Mobile Broadband

Including WiMAX and LTE

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Preface

This book attempts to provide an overview of IP-OFDMA technology, commencing with cellular and IP technology for the uninitiated, while endeavoring to pave the way toward OFDMA theory and emerging technologies, such as WiMAX, LTE, and beyond. The first half of the book ends with OFDM technology, and the second half of the book is targeted at more advanced readers, providing research and development-oriented outlook by introducing OFDMA and MIMO theory and end-to-end system architectures of IP- and OFDMA-based technologies.

The book comprises 13 chapters divided into three parts. Part I – constituted by Chaps. 1–3 – is a rudimentary introduction for those requiring a background in the field of cellular communication and All-IP Networking. Chapter 1 is introductory and is dedicated to discussing the history of cellular communications and the trend toward mobile broadband. Chapter 2 provides an overview of cellular communication with key insights to wireless challenges and features. Chapter 3 provides the same for IP networking.

Part II is comprised of Chaps. 4–7. Following an introduction to orthogonal frequency division multiplexing (OFDM) in Chap. 4, Chap. 5 is one of the core chapters of the book where orthogonal frequency division multiple access (OFDMA) is introduced in detail with resource allocation schemes. Chapter 6 talks about MIMO technologies and Chap. 7 introduces single-carrier frequency division multiple access (SC-FDMA) scheme – an OFDMA variant considered for uplink in LTE.

Part III, including Chaps. 8–13, introduces OFDMA-based access technologies. IEEE 802.16e-2005 based mobile WiMAX physical layer is described in Chap. 8, while IEEE 802.16e-2005 based mobile WiMAX medium access layer is detailed in Chap. 9. This is followed by Chap. 10, which concentrates on the networking layer specified by WiMAX Forum. Chapter 11 introduces air interface and networking framework of long-term evolution (LTE) out of Third Generation Partnership Project (3GPP), which is then followed by Chap. 12 that talks briefly about that of ultra mobile broadband (UMB) out of 3GPP2. In Chap. 13, we conclude the book with interworking solutions of access schemes presented earlier together with common IMS and PCC functions. In addition, we review future OFDMA-based technologies such as upcoming IEEE 802.16j and IEEE 802.16m for multihop relay and advanced air interface respectively as amendments to WiMAX. We then talk about IEEE 802.20 as a complement to UMB and cognitive radio-based IEEE 802.22 for wireless regional area networks.

The purpose of this book is to provide a comprehensive guide to researchers, engineers, students, or anyone else who is interested in the development and deployment of next generation OFDMA-based mobile broadband systems. The book targets to focus on a rapidly evolving area, and we have tried to keep it with up-to-date information. Despite the efforts to provide the text error free, for any errors that remain, comments and suggestions are welcome, which the will be used for preparing future editions. I can be reached via email at `ergen@cal.berkeley.edu`.

Finally, I thank my colleagues and my family for their constant support and patience. This book is dedicated to them.

Berkeley, CA *Mustafa Ergen*

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1.1 Introduction

A long way in a remarkably short time has been achieved in the history of wireless. Evolution of wireless access technologies is about to the reach its fourth generation (4G). Looking past, wireless access technologies has followed different evolutionary paths aimed at unified target: performance and efficiency in high mobile environment. The first generation (1G) has fulfilled the basic mobile voice, while the second generation (2G) has introduced capacity and coverage. This is followed by the third generation (3G), which has quest for data at higher speeds to open the gates for truly "mobile broadband" experience.[1]

What is "mobile broadband" then? Broadband refers to an Internet connection that allows support for data, voice, and video information at high speeds, typically given by land-based high-speed connectivity such as DSL or cable services. On the one hand, it is considered broad because multiple types of services can travel across the wide band, and mobile broadband, on the other hand, pushes these services to mobile devices.

We are seeing that mobile broadband technologies are reaching a commonality in the air interface and networking architecture; they are being converged to an IP-based network architecture with Orthogonal Frequency Division Multiple Access (OFDMA) based air interface technology. Although network evolution has not reached to the point of true and full *convergence*, wireless access networks, all at various stage of evolution, is being designed to support ubiquitous delivery of multimedia services via *internetworking*.

The transition to full convergence itself presents a set of unique challenges that the industry needs to address, however, IP-OFDMA-based technologies, the subject of this book, at one end and common policy control and multimedia services at the other end are good starts for full convergence.

[1] "Gartner predicts that mobile connections will top 3 billion worldwide by 2008 and that overall telecommunications services and equipment total revenue will reach $1.89 trillion (US) in 2009".

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First worldwide debut of IP-OFDMA-based mobile broadband is with WiMAX (Worldwide Interoperability for Microwave Access) technology. This may be followed by Long Term Evolution (LTE), Ultra Mobile Broadband (UMB), and others. These standards are developed by partnership organizations and Internet Engineering Task Force (IETF[2], http://www.ietf.org). The Third Generation Partnership Project[3] (3GPP, http://www.3gpp.org) is responsible for LTE, while Third Generation Partnership Project 2[4] (3GPP2, http://www.3gpp2.org) deals with UMB. WiMAX is the exception to this since it is developed by WiMAX Forum (http://www.wimaxforum.org) and Institute of Electrical and Electronics Engineers (IEEE, http://www.ieee.org).

