Table 2.3 Leading IMT-2000 Candidate Standards as of 1998 (adapted from [Lib99])

Air Interface	Mode of Operation	Duplexing Method	Key Features
cdma2000 US TIA TR45.5	Multi-Carrier and Direct Spreading DS-CDMA a $N = 1.2288$ Mcps with $N = 1, 3, 6, 9, 12$	FDD and TDD Modes	• Backward compatibility with IS-95A and IS-95B. Downlink can be implemented using either Multi-Carrier or Direct Spreading. Uplink can support a simultaneous combination of Multi-Carrier or Direct Spreading • Auxiliary carriers to help with downlink channel estimation in forward link beamforming.
UTRA (UMTS Terrestrial Radio Access) ETSI SMG2	DS_CDMA at Rates of $N \times 0.960$ Mcps with $N = 4, 8, 16$	FDD and TDD Modes	• Wideband DS_CDMA System. • Backward compatibility with GSM/DCS-1900. • Up to 2.048 Mbps on Downlink in FDD Mode. • Minimum forward channel bandwidth of 5 MHz. • The collection of proposed standards represented here each exhibit unique features, but support a common set of chip rates, 10 ms frame structure, with 16 slots per frame. • Connection-dedicated pilot bits assist in downlink beamforming.
W-CDMA/NA (Wideband CDMA) North America) USA T1P1-ATIS			
W-CDMA/Japan (Wideband CDMA) Japan ARIB			
CDMA II South Korea TTA			
WIMS/W-CDMA USA TIA TR46.1			
CDMA I South Korea TTA	DS-CDMA at $N \times 0.9216$ Mcps with $N = 1, 4, 16$	FDD and TDD Modes	• Up to 512 kbps per spreading code, code aggregation up to 2.048 Mbps.
UWC-136 (Universal Wireless Communications Consortium) USA TIA TR 45.3	TDMA - Up to 722.2 kbps (Outdoor/Vehicular), Up to 5.2 Mbps (Indoor Office)	FDD (Outdoor/ Vehicular), TDD (Indoor Office)	• Backward compatibility and upgrade path for both IS-136 and GSM. • Fits into existing IS-136 and GSM. • Explicit plans to support adaptive antenna technology.
TD-SCDMA China Academy of Telecommunication Technology (CATT)	DS-CDMA 1.1136 Mcps	TDD	• RF channel bit rate up to 2.227 Mbps. • Use of smart antenna technology is fundamental (but not strictly required) in TD-SCMA.
DECT ETSI Project (EP) DECT	1150-3456 kbps TDMA	TDD	• Enhanced version of 2G DECT technology.

2.2.1 3G W-CDMA (UMTS)

The Universal Mobile Telecommunications System (UMTS) is a visionary air interface standard that has evolved since late 1996 under the auspices of the European Telecommunications Standards Institute (ETSI). European carriers, manufacturers, and government regulators collectively developed the early versions of UMTS as a competitive open air-interface standard for third generation wireless telecommunications.

UMTS was submitted by ETSI to ITU's IMT-2000 body in 1998 for consideration as a world standard. At that time, UMTS was known as UMTS Terrestrial Radio Access (UTRA), as shown in Table 2.3, and was designed to provide a high capacity upgrade path for GSM. Around the turn of the century, several other competing wideband CDMA (W-CDMA) proposals agreed to merge into a single W-CDMA standard, and this resulting W-CDMA standard is now called UMTS.

UMTS, or W-CDMA, assures backward compatibility with the second generation GSM, IS-136, and PDC TDMA technologies, as well as all 2.5G TDMA technologies. The network structure and bit level packaging of GSM data is retained by W-CDMA, with additional capacity and bandwidth provided by a new CDMA air interface. Figure 2.3 illustrates how the various 2G and 2.5G TDMA technologies will evolve into a unified W-CDMA standard. Today, W-CDMA is the primary focus of the 3GPP world standard body, and while ETSI remains the organizational body that coordinates the W-CDMA standards effort, W-CDMA development now involves leading manufacturers, carriers, engineers, and regulators from throughout the world within the 3GPP community. The 3GPP standards body is developing W-CDMA for both wide area mobile cellular coverage (using FDD) as well as indoor cordless type applications (using TDD).

