Wireless Technology Overview

From 1G to 4G

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Sept 2010

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Acronyms

Term	Definition
1G	1st Generation
1xEV-DO	Evolution-Data Optimized
1xRTT	1 times Radio Transmission Technology
2.5G	2nd and a half Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
4G	4th Generation
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone System
CDG	CDMA Development Group
CDMA	Code Division Multiple Access
CQI	Channel Quality Indicator
D-AMPS	Digital AMPS, also known as IS-136
E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EDGE	Enhanced Data rates for GSM Evolution
eHSPA	Evolved High Speed Packet Access. Also called HPSA+.
EIA	Electronic Industries Association
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
EVRC-B	Enhanced Variable Rate Codec B
FCH	Fundamental Channel
FDMA	Frequency Division Multiple Access
FM	Frequency Modulation
GPRS	General Packet Radio Service
GSA	GSM Suppliers Association
GSM	Global System for Mobile Communications
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPA+	Evolved High Speed Packet Access. Also called eHSPA.

Term	Definition
HSUPA	High Speed Uplink Packet Access
IP	Internet Protocol
IS-95	Interim Standard 95, the first digital standard, pioneered by Qualcomm in the 1990s
ITU	International Telecommunications Union
kbps	Kilobits Per Second
LOS	Line of Sight
LSTI	LTE/SAE Trial Initiative
LTE	Long Term Evolution
Mbps	Megabits Per Second
MDR	Medium Data Rate
MI	Multiple Input
MIMO	Multiple Input Multiple Output
MO	Multiple Output
MVNO	Mobile Virtual Network Operators
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
SAE	System Architecture Evolution
SCCH	Supplemental Code Channel
SIM	Subscriber Identity Module
TDMA	Time Division Multiple Access
TIA	Telecommunications Industry Association
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications Systems
UTRAN	Universal Terrestrial Radio Access Network
VoIP	Voice over Internet Protocol
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access

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Wireless Technology Overview From 1G to 4G

Introduction

Since the early 1980s, different types of wireless communications technologies have been developed and commercially deployed throughout the world. Radio interface standards have been developed to describe how information is transmitted between a base station antenna tower and the user's mobile device (cell phone, wireless laptop, PDA, etc.).

Over the last three decades, cellular networks have evolved from first generation (1G) cellular technology of the 1980s to today's deployed third generation (3G) networks. As we approach the end of this decade, a new fourth generation (4G) of radio technology is in development. This white paper briefly describes the evolution of the most common air interfaces, when they emerged, and to which "generation" of technology they belong.

Early Cellular - Advanced Mobile Phone System (AMPS)

In the late 1960s, the first mobile telephone services were introduced in the U.S. These systems typically used a single high powered transmitter and a tall tower in order to cover approximately a distance of thirty miles. By 1976, Bell Mobile Phone Service of New York City, a market of approximately ten million people, had only twelve radio channels and serviced around 500 subscribers. Obviously, these systems were limited in coverage and capacity.

To provide greater coverage and capacity, a cellular concept was necessary. AT&T had actually proposed this idea in the late 1960s, but the technology and radio spectrum required was not yet available. Finally, in the 1980s, the FCC allocated radio channels for the U.S. Advanced Mobile Phone System, also commonly called AMPS.

AMPS was the first cellular technology to be deployed broadly in the United States and around the world. The radio technology used Frequency Division Multiple Access (FDMA), which means each voice conversation was placed on a different radio frequency channel. This concept is depicted in Figure 1.

