SDR Market Study, Task 3: Wi-Fi®, WiMAX, and Beyond 3G /4G

Or

Broadband Wireless Access (BWA)

Prepared for
The SDR Forum

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About the Author

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He is current developing a series of Software Defined Radio (SDR) market and technology studies for the SDR Forum. The completed reports to date are listed below. He is author of market research reports entitled <u>Wireless Infrastructure: Technology and Markets</u>, which have been published by Forward Concepts. He served as principal investigator on a DARPA SUO project to develop advanced software radio architectures for military and commercial waveforms. He is co-author of "Communication Mediums for Intelligent Transportation Systems" (TRB/National Academy Press), which is a multi-media/multi-medium communication system design guide.

Completed SDR Forum Market Study Reports:

1. <u>SDR Market Study, Task 1: Market Segmentation and Sizing, 2005</u>
2. <u>SDR Market Study, Task 2: Cellular Terminals and Infrastructure, 2005</u>
3. <u>SDR Market Study, Task 3: Wi-Fi, WiMAX and Beyond 3G / 4G</u>, 2006 (this report)

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1 Executive Summary and Conclusions

Broadband, including wireline and wireless initiatives, appears poised to provide the next significant telecom growth opportunities. Users, in order to competitively participate in society, want seamless access to emerging triple play (voice, data/web, and video) services in all their wireline and wireless subscriptions.

Figure 1-1 presents historical key telecommunication indicators including telephone line subscriptions, cellular subscriptions, Internet users and subscriptions, and broadband subscriptions. The figure illustrates that historical telephone (voice) subscriptions are relatively flat and future growth will focus on cellular and broadband. Broadband includes digital subscriber link (DSL), cable, FTTx (e.g., fiber-to-the-node, -premise, etc.), and broadband wireless access (BWA). Internationally, wireline and wireless operators are indicating intentions to evolve their legacy circuit-switched networks to converged “all IP” multimedia networks. Many already have evolutions in progress.

Review of international broadband data, press reports, industry reports, and industry interviews indicates that BWA is an emerging opportunity with essentially insignificant legacy deployment numbers. Wi-Fi® is the significant exception. In reality, cost-effective technologies are only beginning to emerge to support most BWA opportunities. The BWA opportunity appears as if it will start to emerge in 2006 from insignificant historical penetration, experience interesting growth in the 2006–2010 time frame, and have most significant growth ramps beyond 2010. The BWA segments addressed in this report are Wireless Fidelity (Wi-Fi, or wireless local area network (WLAN)); Worldwide Interoperability for Microwave Access (WiMAX, or wireless metropolitan area network (WMAN)); and Beyond 3G/4G (or wireless wide area network, WWAN).

Table 1-1 presents an overview of BWA market segments including Wi-Fi, WiMAX, and cellular’s Beyond 3G/4G initiatives. The table identifies each segments current status and anticipated segment evolution.

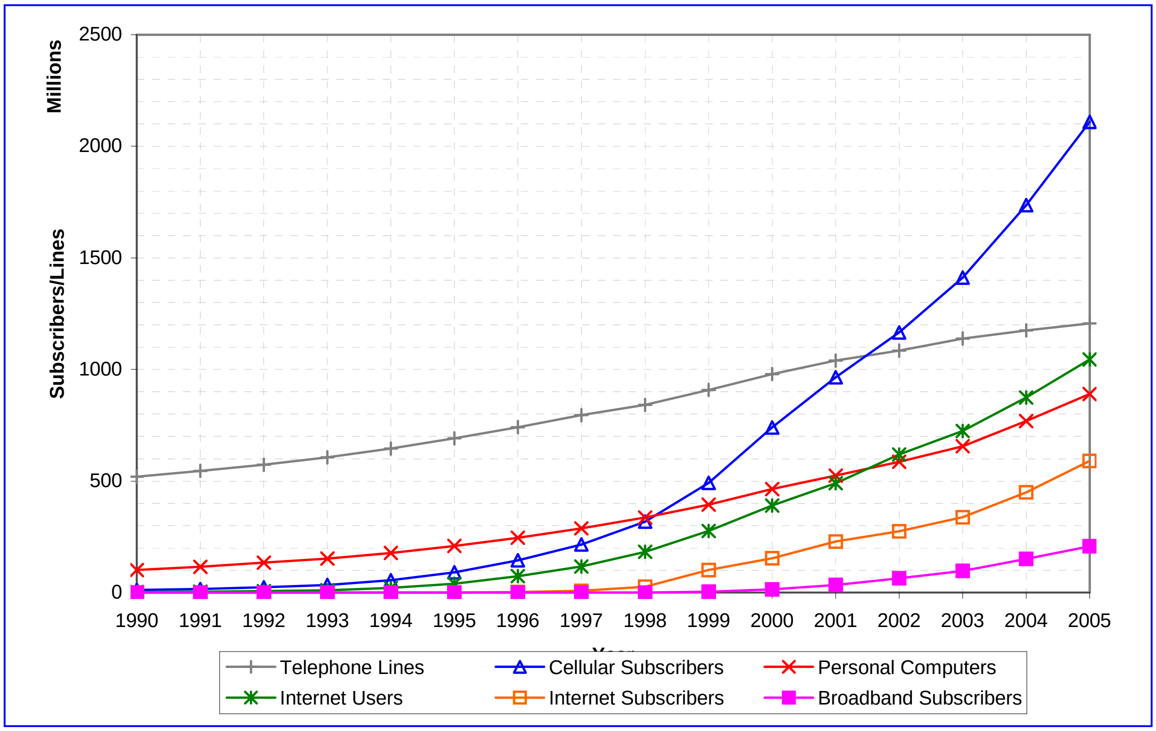

Figure 1-1 Historical Telecommunication Indicators
(*Source:* ITU, DSL Forum, and Author research)

Table 1-1 BWA Market Segments and Status

BWA Segment	Segment Status	Anticipated Segment Evolution
WLAN, 802.11, Wi-Fi	Current notebook computer successes. personal digital assistant (PDA) and cell phone applications are emerging.	Anticipate consumer (digital television (DTV), games, home network), health care, and other emerging successes.
WMAN, 802.16, WiMAX	Some current pre-standard deployments, expect in 2006 some initial WiMAX fixed wireless compliant deployments	Poised to potentially become international BWA standard. Mobile standard compliant deployments anticipated in 2008–2010
Cellular, Beyond 3G/4G, Third Generation Partnership Programs (3GPP and 3GPP2)	High-Speed Downlink Packet Access (HSDPA), High-Speed Uplink Packet Access (HSUPA) in 5 MHz Wideband Code Division Multiple Access (WCDMA) bands in 2004–2005	Orthogonal Frequency Division Multiplexing (OFDM) standards in up to 20 MHz anticipated in 2008-2010 time frame.

(*Source:* Author research)

Executive Summary and Conclusions

Multiradio is a hot industry trend in cellular and BWA segments. It will be important in many segments, perhaps also beneficially impacting military, public safety, telematics, avionics, and other segments. Multiradio refers to inclusion of multiple radio standards (or waveforms) on a single mobile, portable, or infrastructure platform. Multiradio envisions that two or more radio links will operate simultaneously. An example would be a wide area (WWAN) broadband cellular link to a cell phone and a simultaneous WLAN Wi-Fi link to an Internet Protocol television (IPTV) display or a notebook or desktop computer. Global positioning system (GPS) links for location services will typically operate in parallel with other waveforms. Thus, software defined radio (SDR) needs to address both waveform selection (traditional SDR focus) as well as simultaneous operations. Although some variability of opinion exists, commercial industry sources indicate that up to 11 radios might emerge in future cell phones.

Wi-Fi, WiMAX, and Beyond 3G all have initiatives to utilize OFDM in their evolving standards. OFDM appears to be the modulation technology offering superior broadband high signal-to-noise ratio (SNR) performance.

Key emerging market requirements in all BWA include: (1) higher bit rates; (2) quality of service – enabling real-time and multimedia services such as voice over Internet Protocol (VoIP), video over IP (VioIP), multi-player gaming; (3) security; and (4) mobility. Cellular-like mobility in Wi-Fi and WiMAX standards and deployments will require time to evolve competitive functionality.

SDR opportunities appear significant in emerging BWA and ongoing cellular initiatives. SDR should be a key enabler to achieve multiradio, OFDM, and legacy waveform capabilities, as well as to address key emerging market requirements.

This report provides a comprehensive look at BWA which appears to potentially be the next significant commercial wireless growth market opportunity. Subscription forecasts as well as terminal, consumer premise equipment (CPE), and infrastructure data are addressed in this report.

1.1. SDR Forum Study Series Overview

This report is the third of a series of software defined radio market studies commissioned by the SDR Forum. The work to create these SDR market reports is divided into two phases and multiple tasks. The first study, entitled SDR Market Study: Market Segmentation and Sizing provided an overview of the most promising market segments with rough order of magnitude (ROM) estimates and general segment discussions. The second study, entitled SDR Market Study: Cellular Terminals and Infrastucture provides a comprehensive look at the cellular industry. This third study entitled SDR Market Study: Wi-Fi, WiMAX, and Beyond 3G/4G provides a comprehensive look at WLAN and WMAN and anticipated positions within future Fixed Wireless Access (FWA) and 3G evolutions. Follow-on tasks will provide enhanced segmentation and sizing for each segment and more detailed analyses of requirements, drivers, issues, and business models. An overview of the phases and tasks for these studies is presented in Table 1-2.

Table 1-2 SDRF Market Study Phase and Tasks

Phase 1 (completed) Task 1 – Segment and Size – Rough Order of Magnitude (ROM) Task 2 – Cellular – Terminals and Infrastructure
Phase 2 – Follow-on Tasks Task 3 –WLAN, WiMAX, and Beyond 3G (current work) Task 4 – Public Safety (Law Enforcement, Fire, Emergency Management, etc.) Task 5 – Military Task 6 – Telematics Task 7 – Avionics Task n – TBD

For many years, most wireless industry segments have utilized programmable digital signal processors (DSPs) and/or microprocessors for the less throughput intensive algorithms (i.e., essentially baseband functions) deployed in their terminals and infrastructure. Recent advances in semiconductor technologies including 90 nanometers and below digital technologies, radio frequency (RF) technologies, and data acquisition technologies provide imminent market opportunities for software defined radios to extend programmability for more transceiver algorithms and more extensively achieve the long verified software benefits as presented in Table 1-3.

Table 1-3 SDR Benefits/Values Propositions

1. Lower development costs.
2. Provide enhanced mass customization flexibility in development, deployment, and fielded products.
3. Provide critical time-to-market enhancements.
4. Facilitate better reuse of intellectual property.
5. Support multiband and multimode radio frequency (RF) operations
6. Enable the SDR vision of field software-enabled waveform, protocol, and application selection and update.

A fundamental goal of this work is to provide clarity and guidance for the SDR community on "Where are we, where do we need to be, and how do we get there?" based on market opportunities and requirements. However, these are not static conclusions and positions with final end points, but ongoing opportunities that will be enhanced and improved as we progress through these studies, as well as afterwards based on lessons learned and technology advancements.

1.2. Segmentation Overview

Figure 1-2 presents the SDR Market Segmentation developed for these SDR studies. The first report developed first level estimates for total units and total revenues. In subsequent reports, more detailed subsegmentation and market sizing data are developed as appropriate for each segment.

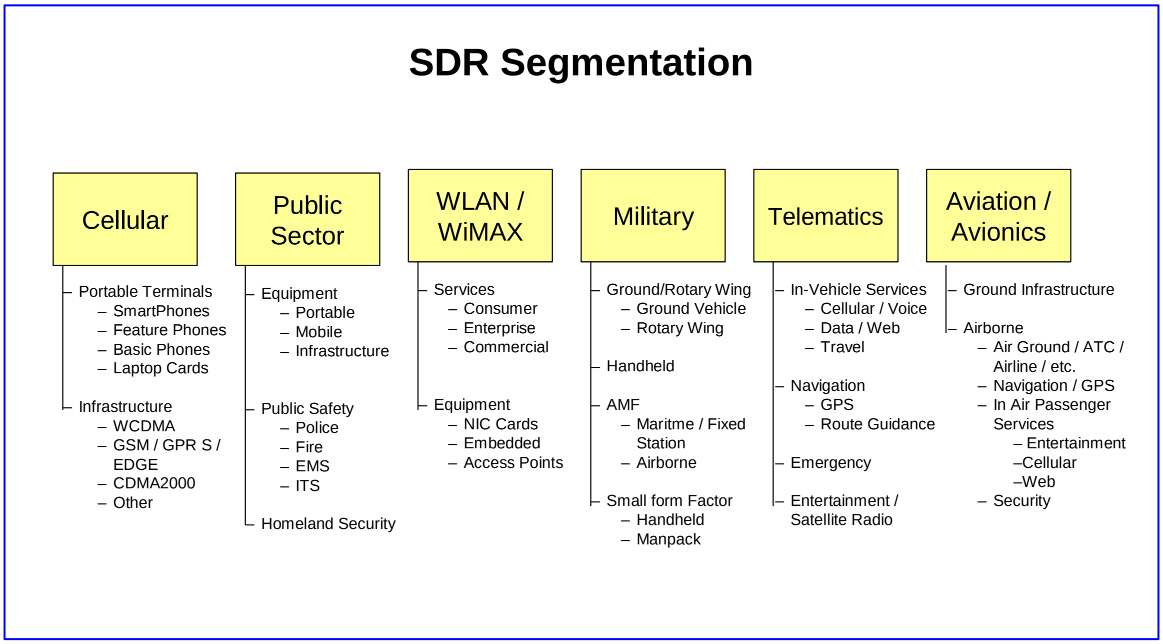

Figure 1-2 SDR Market Segmentation

2 Introduction

This report, “Wi-Fi, WiMAX, and Beyond 3G/4G,” provides a comprehensive look at what could potentially be the next significant commercial wireless growth market segment. It is subtitled “Broadband Wireless Access (BWA)” because industry initiatives are clearly focused on addressing varying flavors of BWA in emerging Wireless Fidelity (Wi-Fi), Worldwide Interoperability for Microwave Access (WiMAX), and cellular networks (Beyond 3G/4G). BWA includes fixed wireless access (FWA) technologies and applications that are intended to provide wireless alternatives for such wired broadband applications as digital subscriber link (DSL) and cable. For conciseness of discussion in this report, we will use the acronym BWA synonymously with “Wi-Fi, WiMAX, and Beyond 3G/4G.” This report is organized as follows:

1. Executive Summary
2. Introduction
3. BWA Trends, Issues, and Drivers
4. BWA Market Forecasts

Figure 2-1 provides an overview of the families of emerging wireless technologies that include wireless personal area networks (PANs), local area networks (LANs), metropolitan area networks (MANs), and wide area networks (WANs).

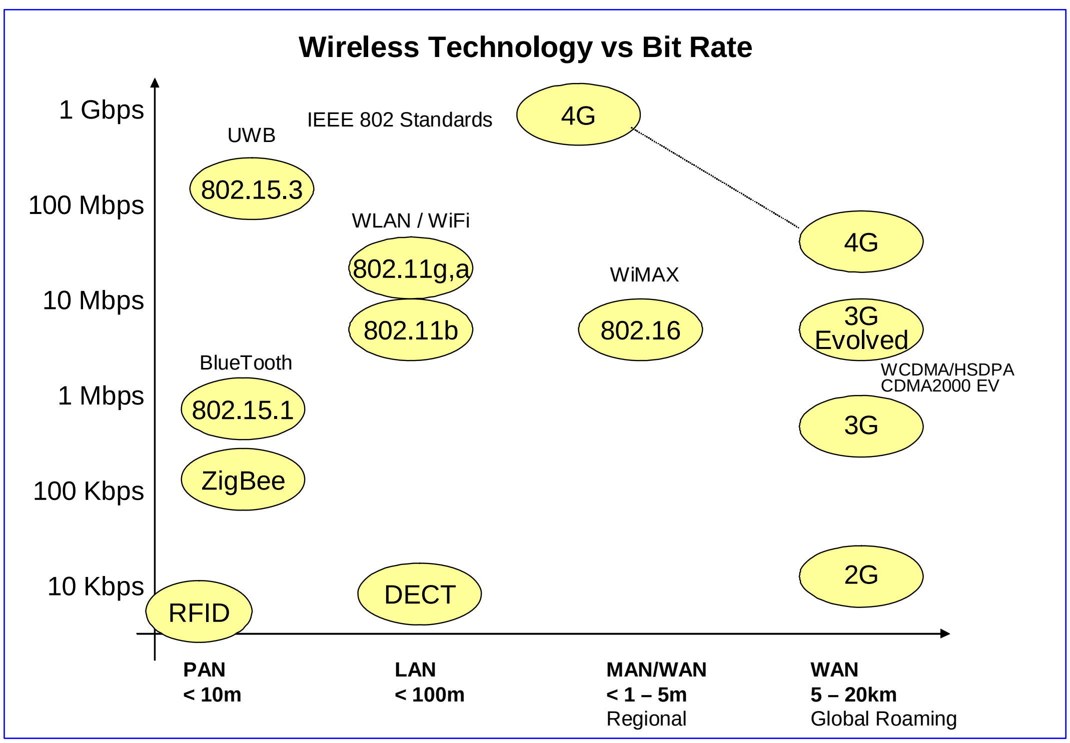

Figure 2-1 PAN, LAN, MAN, WAN Wireless Technologies
(*Note:* DECT = digital enhanced cordless telecommunications; RFID = radio frequency identification; UWB = ultra wideband)

Cellular is generally classified as a wireless WAN (WWAN). With the exception of cellular, most of the technologies and standards depicted in Figure 2-1 are more extensively driven by the semiconductor industry than equipment vendors or service operators. This creates a different market environment and ecosystem for these segments.

Many of the standards in Figure 2-1 are IEEE 802 standards. These include:

- WPAN 802.15
    - Bluetooth 802.15.1
    - Ultra Wideband (UWB) 802.15.3
    - ZigBee 802.15.4
- WLAN (Wi-Fi) 802.11a,b, and g
- WMAN (WiMAX) 802.16 a and e (mobile)

The frequency bands for these technologies are largely in unlicensed spectrum. Even though there is variability in international frequency allocations, most international allocations are similar to US allocations specified in FCC Part 15 rules. These include the industrial, scientific, and medical (ISM) and the Unlicensed National Information Infrastructure (U-NII) bands. WiMAX will have both licensed and unlicensed bands.