The 3G W-CDMA air interface standard had been designed for "always-on" packet-based wireless service, so that computers, entertainment devices, and telephones may all share the same wireless network and be connected to the Internet, anytime, anywhere. W-CDMA will support packet data rates up to 2.048 Mbps per user (if the user is stationary), thereby allowing high quality data, multimedia, streaming audio, streaming video, and broadcast-type services to consumers. Future versions of W-CDMA will support stationary user data rates in excess of 8 Mbps. W-CDMA provides public and private network features, as well as videoconferencing and *virtual home entertainment* (VHE). W-CDMA designers contemplate that broadcasting, mobile commerce (m-commerce), games, interactive video, and virtual private networking will be possible throughout the world, all from a small portable wireless device.

W-CDMA requires a minimum spectrum allocation of 5 MHz, which is an important distinction from the other 3G standards. Although W-CDMA is designed to provide backward compatibility and interoperability for all GSM, IS-136/PDC, GPRS, and EDGE switching equipment and applications, it is clear that the wider air interface bandwidth of W-CDMA requires a complete change out of the RF equipment at each base station. With W-CDMA, data rates from as low as 8 kbps to as high as 2 Mbps will be carried simultaneously on a single W-CDMA 5 MHz radio channel, and each channel will be able to support between 100 and 350 simultaneous voice calls at once, depending on antenna sectoring, propagation conditions, user velocity, and antenna polarizations. As shown in Table 2.3, W-CDMA employs variable/selectable direct sequence

spread spectrum chip rates that can exceed 16 Megachips per second per user. A common rule of thumb is that W-CDMA will provide at least a six times increase in spectral efficiency over GSM when compared on a system wide basis [Buc00].

Because W-CDMA will require expensive new base station equipment, the installation of W-CDMA will likely be slow and gradual throughout the world. Thus, the evolutionary path to 3G will require dual mode or tri-mode cell phones that can automatically switch between the incumbent 2G TDMA technology, EDGE, or W-CDMA service where its available. By 2010, it is likely that W-CDMA will be fully installed, eliminating the need for backward compatibility with GSM/GPRS, IS-136, PDC, and EDGE.

2.2.2 3G cdma2000

The cdma2000 vision provides a seamless and evolutionary high data rate upgrade path for current users of 2G and 2.5G CDMA technology, using a building block approach that centers on the original 2G CDMA channel bandwidth of 1.25 MHz per radio channel. Based upon the original IS-95 and IS-95A (cdmaOne) CDMA standards, as well as the 2.5G IS-95B air interface, the cdma2000 3G standard allows wireless carriers to introduce a family of new high data rate Internet access capabilities in a gradual manner within existing systems, while assuring that such upgrades maintain backward compatibility with existing cdmaOne and IS-95B subscriber equipment. Thus, current CDMA operators may seamlessly and selectively introduce 3G capabilities at each cell without having to change out entire base stations or reallocate spectrum [Tie01], [Gar00], [Kim00].

The cdma2000 standard is being developed under the auspices of working group 45 of the Telecommunications Industry Association (TIA) of the US, and involves the participation of the international technical community through the 3GPP2 working group. The first 3G CDMA air interface, cdma2000 1xRTT, implies that a single 1.25 MHz radio channel is used (e.g. 1X simply implies one times the original cdmaOne channel bandwidth, or, put another way, a multicarrier mode with only one carrier). Within the ITU IMT-2000 body, cdma2000 1xRTT is also known as G3G-MC-CDMA-1X. The initials MC stand for multicarrier, and the initials RTT stand for *Radio Transmission Technology*, language suggested by the IMT-2000 body. For convenience, it is common to omit the MC and RTT designations, and simply refer to the standard as cdma2000 1X.

cdma2000 1X supports an instantaneous data rate of up to 307 kbps for a user in packet mode, and yields typical throughput rates of up to 144 kbps per user, depending on the number of users, the velocity of a user, and the propagation conditions. cdma2000 1X can also support up to twice as many voice users as the 2G CDMA standard, and provides the subscriber unit with up to two times the standby time for longer lasting battery life. As seen in Table 2.3, cdma2000 is being developed for both FDD (mobile radio) and TDD (in-building cordless) applications.