The underlying technology of WiMAX is considered to be a 4G system but early evolution and adoption of WiMAX has led the IEEE and the WiMAX Forum to ask R-ITU (Radiocommunication sector of the International Telecommunication Union) to include mobile WiMAX based on 802.16e into its IMT2000[5] specification (International Mobile Telecommunications 2000). WiMAX is included in IMT2000 in October 2007, which was originally created to harmonize 3G mobile systems. IMT2000 now supports seven different access technologies, including OFDMA (WiMAX), FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access), and CDMA (Code Division Multiple Access) as shown in Table 1.1. This will put OFDMA on a comparable worldwide footing with other recent and planned enhancements to 3G technology. As a result, alternative migration path as seen in Fig. 1.1 is now an option for operators to debut for value-added broadband services.

What remains for 4G then? IMT-Advanced, which is the ITU umbrella name for future 4G technologies has set vision of the characteristic of future 4G IMT-Advanced systems. Although there is no clear definition as of now, the ITU-R M.1645 considers a radio interface(s) that need to support data rates up to approximately 100 Mbps for high mobility such as mobile access and 1 Gbps for low

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[2] "The Internet Engineering Task Force is a large open international community of network designers, operators, vendors, and researchers concerned with the evolution of the Internet architecture and the smooth operation of the Internet. An Internet document can be submitted to the IETF by anyone, but the IETF decides if the document becomes an RFC (Request for Comments), which has started in 1969 when the Internet was the ARPANET. Eventually, if it gains enough interest, it may evolve into an Internet standard. Each RFC is designated by an RFC number. Once published, an RFC never changes...".

[3] The 3GPP is formed by ETSI Europe, T1 USA, CWTS China, TTC Japan, ARIB Japan, TTA Korea.

[4] The 3GPP2 is formed by TIA USA, CWTS China, TTC Japan, ARIB Japan, TTA Korea.

[5] IMT2000 is particularly a framework that defines the criteria of ubiquitous support. The key criterias are:

- High transmission rates
- Fixed line voice quality
- Global roaming and circuit switched services support
- Multiple simultaneous services
- Increased capacity and spectral efficiency
- Symmetric and asymmetric transmission of data

Table 1.1 IMT2000

UMTS/WCDMA	CDMA Direct Spread
CDMA2000	CDMA Multi-Carrier
UMTS-TDD	Time-Code
TD-SCDMA	Time-Code
UWC-136	Single Carrier
IS-136	Single Carrier
EDGE	Single Carrier
DECT	FDMA/TDMA
WiMAX	OFDMA TDD

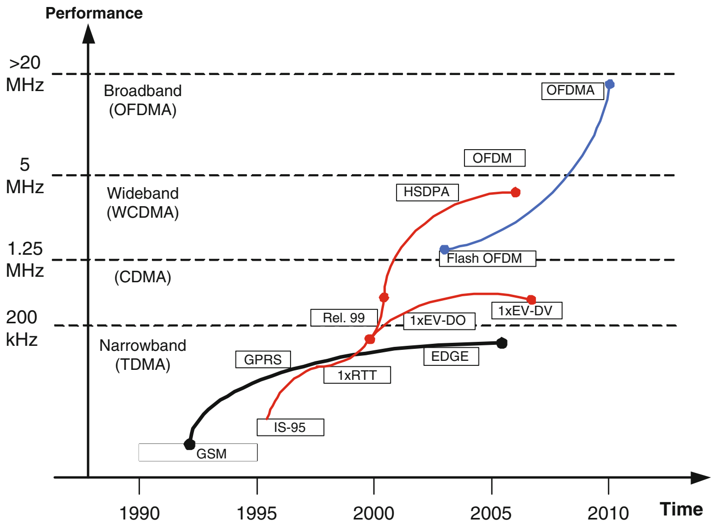

Fig. 1.1 Evolution of radio technologies source: Siemens

mobility such as nomadic/local access. These figures are seen to be the target and be researched and investigated further for feasible implementation. Current targeted landscape is shown in Fig. 1.2.

As can be seen mobile WiMAX based on 802.16e (We call WiMAX-e) would not qualify as a 4G IMT-Advanced standard since data rates even under ideal conditions are much lower but IEEE 802.16m, which is considered as the next Mobile WiMAX technology (we call WiMAX-m) and expected to be ratified in 2009, satisfies 4G requirements by achieving 1 Gbps data rate. Similar to current 802.16e Mobile WiMAX, the 802.16 m standard would use multiple-input, multiple-output (MIMO) antenna technology, while maintaining backward compatibility with the existing standards.

The speed on the order of 1 Gbps reportedly can be reached by using larger antenna arrays but current research shows that the data rate requirements described in ITU-R M.1645 can only be achieved with frequency bands above 100 MHz; however, there are very few large bands available. These requirements might be relaxed for the final release of 4G IMT-Advanced.

