1

Introduction

In less than three decades, the status of cellular telephones has moved from laboratory breadboard via curious luxury item to the world's most pervasive consumer electronics product. Cellular phones have incorporated an ever-growing array of other products including pagers, cameras, camcorders, music players, game machines, organizers, and web browsers. Even though wired telephony is 100 years older and the beneficiary of "universal service" policies in developed countries, the number of cellular phones has exceeded wired phones for a few years and the difference keeps growing. For hundreds of millions of people in developing countries, cellular communications is the only form of telephony they have experienced.

First conceived as a marriage of mature telephony and mature radio communications, cellular communications is now widely recognized as its own technical area and a driver of innovation in a wide range of technical fields including – in addition to telephony and radio – computing, electronics, cryptography, and signal processing.

1.1 Generations

The subject of this book, Single Carrier Frequency Division Multiple Access (SC-FDMA), is a novel method of radio transmission under consideration for deployment in future cellular systems. The development of SC-FDMA represents one step in the rapid evolution of cellular technology. Although technical progress is continuous and commercial systems frequently adopt new improvements, certain major advances mark the transition from one generation of technology to another. First generation systems, introduced in the early 1980s, were characterized by analog

Single Carrier FDMA: A New Air Interface for Long Term Evolution Hyung G. Myung and David J. Goodman

P1: OTA/XYZ P2: ABC
c01 JWBK249/Myung August 27, 2008 19:29 Printer Name: Yet to Come

speech transmission. Second generation technology, deployed in the 1990s, transmits speech in digital format. Equally important, second generation systems introduced advanced security and networking technologies that make it possible for a subscriber to initiate and receive phone calls throughout the world.

Even before the earliest second generation systems arrived on the market, the cellular community turned its attention to third generation (3G) technology with the focus on higher bit rates, greater spectrum efficiency, and information services in addition to voice telephony. In 1985, the International Telecommunication Union (ITU) initiated studies of Future Public Land Telecommunication Systems [1]. Fifteen years later, under the heading IMT-2000 (International Mobile Telecommunications-2000), the ITU issued a set of recommendations, endorsing five technologies as the basis of 3G mobile communications systems. In 2008, cellular operating companies are deploying two of these technologies, referred to as WCDMA (wideband code division multiple access) and CDMA2000, where and when they are justified by commercial considerations. Meanwhile, the industry is looking beyond 3G and considering SC-FDMA as a leading candidate for the "long term evolution" (LTE) of radio transmissions from cellular phones to base stations. It is anticipated that LTE technology will be deployed commercially around 2010 [2].

With respect to radio technology, successive cellular generations have migrated to signals transmitted in wider and wider radio frequency bands. The radio signals of first generation systems occupied bandwidths of 25 and 30 kHz, using a variety of incompatible frequency modulation formats. Although some second generation systems occupied equally narrow bands, the two that are most widely deployed, GSM and CDMA, occupy bandwidths of 200 kHz and 1.25 MHz, respectively. The third generation WCDMA system transmits signals in a 5 MHz band. This is the approximate bandwidth of the version of CDMA2000 referred as 3X-RTT (radio transmission technology at three times the bandwidth of the second generation CDMA system). The version of CDMA2000 with a large commercial market is 1X-RTT. Its signals occupy the same 1.25 MHz bandwidth as second generation CDMA, and in fact it represents a graceful upgrade of the original CDMA technology. For this reason, some observers refer to 1X-RTT as a 2.5G technology [3]. Planners anticipate even wider signal bands for the long term evolution of cellular systems. Orthogonal Frequency Division Multiplexing (OFDM) and SC-FDMA are attractive technologies for the 20 MHz signal bands under consideration for the next generation of cellular systems.

1.2 Standards

The technologies employed in cellular systems are defined formally in documents referred to as "compatibility specifications". A compatibility specification is one type of technical standard. Its purpose is to ensure that two different network elements interact properly. In the context of cellular communications, the two most obvious examples of interacting equipment types are cellular phones and base stations. As readers of this book are aware, standards organizations define a large number of other network elements necessary for the operation of today's complex cellular networks.