The improvements in cdma2000 1X over 2G and 2.5G CDMA systems are gained through the use of rapidly adaptable baseband signaling rates and chipping rates for each user (provided through incremental redundancy) and multi-level keying within the same gross

framework of the original cdmaOne standard. No additional RF equipment is needed to enhance performance—the changes are all made in software or in baseband hardware. As can be seen in Table 2.2, to upgrade from 2G CDMA to cdma2000 1X, a wireless carrier merely needs to purchase new backbone software and new channel cards at the base station, without having to change out RF system components at the base station.

cdma2000 1xEV is an evolutionary advancement for CDMA originally developed by Qualcomm, Inc. as a proprietary *high data rate* (HDR) packet standard to be overlaid upon existing IS-95, IS-95B, and cdma2000 networks. Qualcomm later modified its HDR standard to be compatible with W-CDMA as well, and in August 2001, ITU recognized cdma2000 1xEV as part of IMT-2000. cdma2000 1xEV provides CDMA carriers with the option of installing radio channels with *data only* (cdma2000 1xEV-DO) or with *data and voice* (cdma2000 1xEV-DV). Using cdma2000 1xEV technology, individual 1.25 MHz channels may be installed in CDMA base stations to provide specific high speed packet data access within selected cells. The cdma2000 1xEV-DO option dedicates the radio channel strictly to data users, and supports greater than 2.4 Mbps of instantaneous high-speed packet throughput per user on a particular CDMA channel, although actual user data rates are typically much lower and are highly dependent upon the number of users, the propagation conditions, and vehicle speed. Typical users may experience throughputs on the order of several hundred kilobits per second, which is sufficient to support web browsing, email access, and m-commerce applications. cdma2000 1xEV-DV supports both voice and data users, and can offer usable data rates up to 144 kilobits per second with about twice as many voice channels as IS-95B.

The ultimate 3G solution for CDMA relies upon multicarrier techniques that gang adjacent cdmaOne radio channels together for increased bandwidth. The cdma2000 3xRTT standard uses three adjacent 1.25 MHz radio channels that are used together to provide instantaneous packet data throughput speeds in excess of 2 Mbps per user, although actual throughput depends upon cell loading, vehicle speed, and propagation conditions. Three non-adjacent radio channels may be operated simultaneously and in parallel as individual 1.25 MHz channels (in which case no new RF hardware is required at the base station), or adjacent channels may be combined into a single 3.75 MHz super channel (in which case new RF hardware is required at the base station). With peak user data rates in excess of 2 Mbps, it is clear that cdma2000 3X has a very similar user data rate throughput goal when compared to W-CDMA (UMTS). Advocates of cdma2000 claim their standard gives a wireless service provider a much more seamless and less expensive upgrade path when compared to W-CDMA, since cdma2000 allows the same spectrum, bandwidth, RF equipment, and air interface framework to be used at each base station as the 3G upgrades are introduced over time.

2.2.3 3G TD-SCDMA

In China, GSM is the most popular wireless air interface standard, and the wireless subscriber growth in China is unmatched anywhere in the world. For example, in late 2001 more than eight million cell phone subscribers were added in just one month in China alone! Given the huge potential market for wireless services in China, and China's desire to craft its own wireless

vision, The China Academy of Telecommunications Technology (CATT) and Siemens Corporation jointly submitted an IMT-2000 3G standard proposal in 1998, based on Time Division-Synchronous Code Division Multiple Access (TD-SCDMA). This proposal was adopted by ITU as one of the 3G options in late 1999.