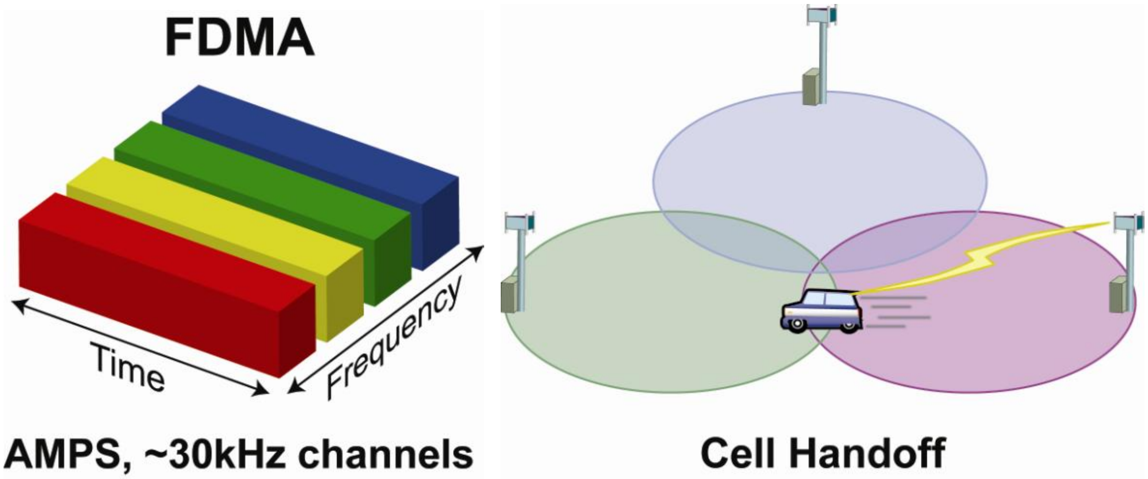

Figure 1. FDMA and the Cellular Concept

Each AMPS radio channel occupied 30 kHz of bandwidth. AMPS coined the term "cellular" to refer to its use of small "cells" within a system. These cells are what made the AMPS system successful, because they allowed radio frequencies to be reused so that more people could use the same radio channel in different geographic areas. This significantly increased system capacity over earlier systems. With the introduction of the cellular concept, mobiles needed to be able to hand off from cell to cell and maintain a voice conversation. AMPS used frequency modulation (FM), to place the users' voice signals on a radio frequency channel or RF carrier. Since FM is an analog form of modulation, we often refer to AMPS as analog.

AMPS' technological deficiencies became apparent as the success of cellular grew. Since it is an analog technology, it is very susceptible to static and noise and has no protection from eavesdropping using a simple FM scanner. In the mid-1980s and early-1990s, "cloning" of phones was an epidemic that cost the industry millions of dollars. This fraudulent practice occurred when criminals using scanners would copy identification numbers from a cell phone, and transfer that information to another phone which was then used for making free calls. The problem became so prevalent that it significantly impacted the user community, as well as operator financial performance. Other limitations were short battery life, poor voice quality, large phones, and "cross talk" where one wireless conversation would be heard over another.

In the 1990s, AMPS was replaced by newer digital standards such as Global System for Mobile Communications (GSM), and Code Division Multiple Access (CDMA) which brought improved performance across all attributes of the wireless network. In 2008, nearly 30 years after its deployment, most major operators have finished removing the few remaining AMPS channels from their networks.

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Second Generation (2G)

To improve the capacity of the first generation radio networks, second generation (2G) radio technologies were introduced and deployed in the 1990s. The key technology advancement in these newer radio technologies was the fact that they employed digital modulation schemes. Digital radio introduced several advantages over analog. Digital signals are more immune to noise, and errors in transmission are more easily corrected via signal processing that can condition the signal to reduce distortion during reception. Also, digital information can be encrypted for privacy. Finally, digital devices are typically smaller, consume less power, and are usually less expensive to produce. Below are the most common 2G radio interface standards deployed. GSM and cdmaOne are still in use today.

Digital AMPS (IS-136)

D-AMPS, also known as IS-136, was used throughout the Americas, particularly in the United States and Canada in the late 1980s and early 1990s. D-AMPS, like GSM, utilized Time Division Multiple Access (TDMA) to share a single radio channel among several voice users. D-AMPS allowed operators to increase capacity over the preceding analog design by digitally compressing the voice data, yielding three times the call capacity of AMPS in a single cell. A digital system also made calls more secure because analog scanners could not receive digital signals. Calls were encrypted, although the algorithm used was later found to be weak.