In addition to cellular phones and base stations, the most familiar cellular network elements are mobile switching centers, home location registers, and visitor location registers. In referring to standards documents, it is helpful to keep in mind that the network elements defined in the documents are "functional" elements, rather than discrete pieces of equipment. Thus, two different network elements, such as a visitor location register and a mobile switching center, can appear in the same equipment and the functions of a single network element (such as a base transceiver station) can be distributed among dispersed devices.

Figure 1.1 shows the network elements and interfaces in one 3G system [4]. The network elements (referred to in the standards as "entities") are contained in four major groups enclosed by dotted boxes. The core network (CN) is at the top of the figure. Below the core network is the radio access network with three sets of elements; a Base Station System (BSS) exchanges radio signals with mobile stations (MS) to deliver circuit switched services, and a corresponding Radio Network System (RNS) exchanges radio signals with mobile stations to deliver packet switched services. This book focuses on the radio signals traveling across the air interfaces. The Um interface applies to circuit switched services carrying signals between mobile stations and Base Transceiver Stations (BTS). Uu applies to packet switched services carrying signals between a mobile station and a base station system.

1.3 Cellular Standards Organizations 3GPP and 3GPP2

Two Third Generation Partnership Projects publish 3GPP cellular standards. The original Partnership Project, 3GPP, is concerned with descendents of the Global System for Mobile (GSM). The 3G technologies standardized by 3GPP are often referred to collectively as WCDMA (wideband code division multiple access). 3GPP uses two other acronyms

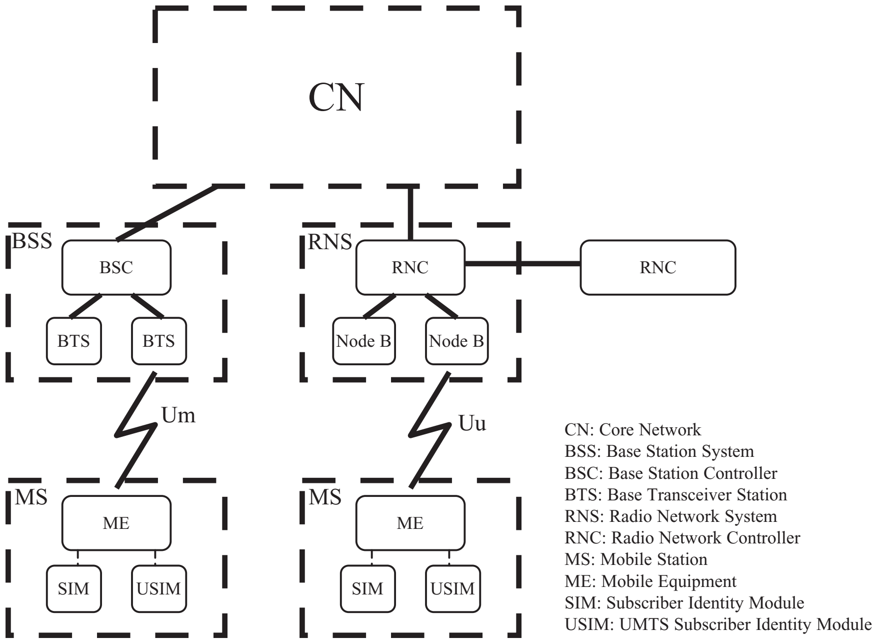

Figure 1.1 Basic configuration of a public land mobile network (PLMN) supporting circuit switched (CS) and packet switched (PS) services and interfaces [4]. *Source:* ETSI (European Telecommunications Standards Institute) © 2007. 3GPP™ TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TTA and TTC who jointly own the copyright in them. They are subject to further modifications and are therefore provided to you "as is" for information purposes only. Further use is strictly prohibited.

to describe its specifications: UMTS (Universal Mobile Telecommunications System) applies to the entire cellular network contained in hundreds of 3GPP specifications; and UTRAN (Universal Terrestrial Radio Access Network) refers to the collection of network elements, and their interfaces, used for transmission between mobile terminals and the network infrastructure. The other project, 3GPP2, is concerned with advanced versions of the original CDMA cellular system. The technologies standardized by 3GPP2 are often referred to collectively as CDMA2000.