TD-SCDMA relies on the existing core GSM infrastructure and allows a 3G network to evolve through the addition of high data rate equipment at each GSM base station. TD-SCDMA combines TDMA and TDD techniques to provide a data-only overlay in an existing GSM network. Up to 384 kbps of packet data is provided to data users in TD-SCDMA [TD-SCDMA Forum]. The radio channels in TD-SCDMA are 1.6 MHz in bandwidth and rely on smart antennas, spatial filtering, and joint detection techniques to yield several times more spectrum efficiency than GSM. A 5 millisecond frame is used in TD-SCDMA, and this frame is subdivided into seven time slots which are flexibly assigned to either a single high data rate user or several slower users. By using TDD, different time slots within a single frame on a single carrier frequency are used to provide both forward channel and reverse channel transmissions. For the case of asynchronous traffic demand, such as when a user downloads a file, the forward link will require more bandwidth than the reverse link, and thus more time slots will be dedicated to providing forward link traffic than for providing reverse link traffic. TD-SCDMA proponents claim that the TDD feature allows this 3G standard to be very easily and inexpensively added to existing GSM systems.

2.3 Wireless Local Loop (WLL) and LMDS

The rapid growth of the Internet has created a concurrent demand for broadband Internet and computer access from businesses and homes throughout the world. Particularly in developing nations where there is inadequate telecommunications backbone infrastructure, there is a tremendous need for inexpensive, reliable, rapidly deployable broadband connectivity that can bring individuals and enterprises into the information age. In fact, as voice over Internet protocols (VoIP) become prevalent, it is quite conceivable that a single broadband Internet connection could someday provide all of the needed telecommunications services, including telephone service, television, radio, fax, and Internet, for a home or business customer.

Fixed wireless equipment is extremely well suited for rapidly deploying a broadband connection in many instances, and this approach is steadily becoming more popular for providing "last mile" broadband local loop access, as well as for emergency or redundant point-to-point or point-to-multipoint private networks.

Unlike mobile cellular telephone systems described earlier in this chapter, fixed wireless communication systems are able to take advantage of the very well-defined, time-invariant nature of the propagation channel between the fixed transmitter and fixed receiver. Furthermore, modern fixed wireless systems are usually assigned microwave or millimeter radio frequencies in the 28 GHz band and higher, which is greater than ten times the carrier frequency of 3G terrestrial cellular telephone networks. At these higher frequencies, the wavelengths are extremely small, which in turn allows very high gain directional antennas to be fabricated in small physical form factors. At higher

frequencies, too, more bandwidth can be easily used. As we see in later chapters, high gain antennas have spatial filter properties that can reject multipath signals that arrive from directions other than the desired line-of-sight (LOS), and this in turn supports the transmission of very wide bandwidth signals (on the order of tens or hundreds of megabits per second) without distortion. Also, since the carrier frequencies of these fixed wireless access terminals are so high, the radio channel behaves much like an optical channel—if you can see an antenna, you can successfully communicate to it! Conversely, if you cannot see the antenna, you will be unable to communicate with it. Thus, fixed wireless networks at very high microwave frequencies are only viable where there are no obstructions, such as in a relatively flat suburban or rural setting.

Microwave wireless links can be used to create a wireless local loop (WLL) such as the one shown in Figure 2.4. As we see in Chapter 10, the local loop can be thought of as the "last mile" of the telecommunication network that resides between the central office (CO) and the individual homes and businesses in close proximity to the CO. In most developed countries, copper or fiber optic cable already has been installed to residences and businesses. However, in many developing nations, cable is too expensive or can take months or years to install. Wireless equipment, on the other hand, can usually be deployed in just a couple of hours. An additional benefit of WLL technology is that once the wireless equipment is paid for, there are no additional costs for transport between the CO and the customer premises equipment (CPE), whereas buried cables often must be leased from a service provider or utility company on a monthly basis. It is possible that WLL systems could compete with copper-wire based Digital Subscriber Loop (DSL) technologies that are rapidly proliferating [Sta99].