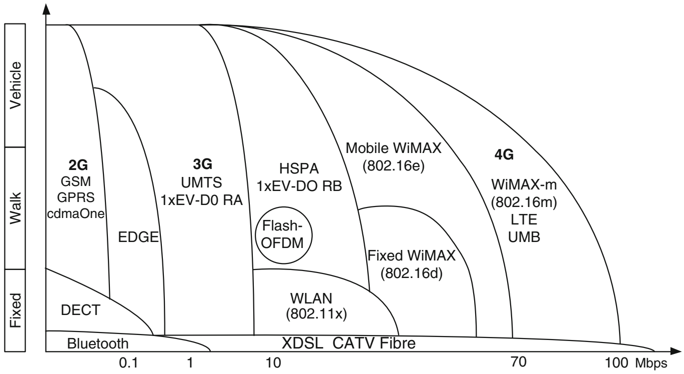

Fig. 1.2 Wireless standard landscape

We now start introducing the cellular evolution and broadband evolution in detail. First, we start with cellular systems that are introduced in the pre-3G era and also talk about the broadband services of that era. Later, we discuss the 3G cellular evaluation of 3GPP/2 and also introduce the broadband wireless access. At the last stage of the evolution, we talk about the motivation toward mobile WiMAX and 4G. Finally, we conclude the chapter with a discussion of key features and market of mobile broadband.

1.2 Before 3G and Broadband

Mobile broadband has two dimensions: mobility and broadband. However, traditionally, mobility first emerged for voice communication with cellular systems, and broadband has started with no mobility. Let us look first how these two have evolved to mobile broadband.

1.2.1 Cellular Communication

The most notable 1G cellular system was called the Advanced Mobile Phone System (AMPS), which was introduced by Bell Labs on the basis of cellular concept in 1947 and deployed worldwide in the 1980s. AMPS is an analog FDMA-based system for voice communication through 30 KHz FM modulated channels.[6] It is still being used in some rural areas of the United States however first generation cellular systems has lacked *uniform standardization*, which throttled the penetration.

[6] FCC has allocated 50 MHz total bandwidth for uplink and downlink.

Standardization has started with the 2G cellular systems. Global Systems for Mobile Communications (GSM) standard of Europe introduced digital communication with a combination of TDMA and slow frequency hopping for the voice communication. In the United States, 2G cellular standardization process at the 900 MHz followed two prong ways: Interim Standard-136 (IS) standard, evolved from IS-54,[7] considered TDMA and FDMA with phase-shift keyed modulation and cdmaOne IS-95 standard, first published in 1993, utilized direct-sequence CDMA with phase-shift keyed modulation and coding. In 2G, although standardization is present, a new challenge arose: *frequency allocation*.[8] The 2G standards are allowed in 2 GHz PCS (Personal Communications System) band but frequency band allocation in Europe is different from the one in the US, which made impossible to roam between systems nationwide or globally without a multimode phone.

The 2G has evolved to offer packet-based data services with GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for GSM Evolution) within GSM systems. GPRS reached peak data rates up to 140 Kbps when a user aggregates all timeslots. EDGE has increased data rates up to 384 Kbps with high-level modulation and coding. Adaptive Modulation and Coding (AMC) is introduced by EDGE to adaptively select the best modulation according to the received Signal-to-Noise-Ratio (SNR) feedback. IS-95A provided circuit-switched data connections at 14.4 Kbps and IS-95B[9] systems has offered 64 Kbps packet-switched data, in addition to voice services.

1.2.2 Broadband and WLAN/WiFi

Another evaluation is as we said broadband connectivity, which has started with Digital Subscriber Line (DSL) and cable modem technology. DSL utilizes the twisted pair copper wire of the local loop of the public switched telephone network (PSTN), which is used to carry Plain Old Telephone Service (POTS) voice communication between 300 and 3.4 KHz. DSL uses the bandwidth beyond 3.4 KHz. The length and quality of the loop determines the upper limit that can be utilized for DSL connection. DSL utilizes Discrete Multitone Modulation (aka Orthogonal Frequency Division Multiplexing (OFDM)) and DSL modem converts digital data

[7] It is the first digital 1G cellular system over TDMA. Also, called Digital-AMPS.

[8] Spectrum allocation and controlling use is governed by government agencies. Federal Communications Commission (FCC) regulates the commercial use and Office of Spectral Management (OSM) regulates the military use in the United States. European Telecommunications Standard Institute (ETSI) regulates the spectrum in Europe and International Telecommunications Union (ITU) governs globally. Frequency bands could be licensed or license-exempt. Band for licensed use is determined through spectrum auctions and primary purpose of license-exempt operation is to encourage innovation and low-cost deployment.

