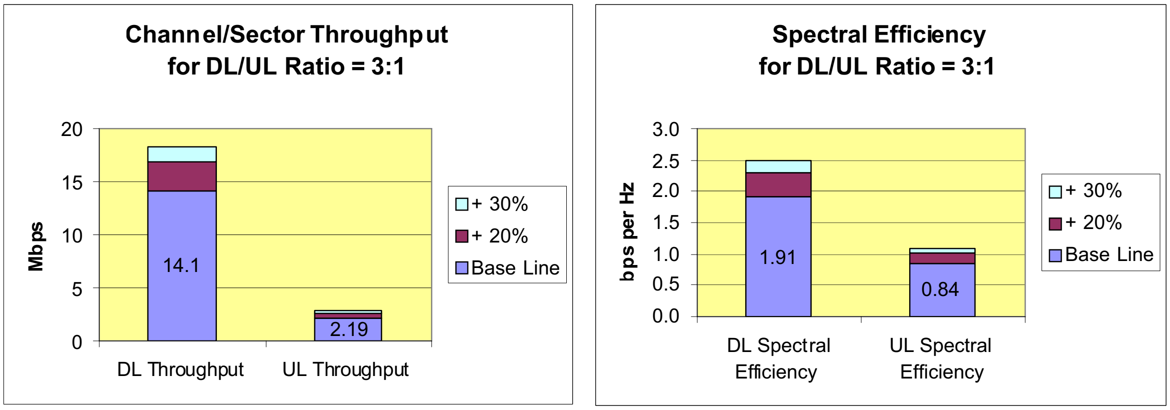


Figure 13: Optimized Mobile WiMAX with MIMO (2x2)

It should also be noted that this performance simulation was based on the Mobile WiMAX baseline MIMO (2x2) configuration. Further performance improvements can be realized with optional advanced Mobile WiMAX features as discussed in Mobile WiMAX – Part I [1], such as AAS.

From a network deployment perspective the throughput and efficiency performance advantages of Mobile WiMAX translate directly to a more cost-effective access network and rich service offering. Costly spectrum licenses can be more efficiently utilized for generating operator revenues through value added services thus providing a greater return on the up-front investment.

5. Conclusion

In this paper, we provided a detailed comparison of Mobile WiMAX, EVDO and HSPA systems. All the systems have adopted advanced technologies to improve data throughput. In particular, various techniques including AMC, HARQ, and DL fast scheduling have been employed in all of these systems. Mobile WiMAX however, is based on OFDM/OFDMA technology which is more suitable for broadband wireless data communication. In fact OFDM/OFDMA is one proposal being considered in 3GPP/3GPP2 as the solution for LTE and is generally accepted as being the basis for 4G. An OFDM/OFDMA-based system has high granular resource allocation, better uplink efficiency, and can support a full range of advanced antenna technologies. These capabilities offer the potential for significant spectral efficiency advantages and better QoS in both the downlink and uplink direction. Mobile WiMAX can also dynamically adjust downlink/uplink ratio with TDD support providing greater flexibility and spectral efficiency advantages in supporting varied types of broadband traffic. In contrast, EVDO and HSPA, based on FDD, have a fixed asymmetric downlink/uplink ratio determined by the difference in downlink/uplink spectral efficiency and fixed FDD channel bandwidths. Additionally, Mobile WiMAX provides superior QoS and offers operators greater flexibility in implementing Service Level Agreements to meet varied customer requirements.

From a performance perspective, only Mobile WiMAX can transport DSL and cable-like services cost-effectively in a mobile environment. This is an essential requirement for the success of Mobile WiMAX, a technology aimed at delivering broadband mobile services ranging from real-time interactive gaming, VoIP, and streaming media to non-real-time web browsing and simple file transfers.

Other benefits of WiMAX include its open standard approach and healthy ecosystem. Hundreds of companies have contributed to the development of the technology and many companies have announced product plans for this technology. The broad industry participation with worldwide adoption of the standard will ensure economies of scale that will help drive low cost of subscription and enable the deployment of broadband mobile services in both developed and emerging markets. With a scalable architecture, high data throughput and low cost of deployment Mobile WiMAX is a leading solution for wireless broadband services. By creating a common platform that addresses a wide range of market segments, Mobile WiMAX is well-positioned to experience a high global take rate.

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