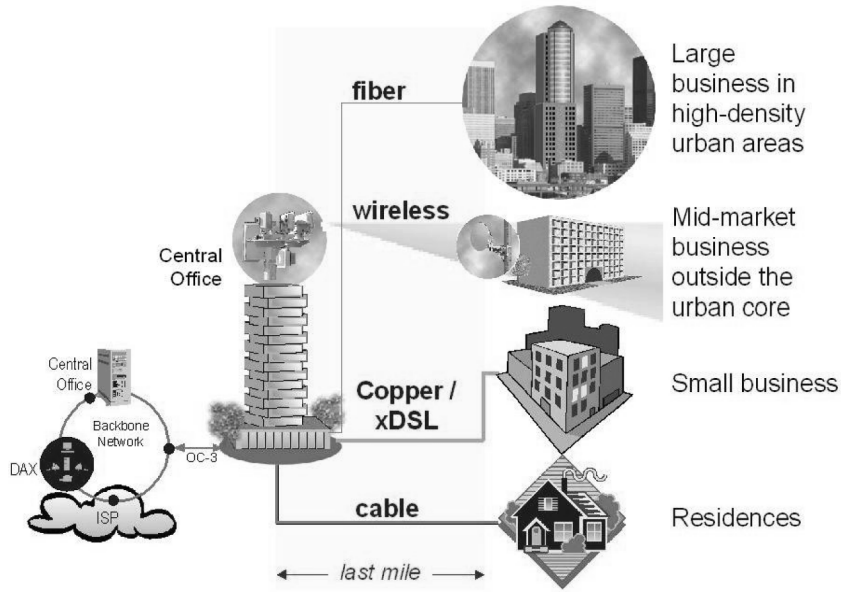


Figure 2.4 Example of the emerging applications and markets for broadband services. (Courtesy of Harris Corporation, ©1999, all rights reserved.)

Governments throughout the world have realized that WLL could greatly improve the efficiency of their citizens while stimulating competition that could lead to improved telecommunications services. A vast array of new services and applications have been proposed and are in the early stages of commercialization. These services include the concept of Local Multipoint Distribution Service (LMDS), which provides broadband telecommunications access in the local exchange [Cor97], [And98], [Xu00].

In 1998, 1300 MHz of unused spectrum in the 27–31 GHz band was auctioned by the US government to support LMDS. Similar auctions have been held in other countries around the world. Figure 2.5 illustrates various spectrum allocations made by countries throughout the world. Note that most LMDS allocations share frequencies with the Teledesic band which was approved by the ITU World Radio Conference for broadband satellite systems. The Teledesic band was originally established for the Motorola Iridium System, whose spectrum was later merged into the Teledesic system. Ironically, as of late 2001, broadband low earth orbit (LEO) satellite services were not yet commercially viable.

To gain a perspective of the enormous amount of bandwidth that is available for fixed wireless services such as LMDS, and how such licenses represent an unprecedented opportunity for wireless carriers, consider Figure 2.6. The figure compares the total spectrum bandwidths of various spectrum offerings for different wireless communication services in the United States from 1983 through 1998. Figure 2.6 also shows the tremendous amount of spectrum in the 59–64 GHz range that is earmarked for unlicensed WLAN use.