[9] The IS-95B revision, also termed TIA/EIA-95, combines IS-95A, ANSI-J-STD-008, and TSB-74 standards into a single document. The ANSI-J-STD-008 specification, published in 1995, defines a compatibility standard for 1.8–2.0 GHz CDMA PCS systems. TSB-74 describes interaction between IS-95A and CDMA PCS systems that conform to ANSI-J-STD-008.

into analog waveform. These waveforms coming from various DSL modems are aggregated at a Digital Subscriber Line Access Multiplexer (DSLAM), which acts as a gateway to other networking transports. *DSL Forum* has driven global standardization with several xDSL standards such as ADSL, SHDSL, VDSL, ADSL2plus, VDSL2, and more. ADSL is holding more than 60% of the broadband subscribers, which was around 350 million worldwide at the end of 2007. ADSL standard can deliver 8 Mbps to the customer over about 2 km. The latest ADSL2plus can go up to 24 Mbps depending on the distance from the DSLAM since increasing the distance to DSLAM decreases the performance. The first DSL debut was for Internet connection, lately it has been converging to provide bundled services like voice, video especially Internet Protocol Television (IPTV), and data.

The cable modem technology comprises several standards to deliver high-speed data transfer over an existing coaxial Cable TV (CATV) system. The *CableLabs* founded in 1988 by cable operation companies defines DOCSIS (Data Over Cable Service Interface Specification), which is an interface requirements for cable modems that are used in data transmission. Another standard from CableLabs is PacketCable built over DOCSIS to define interface specifications for delivering advanced, real-time multimedia services via IP technology. This includes multimedia services, such as IP telephony, multimedia conferencing, interactive gaming, and general multimedia applications. CableLabs also introduces Video on Demand (VoD) Metadata project to define specifications how the content package may be delivered from multiple content providers sent over diverse networks to cable operators. Lately, the CableHome project is introduced to extend high-quality cable-based services to network devices within the home to deliver voice, video especially high-definition TV (HDTV), and data.

The broadband is also evolving with xDSL and cable variants as well as new technologies like FTTH (fiber-to-the-home) over an optical fiber, which run directly onto the customer's premises unlike fiber-to-the-node (FTTN), fiber-to-the-curb (FTTC), or hybrid fibre-coaxial (HFC), all of which depend upon more traditional methods such as copper wire or coaxial cable for "last mile" delivery.

However, the broadband over DSL and cable are only capable to provide last mile connection with no mobility. Limited mobility is introduced with the introduction of Wireless Local Area Networking (WLAN) within the past decade. WLAN systems are confined to deliver wireless connectivity within a small range, and they are utilized to distribute fixed broadband connectivity to nomadic wireless users as well as users with pedestrian speed.

WLAN establishes wireless connection between wireless stations (such as PCs, laptops, handhelds, etc.) and the access point that connects to DSL or Cable modem or Ethernet for broadband connectivity. WLAN operates in unlicensed frequency bands. The primary unlicensed bands are the ISM (Industrial, Scientific, and Medical) bands at 900 MHz, 2.4 GHz, and 5.8 GHz and the Unlicensed National Information Infrastructure (U-NII) band at 5 GHz. WLAN is hosted in ISM band as secondary user and has to vacate if primary users are active. However, U-NII band does not have primary users.

The WLAN has been standardized in IEEE within 802.11 framework. The first standard 802.11b is introduced in 2.4 GHz ISM band for 83.5 MHz spectrum. The 802.11b utilized direct-spread spectrum to offer data rates up to 11 Mbps within 100m range. Later, IEEE 802.11a is introduced in 300 MHz of 5 GHz U-NII band. The 802.11a is the first standard in the wireless domain to use OFDM modulation to provide up to 54 Mbps within less than 100 m range. IEEE 802.11a has also more channels than 802.11b and has the ability to accommodate users with higher data rates. To leverage this system design, later IEEE 802.11g is introduced in the 2.4 GHz band with the same design as in IEEE 802.11a. IEEE 802.11g is designed also to be backward compatible with IEEE 802.11b. These systems, although evolved to support higher rates, lack a MAC protocol that supports Quality of Service (QoS). Later, IEEE 802.11e framework addressed QoS and IEEE 802.11n framework is designed to accommodate MIMO technology with OFDM modulation. In Europe, HiPERLAN (High Performance Radio LAN) standards are designed to introduce WLAN service. The HiPERLAN/2 standard also utilizes OFDM standard as in IEEE 802.11a in 5 GHz U-NII band.

WLAN standard within IEEE frame only defines the physical and MAC layers. The industry formed the *Wi-Fi Alliance* as a nonprofit industry association to enhance the user experience by defining the networking layer as well as testing and certification programs. Currently, wireless LAN is proliferating at homes, enterprises, and even in cities, and has become the standard for “last feet” broadband connectivity. The success of WLAN has accelerated the hype toward broadband wireless access with more mobility and guaranteed QoS.

1.3 3G and Broadband Wireless

Moving toward mobility and high speed from broadband and cellular systems has continued in different angles in the third generation era. The 3GPP and 3GPP2 have introduced the 3G technologies as an evolution to their existing second generation paths. After summarizing these technologies, we give the evolution of broadband to WiMAX from broadband wireless access.