Large D-AMPS networks included Cingular Wireless (then McCaw, AT&T, Bell South, etc.) and US Cellular in the United States, as well as Rogers Wireless in Canada. Many wireless operators in Latin and South America deployed D-AMPS, with lesser penetration in Asia. Although at the time there were massive technology debates about benefits of TDMA versus CDMA, the D-AMPS technology eventually was abandoned in the 1990s as the major operators developed their 2G networks using either CDMA or GSM.

Global System for Mobile Communications (GSM)

GSM was originally developed by a European Standards organization called the European Telecommunications Standards Institute (ETSI). Serious issues arose in Europe, as there was a lack of radio frequency coordination between countries, and radio signals did not stop at borders. As a result, the standardization process, driven by a group of European telecommunications vendors, ended up with a digital standard that could be deployed uniformly across Europe, with a strong set of protocols for "roaming" between countries. The technical fundamentals of the GSM system were defined in 1987. In 1989, the ETSI took control and by 1990 the first GSM specification was completed.

GSM uses Time Division Multiple Access (TDMA) to allow users to share the radio channel. Every voice user occupies one of eight timeslots within a 200 kHz radio channel throughout the call duration.

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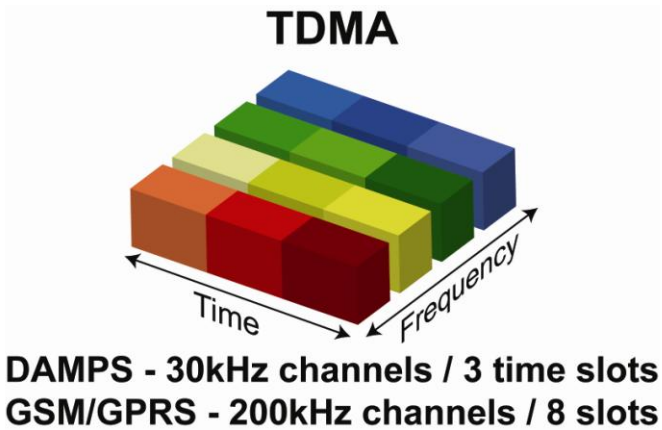

Figure 2. TDMA Concept

As shown in Figure 2, TDMA is a multiple access method in which users are assigned a frequency channel (red, yellow, green, or blue) that is shared over time among several users. However, each user is only allowed to transmit in a predetermined timeslot, as depicted by the different shades in each channel. The user has the sole right of using the frequency channel and the timeslot for the duration of the call. As with FDMA, this means no two users can occupy the same channel within a cell or between adjacent cells at the same time. Should this happen, interference occurs and the quality of the call degrades; eventually the call may drop.

To avoid this co-channel interference, GSM radio channels must be reused and managed in accordance with a frequency plan, as shown in Figure 3.