The Partnership Projects consist of "organizational partners", "market representation partners", and "individual members". The organizational partners are the regional and national standards organizations, listed in Table 1.1, based in North America, Europe, and Asia. The market representation partners are industry associations that promote deployment of specific technologies. The individual members are companies associated with one

P1: OTA/XYZ P2: ABC
c01 JWBK249/Myung August 27, 2008 19:29 Printer Name: Yet to Come

Table 1.1 Organizational members of the Partnership Projects

Organizational member	Nationality	Affiliation
Association of Radio Industries and Businesses	Japan	3GPP and 3GPP2
Alliance for Telecommunication Industry Solutions	United States	3GPP
China Communications Standards Association	China	3GPP and 3GPP2
European Telecommunication Standards Institute	Europe	3GPP
Telecommunications Industry Association	North America	3GPP2
Telecommunications Technology Association	Korea	3GPP and 3GPP2
Telecommunication Technology Committee	Japan	3GPP and 3GPP2

or more of the organizational partners. In October 2006 there were 297 individual members of 3GPP and 82 individual members of 3GPP2.

The technologies embodied in WCDMA and CDMA2000 appear in hundreds of technical specifications covering all aspects of a cellular network. In both Partnership Projects, responsibility for producing the specifications is delegated to Technical Specification Groups (TSG), each covering one category of technologies. In 3GPP, the TSGs are further subdivided into Work Groups (WG). The publication policies of the two Partnership Projects are different. 3GPP periodically "freezes" a complete set of standards, including many new specifications. Each set is referred to as a "Release". Each Release is complete in that it incorporates all unchanged sections of previous standards that are still in effect as well as any new and changed sections. 3GPP also publishes preliminary specifications that will form part of a future Release. By contrast, each TSG in 3GPP2 publishes a new or updated specification whenever the specification obtains necessary approvals.

Release 5 of WCDMA was frozen in 2002, Release 6 in 2005, and Release 7 in 2007 [5]. In 2008, LTE specifications are being finalized as Release 8. Two of the innovations in Release 5 are High Speed Downlink Packet Access (HSDPA) and the IP Multimedia Subsystem (IMS). In Release 6, the innovations are High Speed Uplink Packet Access (HSUPA), the Multimedia Broadcast/Multicast Service (MBMS), and Wireless LAN/cellular interaction, and in Release 7, Multiple Input

P1: OTA/XYZ P2: ABC
c01 JWBK249/Myung August 27, 2008 19:29 Printer Name: Yet to Come

Multiple Output (MIMO) and higher order modulation. Release 8 deliberations focus on the Long Term Evolution (LTE) of WCDMA. In the Radio Access Network (RAN), the LTE goals are data rates "up to 100 Mbps in full mobility wide area deployments and up to 1 Gbps in low mobility, local area deployments" [6]. For best effort packet communication, the long term spectral efficiency targets are 5–10 b/s/Hz in a single (isolated) cell; and up to 2–3 b/s/Hz in a multi-cellular case [6]. In this context, SC-FDMA is under consideration for transmission from mobile stations to a Base Station Subsystem or a Radio Network System.

1.4 IEEE Standards

In addition to the two cellular Partnership Projects, the Institute of Electrical and Electronic Engineers (IEEE) has published standards used throughout the world in products with a mass market. Within the IEEE LAN/MAN standards committee (Project 802), there are several working groups responsible for wireless communications technologies. The one with the greatest influence to date is IEEE 802.11, responsible for the "WiFi" family of wireless local area networks. Two of the networks conforming to the specifications IEEE 802.11a and IEEE 802.11g employ OFDM technology for transmission at bit rates up to 54 Mb/s [7,8]. The other working group standardizing OFDM technology is IEEE 802.16, responsible for wireless metropolitan area networks. Among the standards produced by this working group, IEEE802.16e, referred to as "WiMAX" and described in the next section, most closely resembles technology under consideration by 3GPP for cellular long term evolution.