1.3.1 The 3GPP Family

Universal Mobile Telecommunications System (UMTS), which is based on Wideband Code Division Multiple Access (WCDMA), has been studied in Release-1999 (Rel-99) of 3GPP and published in 2000. UMTS was the next step after GSM, GPRS, and EDGE to offer improved voice and data services with a 5 MHz bandwidth. Rapid growth of UMTS, where future projection is seen in Table 1.2, has led to the next step in evolutionary phase termed, Release-2005 (Rel-5).

Table 1.2 Global UMTS customer forecast by World Cellular Information Service, Informa Telecoms and Media, May 2007

2007	200M
2008	350M
2009	500M
2010	700M
2011	900M
2012	1250M

Rel-5 provided High Speed Downlink Packet Access (HSDPA) that brought spectral efficiency for higher-speed data services. Rel-5 also introduced IP Multimedia Subsystem (IMS) and IP UMTS Terrestrial Radio Access Network (UTRAN) to offer flexibility to operator to provide such hosted services for greater user experience. Meanwhile, Rel-4 is introduced in March 2001, which separated call and bearer in the core network.

On the one hand, Rel-6, introduced in March 2005, came with High Speed Uplink Packet Access (HSUPA), Multimedia Broadcast Multicast Service (MBMS), and advanced receivers. The combination of HSDPA and HSUPA is called HSPA.

Rel-7, on the other hand, focuses on MIMO technology and flat-IP based base stations. GPRS Tunneling Protocol (GTP) has started to be used in order to connect packet switched network to radio access network. Rel-7 is expected to finish in 2008 with new enhancements and it is termed HSPA Evolution, commonly known as HSPA+. Rel-7 has also improved receiver architecture and brought interference aware receivers (referred as type 2i and type 3i, which are extensions to existing type 2 and type 3 receivers). The receiver employs interference aware structure, which not only takes into account the channel response matrix of the serving cell but also the channel response matrix of the interfering cell that has the most significant power. Rel-7 also introduced the use of higher order modulations such as 64QAM with MIMO support since in Rel-6, HSPA systems used 16QAM in the downlink and QPSK in the uplink. To reduce latency when exiting the idle mode, Continuous Packet Connectivity (CPC) has been introduced for data users. This mainly keeps more users in the cell active state. The protocol is modified to ensure the user keep synchronized and the power control ready for rapid resumption (Table 1.3).

In the network side, architecture has been improved as well. HSPA+ has integrated the RNC (Radio Network Controller) to NodeB (base station) to reduce latency and to make the architecture flatter and simpler. It is also a good move toward femtocell[10] deployments and a good step to enable packet-based services toward LTE since HSPA+ is considered to be the "missing link" between HSPA and LTE.[11]

[10] "Femtocells are being standardized in the *Femto Forum* (`http://www.femtoforum.org`) as a low-power wireless access points that operate in licensed spectrum to connect standard mobile devices to a mobile operator's network using residential DSL or cable broadband connections...".

[11] Rel-7 also introduced enhancements in device perspective. Single public identity has been provided to IMS user with multiple device support. Mobile payment or transportation applications has been addressed with Universal Integrated Circuit Card (UICC), collaborated with OMA (Open

Table 1.3 Data speed of various technologies:

Technology	Bandwidth	Technology	DL/UL peak
WCDMA Rel. 99	5 MHz FDD	TDM/CDMA	384/384 Kbps
HSPA Rel. 6	5 MHz FDD	TDM/CDMA	1.8–14.4/5.72 Mbps
HSPA+ Rel. 7	5 MHz FDD	TDM/CDMA	22/11 Mbps
LTE	1.25–20 MHz FDD	OFDMA/SC-FDMA	100/50 Mbps
CDMA2000 1x	1.25 MHz FDD	TDM/CDMA	153/153 Kbps
1xEV-DO Rev-0	1.25 MHz FDD	TDM/CDMA	2.4 Mbps/153 Kbps
1xEV-DO Rev-A	1.25 MHz FDD	TDM/CDMA	3.1/1.8 Mbps
1xEV-DO Rev-B	5 MHz FDD	TDM/CDMA	14.7/5.4 Mbps
UMB	1.25–20 MHz FDD	OFDMA	33-152/17-75 Mbps
WiFi	20 MHz TDD for 802.11a/g	CSMA/OFDM	54 Mbps shared
Fixed WiMAX	TDD, FDD 3.5 MHz, 7 MHz, 10 MHz	TDM/OFDM	9.4/3.3 Mbps with 3:1; 6.1/6.5 Mbps with 1:1
Mobile WiMAX	TDD 3.5 MHz, 7 MHz, 5 MHz, 10 MHz, 8.75 MHz	TDM/OFDMA	46/7 Mbps 2×2 MIMO in 10 Hz with 3:1; 32/4 Mbps with 1:1