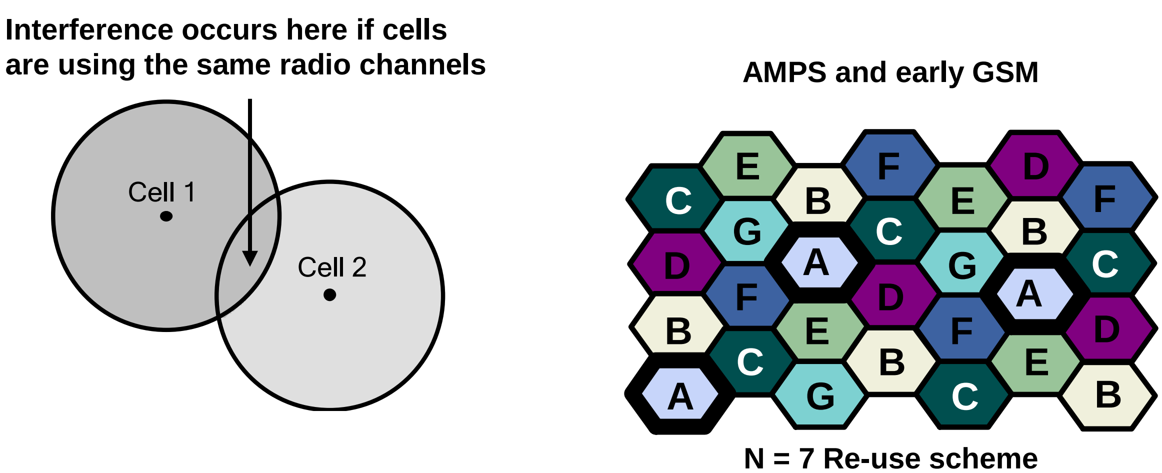

Figure 3. Cell Interference and Frequency Reuse for FDMA and TDMA

A typical reuse plan would re-use a GSM 200 kHz radio channel every 7th cell (cell A). This N=7 reuse scheme (cells A-G) ensures the same radio channel is not reused in adjacent cells. However, this reduces the network's channel capacity in each cell by a factor of 7, which limited early GSM system capacity. Notice that by reusing the radio channels more frequently, say every third cell, the network's capacity increases by about a factor of two.

As the GSM standard continued to develop, it retained backward compatibility with the original GSM phones; for example, GSM introduced frequency hopping to allow it to reuse the radio channels more frequently, thus increasing the network capacity. Packet data capabilities were added in the Release '97 version of the standard, by means of General Packet Radio Service (GPRS). Higher speed data transmission has also been introduced with Enhanced Data rates for GSM Evolution (EDGE) in the Release '99 version of the standard. Currently the GSM standards are managed and coordinated within the 3GPP standards organization, and support interoperability with 3G UMTS/WCDMA networks. The GSM standards are available online at **3gpp.org.**

Today, GSM service is used by over 2 billion people across more than 200 countries and territories. There are currently about 500 GSM operators globally, the majority of which have migrated or will be migrating their networks to "3G" over the coming years. In 2008, there were over 75 GSM operator deployments and there are still more than 100 future deployment commitments. More information on GSM and 3G UMTS/WCDMA market statistics can be found at the Global mobile Suppliers Association website **gsacom.com**.

From the point of view of the consumer, the key advantage of GSM systems has been higher digital voice quality and low cost alternatives to making calls, such as text messaging. The advantage for network operators has been the ability to deploy equipment from different vendors because the open standard allows easy inter-operability. GSM also provides a cellular network evolution path to 3G by leveraging functionality of the existing core network elements. GSM allows network operators to offer roaming services, which means that subscribers can use their mobile phones on different operator networks all over the world. The implementation of a Subscriber Identity Module (SIM) enables users to subscribe to services on different operator networks using any GSM phone.

IS-95/cdmaOne

Interim Standard 95 (IS-95) was the first CDMA-based digital cellular standard, pioneered by Qualcomm in the 1990s. The brand name for IS-95 is cdmaOne. Qualcomm's radio technology employed spread spectrum techniques used in secure military communication to encode and transmit voice and data information over wider bandwidths. The IS-95 radio channel is 1.25 MHz wide, which is 40x the bandwidth of AMPS channels and 6x the bandwidth of GSM. At the time this was considered a very wide band radio channel.

Code Division Multiple Access (CDMA) is a digital radio system that transmits streams of coded bits at a higher rate than the information rate. In doing so, CDMA permits several radios to share a single wideband channel. Unlike TDMA, all the mobile devices can be active on the same radio channel at the exact same time because each user's information is coded uniquely. This is shown in Figure 4, where each user code is represented by a different color.