Although voice is a significant application, BWA generally focuses on enabling converged high speed data and video, as well as voice networks. Broadband generally refers to links that have bit rates greater than historical dial-up wireline access (e.g., ~ 56 Kbps) and 2G/2.5G wireless access (e.g., typically 30–80 Kbps). As will be discussed, longer-term emerging standards include plans for considerably higher-speed wireless links. Voice over IP is eventually anticipated to replace circuit-switched networks with converged all-IP networks offering triple play services and quality of service (QoS) features for video, voice, and other services requiring such real-time functionality.

As seen in Figure 2-1, most of the PAN and some of WLAN (e.g., many Wi-Fi) applications are often embedded in products (e.g., cell phones, consumer devices, etc.), operate at very low RF power and short range, and have aggressive low cost goals. As achieving these goals and related integration goals constraint alternatives, these embedded technologies appear best addressed with focused solutions with somewhat limited SDR opportunities. The SDR opportunities and benefits for these applications generally include reuse, portability, software, time to market, and so on. The PAN segments will not be further covered in the SDR market studies. The first SDR market report[1] provided overviews of these technologies and standards.

2.1. SDR BWA Challenges

As depicted in Figure 2-2, a significant trend is clearly emerging to include multiple radios (multiradio) in a single device. These multiple radios will have multiple antennas, power

[1] *SDR Forum Market Study: Task 1: Market Segmentation and Sizing*, SDRF-05-A-0003-V0.00, 22 March 2005.

amplifiers (PAs), low noise amplifiers, data acquisition devices, base band circuits, and so forth, which will offer challenges for integration into a single, battery-powered, portable device. Co-channel interference must be managed and minimized. Battery life and power consumption will be a challenge that must be carefully addressed. Many of the radios will often be simultaneously operating on different frequencies and bands. The SDR opportunity will focus on reuse, portability, minimizing co-channel interference, optimizing RF links (e.g., multiple input, multiple output (MIMO); beamforming; multiuser detection (MUD)), antenna sharing, and power reduction. Sharing of platform resources will be essential. Wi-Fi and WiMAX in some applications will operate as an alternative WWAN and in other applications will operate simultaneously as a WLAN or PAN to relay WWAN. Although Figure 2-2 was created by Nokia, the largest cellular handset vendor, similar intentions are being discussed by many key industry stakeholders. It is very reasonable to envision this trend to facilitate many synergistic opportunities for public safety, military, telematics, and other applications.

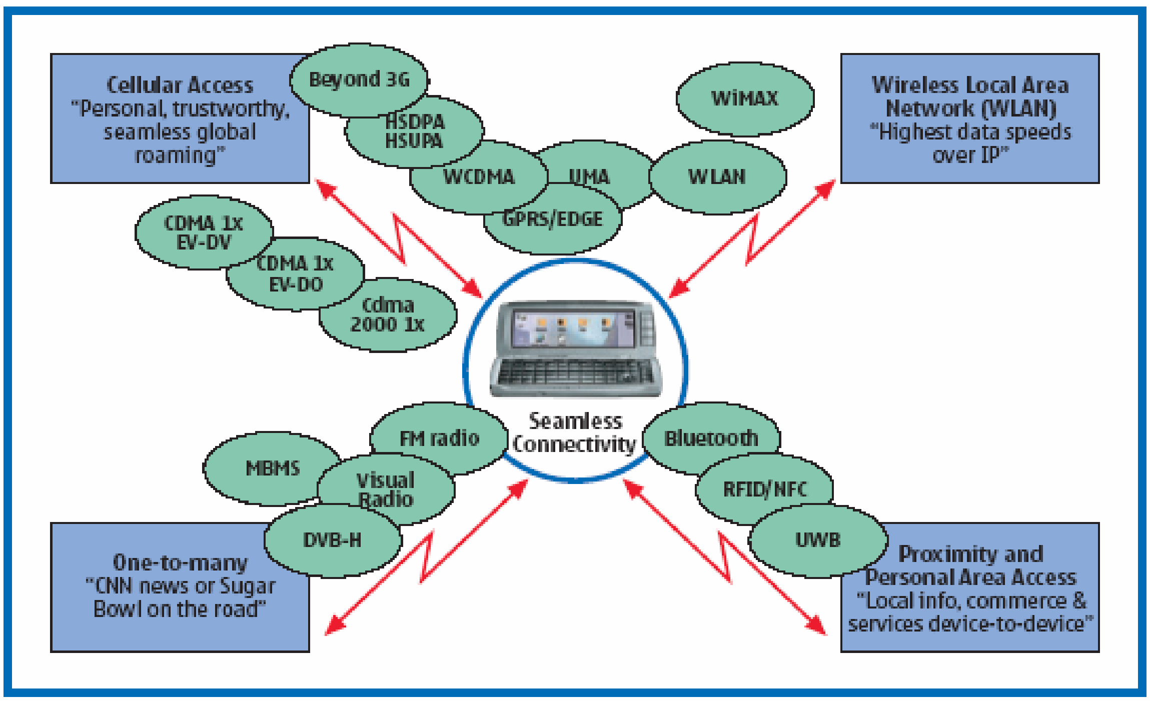

Figure 2-2 "Multiradio – delivering seamless interworking of services to customers"
(*Source:* Nokia, press backgrounder, June 2005)

Another important BWA trend is the inclusion of OFDM modulation in future broadband standards for Wi-Fi, WiMAX, and cellular. The cellular standards for Beyond 3G/4G are being defined in the long-term evolution (LTE) initiatives of 3GPP and similar 3GPP2 initiatives. Most academic and industrial research and development (R&D) experts are concluding that OFDM offers the best performance for broadband applications, particularly in high SNR environments. A key complementary technology for OFDM is MIMO antenna technologies, which provide substantial improvements in both coverage (range) and capacity in equivalent bandwidths.

2.2. SDR BWA Market Opportunity

This report presents many SDR opportunities from the perspective of the Wi-Fi, WiMAX, and Beyond 3G / 4G (BWA) industry addressing drivers and markets. The broadband opportunity, including both the wireline (e.g., DSL, cable, FTTx) and BWA (wireless) industry, appears poised for significant growth. This section summarizes the many key BWR SDR opportunities identified throughout this report.

A recurring question is "What are the SDR market numbers?" A seemingly preferred method of estimating these numbers would be to use the SDR Forum's "SDR Definition: Tiers of Capability and Flexibility" presented in Table 2-1. A significant percentage of cellular as well as BWA industry products appear essentially at Tier 2 for both handset and infrastructure equipment.

Table 2-1 SDR Definition: Tiers of Capability and Flexibility

Tier Name	Description
Tier 0 Hardware Radio (HR)	The radio is implemented using hardware components only and cannot be modified except through physical intervention.
Tier 1 Software Controlled Radio (SCR)	Only the control functions of an SCR are implemented in software – thus only limited functions are changeable using software. Typically this extends to inter-connects, power levels, etc. but not to frequency bands and/or modulation types, etc.
Tier 2 Software Defined Radio (SDR)	SDRs provide software control of a variety of modulation techniques, wide-band or narrow-band operation, communications security functions (such as hopping), and waveform requirements of current and evolving standards over a broad frequency range. The frequency bands covered may still be constrained at the front-end, requiring a switch in the antenna system.
Tier 3 Ideal Software Radio (ISR)	ISRs provide dramatic improvement over an SDR by eliminating the analog amplification or heterodyne mixing prior to digital-analog conversion. Programmability extends to the entire system with analog conversion only at the antenna, speaker, and microphones.
Tier 4 Ultimate Software Radio (USR)	USRs are defined for comparison purposes only. A USR accepts fully programmable traffic and control information and supports a broad range of frequencies, air-interfaces, and applications software. It can switch from one air interface format to another in milliseconds, use GPS to track the user location, store money using smartcard technology, or provide video so that the user can watch a local broadcast station or receive a satellite transmission.

(*Source*: www.sdrforum.org)

However, many of the BWA applications will be for embedded BWA technologies with very aggressive size, integration, power (often battery), and unit cost goals. It is well understood that these goals are most effectively achieved with crafted point solutions, provided the unit volumes are sufficiently large to amortize the high development and design costs of point solutions. Even in these applications, industry input consistently indicates that SDR-centric programmable DSPs or microprocessors are utilized as extensively as possible. Additionally, tailored circuits, required to achieve aggressive size, integration, power, or unit cost goals, are designed as extensively as possible to provide SDR-centric flexibility (programmability) for the addressed functions. Functions typically requiring point solution circuits include FFT (OFDM), correlators (CDMA spreading and dispreading), and decoders (Viterbi and turbo), among others. When these functions are not needed, the circuits are turned off, which is not a significant issue in emerging 65 nm and below CMOS technologies.

Using the Tier 2 definition, a reasonable conclusion is that Tier 2 SDR-centric concepts and technologies are extensively deployed in BWA terminals and infrastructure. Wi-Fi is a technology that often does have very extensive integration, low-power, or low-cost goals. However, and perhaps overly pessimistically, Wi-Fi would be excluded from contributing significantly to the BWA SDR market opportunity. Wi-Fi does still utilize and require many SDR-centric concepts such as reuse, time-to-market, etc. Because many industry sources have indicated intentions for multiradio deployments addressing Wi-Fi, WiMAX, and Beyond 3G waveforms on common platforms, all utilizing OFDM modulation, SDR could be a significant enabler for even Wi-Fi. Therefore, WiMAX and Beyond 3G are expected to extensively use SDR-centric concepts and technologies. Table 2-2 presents the forecast of the BWA SDR market opportunity, including a summary of the total opportunity with and without Wi-Fi.

Table 2-2 BWA SDR Market Opportunity

$ B	2000	2001	2002	2003	2004	2005F	2006F	2007F	2008F	2009F	2010F
Wi-Fi	$0.8	$1.3	$2.6	$4.1	$5.4	$6.8	$8.4	$10.2	$12.4	$15.2	$18.7
BWA	$0.1	$0.1	$0.2	$0.3	$0.5	$0.6	$2.2	$3.0	$4.8	$5.7	$7.4
Beyond 3G/4G	N/A	N/A	$1.6	$3.9	$11.8	$19.1	$23.8	$25.5	$28.7	$33.7	$39.4
Total SDR Opportunity without Wi-Fi	$0.1	$0.1	$1.8	$4.2	$12.3	$19.7	$26.0	$28.5	$33.5	$39.4	$46.8
Total SDR Opportunity with Wi-Fi	$0.9	$1.4	$4.4	$8.3	$17.7	$26.5	$34.4	$38.7	$45.9	$54.6	$65.5

Note: F = forecast; N/A = not applicable
(*Source:* Summarized from data in this report in Table 4-2, Table 4-4, and Table 4-5)

Interestingly, a rigorous application of the SDR Forum's "Tier 3, Ideal Software Defined Radio" criteria would make the available current and foreseeable numbers for BWA's SDR opportunities zero. This assumption does not seem reasonable, as virtually all stakeholders indicate that they have many of the SDR-centric goals articulated in Table 2-3. The key conclusion is that the industry employs SDR concepts to the maximum extent possible with available technologies to achieve the SDR platform benefits that are presented in the table.

Table 2-3 SDR Platform Benefits

- Incur lower development costs
- Provide enhanced mass customization flexibility in development, deployment, and fielded products
- Provide critical time-to-market enhancements
- Facilitate better reuse of intellectual property (IP)
- Support multiband and multimode RF operations
- Enable the SDR vision of field software-enabled waveform, protocol, and application selection and update.

As discussed in the Task 1 report,[2] the DSP/digital technologies at emerging 90 nm and below CMOS technology nodes appear capable of supporting highly flexible SDR functionality and still achieve the required market goals for power, cost, multimode, targeted multiband, and so on. However, RF and data acquisition technologies are progressing at a slower pace than the digital technologies, and do not appear likely to achieve the often-articulated utopian goal of highly flexible 2 MHz to 2+ GHz multiband and multimode functionality over the next 5 to perhaps 10 years. Nevertheless, these technologies are progressing and constantly improving, and more flexible multiband solutions are emerging. Thus, careful engineering, business, market segment, and cost trade-offs will be the norm for the foreseeable future to insert an expanding suite of SDR capabilities and technologies.

Tools are also an important part of the SDR value proposition in the BWA market to facilitate reuse of intellectual property (including software, hardware/circuits/designs, manufacturing processes, etc.) and reduce development cost.

[2] *SDR Forum Market Study: Task 1: Market Segmentation and Sizing*, SDRF-05-A-0003-V0.00, 22 March 2005.

3 BWA Technology Overview, Trends, Issues, and Drivers

The drivers for broadband wireless access are strongly motivated by the general telecommunication industry trend of saturation of legacy wireline opportunities, and to a lesser extent even cellular voice services.[3] As illustrated in Figure 3-1, telephone line subscriptions are experiencing slow year-over-year growth, especially in advanced economies (e.g., US, Western Europe, Japan, Korea, etc.), with most current growth largely coming in emerging economies (e.g., China, India, Central America/Latin America (CALA), Africa, etc.) that have historically lagged in penetration. As Figure 3-1 indicates, telecommunication growth opportunities have shifted to cellular and Internet services. Within Internet services, the recent trend has been the rapid uptake of broadband services in both wireline and wireless that includes DSL, cable (Internet services), FTTx, FWA, and 3G and Beyond 3G/4G data services.

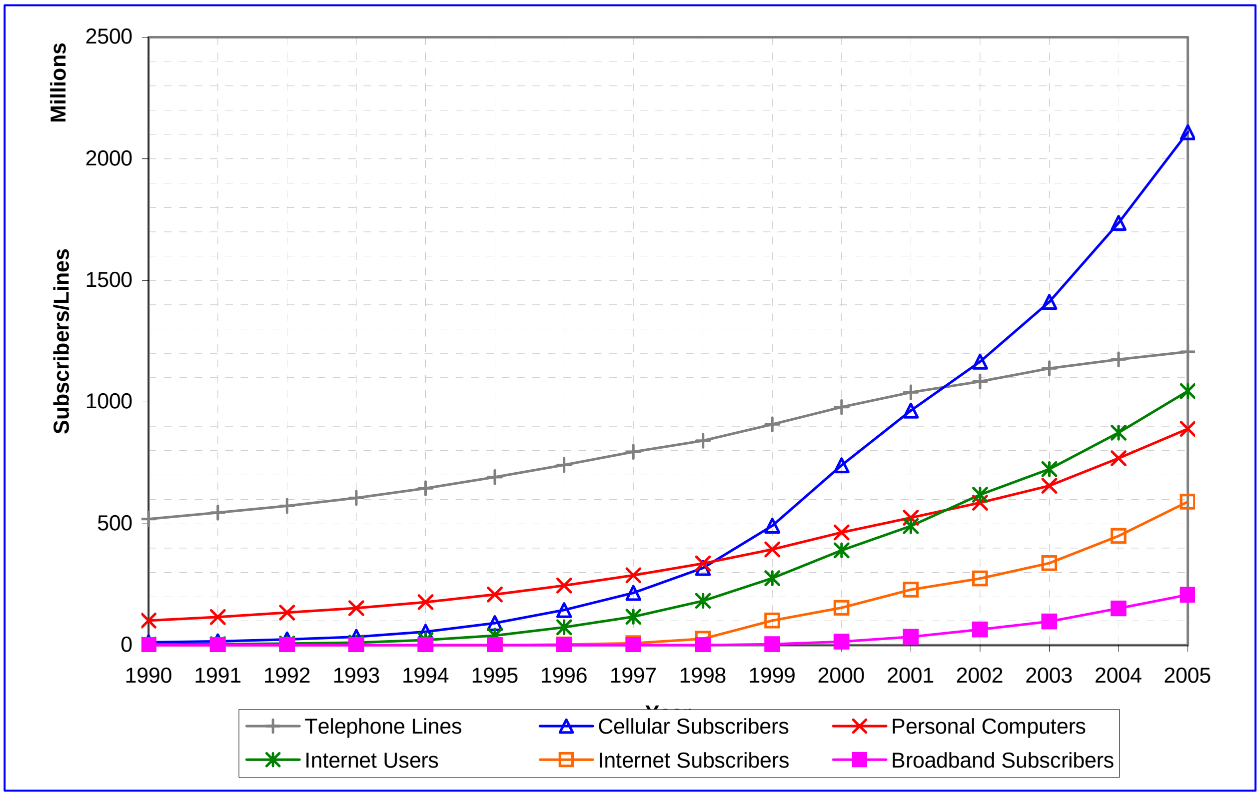

Figure 3-1 Historical Telecommunication Indicators
(*Source:* ITU, DSL Forum, and author research)

Figure 3-1 also illustrates several interesting market characteristics. First, most wireline services typically serve homes or businesses. Typically, Internet service users are approximately twice the number of service subscribers (or subscriptions), as indicated by

[3] *SDR Forum Market Study: Task 2: The Cellular Industry: Terminals and Infrastructure*, SDRF-05-A-0005-V0.00, September 2005.

the plots of Internet users and Internet subscribers. Telephone users typically will represent approximately twice the number of telephone subscribers. Conversely, cellular typically has approximately one user per subscription (or cell phone). Note that early Internet access was predominantly via dial-up telephone lines, which led to significant second line installations to permit non-interfering voice (e.g., no busy signals) and Internet usage. DSL, cable, and FTTx Internet service penetration has grown, as indicated in Figure 3-1, which has led more recently to cancellation of second voice telephone lines due to the availability of "always on" Internet access via dedicated access channels. Remaining dial-up subscribers are a key market opportunity for emerging broadband services, including wireless alternatives. In addition, the Internet, Web, and e-mail increasingly are preferred alternatives to faxes for many users, further decreasing demand for second-line telephone services. Concurrently, fixed (i.e., wireline) VoIP services provided by such operators as Vonage, AT&T, and Skype offer lower-cost telephone service, often with minimal or unlimited long distance (national footprint) at very competitive prices (e.g., Vonage is approximately US$25 per month with extensive features included). These VoIP services require a broadband access connection to the Internet (e.g., DSL, cable modem, FTTx).