1.5 Advanced Mobile Wireless Systems Based on FDMA

Three standards organizations, IEEE, 3GPP, and 3GPP2, have work in progress on advanced mobile broadband systems using frequency division transmission technology. The following subsections describe key properties of Mobile WiMAX (developed by the IEEE), Ultra Mobile Broadband (developed by 3GPP2), and 3GPP Long Term Evolution (LTE). SC-FDMA, the subject of this book, is a component of LTE.

1.5.1 IEEE 802.16e-Based Mobile WiMAX

Following in the footsteps of the highly successful IEEE 802.11 family of wireless local area network (WLAN) standards, the IEEE 802.16 Working Group on Broadband Wireless Access (BWA) began its work of

P1: OTA/XYZ P2: ABC
c01 JWBK249/Myung August 27, 2008 19:29 Printer Name: Yet to Come

Table 1.2 Evolution of the IEEE 802.16 standard

Standards	Publication date	Highlights
802.16	Apr. 2002	Line-of-sight fixed operation in 10 to 66 GHz band.
802.16a	Apr. 2003	Air interface support for 2 to 11 GHz band.
802.16-2004 (802.16d)	Oct. 2004	Minor improvements and fixes to 802.16a.
802.16e	Feb. 2006	Support for vehicular mobility and asymmetrical link.
802.16m	In progress	Higher peak data rate, reduced latency, and efficient security mechanism.

developing the IEEE 802.16 wireless metropolitan area network (WMAN) standards in July 1999. Initially, IEEE 802.16 primarily focused on a point-to-multipoint topology with a cellular deployment of base stations, each tied into core networks and in contact with fixed wireless subscriber stations.

Since the first publication of the standard in 2002, the IEEE 802.16 standard has evolved through various amendments and IEEE 802.16e, published in February 2006, specifies physical and medium access control layers for both fixed and mobile operations [9]. Currently, 802.16m is being developed for the next generation system. Table 1.2 summarizes the IEEE 802.16 evolution.

Mobile WiMAX is an IEEE 802.11e-based technology maintained by the WiMAX Forum [10], which is an organization of more than 400 operators and communications component/equipment companies. Its charter is to promote and certify the compatibility and interoperability of broadband wireless access equipment that conforms to the IEEE 802.16 specifications. The WiMAX Forum Network Working Group (NWG) develops the higher-level networking specifications for Mobile WiMAX systems beyond what is defined in the IEEE 802.16 specifications, which address the air interface only.

Key features of the 802.16e-based Mobile WiMAX are:

- Up to 63 Mb/s for downlink and up to 28 Mb/s for uplink per sector throughput in a 10 MHz band.
- End-to-end IP-based Quality of Service (QoS).

P1: OTA/XYZ P2: ABC
c01 JWBK249/Myung August 27, 2008 19:29 Printer Name: Yet to Come

- Scalable OFDMA and spectrum scalability.
- Robust security: Extensible Authentication Protocol (EAP)-based authentication, AES-CCM-based authenticated encryption, and CMAC/HMAC-based control message protection schemes.
- Optimized handoff scheme and low latency.
- Adaptive modulation and coding (AMC).
- Hybrid automatic repeat request (HARQ) and fast channel feedback.
- Smart antenna technologies: beamforming, space-time coding, and spatial multiplexing.
- Multicast and broadcast service (MBS).

1.5.2 3GPP2 Ultra Mobile Broadband

3GPP2 developed Ultra Mobile Broadband (UMB) based on the frameworks of CDMA2000 1xEV-DO revision C [11], IEEE 802.20 [12], and Qualcomm Flarion Technologies' FLASH-OFDM [13]. The UMB standard was published in April 2007 by the 3GPP2 and the UMB system is expected to be commercially available in early 2009.

The key features of UMB include [11]:

- OFDMA-based air interface.
- Multiple Input Multiple Output (MIMO) and Space Division Multiple Access (SDMA).
- Improved interference management techniques.
- Up to 280 Mb/s peak data rate on forward link and up to 68 Mb/s peak data rate on reverse link.
- An average of 16.8 msec (32-byte, round trip time) end-to-end network latency.
- Up to 500 simultaneous VoIP users (10 MHz FDD allocations).
- Scalable IP-based flat or hierarchical architecture.
- Flexible spectrum allocations: scalable, noncontiguous, and dynamic channel (bandwidth) allocations and support for bandwidth allocations of 1.25 MHz, 5 MHz, 10 MHz, and 20 MHz.
- Low power consumption and improved battery life.