HSPA operates in 800, 900, 1,800, 1,900, 2,100 MHz; EV-DO operates in 800, 900, 1800, 1,900 MHz; WiFi operates in 2.4 GHz, 5 GHz; fixed WiMAX operates in 3.5 GHz, and 5.8 GHz (unlicensed) initially; mobile WiMAX operates in 2.3 GHz, 2.5 GHz, and 3.5 GHz initially. The 3:1 and 1:1 stands for DL:UL ratio in TDD mode

1.3.2 The 3GPP2 Family

The 3GPP2 has continued to evolve its second generation (IS-95) based systems with EV-DO (Evolution-Data Optimized) series of CDMA2000 standard.[12] First standard of series, termed CDMA2000 1xEV-DO, introduces data-centric broadband network to deliver data rates beyond 2 Mbps in a mobile environment. In 2001, CDMA2000 1xEV-DO was approved as an IMT2000 standard as CDMA2000 High Rate Packet Data (HRPD) Air Interface, IS-856. CDMA2000 1xEV-DO Release 0 (Rel-0) offers high-speed data access up to 2.4 Mbps and it was the first mobile broadband technology deployed worldwide.[13]

Rel-0 provides a peak data rate of 2.4 Mbps in the forward link (FL) and 153 Kbps in the reverse link (RL) in a single 1.25 MHz FDD (Frequency Division Duplexing) carrier. In commercial networks, Rel 0 delivers average throughput of 300–700 Kbps in the forward link and 70–90 Kbps in the reverse link. Rel-0 has also

Mobile Alliance) and ETSI-SCP. Smart Card Server located in UICC offers secure and portable contactless exchanges with the Single Wire Protocol.

[12] "The CDMA2000 standards CDMA2000 1xRTT, CDMA2000 EV-DO, and CDMA2000 EV-DV are approved radio interfaces for the ITU's IMT-2000 standard. CDMA2000 is a registered trademark of the Telecommunications Industry Association (TIA-USA) in the United States, not a generic term like CDMA. CDMA2000 is defined to operate at 450, 700, 800, 900, 1,700, 1,800, 1,900, and 2,100 MHz. Source: Wikipedia".

[13] South Korea adopted first in 2002.

started "always on" user experience as in IP and also supports IP-based network connectivity and applications. CDMA2000 1xEV-DO devices include a CDMA2000 1X modem in order to be compatible with CDMA2000 1X and cdmaOne systems.

In addition to the air interface techniques of CDMA2000 1X, the following new high-speed packet data transmission enhancements are incorporated into Rel-0: downlink channelization to offer higher rate with bundling, Adaptive Modulation and Coding, Hybrid-ARQ, etc.

CDMA2000 1xEV-DO Revision A (Rev-A) is an evolution of CDMA2000 1xEV-DO Rel-0 to increase peak rates on reverse and forward links to support a wide-variety of symmetric, delay-sensitive, real-time, and concurrent voice and broadband data applications. It also incorporates OFDM technology to enable multicasting (one-to-many) for multimedia content delivery. Rev-A has introduced first All-IP based broadband architecture in 2006 to support time-sensitive applications such as VoIP, etc. Rev-A provides a peak data rate of 3.1 Mbps in the forward link and 1.8 Mbps in the reverse link with a 1.25 MHz FDD carrier. However, in commercial networks, Rev–A achieves average throughput of 450–800 Kbps in the forward link and 300–400 Kbps in the reverse link.

As the successor of Rev-A, CDMA2000 1xEV-DO Revision B (Rev-B) introduces dynamic bandwidth allocation to provide higher performance by aggregating multiple 1.25 MHz Rev-A channels. Consequently, peak data rates scales with the number of carriers aggregated. When 15 channels are combined within a 20 MHz bandwidth, Rev-B delivers up to 46.6 Mbps in the forward link and 27 Mbps in the reverse link. However, with 5 MHz aggregation, the peak data rates are around 14.7 Mbps.[14] Rev-B also supports OFDM based multicasting and introduces lower latency for delay sensitive applications.

1.3.3 Broadband Wireless Access

Broadband Wireless Access (BWA) has started with a fixed access in mind to compete with DSL and cable modem since rapid growth of broadband access has created demand for new wireless technologies to reduce the cost of operation and by pass monopoly of service providers in wire-line access. We give a chronological listing of BWA toward fixed WiMAX in this section and mobile WiMAX in the next section.

The Local Multipoint Distribution Systems (LMDS) is the first notable BWA that showed a short-lived rapid success as a wireless alternative to fiber and coaxial cables in the late 1990s. LMDS has utilized 28 & 31 GHz with two types of

[14] "With the 64QAM scheme, the peak data rate in the forward link increases in a single 1.25 MHz carrier to 4.9 Mbps however an aggregated 5 MHz will deliver up to 14.7 Mbps and within 20 MHz of bandwidth, it is up to 73.5 Mbps...".

LMDS licenses to or in? Offer up to several hundreds of megabits per second. However, LMDS system requires roof-top antennas to achieve line-of-sight (LOS) connection.