Broad industry goals are to evolve to converged "triple play" (voice, video, and data) services offered by operators on converged common network platforms. As an illustrative example, a subscription in the Dallas, Texas, area in the United States currently costs a total of approximately US$85 per month.[4] Recently, a regional Bell operating company (RBOC) operator, SBC, deployed a fiber-to-the-premise (FTTP) service in some areas of Dallas. Although details on exact longer-term services, features, and schedule information are still pending, the provider's intention is to offer converged services on their FTTx (i.e., FTTP, FTTC (curb), etc.) networks that include video (IPTV), voice, and high-speed data, whereas the current subscription includes only telephony and broadband DSL services. The goal is to replace declining circuit-switched voice subscriptions and revenues with the enhanced triple play services and revenues. Eventually, all services will be Internet Protocol (IP)-based technologies and services. Verizon has indicated a similar strategy in its US coverage areas. The substantial cable modem subscriber count, which has historically exceeded DSL subscriber count, has created a competitive triple play environment in the United States.

Most reports indicate that the United States is lagging broadband penetration in Europe and Asia and that the most aggressive international broadband initiatives are occurring elsewhere, such as in Korea and Japan. NTT (Japan) states on its website that its broadband strategy is:

> NTT promotes R&D efforts to build a safe and secure full-IP next-generation network as a primary task according to the 'NTT Group's Medium-Term Management Strategy' and actively engages in the development of cutting-edge basic technologies with a forward-looking approach 10 years out. In response to the paradigm shift of communication

[4] Telephone services cost ~US$30/month per line with features; DSL service cost ~US$15/month on a special one year offer, typically ~US$30-50/month; and satellite TV service cost ~US$40/month.

> tools from telephone to IP, NTT reinforces R&D toward the realization of a next-generation IP network that maintains properties of both the Internet and telephone networks as a shared infrastructure with high quality, security and reliability by integrating long-accumulated telephone networking technology and leading-edge IP technology.

Also indicated is an intention to provide broadband access via fiber, wire, and wireless. Japan and Korea have been pioneering leaders in 3G cellular deployments and services, and they appear poised to lead the convergence of broadband wireline and wireless deployments and services. Triple play on converged wireline and wireless networks is often described by the term "grand slam," and many international initiatives are described as "quadruple play," referring to converged fixed, mobile, TV, and broadband services by an operator on common networks. This should create a highly competitive and creative growth international environment for years to come.

Table 3-1 presents an overview of international broadband rankings at year-end 2004 and mid-year 2005.

Table 3-1 Broadband Subscriber Rankings

2004 Rank Penetration	Country	Population *	4Q 2004 % * Penetration	4Q 2004 * Subscribers	2Q 2005 ** Subscribers	2Q 2005 Rank** Subscribers
1	Korea (Rep. of)	48,082,160	24.9%	11,972,458	12,260,915	4
2	Hong Kong	7,115,000	20.9%	1,487,035		
3	The Netherlands	16,277,000	19.4%	3,157,738	3,566,566	12
4	Denmark	5,375,000	19.3%	1,037,375		
5	Canada	31,743,000	17.6%	5,586,768	6,086,959	8
6	Switzerland	7,415,000	17.0%	1,260,550		
7	Taiwan, China	22,762,000	16.3%	3,710,206	4,025,000	11
8	Belgium	10,339,000	16.0%	1,654,240		
9	Iceland	293,000	15.5%	45,415		
10	Sweden	9,011,392	15.1%	1,360,720		
11	Norway	4,552,000	15.0%	682,800		
12	Israel	6,862,000	14.3%	981,266		
13	Japan	127,799,000	14.1%	18,019,659	20,650,500	3
14	Finland	5,216,000	12.8%	667,648		
15	Singapore	4,315,000	11.6%	500,540		
16	United States	297,043,008	11.4%	33,862,903	38,200,981	1
17	France	60,434,000	11.2%	6,768,608	8,323,000	5
18	United Kingdom	59,428,000	10.3%	6,121,084	7,961,938	6
19	Austria	8,206,500	10.1%	828,857		
20	Portugal	10,072,000	8.5%	856,120		
na	China	1,313,309,056			30,843,000	2
na	India	1,081,229,056				
na	Brazil	180,655,008			2,562,157	13
na	Australia	19,913,000			2,117,300	14
na	Germany	82,526,000			7,878,497	7
na	Italy	58,000,000			5,460,555	9
na	Spain	41,128,000			4,094,017	10

(*Sources:* * ITU Broadband top 20 by penetration supplemented by author research and calculations, and ** DSL Forum Press Releases

The 2004 top 20 penetration ranking is based on data from the ITU, while the 2nd Quarter 2005 ranking is based on more recent data available from the DSL Forum of the top 14 countries by broadband subscribers. Interestingly, India does not currently make either list, but is likely to appear in the future due to its large population and improving GDP. The United States and China, while not obtaining high rankings in penetration, achieve the number 1 and 2 ranking, respectively, based on number of broadband subscribers as a result of larger populations than other counties.

BWA has essentially evolved into three market segments (Wi-Fi, WiMAX, and Beyond 3G/4G), as depicted in Figure 3-2. The first, Wi-Fi, had its origin as a WLAN link with a key benefit to provide mobility and reduce costs for installation and moves for wireline 802 (Ethernet) deployments. The second, WiMAX ,targets wireless metropolitan area network (WMAN) services including fixed wireless access (FWA), to supplement and perhaps compete with wireline broadband DSL, cable modem, and FTTx, mobile broadband services, and eventually VoIP services. WiMAX provides FWA, mobility, and microwave backhaul services and technologies. The third is the evolution of the currently deployed wireless wide area networks (WWAN) 3G cellular services to the higher-speed Beyond 3G / 4G services that are being defined in the LTE activities of 3GPP.

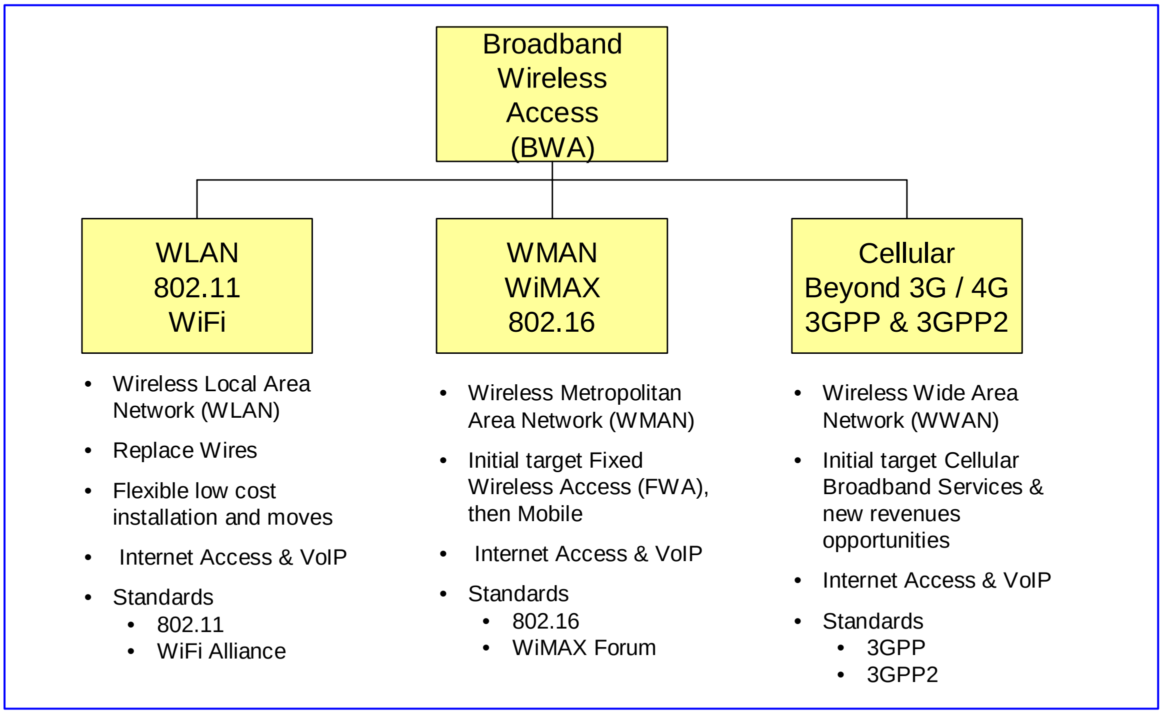

Figure 3-2 Broadband Wireless Access Market

In many ways these segments appear to be noncompeting segments with distinct focuses: Wi-Fi focuses on WLAN, WiMAX focuses on WMAN, and Beyond 3G focuses on WWAN. Yet clear trends indicate that each will, over time, compete for subscribers with overlapping services and products not at the core of its targeted application space. In many ways, these three segments appear to be converging toward broader common market requirements, with each using similar OFDM modulation technologies that will eventually experience convergence. Each segment over time will expand its targeted market base, creating more competitive yet growing market opportunities and economies of scale for all.

Wi-Fi, WiMAX, and Beyond 3G / 4G appear on track to offer extensive SDR opportunities. Each segment is targeting OFDM as the modulation technology. However, the OFDM variations and frequency bands are diverse. Additionally, Wi-Fi, WiMAX, and Beyond 3G / 4G each have varying legacy waveforms that devices and infrastructure will have to support. Both multiband and multimode requirements are present. An increasing variety of voice, data, and video applications collectively create compelling requirements and opportunities for SDR technologies in all three segments.

3.1. *Wireless Fidelity (Wi-Fi) / 802.11*

The Wi-Fi, or WLAN, market has experienced significant success in recent years, achieving the status of the largest BWA segment. WLAN is intended to provide untethered nomadic wireless access to the Internet, thus allowing consumers to connect easily to their home networks without the hassle and expense of installing or connecting wires. The enterprise market has also been a strong adopter, with goals for more flexible access and reducing installation and moving costs. Not as successful has been commercial "hot spots," which have experienced problems developing profitable business cases to date. This report uses the terms Wi-Fi, WLAN, and 802.11 synonymously because the combination is the clear market intention.

3.1.1 WLAN Standards

The standards for WLAN are under the responsibility of the Institute of Electrical and Electronics Engineers (IEEE) 802 standards organizations. Historical and planned IEEE 802.11 WLAN standards as adapted from the IEEE website are presented in Table 3-2. The IEEE 802.11 standards generally define physical and link layer standards. However, market experience has clearly demonstrated that these standards are not sufficient and that additional standards are desirable to provide for interoperability, testing, and certification of products. Additionally, marketing and technology insertion activities have proved very important for successes of standards.

The IEEE 802.11 standards are a family of specifications for WLANs developed by working groups within the IEEE. The standards essentially use the wireline Ethernet protocols and a medium access control (MAC) based on carrier sense multiple access with collision avoidance (CSMA/CA) to share the Time Division Duplex (TDD)-allocated RF links. An overview of the key air interface standards is presented in Table 3-3.

Table 3-2 IEEE Historical and Planned IEEE 802.11 WLAN Standards

IEEE Standard	Project Authorization Request (PAR) Description	IEEE Publish	ANSI* Approved
IEEE P802.11w	Protected Management Frames	Apr-08	
IEEE P802.11v	Wireless Network Management	Oct-08	
IEEE P802.11u	InterWorking with External Networks	Jan-08	
IEEE P802.11.2	Wireless Performance	Jan-08	
IEEE P802.11s	ESS Mesh Networking	Jul-08	
IEEE P802.11r	Fast Roaming	Apr-07	
IEEE P802.11p	Wireless Access for the Vehicular Environment	Jul-07	
IEEE P802.11n	High Throughput	Apr-07	
IEEE P802.11-REVma	802.11 Standard Maintenance	Oct-06	
IEEE P802.11k	Radio Resource Measurement	Jan-07	
IEEE P802.11j - 2004	4.9–5 GHz Operation in Japan	10/29/04	2/2/05
IEEE P802.11i - 2004	MAC Security Enhancements	7/24/04	2/14/05
IEEE P802.11h - 2003	Spectrum and Transmit Power Management Extensions in the 5 GHz Band in Europe	10/14/03	12/29/03
IEEE P802.11g - 2003	Further Higher Data Rate Extension in the 2.4 GHz Band	6/27/03	12/20/03
IEEE P802.11F - 2003 [IEEE P802.11.1]	Inter-Access Point Protocol Across Distribution Systems Supporting IEEE 802.11 Operation	7/14/03	
IEEE P802.11e - 2005	MAC Enhancements (QoS)	11/11/05	
IEEE P802.11d - 2001	Operation in Additional Regulatory Domains	7/1/05	
IEEE P802.11c - 1998 [Part of ISO/IEC 10038 (IEEE 802.1D-2004) Standard]	MAC Bridges – Supplement for Support by IEEE 802.11	10/1/98	
IEEE P802.11b -Cor1 - 2001	Corrigenda to IEEE 802.11b-1999	11/1/05	1/30/02
IEEE P802.11b- 1999	Higher-Speed Physical Layer (PHY) Extension in the 2.4 GHz Band	10/1/99	2/11/00
IEEE P802.11a - 1999	Higher-Speed PHY Extension in the 5 GHz Band	10/1/99	2/11/00
ISO/IEC 8802.11: 1999 [IEEE Std 802.11-1999 (R2003)]	Part II: Wireless LAN MAC and PHY Specifications	4/1/99	9/30/05
IEEE P802.11 - 1999 [Superseded by ISO/IEC 8802.11: 1999 on 09/30/05]	Part II: Wireless LAN MAC and PHY Specifications	4/1/99	7/15/99
IEEE P802.11 – 1997 [Superseded by ISO/IEC 8802.11: 1999 on 07/15/99]	IEEE Standard for Wireless LAN MAC and PHY Specifications	7/1/97	

(*Source*: Adapted from IEEE web site: http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm,)
*ANSI is the American National Standards Institute.

Table 3-3 Key IEEE 802.11 WLAN Air Interface Standards

Standard	Frequency	Bit Rate	Modulation	Channel Spacing	MAC
802.11b	2.4 MHz Unlicensed Part 15, ISM (same as Bluetooth)	1, 2, 5.5, and 11 Mbps	DSSS, BPSK, CCK	5 MHz 25 MHz (no interference)	Distributed, adapted from 802 LAN/WAN Standards
802.11g	2.4 MHz Unlicensed Part 15, ISM (same as Bluetooth)	Same as 802.11b plus Up to 54 Mbps	Same as 802.11b plus OFDM	Same as 802.11b	Distributed, adapted from 802 LAN/WAN Standards
802.11a	5 GHz Part 15 ISM, NII	6, 9, 12, 18, 27, 36, 54 Mbps	OFDM, (64 FFT), BPSK, QPSK, 16/64 QAM	20 MHz	Distributed, adapted from 802 LAN/WAN Standards
802.11n	Both 802.11a,b, and g bands (see above)	To over 600 Mbps with MIMO	OFDM, (64 FFT), BPSK, QPSK, 16/64 QAM	20 & 40 MHz	Adds lower latency MAC features

(*Source:* Author research)
Legend: BPSK: binary phase shift keying; CCK: complementary code keying; FFT: Fast Fourier Transform; MAC: medium access control; MIMO: multiple input, multiple output (antenna); OFDM: Orthogonal Frequency Division Multiplexing; PHY: physical layer (wireless: air interface); QAM: quadrature amplitude (and phase) modulation; QPSK: quadrature phase shift keying

The original IEEE 802.11 WLAN standard provided for 1 or 2 Mbps transmission in the 2.4 GHz band using either frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS). The modulation format of 802.11 was phase shift keying (PSK). This standard did not achieve significant deployments or commercial successes although it is generally a fall back in very successful later standards.

The standard that initiated spectacular success was the IEEE 802.11b, which is backward compatible with 802.11. 802.11b is often considered to be Wi-Fi, although Wi-Fi more correctly includes 802.11a, g and other 822.11 standards. The band of operation is the same 2.4 GHz ISM band. The modulation method for 802.11b is complementary code keying (CCK), which provides higher data rates and better immunity to multipath. 802.11b added data rates of 5.5 Mbps and 11 Mbps. It was the standard that was the focus of initial successful activities of the Wi-Fi Alliance, a nonprofit international association formed in 1999 to certify interoperability of IEEE 802.11 products (see Section 3.1.2).

The IEEE 802.11a provides standards for the 5 GHz ISM bands and provides data rates up to 54 Mbps. However, due to link budget constraints, fallback to lower data rates of 6 Mbps, 12 Mbps, or 24 Mbps are frequently used, especially at longer distances. 802.11a was the original 802.11 standard to use orthogonal frequency division multiplexing (OFDM) modulation. The 802.11a standard has not achieved the success of the 802.11b and g standards that operate in the 2.4 GHZ band. The Wi-Fi Alliance also supports 802.11a.

The IEEE 802.11g adds an OFDM modulation format similar to 802.11a to the 802.11b standard family in the 2.4 GHz band. This standard provides bit rates over shorter distances at peak rates up to 54 Mbps and fallback to the 11 Mbps or lower bit rates of the 802.11b standard when link conditions dictate. In reality, 802.11g has essentially replaced 802.11b, except for a very few residual, generally low cost 80.211b products.

The BWA community consistently identifies several emerging requirements for successful evolution: (1) security, (2) quality of service for real-time services such as voice over IP and video over IP, (3) mobility, and (4) higher bit rate links. The following paragraphs discuss emerging Wi-Fi standards that address these requirements.

The IEEE standards community adopted the 802.11i security standard in 2004. Security in the early 802.11 standards employed the Wired Equivalent Privacy (WEP) Protocol, which was easily cracked and was inadequate. This particularly slowed deployment in the enterprise market. The Wi-Fi Alliance added Wi-Fi Protected Access (WPA), which addresses the problems in WEP. WPA is a subset of 802.11i that facilitates backward compatibility with most legacy products and deployments. Two key elements[5] of 802.11i are Temporal Key Integrity Protocol (TKIP) and Counter-Mode/CBC-MAC Protocol (CCMP). TKIP is intended to improve security on legacy WEP products by using a mixing function to create a per-frame key to avoid easy passive observation and interception of data. CCMP is a security protocol that provides both packet authentication and encryption.

WPA2 is the Wi-Fi Alliance’s designation for 802.11i certification testing. The Wi-Fi Alliance[6] claims that WPA2 implements all IEEE 802.11i mandatory features. When appropriately configured, WPA2 is capable of supporting government-grade security by utilizing the National Institute of Standards and Technology (NIST) FIPS 140-2–compliant advanced encryption standard (AES) algorithm. The 802.11i standard uses 802.1x for authentication and dynamic key management.