1.5.3 3GPP Long Term Evolution

3GPP's work on the evolution of the 3G mobile system started with the Radio Access Network (RAN) Evolution workshop in November 2004

[14]. Operators, manufacturers, and research institutes presented more than 40 contributions with views and proposals on the evolution of the Universal Terrestrial Radio Access Network (UTRAN), which is the foundation for UMTS/WCDMA systems. They identified a set of high level requirements at the workshop: reduced cost per bit, increased service provisioning, flexibility of the use of existing and new frequency bands, simplified architecture and open interfaces, and reasonable terminal power consumption. With the conclusions of this workshop and with broad support from 3GPP members, a feasibility study on the Universal Terrestrial Radio Access (UTRA) and UTRAN Long Term Evolution started in December 2004. The objective was to develop a framework for the evolution of the 3GPP radio access technology towards a high-data-rate, low-latency, and packet-optimized radio access technology. The study focused on means to support flexible transmission bandwidth of up to 20 MHz, introduction of new transmission schemes, advanced multi-antenna technologies, signaling optimization, identification of the optimum UTRAN network architecture, and functional split between radio access network nodes.

The first part of the study resulted in an agreement on the requirements for the Evolved UTRAN (E-UTRAN). Key aspects of the requirements are as follows [15]:

- Up to 100 Mb/s within a 20 MHz downlink spectrum allocation (5 b/s/Hz) and 50 Mb/s (2.5 b/s/Hz) within a 20 MHz uplink spectrum allocation.
- Control-plane capacity: at least 200 users per cell should be supported in the active state for spectrum allocations up to 5 MHz.
- User-plane latency: less than 5 msec in an unloaded condition (i.e., single user with single data stream) for small IP packet.
- Mobility: E-UTRAN should be optimized for low mobile speeds 0–15 km/h. Higher mobile speeds between 15 and 120 km/h should be supported with high performance. Connections shall be maintained at speeds 120–350 km/h (or even up to 500 km/h depending on the frequency band).
- Coverage: throughput, spectrum efficiency, and mobility targets should be met for 5 km cells and with a slight degradation for 30 km cells. Cells ranging up to 100 km should not be precluded.
- Enhanced multimedia broadcast multicast service (E-MBMS).
- Spectrum flexibility: E-UTRA shall operate in spectrum allocations of different sizes including 1.25 MHz, 1.6 MHz, 2.5 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz in both uplink and downlink.

- Architecture and migration: packet-based single E-UTRAN architecture with provision to support systems supporting real-time and conversational class traffic and support for an end-to-end QoS.
- Radio Resource Management: enhanced support for end-to-end QoS, efficient support for transmission of higher layers, and support of load sharing and policy management across different radio access technologies.

The wide set of options initially identified by the early LTE work was narrowed down in December 2005 to a working assumption that the downlink would use Orthogonal Frequency Division Multiplex (OFDM) and the uplink would use Single Carrier Frequency Division Multiple Access (SC-FDMA). Supported data modulation schemes are QPSK, 16QAM, and 64QAM. The use of Multiple Input Multiple Output (MIMO) technology with up to four antennas at the mobile side and four antennas at the base station was agreed. Re-using the expertise from the UTRAN, they agreed to the same channel coding type as UTRAN (turbo codes), and to a transmission time interval (TTI) of 1 msec to reduce signaling overhead and to improve efficiency [16,17].

The study item phase ended in September 2006 and the LTE specification is due to be published in 2008.

1.5.4 Summary and Comparison of Mobile WiMAX, LTE and UMB

In summary, the upcoming systems beyond 3G overviewed in the previous sections have the following features in common:

- Up to 20 MHz transmission bandwidth.
- Multi-carrier air interface for robustness against frequency-selective fading and for increased spectral efficiency: OFDM/OFDMA and its variant forms are the basic modulation and multiple access schemes.
- Advanced multi-antenna techniques: various MIMO techniques are integrated to the system to increase spectral efficiency and to make the link more reliable.
- Fast time-frequency resource scheduling.
- Flat all-IP network architecture: reduced network overhead by eliminating network layers.
- Multicast and broadcast multimedia service.