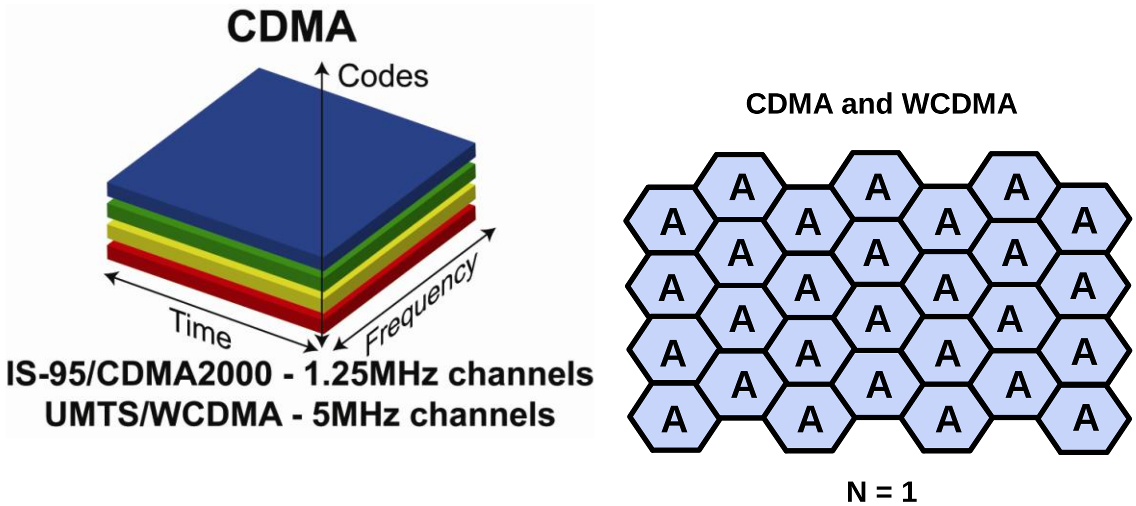

Figure 4. CDMA Concept and CDMA Frequency Reuse

Notice that each user occupies the entire frequency channel at the same time. As a result, CDMA radio channels can be reused in every cell in the network, which significantly increases capacity over the early FDMA- and TDMA-based standards.

CDMA is sometimes best described by what's known as the "cocktail party" analogy. FDMA, or Frequency Division, is like having folks in their own little rooms having a conversation. TDMA, or Time Division, is like having folks in a room, but taking turns speaking. CDMA, or Code Division, is like having folks all talking in a room at the same time, but speaking different languages that can only be "decoded" by the person with whom they are speaking the same language.

As in a cocktail party, if someone speaks too loudly, they start "drowning out" others in the room. CDMA compensates for this issue by a technique called "power control," which regulates the power level 800 times a second, keeping everyone "speaking softly" so more people can "talk in the room" simultaneously. Even with power control, as more and more users talk at the same time, the "noise in the room" eventually gets so loud that no one can hear anyone else. This noise rise is what you experience during happy hour at the local brew pub; for a CDMA network this is referred to as the overloading of a CDMA radio channel. For this reason, CDMA requires all mobile devices to be continuously power controlled, and the number of users on the CDMA channel is kept below this overload condition.

IS-95 was first deployed in Hong Kong in the fall of 1995, followed by large scale launches in South Korea in early 1996, and in the United States in the fall of 1996. The CDMA air interface has been widely deployed in the U.S.A., Canada, Mexico, Brazil, Israel, India, South Korea, China, and New Zealand. Actual deployment and subscriber numbers for IS-95 based technologies are provided in detail at the CDMA Development Group web site at cdg.org. Over 280 operators deploy CDMA-based radio technology worldwide. Currently, cdmaOne and its 3G successor, CDMA2000, have over 460 million subscribers in more than 102 countries around the world. Interestingly, less than one percent of those subscribers are still using the original cdmaOne technology.

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From the point of view of the consumer, the key advantages of CDMA systems have been better voice quality, handoff reliability, and significantly longer battery life. The advantage for network operators has been the ability to deploy high capacity cellular networks with universal frequency reuse. IS-95 also provides an attractive cellular network evolution path to 3G by leveraging the existing CDMA air interface standards. This has allowed operators to upgrade the radio access portion of the cellular network with little change to the existing radio frequency plan.

CDMA2000 also allows network operators to provide roaming services to other CDMA networks. In addition, some CDMA operators offer dual-mode phones that can operate on both CDMA and GSM networks; this allows CDMA subscribers to use either CDMA or GSM networks, worldwide.

Two and a Half G (2.5G)

Invented by the industry, the term "two and a half G" is used to describe 2G-systems that began to implement data services over what had been predominantly voice-centric wireless networks. Defining which technologies were 2.5G versus 3G was the subject of furious debate around the globe. Qualcomm used as a definition the International Telecommunications Union (ITU) description, which used data rates of 144 kilobits per second (kbps) as the threshold between 2G and 3G technologies.