The IEEE standards community adopted the *802.11e* quality of service standard in 2005. The standard adds QoS features and multimedia support to the existing standards and maintains backward compatibility. Real-time voice, audio, and video services, over all-IP networks are considered key services for future growth. 802.11e provides improved QoS[7] via two new MAC access functions and a resource reservation system. Enhanced distributed channel access (EDCA) is a new contention-based MAC access function utilizing up to four priority access queues. Legacy standards provide for only a single queue. Hybrid Coordination Function (HCF) controlled-channel access (HCCA) is a new centrally controlled poll-and-response channel access that offers strict control of mobile station channel access times and durations. Finally, a new resource reservation and admission control function allocates or refuses real-time resource requests based on network resource availability.

[5] “IEEE 802.11i and wireless security”, by David Halasz, Cisco, Embedded.com, Aug 25, 2004
[6] Wi-Fi Alliance Web site, WPA2 Questions and Answers
[7] “WLAN, a Converged data and Voice Mobility Solution for Enterprise”, Alcatel White Paper, 2004

If Wi-Fi/802.11 WLANs are to offer services comparable to the very successful cellular services, then Wi-Fi should support comparable mobility capabilities. As listed in Table 3-2, an IEEE 802.11r standard is planned that will provide for mobility. The Internet Engineering Task Force's (IETF) Mobile IP recommendations[8] provide mobility targeted for data applications on best effort data networks and allow break-before-make mobility that is too slow and inadequate for high speed real time voice, video, and audio applications. 802.11r was created in 2004 with a future IEEE publish date in April 2007 and targets make-before-break functionality sufficient for real time applications and competitive mobility.

The most anticipated and controversial 802.11 WLAN activities are the high-speed *802.11n* standard addendums. The goal is to increase the supported bit rates (and capacity) to more than 100 Mbps, and in some applications to more than 600 Mbps. A key component of achieving 802.11n's high bit rate goals is the use of MIMO antenna technologies. Table 3-4 presents an overview of 802.11 standards and anticipated peak data rates indicating the potential benefits of MIMO.

Table 3-4 802.11 Peak data rates showing the impact of MIMO

Year	IEEE 802.11 Standard	MIMO Technology	Peak Data Rate
1998	802.11b	None	11 Mbps
2002	802.11g	None	54 Mbps
2004	Pre 802.11i	Airgo Pre-Standard	108 Mbps
2006	802.11n	2x2 MIMO	140 Mbps
2007	802.11n	4x4 MIMO	600 Mbps

(*Source:* Adapted from information in "802.11n or UWB," NE Asia, October 2005.)

The 802.11n standard development has been a highly competitive process with multiple organizations promoting different standards. One such organization is the TGn Sync group and another is the World Wide Spectrum Efficiency (WWiSE) group. However, despite many efforts, these groups could not reach agreement during early 2005 on a unified standard with neither being able to achieve the IEEE required 75% majority vote (of attending people, not companies voting). Due to industry pressures to complete the standard, a Joint Proposal Group was formed within the IEEE 802.11 Task Group n working group at the September 2005 meeting to formalize a mutually acceptable joint proposal. Still not pleased with progress, in an October 10 2005 press release, a group of 27 "Wi-Fi Industry Leader" companies, including members from TGn Sync and WWiSE, announced the initiation of a coalition, the Enhanced Wireless Consortium (EWC), to accelerate the IEEE 802.11n standard development process. In a press announcement,[9] the EWC indicated that it "will make its draft product specification available for public download and will provide implementation rights to all silicon suppliers and system vendors who join the organization." Moreover, if its specification was ratified by the IEEE, "EWC members have agreed to make their intellectual property (IP) necessary to the specification available to all parties on reasonable and non-discriminatory (RAND) terms."

[8] www.ietf.org
[9] See http://www.enhancedwirelessconsortium.org

In the press announcement, EWC indicated that the specification comprises a number of technical elements, including:

- *Mixed-mode interoperability with 802.11a/b/g networks* – Provides enhanced performance while maintaining communication with legacy devices;
- *PHY transmission rates up to 600Mbps* – Supports applications requiring high data rates (such as transmitting multiple HDTV streams), and reduces battery drain by minimizing the time required to send and receive data streams;
- *Enhanced efficiency MAC with frame aggregation* – Brings actual throughput closer to the raw PHY rate, providing end users with at least 100 Mbps application level bandwidth;
- *Use of 2.4GHz and/or 5GHz unlicensed bands* – Matches the frequency plan of existing 802.11 devices;
- *20 MHz and/or 40 MHz channel support* – Uses more of the wireless spectrum when available to enhance performance;
- *Spatial multiplexing modes for simultaneous transmission using one to four antennas* – Increases robustness of wireless connections to support very high data rates; and
- *Enhanced range via multiple antennas and advanced coding (e.g., space time coding)* – Provides for a wider coverage area with consistent wireless speeds.

Although 802.11 generally is associated with PCs and PC-related networks, the applications that suppliers are targeting is expanding into multiple segments, including:

1. PC and enterprise networking.
2. Consumer electronics (CE) for high-speed HDTV signal and related audiovisual home entertainment systems. Also addressed are digital photography, gaming, and so on. This segment is also being competitively targeted by emerging UWB standards.
3. Embedded market including mobile phones, digital cameras, iPODS, etc.

These three segments have different requirements. Devices in the CE segment need very high bit rates for video and have less aggressive power goals than battery-operated devices. Thus, a focus on aggressive MIMO antenna technologies that enable 600 Mbps or greater links is targeted. The embedded segment has lower power, less available space for circuits and multiple antenna, and usually lower cost goals. Each segment could potentially require unique specifications. However, more desirable and likely specifications would include common mandatory specifications and tailored optional specifications. This would seem to provide the best economy of scale benefits as well as appropriate interoperability of diverse equipment.

3.1.2 Wi-Fi Alliance

The Wi-Fi Alliance,[10] a non-profit organization, was originally established as the Wireless Ethernet Compatibility Alliance (WECA) in August 1999 to certify interoperability of IEEE 802.11 products. "The Wi-Fi Alliance has instituted a test suite that defines how member products are tested to certify that they are interoperable with other Wi-Fi Certified™ products. These tests are conducted at an independent laboratory." The Wi-Fi certification program consists of (1) published compliance testing procedures, (2) independent lab tests, and (3) the Wi-Fi seal of certified interoperability. Prior to the Wi-Fi certification program, IEEE 802.11 market penetration had been languishing. Additionally, the Wi-Fi Alliance serves as a technology marketing organization to "promote Wi-Fi as the global wireless LAN brand across all market segments, including the home, small office, large enterprise, and public access areas."

The Wi-Fi Alliance has attracted more than 250 member companies and has certified more than 2,800 products since it began its certification process in 2000. The Wi-Fi Alliance membership includes system companies, chip suppliers, and operators. Its board currently includes representatives of the world's leading technology and consumer product companies, including Agere, Cisco, Conexant, Dell, Intel, Microsoft, Nokia, Philips, Sony, Symbol Technologies and Texas Instruments.

The Wi-Fi Alliance has several goals including:

- Promoting 802.11 WLAN technologies, equipment, and systems
- Developing application profiles for Wi-Fi deployments that define the physical layer, link layer, and higher layers as needed for interoperation of systems and devices procured from multiple vendors.
- Developing certification programs and specifications to provide compatible and interoperable wireless equipment

The Wi-Fi Alliance's certification[11] currently includes three categories:

- Wi-Fi products based on IEEE "radio" standards: 802.11b and 802.11g devices operating in the 2.4 GHz range as well as 802.11a devices operating in the 5 GHz range. Many products support various combinations, including dual-mode (802.11b and 802.11g) or trimode (802.11a and 802.11b and 802.11g).
- Wi-Fi wireless network security: WPA™ (Wi-Fi Protected Access™) - Personal and Enterprise, WPA2™ (Wi-Fi Protected Access 2™) - Personal and Enterprise.
- Support for multimedia content over Wi-Fi networks: WMM™ (Wi-Fi Multimedia).

The future IEEE standards, including 802.11r (mobility), 802.11n (high-speed), and others, will be part of the Wi-Fi certification program at appropriate future dates. The Wi-Fi Alliance adopted a proactive approach for the more recently ratified IEEE standards

[10] www.wifialliance.org
[11] "Wi-Fi CERTIFIED™: The Safe Buy" white paper, The Wi-Fi Alliance, October 5, 2004, www.wifialliance.org

for QoS (802.11e) and security (802.11i) by providing certification prior to final formal completion and publishing of the standards. This was done to facilitate time-to-market opportunities for industry, motivated by general frustration with the slowness of the consensus-based IEEE standards process. In a white paper,[12] the Wi-Fi Alliance outlines its reasoning for its proactive position and provided a very interesting overview of WMM and related certification for its QoS-based on the 802.11e standard.

Wi-Fi public access (typically hotspots) has achieved modest commercial successes to date. Although reasons are debatable, the frequently identified problem areas are:

- *Complex and expensive rate plans* – Lack of simple rate plans similar to those models offered by the cellular industry.
- *Roaming costs* – Most public operators offer very limited coverage for subscription. Subscribers must maintain multiple, often expensive, subscriptions for reasonably useful coverage. The cellular industry has long demonstrated that sufficient subscriber-valued coverage and reasonable roaming costs are essential for desired success.
- *Security concerns* – Wi-Fi has historically lacked adequate enterprise and public access security.
- *Public awareness* – With a fragmented service provider community, potential subscribers are often not aware of locations and availability of hotspot services and cannot easily obtain this information.
- *High backhaul costs* – Costs incurred to connect remote base stations to the core network.
- *Inadequate business cases* – It is difficult to make money given small coverage areas, low density of prospective users, insufficient customers, and low usage.

The Wi-Fi Alliance[13] indicates that it is committed to promote and develop certification programs for public access and will focus on three key areas:

- The development of public access certification programs that will enhance the user experience.
- The development of international standards to promote interoperability and enable roaming.
- The development of a framework for sound business models that will enable the continued growth of the industry.

The WLAN enterprise market, after a slow start, is achieving increasing successes. The more successful home markets and early Enterprise WLAN systems deploy access points (APs) that are generally described as "fat" APs. These APs have all the needed intelligence onboard. Their network connection (DSL, cable modem, switch, etc.) doesn't need to know anything about wireless. The fat APs carry out all functions, including

[12] "Wi-Fi Certified™ for WMM – Support for Multimedia Applications with Quality of Service in Wi-Fi® Networks," Wi-Fi Alliance, September 1, 2004.
[13] "Enabling the Future of Wi-Fi® Public Access" white paper, Wi-Fi Alliance, February 2, 2004.

wired to wireless packet format conversion, encryption, QoS application, RF stats monitoring, and so on. In large distributed enterprise applications, this creates large scale configuration and support problems. Claiming lower total cost of ownership (TOC), so-called "thin" APs have been offered. The very thinnest APs allocate most intelligence to their central controller, and a thin AP acts basically as just a media converter. Various degrees of thinness (distributed intelligence) are available with various claims of superior TOC.

802.11/Wi-Fi equipment operates in unlicensed bands. The US Federal Communications Commission (FCC) defines these bands in Part 15 of its rules. **Error! Reference source not found.** lists the bands of relevance to Wi-Fi and 802.11 operations. The unlicensed personal communication system (PCS) bands are also listed in the table, although they are not used in Wi-Fi equipment. Other countries and regions often use the term "license-exempt" instead of unlicensed. Despite international variability, often due to historical allocations and uses of spectrum, the table is representative.

Table 3-5 US FCC Unlicensed Bands, 802.11 / Wi-Fi

Band	Frequencies	Time Frame of Introduction
Industrial, scientific, and medical (ISM)	902 – 928 MHz 2,400 – 2,483.5 MHz 5,725 – 5,850 MHz	1985 by US FCC
Unlicensed National Information Infrastructure (U-NII)	5,150 – 5,350 MHz 5,725 – 5825 MHz	1998 by US FCC
Unlicensed PCS*	1,910 – 1930 MHz 2,390 – 2,400 MHz	1993 by US FCC

Source: www.FCC.org, Part 15
*Not used in Wi-Fi equipment.

3.2. *Worldwide Interoperability for Microwave Access (WiMAX)*

When the air interface was first introduced, in 2004 and 2005, the WiMAX community created considerable buzz in its endeavors to promote and serve BWA applications. As indicated in Figure 3-3, WiMAX serves a wide array of applications, including fixed wireless access; nomadic and mobile applications; and backhaul for Wi-Fi hotspots, WiMAX base stations, and cellular base stations.

3.2.1 WiMAX Standards

A significant amount of effort has gone into standards. Fixed access and portability with simple nomadicity is addressed in the IEEE 802.16-2004 standard that was approved by the IEEE in June 2004. Mobility was added as a result of approval of IEEE 802.16e by the IEEE-SA Standards Board on December 7, 2005. According to the IEEE December 2005 announcement[14] "The operative version of IEEE Std 802.16 is now IEEE Std 802.16-2004, as modified by the corrigendum IEEE 802.16-2004/Cor1 and amended by IEEE Stds 802.16e and 802.16f. The WirelessMAN standard has gone mobile!"

[14] IEEE 802.16 web site

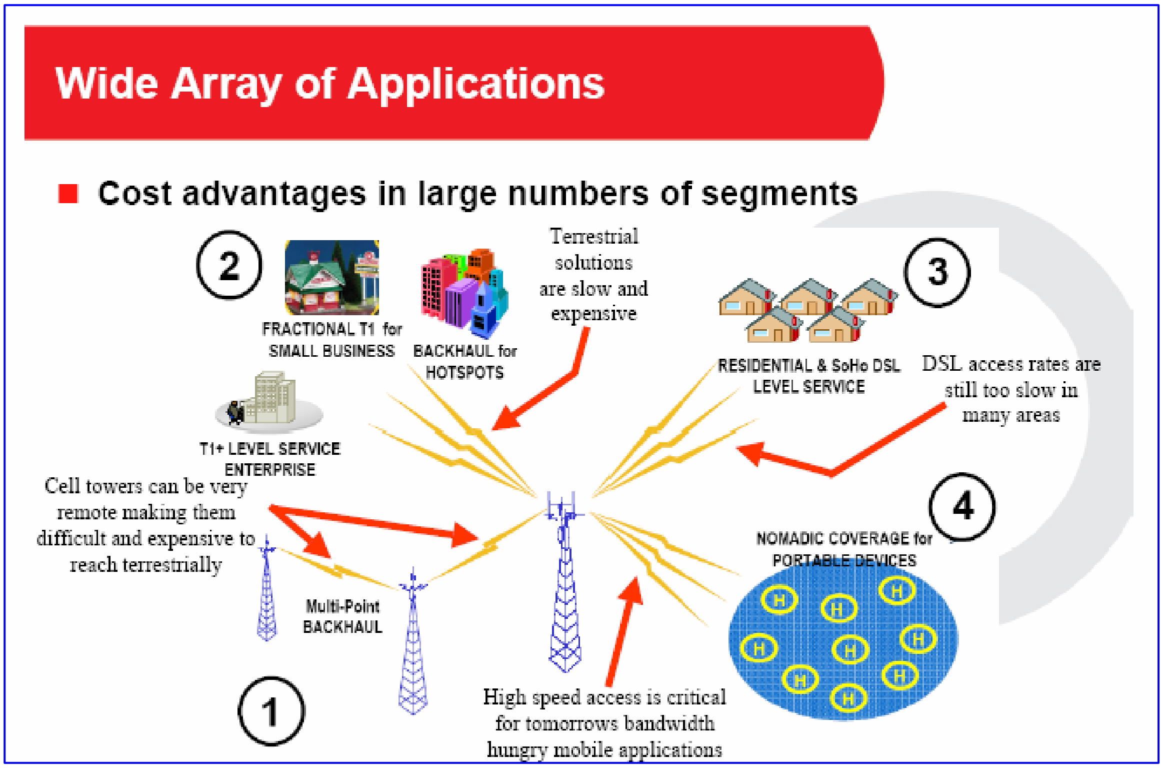

Figure 3-3 WiMAX applications
(*Source:* Fujitsu, WiMAX IEEE Dallas Communicatioon and Vehicle Technology presentation, September 2004.)

The market opportunities for WiMAX are presented in Table 3-6. Interoperability profiles, certification, and conformance statements are anticipated for equipment in each band, bandwidth, division duplex method (time (TDD) or frequency (FDD)), and applications, as necessary to enhance market insertion and acceptance.

Early very active promoters have included Intel and Fujitsu with historical semiconductor and computer successes. A key motivation appears to be enhanced market presence for these players in the emerging BWA. It is generally recognized that these players have achieved less than desired presence in the historical voice-centric cellular market. With triple play opportunities adding VoIP and IPTV applications to data, the emerging BWA market opportunities seem very appealing, and are enhanced by potential new international spectrum allocations. The inclusion of opportunities in computer, Internet access, video on demand (VOD), IPTV, consumer devices, and related emerging broadband wireless opportunities creates competitive opportunities for new and existing stakeholders from historically diverse market segments.

Table 3-6 WiMAX Market Opportunities

- **Regional Bell operating companies (RBOCs) are looking to WiMAX to**
    - Reach customers outside of their serving areas
    - Provide out-of-region access to in-region based customers
    - Fill in the gaps in DSL coverage
- **Multi-Service Operators are looking to WiMAX to**
    - Limit service opportunities lost to 3G wireless
    - Access out-of-franchise customers
    - Provide value-added services to existing customers
- **Wireless service providers are looking to WiMAX to**
    - Provide a less costly method for providing high-capacity services
    - Provide 3G-type data services in the public spectrum
- **Inter-eXchange Carriers are looking to WiMAX to**
    - Rapidly reach off-network customers
    - De-risk expensive last-mile builds by spreading the cost over multiple customers
    - Reach customers in other countries
- **State and local governments are looking to WiMAX to**
    - Provide data services to public safety offices
    - Provide emergency backup for wireline services
    - Provide public data services

The end result is that there are likely to be overlapping WiMAX networks in the same key metropolitan markets.

(*Source:* Fujitsu Wireless System Design Symposium, March 2004)

The Air Interfaces (identified as designations in the standards) that IEEE 802.16 standards target are presented in Table 3-7. WiMAX, like the higher speed versions of Wi-Fi, employs Orthogonal Frequency Division Multiplexing. OFDM will scale to varying bandwidths and bit rates with conceptually similar, although not interoperable, physical layers. Based on IEEE 802.16 standards and WiMAX Forum[15] standards and interoperability certification, WiMAX will address a potentially diverse range of BWA applications including backhaul, FWA, and nomadic and mobile applications.