Table 1.3 compares the air interfaces of the three beyond-3G systems.

P1: OTA/XYZ P2: ABC
c01 JWBK249/Myung August 27, 2008 19:29 Printer Name: Yet to Come

Table 1.3 Summary and comparison of Mobile WiMAX, LTE and UMB

	Mobile WiMAX	3GPP LTE	3GPP2 UMB
Channel bandwidth	5, 7, 8.75, and 10 MHz	1.4, 3, 5, 10, 15, and 20 MHz	1.25, 2.5, 5, 10, and 20 MHz
DL multiplex	OFDM	OFDM	OFDM
UL multiple access	OFDMA	SC-FDMA	OFDMA and CDMA
Duplexing	TDD	FDD and TDD	FDD and TDD
Subcarrier mapping	Localized and distributed	Localized	Localized and distributed
Subcarrier hopping	Yes	Yes	Yes
Data modulation	QPSK, 16-QAM, and 64-QAM	QPSK, 16-QAM, and 64-QAM	QPSK, 8-PSK, 16-QAM, and 64-QAM
Subcarrier spacing	10.94 kHz	15 kHz	9.6 kHz
FFT size (5 MHz bandwidth)	512	512	512
Channel coding	Convolutional coding and convolutional turbo coding: block turbo coding and LDPC coding optional	Convolutional coding and turbo coding	Convolutional coding, turbo coding, and LDPC coding
MIMO	Beamforming, space-time coding, and spatial multiplexing	Multi-layer precoded spatial multiplexing, space-time/ frequency block coding, switched transmit diversity, and cyclic delay diversity	Multi-layer precoded spatial multiplexing, space-time transmit diversity, spatial division multiple access, and beamforming

1.6 Figures of Merit

Standards organizations, in principle, provide a venue for interested parties to establish the technologies that provide the best tradeoff among a variety of performance objectives. In practice, the aim for excellence is modulated by the need for industry participants to advance the interests of

P1: OTA/XYZ P2: ABC
c01 JWBK249/Myung August 27, 2008 19:29 Printer Name: Yet to Come

their employers. In balancing these conflicting interests, the organizations measure possible solutions with respect to several figures of merit. The figures of merit most relevant to the systems covered in this book are spectral efficiency, throughput, delay, and power consumption in mobile portable devices.

SC-FDMA, which utilizes single carrier modulation, DFT-precoded orthogonal frequency multiplexing, and frequency domain equalization, is a technique that has similar performance and essentially the same overall complexity as OFDMA. One prominent advantage over OFDMA is that the SC-FDMA signal has better peak power characteristics because of its inherent single carrier structure. SC-FDMA has drawn great attention as an attractive alternative to OFDMA, especially in the uplink communications where better peak power characteristics greatly benefit the mobile terminal in terms of transmit power efficiency and manufacturing cost. SC-FDMA has been adopted for the uplink multiple access scheme in 3GPP LTE.

A major purpose of this book is to show how the details of an SC-FDMA transmission scheme influence the tradeoffs among these figures of merit.

1.7 Frequency Division Technology in Broadband Wireless Systems

Frequency division was a mature radio technology, and therefore the earliest cellular systems used it to separate different analog speech transmissions: frequency division multiplexing in the forward (downlink) direction and frequency division multiple access in the reverse (uplink) direction. Second generation systems use either code division technology or a hybrid of time division and frequency division to convey speech and other signals in digital form. Although the two 3G systems are based on code division technologies, all of the advanced broadband systems are reverting to frequency division. As explained in Chapter 2, frequency division technology is well-suited to transmission through mobile radio channels subject to frequency-selective fading due to multipath propagation. Orthogonal frequency division techniques, which effectively transmit a high-speed data signal as a composite of a large number of low-speed signals, each occupying a narrow frequency band, have been employed in digital audio and digital television broadcasting, wireless metropolitan area networks, and wireless local area networks. The same reasons that make them effective in those environments, also make frequency division techniques attractive for the long term evolution of cellular networks. In establishing standards for LTE, 3GPP recognized that OFDMA places significant implementation burdens on mobile terminals. From the point of view of implementation, SC-FDMA can be viewed as a modification of OFDMA with extended battery life in mobile terminals due to low peak power characteristics.