Multichannel Multipoint Distribution Services (MMDS or Wireless Cable) technology has emerged at 2.5 GHz and become popular in sparsely populated rural areas. LMDS and MMDS have adapted the modified version of DOCSIS for wireless broadband also known as DOCSIS+. MMDS provided greater range than LMDS but still required LOS link to operate.

The LOS challenge of broadband wireless has tackled with OFDM modulation and standardization activities have begun in 1998 by IEEE under the 802.16 working group. This group has targeted to standardize the technology for Wireless Metropolitan Area Network (Wireless MAN), also adopted by ETSI HiPERMAN (High Performance Radio Metropolitan Area Network). In 2001, first standard is approved as Wireless MAN-SC that specifies a single-carrier technology for operation in the 10–66 GHz band like LMDS. Non-LOS (NLOS) has been addressed in 2–11 GHz band for licensed and unlicensed frequencies as amendments to existing 802.16 standard. The IEEE 802.16a, completed in 2003 introduced three access schemes: single-carrier, OFDM and OFDMA for fixed NLOS access. It also specifies a common MAC layer for all three access schemes where concepts were mainly adapted for wireless from DOCSIS. The IEEE 802.16-2004 standard ratified in 2004 replaced IEEE 802.16, 802.16a, and 802.16c standards with a single standard and formed the basis for fixed WiMAX solution. In 2005, IEEE 802.16e-2005 amendment, which forms the basis for mobile WiMAX, is ratified to introduce enhancements for high-speed mobility. The IEEE 802.16 framework specifies the physical and media access control layers but does not deal with the end-to-end systems' requirements and interoperability criteria of systems built on these requirements. The industry-led *WiMAX Forum* was organized to fill this void to address fixed WiMAX and mobile WiMAX network architectures and protocols including interoperability and certification.

Currently, WiMAX Forum introduced two system profiles: fixed system profile based on IEEE 802.16-2004 OFDM physical layer, and mobile system profile based on IEEE 802.16e-2005 scalable OFDMA physical layer. Besides system profile, certification profiles are defined to specify the operating frequency, channel bandwidth, and duplexing mode as seen in Tables 1.4 and 1.5.

Table 1.4 Fixed WiMAX initial certification profiles

Band (GHZ)	Channel Bandwidth (MHz)	OFDM FFT size	Duplexing
3.5	3.5	256	FDD
3.5	3.5	256	TDD
3.5	7	256	FDD
3.5	7	256	TDD
3.5	10	256	TDD

Table 1.5 Release-1 System Profiles for Mobile WiMAX

Channel BW (MHz)	FFT size	2.3–2.4 GHz	2.305–2.32, 2.345–2.36 GHz	2.496–2.69 GHz	3.3–3.4 GHz	3.4–3.8 GHz
1.25	128					
5.0	512	TDD	TDD	TDD	TDD	TDD
7.0	1024				TDD	TDD
8.75	1024	TDD				
10	1024	TDD	TDD	TDD	TDD	TDD
20	2048					

FDD mode is being designed. WiBro, Mobile WiMAX in Korea, operates in 2.3 GHz band with 9 MHz channel spacing in IEEE 802.16e-2005 TDD mode

1.4 Mobile WiMAX and 4G

Mobile WiMAX has evolved from fixed wireless access and inherits its features for optimized broadband data services. EV-DO and HSPA, 3G CDMA standards, have been originally conceived for mobile voice services and inherit both advantages and limitations of legacy 3G systems. Consequently, mobile WiMAX faces the challenge to support mobility whereas 3G systems faces the challenge to support higher data rates.

Mobile WiMAX provides higher data rates with OFDMA support and introduces several key features necessary for delivering mobility at vehicular speeds with QoS comparable to broadband access alternatives. Several features that are used to enhance data throughput are common to EV-DO and HSPA: Adaptive Modulation and Coding (AMC), Hybrid-ARQ, fast scheduling, and bandwidth efficient handover. The key differenc is in duplexing where EV-DO and HSPA are FDD operating on a carrier frequency of 2.0 GHz, whereas mobile WiMAX is currently TDD (Time Division Duplexing) operating at 2.5 GHz. Mobile WiMAX has higher tolerance to multipath and self-interference and provides orthogonal uplink multiple access with frequency selective scheduling and fractional frequency reuse.

Unlike EV-DO and HSPA, Mobile WiMAX is also capable of utilizing 2×2 MIMO in addition to 1×2 SIMO. Performance comparison has shown that in 10 MHz channel, mobile WiMAX has a net downlink throughput by 9–14 Mbps with MIMO and 6–9 Mbps with SIMO per channel/sector as compared to $\sim$4 Mbps with EV-DO Rev-B and HSPA. This leads to a downlink spectral efficiency around 1.9 bps/Hz with MIMO at maximum when compared with 0.8 bps/Hz with EV-DO Rev-B and HSPA. Consequently, fewer base stations are required to achieve the desired data density.