[15] www.wimaxforum.org

Table 3-7 IEEE 802.16 Standard Designations Overview

Air Interfaces	Frequency Band & Duplex Method	Options	Comments
WirelessMAN-SC™	10-66 GHz TDD, FDD		Backhaul and Wireless T1 & Fractional T1 services
WirelessMAN-SCa™	Below 11 GHz, licensed bands; TDD, FDD	AAS ARQ STC	Backhaul and Wireless T1 & Fractional T1 services
WirelessMAN-OFDM™ 256 FFT	Below 11 GHz, licensed bands; TDD, FDD	AAS ARQ STC	Fixed, Nomadic 802.16-2004 (final version of 802.16a, b, c, d)
WirelessMAN-OFDMA™ Up to 2048 FFT	Below 11 GHz, licensed bands; TDD, FDD	AAS ARQ STC	Adds Mobility 802.16e (approved Dec. 7, 2005)
WirelessHUMAN™	Below 11 GHz, license-exempt bands, TDD	AAS ARQ STC Mesh	Essentially compatible with above Below 11 GHz standards; MAC support for DFS
AAS – Adaptive Antenna System DFS – Dynamic Frequency Selection OFDM – Orthogonal Frequency Division Multiplexing OFDMA – Orthogonal Frequency Division Multiple Access STC – Space Time Coding	ARQ – Automatic Repeat Request FDD – Frequency Division Duplexing TDD – Time Division Duplexing		

(*Source:* Adapted from IEEE 802.16e draft Standard)

The original 802.16 standard, approved in late 2001 and published in April 2002, targeted fixed point-to-multipoint (PMP) broadband wireless systems operating in the 10-66 GHz licensed spectrum. In January 2003, an amendment (802.16a) was approved that defined non-line-of-sight (NLOS) extensions in the 2-11 GHz spectrum with the claim of being able to deliver up to 70 Mbps at distances up to 31 miles (50 km). The IEEE coined the term WirelessMAN™. The goals of 802.16 standards are to enable multimedia applications with wireless connection and provide a viable last mile technology. Key IEEE 802.16 standards timelines are summarized in Table 3-7.

Non-line-of-sight (NLOS) air interfaces are considered important to facilitate customer installation of consumer premise equipment (CPE) to reduce (and hopefully eliminate) expensive onsite maintenance. Note that a great deal of misunderstandings and misstatements about achievable bit rates and range have existed. WiMAX and other OFDM alternatives do appear to provide enhanced bit rate and range performance, but do not achieve beyond the laws of physics (i.e., propagation and Shannon's Law). 70 Mbps and 31-mile (50-km) range may be achievable in point-to-point microwave (backhaul) applications. Substantially lower bit rates and ranges will be possible in NLOS fixed point-to-multipoint application (e.g., fixed broadband wireless access alternatives to DSL and cable) and more mobile cellular-like broadband alternatives.

Table 3-8 Key 802.16 Standard Timelines

Standard	Description of Amendments	Standards Status
802.16-2001, 802.11a. b. c, & d	Superceded by 802.16-2004	First: April 2002
802.16-2004	Add fixed, NLOS, features	Published: October 2004
802.16e	Add mobile	Approved: December 6, 2005; Published in late 2005
802.16f	Air interface BWA systems – management information base	Approved September 2005 Published December 2005
802.16g	Fixed and mobile BWA management plane procedures and services	Predraft, Working Group Draft
802.16h	License-exempt	Predraft, Call for contributions, Mid 2005
802.16i add	mobile management information base	Approved: December 2005

(*Source:* IEEE 802.16 SA website)

The targeted applications for WiMAX (also see Figure 3-3) include:

1. Backhaul
   a. Telecommunications backhaul including cellular and wireline
   b. T1 for enterprise and fractional T1 for SOHO (small office home office)
   c. Wi-Fi hotspot backhaul
2. Fixed wireless access
   a. Mature market DSL and cable broadband alternative
   b. Emerging market and other greenfield broadband deployments
3. Nomadic, Portable, and Mobile
   a. Always best connected applications to provide WAN coverage to supplement limited Wi-Fi hotspot coverage.
   b. VoIP competitive opportunities will emerge to compete with cellular

Most academic and industrial experts deem OFDM to be the superior modulation technology (compared to Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), and other technologies) for multimedia broadband applications due to its less strenuous equalization requirements resulting from the use of the Fast Fourier Transform (FFT) to demultiplex high bit rate signals into parallel lower bit rate signals for transmission over difficult RF channels. Lower bit rate signals have lower symbol rates and narrower bandwidths and are thus less susceptible to in-band frequency-selective fading or channel distortions. High data rates are achieved by de-multiplexing high bit rate data onto lower bit rate parallel channels on the individual tones of the FFT. Tones that are experiencing excessive multipath fading are either adaptively configured for lower bit rates or not used. The OFDM specified in the 802.16-2004 standard utilizes a 256 (2^8)-sample FFT. The OFDMA specified in the 802.16e amendment utilizes up to a 2048 (2^{11})-sample FFT. The OFDMA for the uplink is not a specified option in 802.16-2004 for fixed and nomadic application, but is an option for the downlink. 802.16e adds OFDMA for the uplink to support lower bandwidth uplink signals for battery-constrained portable and mobile applications. OFDMA introduces subchannelization by permitting assignment of combinations of FFT tones (and narrower bandwidths) to individual uplink (or downlink) subscribers. This helps to improve performance by allowing individual tone adaptive modulation and coding (AMC) and power control for each FFT tone. This also adds an OFDMA multiple access feature comparable to those in CDMA and TDMA. OFDM and OFDMA are in reality multicarrier modulation technologies aided by the FFT ability to more closely space orthogonal carriers than traditional Frequency Division Multiplex (FDM) systems. This can create inter-tone interference in distorted RF channels, which are addressed with null tones, or guard bands. Additionally, OFDM is very sensitive to synchronization and pilot tones are allocated for synchronization purposes. It should be noted that a key OFDM technology advantage identified for BWA is its superior performance on NLOS RF links that appear essential to minimize installation costs (e.g., self-install, no onsite maintenance). This, of course, degrades link performance and creates requirements for link enhancement technologies, such as AMC, turbo coding, and adaptive antennas, including beam forming and MIMO.

Key goals of the IEEE 802.16 standards community are presented in Table 3-9.

Table 3-9 WiMAX – Key Goals of 802.16 Standards Community

WiMAX – 802.16 Properties

- Support for backhaul; fixed, and nomadic, portable, and mobile wireless applications
- OFDM and OFDMA for NLOS applications (non-onsite installations) in lower than 11 GHz bands
- LOS operations in greater than 11 GHz Bands
- MAC support of very high bit rates up to 268 Mbps, uplink or downlink
- Time Division Duplex (TDD) and Frequency Division Duplex (FDD) operations
- Full and half duplex operations
- PHY and MAC standards
- Point-to-point (PTP) and point-to-multipoint (PMP) access standards with mesh extensions
- Support for multiple frequency allocations serving international regulatory requirements
- Support for flexible modulation bandwidths (e.g., multiples of 1.25, 1.5, and 1.75 MHz up to 20 MHz)
- Flexibility for multiple services with differing QoS requirements (e.g., bandwidth, latency)
- Frame-by-frame bandwidth allocations on demand
- Common platform for global deployment of IP-based broadband wireless services
- Support for higher layer and transport protocols, such as ATM, Ethernet, or Internet Protocol, and flexibility to support required future emerging protocols
- Adaptive modulation and coding (AMC)
- Comprehensive and extensible security
- Support for adaptive antennas, MIMO, etc.
- Extensions for mobility (802.16e)

(*Source:* Author research)

The potential spectrum for WiMAX applications is presented in Figure 3-4. As mentioned earlier, the terms “unlicensed” and “license-exempt” are equivalent.

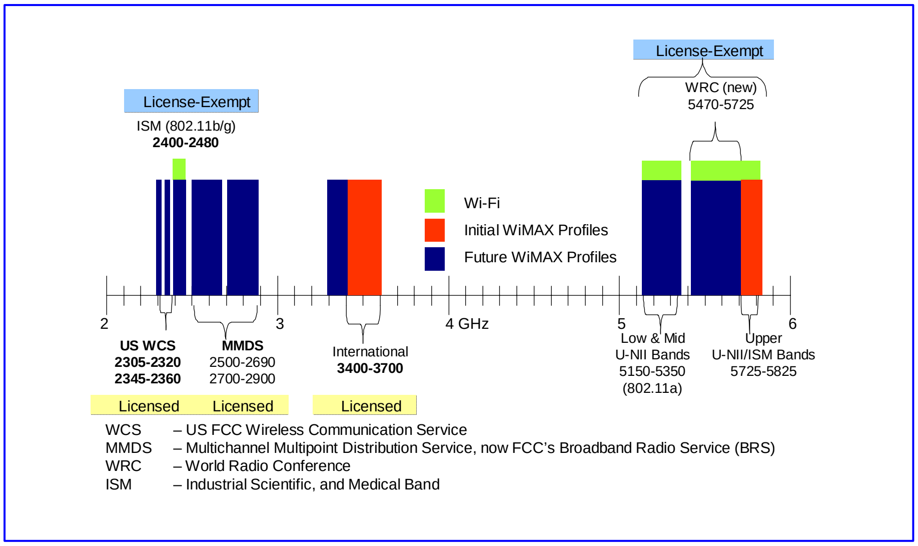

Figure 3-4 Potential WiMAX Spectrum
(*Sources:* WiMAX Forum website (www.wimaxforum.org), Intel website (www.intel.com), FCC, and author research)

3.2.2 WiMAX Forum

The WiMAX Forum originated in 2001 when several wireless companies, including Intel, Proxim, and Nokia, recognized an opportunity and need for such an alliance. They created the WiMAX Forum with a charter to actively promote and certify compatibility and interoperability of devices based on the IEEE 802.16 specification and to commit to develop compatible devices for the BWA market. According to recent website information, the WiMAX Forum has more than 430 members, including leading equipment suppliers, operators, system integrators, silicon and component makers, and application providers. The Forum on its website claims that Wireless Broadband Access (BWA) systems from WiMAX Forum members are already deployed in more than 125 countries around the world, although all to date are pre-certified products. The companies represented on the board of the WiMAX Forum include Airspan Networks, Alvarion, Aperto Networks, AT&T, British Telecom, Fujitsu, Intel Corporation, KT Corp., Samsung, Sprint Nextel, Wi-LAN, and ZTE Corporation.

The mission of the WiMAX Forum, as stated on its website is:

> The WiMAX Forum™ is an industry-led, non-profit corporation formed to promote and certify the compatibility and interoperability of Broadband Wireless Access (BWA) products using the IEEE 802.16 and ETSI HiperMAN wireless MAN specifications. The forum’s goal is to accelerate the introduction of these systems into the marketplace. WiMAX Forum Certified™ products will be fully interoperable and are expected to support both Broadband Fixed and Portable Applications. Through WiMAX Forum-led efforts, the economies of scale made possible by

> standards-based, interoperable products will drive price and performance levels unachievable by proprietary approaches. As a result, service providers worldwide will be able to deliver economical broadband data, voice and video services to both residential and business customers.
>
> Designed for carrier-class deployments as well as low-cost, license-exempt deployments, WiMAX Forum Certified systems will provide fixed, nomadic, portable and, eventually, mobile wireless broadband connectivity without the need for direct line-of-sight with a base station. In a typical cell radius deployment of three to ten kilometers, WiMAX Forum Certified™ systems can be expected to deliver capacity of up to 40 Mbps per channel, for fixed and portable access applications. This is enough bandwidth to simultaneously support hundreds of businesses with T-1 speed connectivity and thousands of residences with DSL speed connectivity.

The IEEE 802.16 standards are very complex, comprising more than 800 pages and later addendums including previous standards with additions to address new defined capabilities and features. An implementer must select among the many alternatives for targeted applications as well as standard-defined options and allowable company-specific differentiating options. Note that standards typically define only those features and parameters required to ensure interoperability of individual functions, leaving other required details for the implementer to differentiate specific products. Due to the wealth of options available, an implementer must make many decisions. Additional activities are required to ensure interoperability of equipment from multiple vendors. System profiles by organizations such as the WiMAX Forum define features that are mandatory or optional for the targeted MAC or PHY scenarios that are most likely to arise in the deployment of real systems. The key defining parameters of WiMAX system profiles[16] are:

1. Specific frequency band of operation
2. Duplexing scheme
3. Channel size (i.e., total modulation bandwidth or carrier spacing)
4. FFT carriers or tones

Note that much more detail must be defined to ensure interoperability including sufficient higher layer protocols than those defined in the IEEE 802.16 PHY and MAC layer standards.

[16] WiMAX web site, www.wimaxforum.org

Table 3-10 presents a list of current profiles that have been developed by the WiMax Forum based on IEEE 802.16-2004.

Table 3-10 Current WiMax Forum Certification Profiles

Frequency Band (MHz)	Duplex Method	Bandwidth (MHz)
3,400 – 3,600 MHz	TDD & FDD Profiles	3.5 MHz & 7 MHz Profiles
5,725 – 5,850 MHz	TDD 10	MHz

(*Source:* Adapted from information in "Fixed, Nomadic, Portable, and Mobile Application for 802.16-2004 and 802.16e WiMAX Networks," WiMax Forum, November 2005)
Notes: (1) IEEE 802.16-2004, 256 FFT, Fixed Applications, common system profile. (2) Total of five current profiles, others expected in the future.

The IEEE specifications focus on defining requirement specifications. WiMAX is defining test specifications[17] to:

1. Ensure that equipment and systems claiming compliance to a standard or a profile have been sufficiently tested to demonstrate that compliance.
2. Guarantee that equipment from multiple vendors have been tested in the same way, to the same interpretation of the standard, which increases the interoperability of the equipment.
3. Enable independent conformance testing, giving further credibility to the previous two items.

Additionally, the WiMAX Forum develops conformance documents to define mandatory and optional capabilities implemented and then tested in a certified product. These conformance documents are developed in accordance with ISO/IEC recommendations and then submitted to appropriate IEEE 802.16 Working Groups.

At the WiMax World Congress in Boston in October 2005 the progress of the WiMAX Forum's certification activities garnered much interest and some controversy. The WiMAX Forum's official certification laboratory is Cetecom Spain. In July 2005, Cetecom began testing WiMAX Forum member products to certify that they meet WiMAX Forum conformance and interoperability standards. Figure 3-5 presents a slide from a presentation by Alvarion, an equipment supplier that has substantial pre-WiMAX BWA deployments. The figure illustrates the wave of certifications. Wave 1, conducted in the fourth quarter of 2005, focused on primary air protocol testing. Wave 2, scheduled for the first half of 2006, will focus on FWA testing of outdoor service applications (e.g., CPE outdoor antenna systems). Wave 3, scheduled for the second half of 2006, will focus on indoor services applications with portability that will address NLOS indoor applications (e.g., no onsite installation). Wave 4, scheduled for 2007, will focus on mobile services, initially intended to provide Wi-Fi-like WAN services and eventually mobile services competitive with cellular services.

[17] WiMAX web site, www.wimaxforum.org

The WiMAX Forum's website[18] provides information on consumer premise equipment trends and costs. The first generation of WiMAX Forum Certified CPEs are expected to require outdoor antennas (for LOS and perhaps some electronics) CPE stations similar to a small satellite dish. The second generation of WiMAX CPEs will be NLOS modems suitable for indoor self-installation that will be priced around US$250. Third generation CPEs, which target integration into laptops and other portable devices (802.16e, mobility), are expected to initially cost approximately US$100 and be available in the 2007.

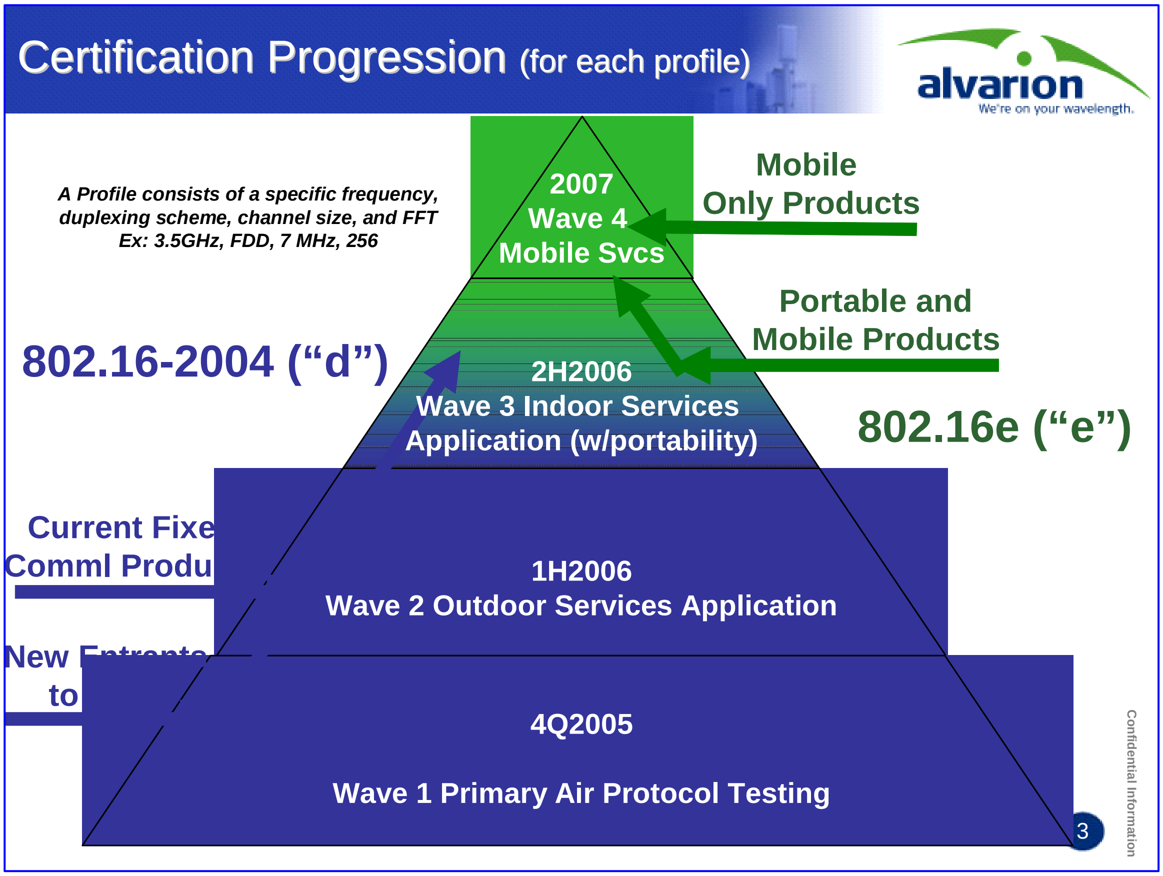

Figure 3-5 WiMax Certification Process
(*Source:* Alvarion WiMAX World Congress Presentation, October 2005)

3.3. Beyond 3G/4G: Long-Term Evolution

Beyond 3G/4G refers to initiatives by the cellular industry for air interface, core network, and related goals to develop improved future technologies to address emerging triple play multimedia opportunities. Long-term evolution (LTE)[19] is the commonly used term to

[18] WiMAX web site, www.wimaxforum.org
[19] "3rd Generation Partnership Project (3GPP); Technical Specification Group Radio Access Network; Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN); (Release 7), 3GPP TR 25.913 v7.1.0 (2005-9), December 2005

identify the work within 3GPP on their study activities to define Evolved Universal Terrestrial Radio Access Network (E-UTRAN) technologies.