General Packet Radio Service (GPRS)

GPRS is a mobile data service available to users of GSM mobile phones. Initial standardization was conducted by ETSI, but was handed off to 3GPP—Third Generation Partnership Project—which became responsible for the further definition of GSM towards 3G and beyond. GPRS is often described as “2.5G,” that is, a technology between the second and third generations of mobile telephony. The technology was integrated into GSM standards releases starting with Release ‘97 and onwards. It provides moderate-speed data transfer in the area of 40-70 kbps (similar to dial up wired modem speeds), by sending packet data on unused TDMA time slots in the GSM network. GPRS defines a core network architecture that subsequently became the blueprint for the architecture of the 3G core network used in UMTS.

Enhanced Data rates for GSM Evolution (EDGE)

EDGE is a digital mobile phone technology that is a packet data enhancement to GSM and GPRS networks. EDGE can function on any network with GPRS deployed on it, provided the operator implements the necessary upgrades to the core and access network. EDGE can carry data speeds up to 236.8 kbps for 4 timeslots and its theoretical maximum is 473.6 kbps for 8 timeslots. However, as with all peak rate claims, EDGE in reality provides about 60-100 kbps, and that can be highly variable due to network design and the amount of voice traffic being used concurrently on the network. EDGE has been introduced into GSM networks around the world since 2003, and has been moderately successful. However, EDGE does not allow for much variance in system speeds or capacities over GPRS, and does not have the performance or capacity of GSM’s 3G evolutionary path to Wideband CDMA (WCDMA) and beyond.

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TIA/EIA-95 (IS-95B)

While the working title of the IS-95A revision was known as IS-95B, the standard was formally released as TIA/EIA-95. The new revision combined IS-95A, TSB-74 (for analog interworking support), and ANSI J-STD-008 (for 1900 MHz operation) into a single air interface standard and eliminated much of the redundancy between the three documents.

A significant performance improvement to IS-95 was the addition of the Medium Data Rate (MDR) service to provide 2.5G data rates. This TIA/EIA-95 compatible mode includes Rate Set 1 and 2 traffic channels operating at 9.6 and 14.4 kbps respectively. MDR assigns multiple traffic channels to a user to improve peak data rate performance. The Fundamental Channel (FCH) carries signaling, and/or user data. In addition, up to 7 Supplemental Code Channels (SCCH) can be used to carry user data. Each FCH and SCCH has the same data rate performance as the Rate Set 1 and 2 traffic channels. IS-95B theoretically supports a peak data rate of 115.2 kbps, and commercial MDR services could typically provide users with a 32-64 kbps connection.

Third Generation (3G)

3G is short for third-generation technology and is used in the context of mobile phone standards. The services associated with 3G provide the ability to transfer simultaneously both voice data (a telephone call) and packet data (such as downloading information, exchanging email, and text messaging).

The ITU definition of 3G, used by various groups in developing their 3G standards, set the “3G Bar” at the transmission of 384 kbps for mobile systems and 2 Megabits per second (Mbps) for stationary systems. 3G also has greater spectral efficiency, meaning that scarce spectrum resources are used more efficiently. This means that operators have significantly higher capacity than earlier 2G systems for the provisioning of emerging data and multimedia services at both higher speeds and lower cost.

The evolution from the initial AMPS cellular phones to 3G technology is depicted in Figure 5. Notice that after AMPS deployments in the 1980s, operators had to choose between TDMA and CDMA technology for their 2G network. This important decision, made almost 20 years ago, affected the future direction of an operator’s network evolution to 3G. Once an operator like Sprint or Verizon chose to deploy IS-95 based technology in the 1990s, they essentially chose their 3G destiny, CDMA2000. In a similar fashion, GSM operators naturally evolved to UMTS/WCDMA since the standard was built around the GSM/GPRS core network architecture. Operators who tried to go with D-AMPS eventually were forced to evolve to GSM or cdmaOne 2G networks.