There are already other contenders for mobile broadband besides WiMAX as seen in Fig. 1.3: Long Term Evolution (LTE) (Release 8) out of 3GPP and Ultra Mobile Broadband (UMB) (formerly CDMA2000 1xEV-DO Rev-C) out of 3GPP2. The good news is that they are being designed with the same air interface (OFDMA) as WiMAX. Change from WCDMA to OFDMA will be the second significant change

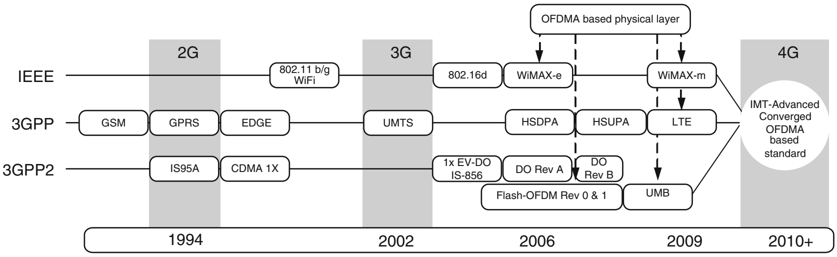

Fig. 1.3 Evolutionary path of cellular technology

in 3GPP standards after TDMA to WCDMA change during the shift from 2G to 3G systems. OFDMA selection is driven by the demand for higher spectral efficiency and low cost per bit since the basic problem for a service provider is to get more data to users, quicker and cheaper. Because WCDMA has a restriction to scale in bandwidth, OFDMA is selected. OFDMA solves this problem by splitting the high-speed data stream into several lower speed data streams and sending the lower speed streams on individual frequency channels. In the receiver, the user recombines these lower streams to construct a high-speed data stream.

Besides OFDMA technology, all three are based on IP services with no backward compatibility for circuit-switched services. This is another real break in technologies when moving to 4G since it gives a significant advantage to technologies that are coming out of blue like WiMAX. Operators now have a choice thereby they need not to follow the evolution path of 2G or 3G standard that they are currently using. WiMAX is also seen as the only player that can offer a unified fixed-mobile solution in broadband wireless as well as mobile broadband markets.

In brief, there are certainly similarities and few differences in the technology: performance, time-line, cost of operation, and IPR[15] are ingredients to determine a selection for mobile operators with regard to what the ecosystem is like and what the mobile community as a group wants to do.

1.5 Key Features

From technical perspective, fundamental goal of mobile broadband is to offer higher data rates with reduced latency. The key characteristics of a typical mobile broadband system are summarized here:

- *Increased data rates:* OFDMA based air interface is the key technology to offer higher data rates with higher order modulation schemes such as 64QAM, and

[15] "The patents and other intellectual property is one of the key requirements of technological and market development. WiMAX and other wireless technologies are built on the accomplishments of thousands. A favorable patent regimen with lower cost and converging Intellectual Property Rights (IPR) may foster the technology...".

sophisticated FEC (Forward Error Correction) schemes such as convolutional coding, turbo coding, alongside complementary radio techniques like MIMO and beamforming with up to four antennas per station.

- *High spectral efficiency:* Operators seek to increase the number of customers within their existing spectrum allocations, with reduced cost of per bit.
- *Flexible radio planning:* Deployment flexibility gives operators to change the cell size depending on the demand.
- *Reduced latency:* Next generation applications requires reduced round-trip times to 10 ms or even less. Responsiveness enables interactive, real-time services such as high-quality audio/videoconferencing and multi player gaming.
- *All-IP architecture:* Transition to a "flat", all-IP based core network will enable PC-like services such as voice, video, data and improves the interworking to other fixed and mobile networks.
- *Interworking:* Mobile broadband requires interworking to existing technologies to support fixed-mobile convergence.
- *Open interfaces:* Open interfaces enable multi-vendor network operation to give operator great flexibility to select best solutions. This leverages developments in other industries including Internet, PC, and network systems, etc.
- *Spectral flexibility:* Scalable bandwidths give operators flexibility to reuse their existing spectrum allocations. This is called "refarming" in the mobile telecommunications value chain as a cost-efficient option to address increasing traffic demands.
- *Cost reduction capabilities:* New features like Mobile Virtual Network Operation (MVNO), network sharing, or self optimizing networks are needed to reduce the OPEX (OPerational EXpenditure).
- *Support for data centric services:* Operators are looking for solutions to revert their declining ARPU (Average Revenue Per User).

1.6 Mobile Broadband Market

In the near future, OFDMA-based mobile broadband with the recent progress made by technical specifications and vendor technology demonstrations will emerge as successor to cellular systems as a broadband wireless solution.

Higher data rates and higher spectral efficiency become imminent with growing demands for wireless data services. 3G networks, which are being deployed worldwide, demonstrated a good example for an operator to increase their ARPU from broadband data services. Cost of network together with spectral cost will determine how far the current existing 3G networks advocate the current rise in ARPU with data services. In parallel, new services are created to boost the consumer demand such as mobile content, entertainment, advertising, MMS, video, etc. The most important part that will drive the convergence is content created by user (UGC), which will make "ease of use" as the next "big thing" in terms of technology.