Table 3-11 presents an overview of the key system parameters of LTE and comparisons with initial WCDMA (release 99/R4); the current mid-term evolution, which is in early phases of deployment of HSDPA/HSUPA technologies; and the Super 3G, which is the focus of the LTE study that is scheduled for deployment in 2008 and beyond.

Table 3-11 3G Radio Access and Core Network Evolution Overview

		3G and Enhanced 3G			4G
		R99/R4	Mid-term evolution	Super 3G	New mobile access
Spectrum		3G spectrum (2GHz band and the additional band(s))			New spectrum
Radio aspect		WCDMA	HSDPA, HSUPA, etc	Ultimate enhancement	New radio Interface
	Radio Access	Direct-Sequence CDMA		New elements such as OFDM, MIMO, etc	New access technology
	Min. TTI (Latency)	10 msec	2 ms	≤ 0.5 ms	
	Carrier Bandwidth	5 MHz		5-20 MHz, Fit in 5MHz	100 MHz
	Data Rate	384k – 2 Mbps	DL: 14 Mbps UL: 5.8 Mbps	30-100 Mbps	100 Mbps-1Gbps
NW aspect		CS and PS		PS only	
		GTP(tunneling) [IP routing in CN]		IP routing in CN and RAN	

(*Source:* Adapted from "View on 3G Evolution and Requirements – 3G Long-term Evolution Scenario: Super 3G," NTT DoCoMo, Inc., presented at 3GPP TSG-RAN Future Evolution Workshop, Toronto, Canada, 2-3 November 2004.)

The current 3G technologies[20] were first launched by DoCoMo in Japan in September 2001 and began to achieve mass international deployments during 2005 with continued significant ramps in 2006 and beyond. High-Speed Downlink Packet Access (HSDPA, 14 Mbps peak) and High-Speed Uplink Packet Access (HSUPA, 5.8 Mbps peak) technologies were added to 3GPP specifications in Release 5 (2002 specification) and Release 6 (2004 specification), respectively, and early deployments progressed in late 2005. LTE addresses higher bit rates and other initiatives, sometimes referred to as Super 3G, which will be enhancements to the current WCDMA/UTRAN technologies. OFDM technologies are being proposed for bit rates up to 100 Mbps in 20 MHz of bandwidth. The schedule of these technologies, presented in Figure 3-6, envisions standard developments in 2006-07 and deployments commencing in 2008. 4G technologies target

[20] *SDR Forum Market Study: Task 2: The Cellular Industry: Terminals and Infrastructure*, SDRF-05-A-0005-V0.00, September 2005.

100 Mbps to 1 Gbps bit rates in 100 MHz of spectrum. New international spectrum identification and allocations are a key goal for 4G, whereas use of existing spectrum is a key goal for Super 3G.

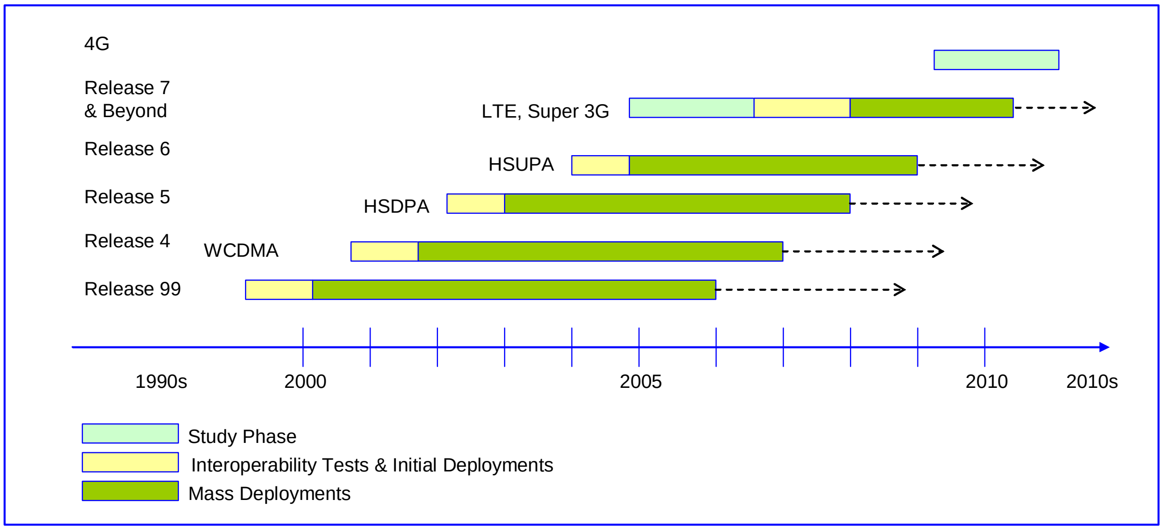

Figure 3-6 Anticipated Long Term Evolution (LTE) Development and Deployment Schedule
(Source: www.3GPP.org and author research)

The LTE study was initiated by 3GPP in December 2004 and is scheduled to be completed in June 2006. Review of LTE plans and documents on the 3GPP website[21] reveals the consensus nature of the standard process. Many early meeting documents comprise presentations and papers from various 3GPP members providing their input on proposed goals and requirements. During 2005, various meetings were conducted to reach "agreement of the requirements for the Evolved UTRAN," which resulted in TR25.913, an evolving 3GPP document that defines these requirements.[21]

[21] http://www.3gpp.org/Highlights/LTE/LTE.htm

Table 3-12 presents a summary of LTE requirements that were adapted from TR25.913.

Table 3-12 Summary of Requirements for Evolved UTRAN (LTE)

1. Higher data rates: peak wireless bit rates in 20 MHz spectrum of 100 Mbps (5 bits/sec/Hz) in the downlink and 50 Mbps (2.5 bits/sec/Hz) in the Uplink.
2. Scale linearly with bandwidth: 5, 10, 15, and 20 MHz. For narrow spectral allocation, support 1.25, 2.5 MHz
3. Ability to deploy in existing spectrum
4. Significantly improved spectrum efficiency (e.g., 2-4 x Release 6)
5. Improved latency including higher layer protocol (e.g., TCP) and signaling. Target: 10 ms UE –RAN (User Equipment – Radio Access Network (RAN))
6. Packet optimized Radio Access Network and Core Network (CN) (All-IP)
7. Reduced operational expenses (OPEX) and capital expenses (CAPEX), including backhaul
8. Improved service provisioning
9. Improved coverage – Increase “cell edge bitrate” while maintaining same site locations as deployed today
10. Improved capacity – Threefold compared to current standards.
11. Enhancement of Multimedia Broadcast/Multicast Service (MBMS)
12. Enhanced IMS and core network features
13. Reasonable system and terminal complexity, cost, and power consumption. System should be optimized for low mobile speed but also support high mobile speed
14. Efficient support of the IP multimedia services, especially from the PS domain (e.g., voice over IP, presence)
15. Smooth migration from current systems, equipment, and services. Use of existing systems where new technologies are not cost effective, which requires service continuity and mobility between systems.
16. System should be optimized for low mobile speed for broadband wireless access, but should support high mobile speeds (e.g., up 350 km/hour for high-speed trains)

(*Source:* Adapted from 3GPP TR25.913 v7.1.0 September 2005)

A key non-air interface goal for LTE is an all-IP network, eventually reaching the mobile terminal (user equipment). To support real time IP services (e.g., VoIP, IPTV) latency must be reduced. A key element of this is to support intersystem mobility between, for example, cellular and Wi-Fi or WiMAX. Figure 3-7 is an input by DoCoMo on the core network migration. A key goal is to “flatten” the architecture and use standard IP interfaces at both the RAN and CN for payload. However, industry input indicates that the signaling/control will probably retain some proprietary cellular features. Note that the early 3GPP standards have proprietary protocols (i.e., not standard Transmission Control Protocol with Internet Protocol, or TCP/IP) in the core network. Interestingly, the cdma2000 community (3GPP2) has used standard protocols and has claimed this as an advantage. The current 3GPP proprietary network nodes include the Serving GPRS Support Node (SGSN, where GPRS is General Packet Radio Service) that interfaces to the RAN and the Gateway GPRS Support Node (GGSN) interface to the Public Data Serving Node (PDSN). The functions in these nodes will be distributed to other network elements. Time-critical functions will be distributed to the RAN to reduce latency, and other, less time-critical functions will be distributed to enhanced core network nodes. Note that legacy circuit-switched (CS) networks allocate dedicated resources for the duration of a call (e.g., voice), whereas packet-switched (PS) networks are based on sharing of links (statistical multiplexing). Thus, efficient MAC functions become very important for “all-IP” multimedia networks with real-time voice and video multimedia payloads as well as traditional “best-effort” IP networks.

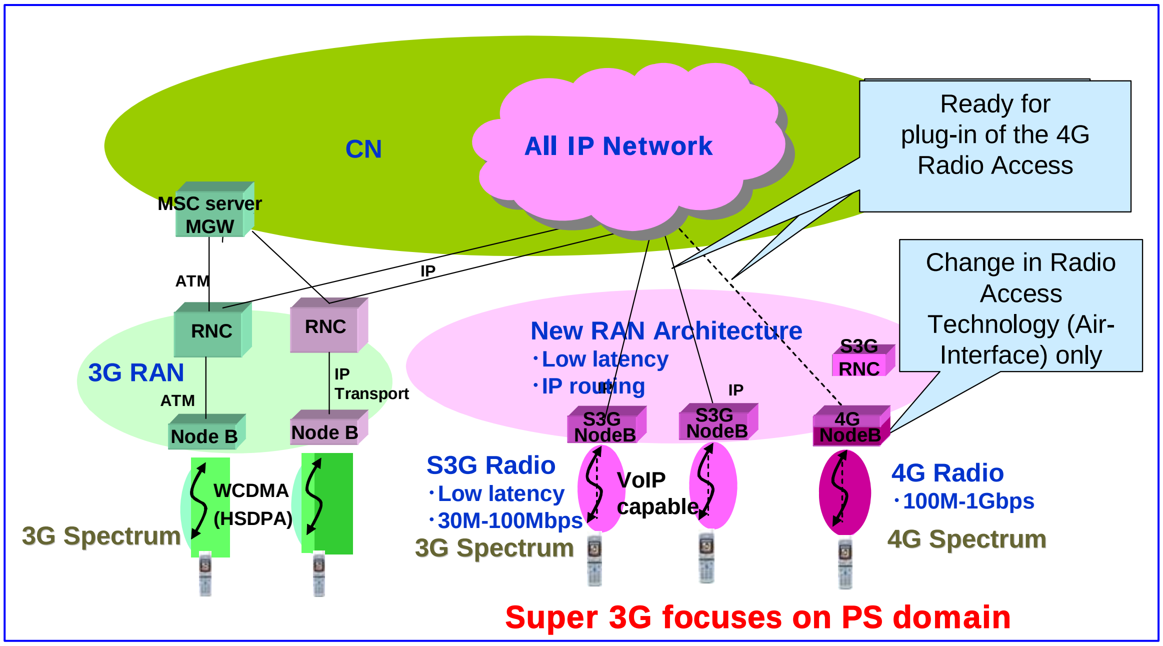

Figure 3-7 Core Network Migration Scenario
(Source: DoCoMo Presentation)

4 Broadband Wireless Access Markets

The BWA markets appear poised to become the next significant wireless growth market. Inclusively broadband multimedia services appear on track to be the next growth engine for all of the telephony industry. Figure 4-1 presents forecasts for 2000 to 2010 for key subscriber indicators relevant to broadband multimedia services, which include traditional wireline telephony, cellular, personal computers, Internet, and total broadband (e.g., DSL, cable, BWA). Interestingly, the forecast for cellular subscribers is 3.4 billion (from 3 billion) subscribers by year-end 2010 as a result of data indicating that third quarter 2005 international cellular subscribers reached 2 billion, more rapidly than the anticipated year-end 2005 date. Wireless is a growth engine, and indications are that broadband wireless will increasingly contribute to this growth.

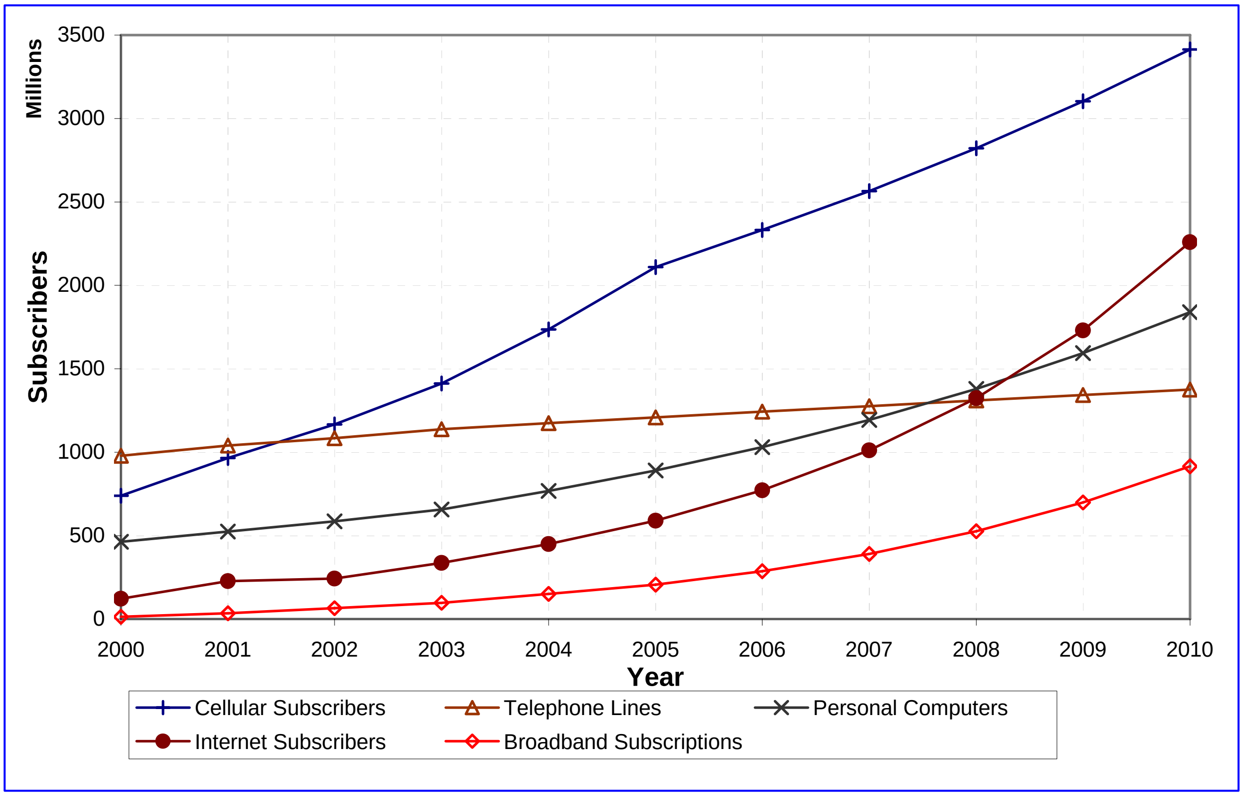

Figure 4-1 Broadband Access Subscriber Forecasts
(Source: ITU, DSL Forum, and author research and forecasts)

The BWA market comprises three segments, as previously presented in Figure 3-2. The status of these segments is presented in
Table 4-1. Note that in early 2006, except for Wi-Fi, these market segments have very minimal current deployment and available historical market data. However, as demand for broadband services builds, each of these BWA segments is anticipated to have significant growth potential going forward.

BWA Segment	Segment Status	Anticipated Segment Evolution
WLAN, 802.11, Wi-Fi	Current notebook computer successes. PDA and cell phone applications are emerging.	Anticipate consumer (DTV, games, home network), health care, and other emerging successes.
WMAN, 802.16, WiMAX	Some current pre-standard deployments, expect in 2006 some initial WiMAX fixed wireless compliant deployments	Poised to potentially become international BWA standard. Mobile standard compliant deployments anticipated in 2008–2010
Cellular, Beyond 3G/4G, 3GPP and 3GPP2	HSDPA, HSUPA in 5MHz WCDMA bands in 2004–2005	OFDM standards in up to 20MHz anticipated in 2008–2010 time frame.

Table 4-1 BWA Market Segments and Status
(Source: Author Research)

4.1. The Wi-Fi Market

As previously noted, the WLAN, or Wi-Fi, market has experienced spectacular success in recent years. The consumer market has been the largest segment allowing consumers to connect easily to their home networks without the inconvenience and expense of installing or connecting wires. The enterprise segment has requirements for more flexible access and reduced network access installation and moving costs. The commercial "hot spot" segment has experienced marginal profitability to date.

The current significant Wi-Fi market segment is the notebook (or laptop) market. Figure 4-2 presents total yearly shipments from 2000 to 2010 of computers and notebooks. Also shown are notebook shipments as a percentage of total computer shipments, and the percentage of notebook shipments with embedded Wi-Fi technology.