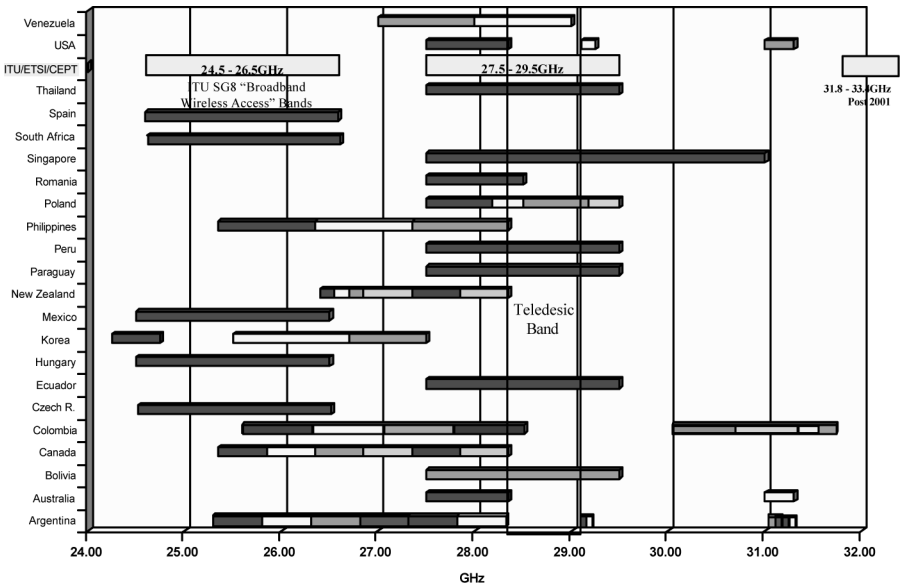
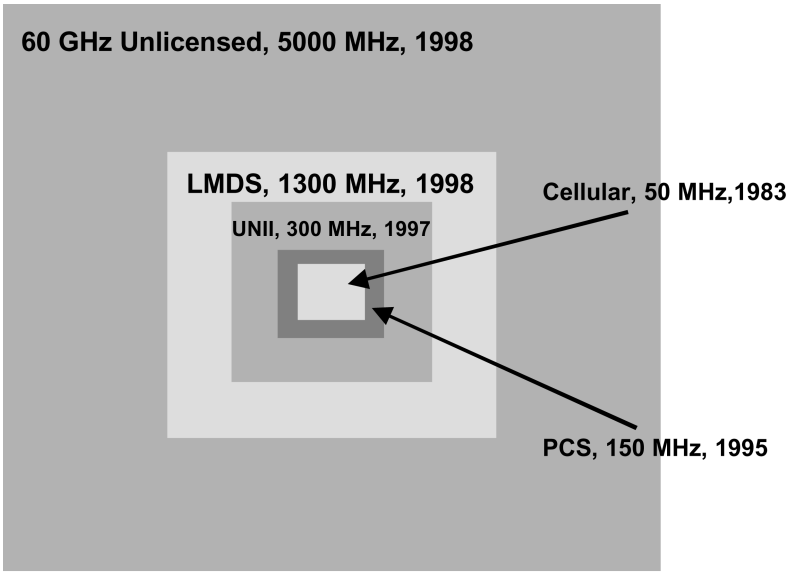


Figure 2.5 Allocation of broadband wireless spectrum throughout the world. (Courtesy of Ray W. Nettleton and reproduced by permission of Formus Communications.)



- A voice channel occupies ≈ 10 kHz of spectrum.
- A TV channel occupies ≈ 5 MHz of spectrum.

Figure 2.6 Comparison of spectrum allocations for various US wireless communications services. The areas of the rectangles are proportional to the amount of bandwidth allocated for each service.

The US LMDS band is 27.5–28.35 GHz, 29.1–29.25 GHz, and 31.075–31.225 GHz. The IEEE 802.16 Standards Committee is developing interoperability standards for fixed broadband wireless access. In Europe, a similar standard, HIPERACCESS, is being developed by a standardization committee for Broadband Radio Access Networks (BRAN) for operation in the 40.5–43.5 GHz band; it will use TDMA. Also, HIPERLINK is a very high speed short range interconnection for HIPERLANs and HIPERACCESS, up to 155 Mbps within 150 meters, and is planned to operate in the 17 GHz band in Europe.

In Figure 2.6, each rectangle has an area proportional to the amount of radio spectrum allocated to the specified service. For example, the US cellular service was first issued spectrum in 1983 and currently occupies 50 MHz of total bandwidth. The PCS service occupies 150 MHz of bandwidth, and the unlicensed National Information Infrastructure (UNII) band, discussed in Section 2.4, occupies 300 MHz. LMDS, on the other hand, was allocated a whopping 1300 MHz of bandwidth—enough spectrum to provide over 200 broadcast quality television channels or 65,000 full duplex voice channels! Yet, the revenues generated from the auction of all the US LMDS licenses was a paltry $500 million, compared to the more than $30 billion generated from the PCS auctions held three years earlier! This market difference is due to the fact that LMDS is a brand new type of service, vastly unproven, and dependent upon millimeter wave equipment that is still expensive. Nevertheless, the vast bandwidth capabilities of LMDS for WLL applications