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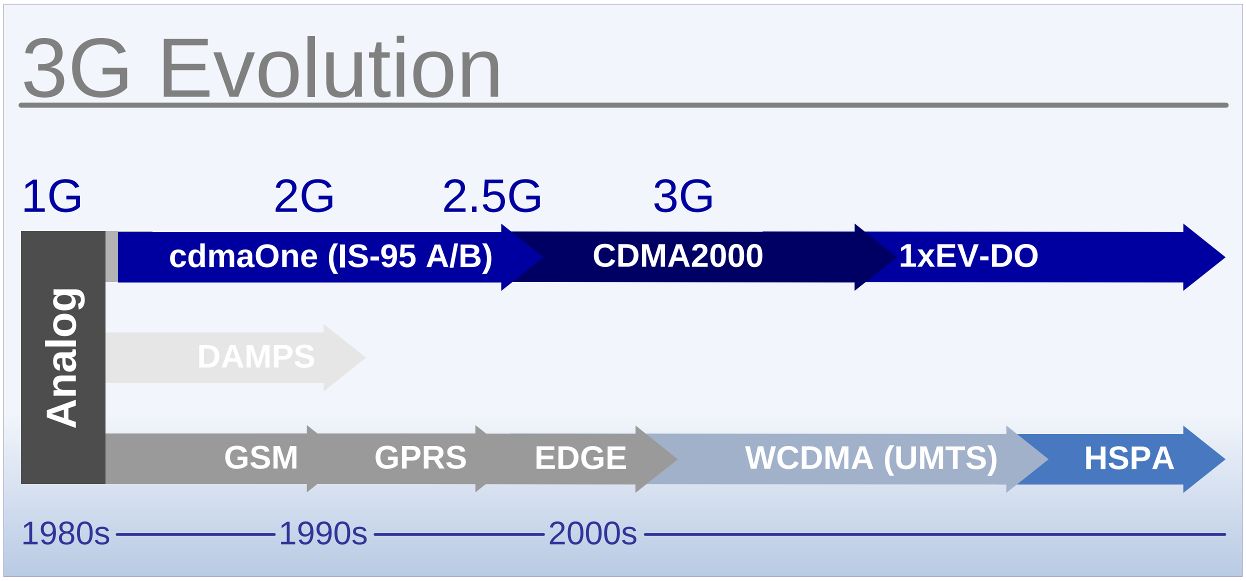

Figure 5. Evolution of Wireless to 3G

Figure 5 also shows that CDMA-based technology was the dominant choice for 3G deployments. In this recent decade, we can see the evolution of these 3G CDMA networks as operators around the world continue upgrading the networks to meet subscriber demand. Past forecasts suggested that by 2010 almost half the world's subscribers would have 3G services. As the end of the decade approaches, we are not far away from realizing that prediction. Below is a brief description of the key 3G radio technologies.

UMTS/WCDMA

Wideband Code Division Multiple Access (WCDMA) is the radio access technology behind the 3G Universal Mobile Telecommunications System (UMTS) standard, and is aligned with the evolution of the GSM standard according to the International Telecommunication Union (ITU). WCDMA is a wideband spread-spectrum air interface that utilizes Code Division Multiple Access in a fashion similar to cdmaOne. UMTS is sometimes marketed as 3G or WCDMA and its initial release supports up to a 384 kbps peak data rate. WCDMA requires a 5 MHz frequency channel, which is 4x wider than the channel used in IS-95.

Although UMTS/WCDMA was designed as the evolution of GSM, the radio access portion of the network is not backward compatible with GSM and therefore was designed to be interoperable with GSM handsets. This means an entire new radio access network (UTRAN) must be built over the existing GSM network in order for the operator to implement a 3G UMTS network. For this reason it took longer for WCMA technology to be widely deployed when compared to CDMA2000.

UMTS standards are developed by the Third Generation Partnership Project (3GPP). The initial release of the UMTS/WCDMA standard was called Release 99 and supported voice and packet data services. The standard leveraged the existing GSM core network design and was a key driver in the UMTS standards. For this reason, GSM operators migrated to UMTS as a 3G solution. Both AT&T and T-Mobile are GSM operators deploying UMTS in the United States and Europe. Currently there are over 280 WCDMA operators in 120 countries worldwide. To

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improve packet data performance, subsequent releases of the standard were developed to provide High Speed Packet Access (HSPA).