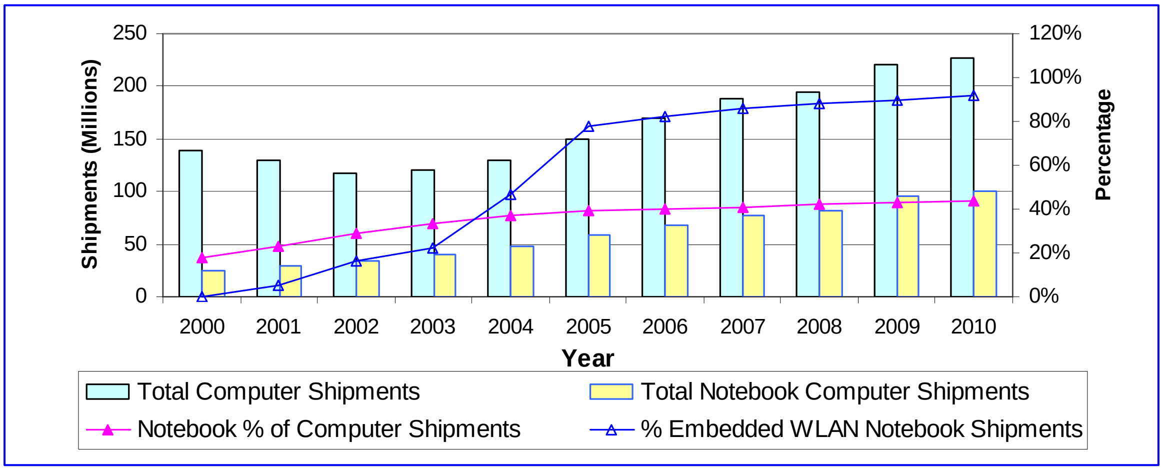

Figure 4-2 Notebook Shipments

(*Sources:* "Enabling Notebook Users with Wide-Area Broadband Access," Qualcomm, Inc White Paper, September 2005, based on Gartner data; Intel presentations; and author research and forecasts.)

Understandably, all BWA market segments target the notebook market represented in Figure 4-2 and hope over time to gain a share of this potential market where Wi-Fi already has a strong presence. Thus, it is anticipated that WiMAX and Beyond 3G technologies will also penetrate the notebook market. The current HSDPA and emerging HSUPA technologies as well as cdma2000 1x-EV-DO already have some minimal emerging penetration (e.g. Verizon Wireless, Sprint Nextel, Cingular, among others). These technologies are not currently OFDM, but are anticipated to deploy OFDM and MIMO technologies in the future as the 3GPP LTE initiative progresses to deployment. This should create significant SDR opportunities to share baseband resources for what will be similar, although not compatible OFDM waveforms. OFDM modulation is used in a variety of standards and frequency bands, and the parameter of use can vary. This is a vary favorable application area for SDR.

As presented in Table 4-2, the WLAN market has been characterized by rapid unit growth and significant declining year-over-year (YOY) average sale price (ASP). Thus, spectacular growth is mainly represented in the unit numbers, and the total revenue growth numbers are less significant. A key factor on this market trend is that the WLAN market is significantly dominated by the semiconductor manufacturers with business models driven by high-volume production goals. Thus, WLAN chips integrate more functionality early in the market cycle and reach lower system and product pricing levels earlier in product and market cycles. Similar product cycles driven by system integrators and equipment manufacturers tend to require longer to achieve comparable integration levels and lower price point. Whereas notebooks and related broadband access dominate the Wi-Fi market segment, consumer and embedded multiradio cellular applications are becoming increasingly important.

	2000	2001	2002	2003	2004	2005F	2006F	2007F	2008F	2009F	2010F
All Revenue ($Mil)	$753.5	$1,309.9	$2,580.0	$4,118.0	$5,399.0	$6,807.6	$8,392.6	$10,168.2	$12,370.8	$15,195.6	$18,691.9
ASP Average ($)	$167.2	$154.7	$137.2	$93.6	$68.4	$55.0	$44.7	$36.7	$30.0	$24.2	$19.9
802.11 Shipments (M)	4.5	8.5	18.8	44.0	78.9	123.9	187.8	276.7	412.7	627.4	941.3
Sales Growth %	NA	73.8%	97.0%	59.6%	31.1%	26.1%	23.3%	21.2%	21.7%	22.8%	23.0%
ASP Change %	NA	–7.4%	–11.3%	–31.8%	–26.9%	–19.7%	–18.7%	–17.8%	–18.4%	–19.2%	–18.0%
Unit Growth %	NA	87.8%	119.0%	188.0%	46.0%	57.0%	51.6%	47.3%	49.1%	52.0%	50.0%

Table 4-2 Total WLAN Market Numbers
(*Source:* Forward Concepts, updated by author with 2005 and 2006 data)
Note: F = forecast

WLAN market segments include:

1. Clients, Network Interface Cards (NICs)—Examples include plug-in PC cards, diminishing in number as embedded WLANs are shipped in PCs.
2. Embedded—Examples include laptop computers, cellular phones, PDAs digital cameras, digital TVs, and MP3 players. Increasingly, embedded laptops are taking market share from separate NIC cards.
3. Multimedia—As HDTV-, DTV-, and IPTV-type markets emerge, WLANs are anticipated to increasingly serve as the wireless link from set-top boxes, computers, etc. to the TV or display.
4. Wireless Residential Gateways (WRGs)—These are the emerging WLANs and routers that are the dominant home network access points.
5. Access Points (APs)—These are increasingly becoming enterprise and commercial hotspot APs as residential users use WRGs. As previously discussed, enterprise and hotspot APs have varying degrees of stand-alone intelligence. Centralized (thin) intelligence is often preferable to optimize total cost of ownership (TCO) for system administrators.

WLAN numbers for the above market segments are presented in Table 4-3. The most significant growth is anticipated to be embedded (e.g., notebooks, digital cameras, MP3, and other sound devices); WRG for home wireless networks; and multimedia (e.g., set-top boxes and DTVs).

Equipment	2000	2001	2002	2003	2004	2005F	2006F	2007F	2008F	2009F	2010F
802.11 Clients (Mil)	3.06	5.77	11.86	20.30	27.70	28.25	29.10	27.20	24.48	28.15	22.52
802.11 Embedded (Mil)	0.50	0.77	1.50	3.50	18.90	36.86	59.89	94.21	144.32	216.63	322.13
802.11 Multimedia (Mil)				2.40	7.80	21.80	42.21	68.16	108.72	171.67	269.18
802.11 WRG (Mil)	0.51	1.00	3.24	13.80	19.20	31.33	50.61	80.66	128.18	203.42	319.36
802.11 AP (Mil)	0.44	0.93	2.18	4.00	5.20	5.63	6.05	6.51	7.00	7.51	8.06
ASP Client ($)	$127	$111	$95	$74	$55	$50	$41	$34	$28	$19	$19
ASP Embedded ($)	$61	$57	$50	$37	$30	$24	$21	$18	$14	$12	$10
ASP Multimedia ($)			$110	$103	$86	$73	$62	$56	$47	$40	$33
ASP WRG ($)	$225	$223	$175	$77	$65	$53	$42	$34	$27	$22	$17
ASP AP ($)	$503	$432	$371	$295	$265	$227	$196	$163	$138	$118	$102
Revenue NICs ($Mil)	$388	$643	$1,129	$1,495	$1,531	$1,419	$1,184	$918	$689	$537	$424
Revenue Embedded ($Mil)	$30	$44	$75	$129	$568	$880	$1,277	$1,666	$2,091	$2,540	$3,061
Revenue Multimedia ($Mil)				$245	$673	$1,584	$2,614	$3,790	$5,155	$6,856	$8,913
Revenue WRG ($Mil)	$115	$222	$567	$1,068	$1,245	$1,649	$2,133	$2,734	$3,472	$4,375	$5,469
Revenue AP ($Mil)	$221	$401	$809	$1,181	$1,383	$1,275	$1,185	$1,060	$965	$887	$825

Table 4-3 WLAN Segment Market Numbers
(*Source:* Forward Concepts, updated by author with 2005 and 2006 data)
Note: F = forecast

4.2. WiMAX Market

As discussed in Section 3.2, WiMAX (IEEE 802.16) addresses three general BWA market segments. The first is fixed wireless access (FWA), which is addressed by the IEEE 802.16-2004 standard; it has WiMAX profiles developed and has products in certification testing in the WiMAX Forum's certification laboratory in Spain. The second includes the backhaul (microwave-centric) applications that were the focus of early 802.16 standards (see Table 3-7) for frequencies above 10 GHz. The third includes the portable/mobile broadband wireless applications (BWA) that are addressed by the IEEE 802.16e standard that was approved in December 2005. Over time, as full mobile functionality is added to the 802.16e standard, WiMAX could fully compete with cellular for both broadband as well as voice (likely VoIP) applications. Note that, although the 802.16e standard for mobility has been ratified by the IEEE, industry sources indicate that the current standard does not support full mobility for high speed cellular-like handoff (make before break handoff at higher speeds sufficient for real time applications). The current IEEE 802.16e standard does support the "best-effort" portable mobility that is sufficient for FWA and low-speed (terminal movement) data applications. However, full mobility is required to eventually provide a truly mobile Wi-Fi WWAN alternative as well as support for real time applications such as VoIP, video, and multiplayer gaming. Mobility will also be needed to support possible cellular WiMAX services in emerging international WiMAX frequency allocations.

Because WiMAX is essentially an emerging technology and market, traditional market forecast techniques that use historical data to assess trends is not possible. Although a few current pre-standard WiMAX-centric deployments are in existence, previous broadband FWA deployments have not achieved significant successes. Examples of disappointing performance include the local multipoint distribution system (LMDS) and multichannel multipoint distribution system (MMDS). Industry sources and literature generally cite the reasons for low success rates as lack of previous NLOS capability (due to expensive maintenance and outside installation requirements) and lack of economies of scale in deployments. However, the current IEEE 802.16 standards provide for NLOS, and the WiMAX Forum activities seem on-track to provide economy-of-scale benefits. Further, with Intel as a leading proponent of WiMAX technologies, and indicating an intent to integrate WiMAX in the future into their notebook chip offerings, similar to their successful Centrino Wi-Fi initiatives, critical factors for success appear in place. Emerging lower-cost semiconductor-centric and economy-of-scale benefits appear increasingly positioned to enable a mass market opportunity.

Industry sources[22] generally agree that the BWA will not replace the wireline market services (e.g. DSL, cable modem, FTTx), but will generally complement them as follows:

1. In urban and suburban areas with dense populations, wireline should provide greater bit rates and cost efficiencies. However, certain urban and suburban areas can have unique coverage and cost situations that are most cost effectively served by BWA. These situations include installation, coverage, cost, and competitive provider considerations. Various wireline DSL, cable, and FTTx service providers might need a wireless service capability to effectively compete in the triple play market. BWA with additional frequency allocations might be the best alternative to address this requirement.
2. In less dense rural areas, wireline broadband is often not feasible due to the wide coverage area and high cost. BWA can often provide cost effective service and business cases.
3. In emerging lower-tier economies with lower percentages of economically able subscribers, BWA may be the most cost-effective alternative. Voice and Internet

[22] The development of these forecasts has heavily relied on industry interviews, papers, and press reports. Industry interview sources include: Alvarion, Inc. (Carlton O'Neal, VP Marketing, and Dr. Mo Shakouri, AVP Business Development and Chair Marketing Working Group of WiMAX Forum); TeleCIS Wireless (David Sumi, Vice President Marketing and Business Development and Secretary of the WiMAX Forum); Intel, Inc. (Ed Agis, CoChair WiMAX Forum Certification Working Group, and Prahash Iyer, Intel R&D and Chair Network Working Group of WiMAX Forum); and Nortel, Inc. (Bruce Gustafson, WiMAX Director of Product Marketing).

services are generally recognized as key enablers of economic growth as well as enabling a growing middle class.

Carlton O'Neal, VP Marketing, Alvarion, indicated that in 2005 the BWA subscriber market was approximately 1 percent of the total broadband market and that it is anticipated to grow to 10 percent in 2010. Using this guidance and data in Figure 4-1 for total broadband subscriptions, Figure 4-3 presents revised forecasts of the BWA subscriber market through 2015. BWA provided service to 2 million subscribers in 2005, representing 1 percent of broadband subscribers; it is forecast to grow to 91.5 million subscribers in 2010, representing 10 percent of broadband subscribers, and to grow further to 708.7 million subscribers in 2015 and represent 20 percent of all broadband subscribers. Based on lack of current available historical data, this forecast could be highly optimistic or highly pessimistic, and only emerging historical data will provide resolving guidance. There is little doubt of the growth of the broadband market, but the potential penetration of BWA is less clearcut. We like the activities of the IEEE 802.16 and WiMAX Forum communities and are optimistic that the opportunities and probable success scenarios could be similar to cellular.

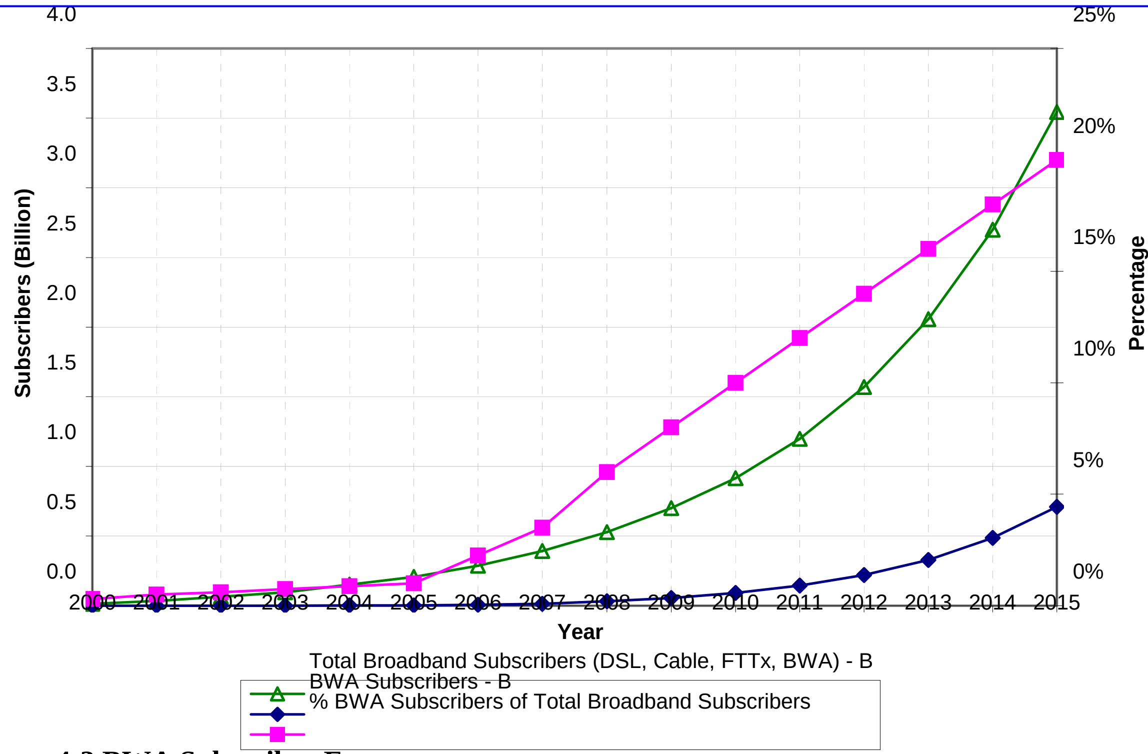

Figure 4-3 BWA Subscriber Forecasts
(*Source:* Author research based on Alvarian input)

Table 4-4 presents a forecast of the BWA market revenue potential, which assumes that BWA is 1 percent of total broadband subscribers in 2005, grows to 10 percent in 2010, and to 20 percent in 2015. This forecast does not assume any replacement, so it may be understated significantly in later years. However, the assumption of 20 percent penetration of BWA subscribers in 2015 may be optimistic (or pessimistic).

	2000	2001	2002	2003	2004	2005	2006F	2007F	2008F	2009F	2010F	2011F	2012F	2013F	2014F	2015F
Total Broadband Subscribers (DSL, Cable, FTTx, BWA) - M	14.0	33.7	64.4	96.9	151.0	207.3	286.9	391.6	527.1	699.5	915.0	1,197.7	1,569.0	2,057.0	2,698.8	3,543.5
BWA Subscribers - k	42.0	168.7	386.2	726.9	1,321.3	2,072.5	6,454.2	13,705.3	31,626.1	55,960.7	91,500.7	143,729.2	219,666.2	329,122.7	485,785.1	708,706.5
% BWA Subscribers of Total Broadband Subscribers	0.3%	0.5%	0.6%	0.8%	0.9%	1.0%	2.3%	3.5%	6.0%	8.0%	10.0%	12.0%	14.0%	16.0%	18.0%	20.0%
BWA Subscriber Growth	105	127	218	341	594	751	4,382	7,251	17,921	24,335	35,540	52,229	75,937	109,457	156,662	222,921
BWA Base Stations	525	634	1,088	1,704	2,972	3,757	14,606	18,128	35,842	40,558	50,772	65,286	94,922	136,821	195,829	278,652
BWA Base Station Revenues ($M)	$65.6	$79.3	$136.0	$187.4	$297.2	$375.7	$1,314.5	$1,595.3	$3,046.6	$3,244.6	$3,807.9	$4,570.0	$6,169.9	$8,209.3	$11,749.7	$16,719.1
BWA CPE Equipment Market	$52.5	$63.3	$97.9	$136.3	$208.0	$225.4	$876.3	$1,450.2	$1,792.1	$2,433.5	$3,554.0	$5,222.9	$7,593.7	$10,945.7	$15,666.2	$22,292.1
BWA Total Equipment Market	$118	$143	$234	$324	$505	$601	$2,191	$3,045	$4,839	$5,678	$7,362	$9,793	$13,764	$19,155	$27,416	$39,011
BWA Subscribers per Base Station	200	200	200	200	200	200	300	400	500	600	700	800	800	800	800	800
BWA Average Cost per Base Station	$125,000	$125,000	$125,000	$110,000	$100,000	$100,000	$90,000	$88,000	$85,000	$80,000	$75,000	$70,000	$65,000	$60,000	$60,000	$60,000
BWA Average Cost per CPE	$500	$500	$450	$400	$350	$300	$200	$200	$100	$100	$100	$100	$100	$100	$100	$100

Table 4-4 Broadband Wireless Access (BWA) Market Forecast

(Source: Author estimates based on interviews and guidances in "WiMAX: The Business Case Models for Fixed Broadband Wireless Access based on WiMAX Technology and the 802.16 Standard," WiMAX Forum, October 10, 2004 and "WiMAX: The Business Case for Fixed Wireless Access in Emerging Markets," WiMAX Forum, June 2005; www.wimaxforum.org.)