Chapter 2 describes the propagation characteristics of broadband mobile radio signals that make frequency division techniques attractive for high-speed data transmission. It also provides a summary of the main characteristics of OFDM and OFDMA, the predecessors of SC-FDMA. Finally, before presenting details of SC-FDMA in the remainder of this book, Chapter 2 describes in general terms single carrier high-speed data transmission with frequency domain equalization.

References

[1] International Telecommunication Union, "About Mobile Technology and IMT-2000," http://www.itu.int/osg/spu/imt-2000/technology.html.

[2] Toskala, A., Holma, H., Pajukoski, K., *et al*., "UTRAN Long Term Evolution in 3GPP," *Proc. International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) '06*, Helsinki, Finland, Sep. 2006.

[3] Smith, C. and Collins, D., *3G Wireless Networks*, McGraw Hill, 2002, pp. 201–213.

[4] 3rd Generation Partnership Project, *3GPP TS 23.002 – Technical Specification Group Services and Systems Aspects; Network Architecture (Release 8)*, June 2007, Section 5.1.

[5] Holma, H. and Toskala, A., *WCDMA for UMTS – HSPA Evolution and LTE*, John Wiley & Sons, Ltd, 4th edition, 2007, p. 5.

[6] 3rd Generation Partnership Project, *3GPP TR 21.902 – Technical Specification Group Services and System Aspects; Evolution of 3GPP system; (Release 7)*, June 2007.

[7] Institute of Electrical and Electronics Engineers, *IEEE Std 802.11a – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; High-Speed Physical Layer in the 5 GHz Band*, 1999.

[8] Institute of Electrical and Electronics Engineers, *IEEE Std 802.11g – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 2003.

[9] Balachandran, K., Calin, D., Cheng, F-C., *et al*., "Design and Analysis of an IEEE 802.16e-based OFDMA Communication System," *Bell Labs Tech. Jour.*, vol. **11**, no. 4, Mar. 2007, pp. 53–73.

[10] WiMAX Forum, "Mobile WiMAX - Part I: A Technical Overview and Performance Evaluation," http://www.wimaxforum.org/technology/downloads/Mobile_WiMAX_Part1_Overview_and_Performance.pdf, Aug. 2006.

[11] Das, S., Li, S., Monogioudis, P., *et al*., "EV-DO Revision C: Evolution of the cdma2000 Data Optimized System to Higher Spectral Efficiencies and Enhanced Services," *Bell Labs Tech. Jour.*, vol. **11**, no. 4, Mar. 2007, pp. 5–24.

[12] Institute of Electrical and Electronics Engineers, *IEEE 802.20 Mobile Broadband Wireless Access (MBWA)*, 2008, http://www.ieee802.org/20/.

[13] Laroia, R., Uppala, S., and Li, J., "Designing a Mobile Broadband Wireless Access Network," *IEEE Sig. Proc. Mag.*, vol. **21**, no. 5, Sep. 2004, pp. 20–28.

[14] 3rd Generation Partnership Project, "UTRA-UTRAN Long Term Evolution (LTE) and 3GPP System Architecture Evolution (SAE)," http://www.3gpp.org/Highlights/LTE/LTE.htm.

[15] 3rd Generation Partnership Project, *3GPP TR 25.913 – Technical Specification Group Radio Access Network; Requirements for Evolved UTRA and Evolved UTRAN (Release 7)*, Mar. 2006.

[16] Ekström, H., Furuskär, A., Karlsson, J., *et al*., "Technical Solutions for the 3G Long-Term Evolution," *IEEE Commun. Mag*., vol. **44**, no. 3, Mar. 2006, pp. 38–45.

[17] Bachl, R., Gunreben, P., Das, S., *et al*., "The Long Term Evolution towards a New 3GPP Air Interface Standard," *Bell Labs Tech. Jour.*, vol. **11**, no. 4, Mar. 2007, pp. 25–51.