Note: F = forecast

4.3. Beyond 3G/4G Market

As background for Beyond 3G discussions, Figure 4-4 presents forecasts of international 3G subscribers from 2000 to 2015. Note that based on faster growth than anticipated in 2005, the figure in this report increases the forecast of total international cellular subscribers compared to the Task 2 report.[23] Total international subscribers are forecast to grow to more than 3 billion in 2010 and reach more than 4 billon subscribers in 2015, representing a penetration of approximately two-thirds of the world population.

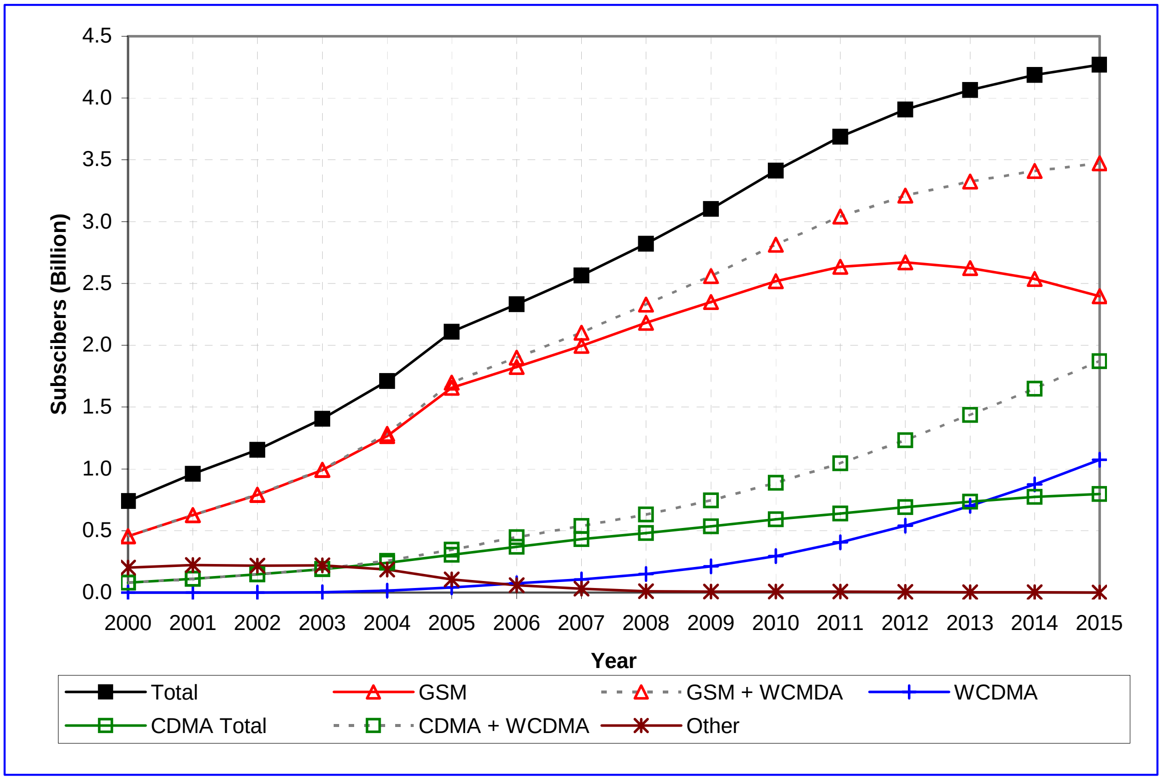

Figure 4-4 Total and 3G Cellular Market Subscriber Forecasts
(Source: ITU, GSM Association, CDG, and author research and forecasts)

Figure 4-4 includes subscriber numbers for Global System for Mobile Communications (GSM), CDMA, WCDMA, and others (personal digital cellular (PDC), TDMA, analog, etc.). Note that the figure forecasts GSM subscribers to continue growth through 2012 and then decline. In actuality, in later years multiradio cell phones and data terminals (notebooks, PDA, etc.) appear on track to proliferate, and the number of subscribers with GSM-capable phones and GSM service is not anticipated to decline. Figure 4-4 counts a subscriber as part of the emerging new technologies. To provide perspective on this, the figure also contains GSM + WCDMA subscribers, as frequently quoted by the GSM Association (GSMA), and CDMA + WCDMA (both CDMA technologies) subscribers, as frequently stated by the CDMA Development Group (CDG) and Qualcomm. Note the

[23] *SDR Forum Market Study: Task 2: The Cellular Industry: Terminals and Infrastructure*, SDRF-05-A-0005-V0.00, September 2005.

decrease in YOY percentage to 10.5 percent in 2006 and lower in following years, although such forecasts of such significant decreases from higher levels have been wrong in previous years. Growth rates slow as penetration levels continue toward saturation.

As presented in Table 3-11 and Figure 3-6, Beyond 3G/4G encompasses several initiatives:

1. The early 3G deployments include 3GPP Release 99 and Release 4. These initiatives address WCDMA that is now deployed by many international operators, and are often referred to as 3G.
2. HSDPA and HSUPA were defined in 3GPP Releases 5 and 6, respectively. This is perhaps early "Beyond 3G," as these technologies add high-speed wireless wide area networks and inherently support mobility.
3. Super 3G adds OFDM modulation formats, continues MIMO technology enhancements, and increases bandwidths supported up to 20 MHz. These are the 2008 3GPP Release 7 and Beyond deployments. This represents the essence of Beyond 3G technologies.
4. 4G adds new frequency bands and substantially increases bit rates to the range 100 Mbps to 1 Gbps in bandwidths up to 100 MHz. 4G targets deployments after 2010. 4G is in the early phases of definition.

Figure 4-5 presents forecasts for Beyond 3G/4G subscribers. The figure also contains historical and forecast data for cdma2000 1x and WCDMA subscribers.

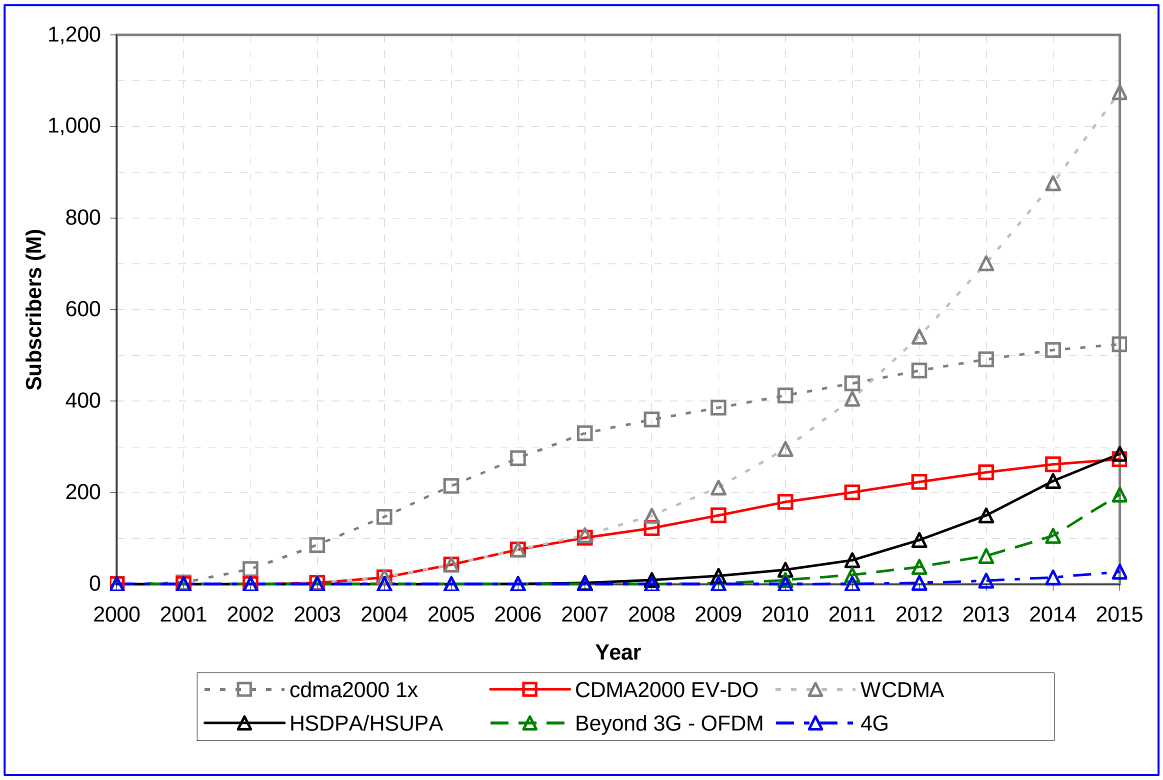

Figure 4-5 Beyond 3G Subscriber Forecasts
(*Source:* ITU, CDG, GSMA, and author forecasts)

With the exception of cdma2000 1x EV-DO and HSDPA/HSUPA, Beyond 3G/4G has some initial deployments beginning in 2008 and most significant deployment ramps occurring in the 2010–2015 time frame. Cdma2000 1x EV-DO and HSDPA/HSUPA will set important precedence for market opportunities for the cellular industry's high-speed BWA initiatives. Ultimately, however, Beyond 3G and 4G technologies using OFDM, MIMO, and other advanced technologies appear to be the objectives of the cellular industry for competitive broadband technologies and services. For these reasons, an alternative forecasting methodology appears most appropriate for markets whose emergence is 5 yeasr in the future.

The Task 2 report[24] presented Figure 4-6 as guidance that network depreciation (and CAPEX) trend down to approximately 15 percent as a telecom segment matures. Note that CAPEX is the current year capital expenditures, and depreciation is the allocation of previous years' CAPEX expenditures. Although not the same, as industries mature, CAPEX and depreciation tend to track each other as initial start-up CAPEX depreciations expire.

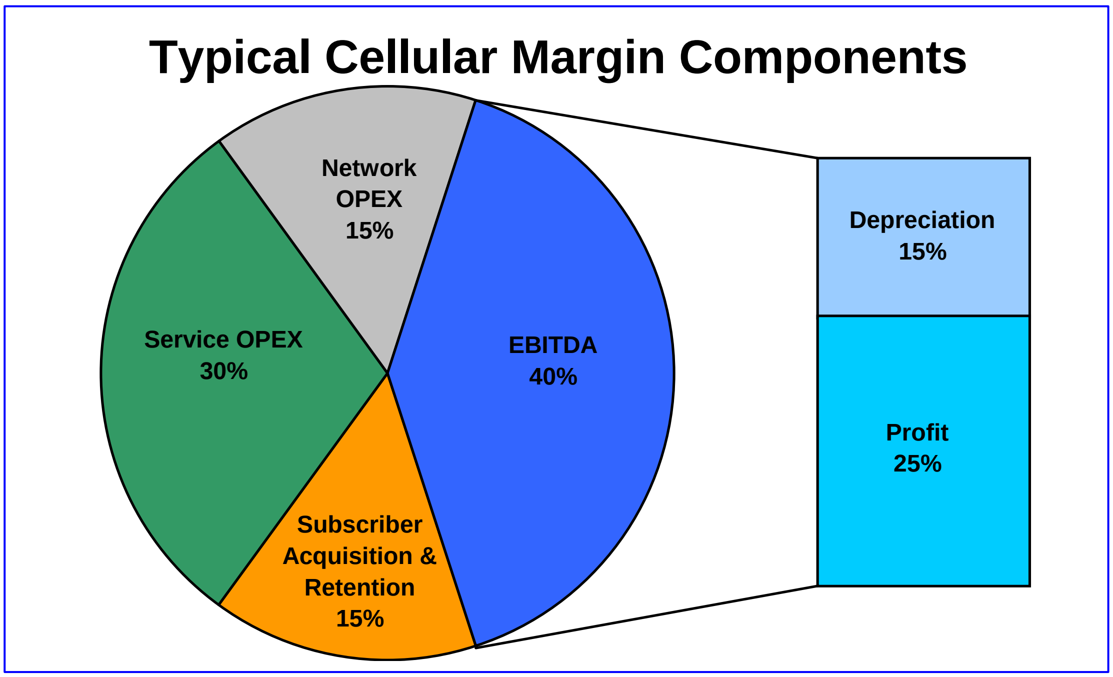

Figure 4-6 Typical Cellular Margin Components
(*Source*: Re-created from Nokia, "The Prerequisites for Profitable Entry Business," April 2004, www.nokia.com and presented as Figure 4-2 in *SDR Forum Market Study: Task 2: The Cellular Industry: Terminals and Infrastructure*, SDRF-05-A-0005-V0.00, September 2005.)

As cellular has been maturing for more than 20 years, industry financial reports are indicating that industry CAPEX/depreciation budgets are, in fact, trending to 15 percent. Network equipment budgets for Beyond 3G/4G will be drawn from this budget,

[24] *SDR Forum Market Study: Task 2: The Cellular Industry: Terminals and Infrastructure*, SDRF-05-A-0005-V0.00, September 2005.

increasingly commanding over time a higher percentage of totals from 2G and 3G upgrades as operators increasingly allocate budgets to next-generation technologies.

Table 4-5 presents forecasts of the Beyond 3G/4G market that include subscribers, infrastructure, and terminals. Operator network equipment procurement budgets are typically around 50 percent of CAPEX budgets. To develop total industry service revenue, average international average revenue per unit (ARPU) (or subscriber) is used, as indicated in the table. Much of the data is based on historical and forecast data from the SDRF Task 2 report,[25] updated appropriately, based on available more recent data. For subscriber terminals, the table assumes no replacement market (more conservative estimates) for Beyond 3G/4G forecasts and uses historical terminal data from the Task 2 report.

Network equipment vendors have repeatedly indicated that HSDPA and HSUPA will be software upgrades to legacy WCDMA (after specified manufacture date or model). Additionally, as modern base stations use multi-carrier power amplifiers (MCPAs), upgrades to OFDM should largely be channel card updates. Thus, the financial estimates for Beyond 3G infrastructure in Table 4-5 are consolidated because this provides the best picture of the potential market.

[25] *SDR Forum Market Study: Task 2: The Cellular Industry: Terminals and Infrastructure*, SDRF-05-A-0005-V0.00, September 2005.

Subscribers by Technology - M	**2000**	**2001**	**2002**	**2003**	**2004**	**2005F**	**2006F**	**2007F**	**2008F**	**2009F**	**2010F**	**2011F**	**2012F**	**2013F**
Total	739.4	960.0	1154.8	1403.8	1709.3	2109.9	2331.4	2564.6	2821.0	3103.1	3413.4	3686.5	3907.7	4064.0
WCDMA			0.2	2.8	16.1	42.3	75.4	106.6	149.3	210.9	295.6	405.3	540.6	701.3
HSDPA/HSUPA							0.8	2.8	9.1	17.9	31.7	52.5	96.3	150.3
Beyond 3G - OFDM									0.3	1.2	8.9	20.5	37.4	61.2
4G												0.9	2.5	7.5
Infrastructure	**2000**	**2001**	**2002**	**2003**	**2004**	**2005F**	**2006F**	**2007F**	**2008F**	**2009F**	**2010F**	**2011F**	**2012F**	**2013F**
Int. ARPU per month - $	$33.00	$32.34	$31.69	$31.06	$30.44	$29.83	$29.23	$28.65	$28.08	$27.51	$26.96	$26.42	$25.90	$25.38
Int. ARPU per year - $	$396.00	$388.08	$380.32	$372.71	$365.26	$357.95	$350.79	$343.78	$336.90	$330.16	$323.56	$317.09	$310.75	$304.53
Industry Service Revenue $M	$292,787	$372,545	$439,202	$523,231	$624,318	$755,241	$817,851	$881,643	$950,411	$1,024,543	$1,104,458	$1,168,958	$1,214,313	$1,237,628
Total CAPEX - $M	$98,500	$87,200	$76,100	$81,500	$94,400	$113,286	$122,678	$132,246	$142,562	$153,681	$165,669	$175,344	$182,147	$185,644
Network Equipment CAPEX $M	$54,700	$52,500	$45,900	$43,800	$52,300	$56,643	$61,339	$66,123	$71,281	$76,841	$82,834	$87,672	$91,074	$92,822
Beyond 3G Networks														
WCDMA/HSDPA/HSUPA CAPEX $M			$1,540	$3,140	$8,125	$12,540	$16,200	$18,900	$20,125	$22,340	$23,500	$25,600	$28,700	$31,150
4G CAPEX												$1,950	$2,980	$4,050
Total Beyond 3G Equipment			$1,540	$3,140	$8,125	$12,540	$16,200	$18,900	$20,125	$22,340	$23,500	$27,550	$31,680	$35,200
Beyond 3G / 4G Terminals	**2000**	**2001**	**2002**	**2003**	**2004**	**2005F**	**2006F**	**2007F**	**2008F**	**2009F**	**2010F**	**2011F**	**2012F**	**2013F**
Total Cellular Terminal Units - M	409.5	399.0	410.5	520.5	640.3	720.0	805.0	889.0	980.0	1,070.0	1,150.0	1,215.0	1,260.0	1,290.0
WCDMA/HSDPA/HSUPA Units			0.2	2.6	13.3	26.2	33.9	33.2	49.3	71.3	106.2	142.1	196	238.5
4G Units												0.9	2.5	7.5
Terminal ASP (Average Sale Price)														
Total Cellular Terminal ASP - $	$205	$195	$178	$155	$137	$129	$122	$115	$110	$106	$102	$98	$96	$95
WCDMA/HSDPA/HSUPA ASP			$325	$300	$275	$250	$225	$200	$175	$160	$150	$145	$140	$135
4G ASP												$300	$290	$280
Terminal Revenues - $B														
Total Cellular Terminals	$83.9	$77.8	$73.1	$80.7	$87.7	$92.9	$97.8	$102.2	$107.8	$112.9	$116.7	$119.5	$121.1	$122.3
WCDMA/HSDPA/HSUPA			$0.1	$0.8	$3.7	$6.6	$7.6	$6.6	$8.6	$11.4	$15.9	$20.6	$27.4	$32.2
4G												$0.27	$0.73	$2.10

Table 4-5 Beyond 3G/4G Market Forecasts: Subscribers, Infrastructure, and Terminals

(Sources: *SDR Forum Market Study: Task 2: The Cellular Industry: Terminals and Infrastructure*, SDRF-05-A-0005-V0.00, September 2005; International Telecommunication Union (ITU); GSMA; company reports; and author forecasts)