High-Speed Downlink Packet Access (HSDPA)

HSDPA is also sometimes referred to as Release 5, in reference to the version number of the standard that introduced the technology. An evolution of the WCDMA Release-99 air interface, HSDPA achieves an increase in data transfer speeds by time-multiplexing users on the downlink and using advance modulation and coding. A new high-speed downlink shared channel that time-shares high-speed WCDMA channels is used for downlink communications to the mobile. HSDPA specifies peak data rates up to 14 Mbps. In real networks, it provides average download speeds of 400-700 kbps, with bursts to more than 1 Mbps. HSDPA does not improve the uplink data rate performance of Release-99. AT&T has been upgrading its U.S. network to HSDPA since 2006.

One important change made with HSDPA was the idea of replacing a power-controlled, fixed data rate connection with a channel-quality-dependent, variable data rate connection. Voice services are very different from packet data service in terms of latency, error tolerance, and throughput. Since most packet service throughputs vary over time and tolerate delay, it is more efficient to "schedule" users opportunistically when their radio channel conditions are most favorable. HSPDA uses channel quality indication (CQI) feedback from each phone to the network so it can maximize data rate performance for all users. As the channel quality improves, HSDPA adapts the modulation and coding (AMC) of data to use the WCDMA channel at the maximum data rate possible. This technique is often referred to as link adaptation.

High-Speed Uplink Packet Access (HSUPA)

HSUPA, or Enhanced Uplink (EUL), is the next step in the upgrading the UMTS network, improving uplink data speeds up to 5.76 Mbps. The specifications for HSUPA are included in the UMTS Release 6 standard. HSUPA improves performance by introducing enhanced uplink WCDMA channels and allowing the base station to accept more user load. An additional characteristic of HSUPA is that it has much lower connection and latency times, enabling operators to offer high quality internet-based voice services called Voice over Internet Protocol (VoIP). HSUPA does affect the downlink data rate performance of HSDPA. The technology has been deployed commercially in the U.S. since 2008.

In the uplink, there is a problem of many users accessing one network resource—the base station—and WCDMA requires power control to share that resource. Hence, improving data rate performance on the uplink is done somewhat differently than in HSDPA. First, HSUPA maintains the power control of the new enhanced uplink channels. Second, more user data can be placed on a channel; then multiple channels can be combined to increase user data rates. To improve the throughput over the entire channel, HSUPA schedules users' uplink transmissions and allows greater loading of the WCDMA radio channel.

Today, there are over 330 million UMTS/WCDMA subscribers; including over 100 million with HSPA services. Notice this is still smaller than the CDMA2000 subscriber numbers mentioned earlier. However WCDMA subscriptions are growing, and at a much faster rate than CDMA2000, which saw its greatest growth rates earlier this decade. In 2008 alone, over 100 million UMTS subscribers were added—about a 55% growth rate. Of the roughly 280

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operators worldwide, over 200 have HSDPA networks commercially launched in more than 100 countries. The number of HSUPA deployments is approaching 100.

Evolved High Speed Packet Access (eHSPA/HSPA+)

Evolved HSPA is designed to provide a simple evolution path for UMTS service providers as they upgrade their UMTS and HSPA technology. In each step, operators see an increase in functionality, higher data speeds, and better spectral efficiency. Although UMTS delivers high data transfer rates, wireless data usage is expected to increase significantly over the next decade. The emergence of competitive 4G technologies is driving some UMTS operators to consider evolving their networks to HSPA+ in order to maintain their competitive advantage. How long 3G radio technology will last and the success of eHSPA will depend somewhat on the timeframe and success of upcoming 4G deployments.

Evolved HSPA is defined in Release 7 and 8 of the UMTS standards and specifies peak data rates up to 42 Mbps on the downlink and 22 Mbps on the uplink. The actual peak downlink speed for a user is expected to be about 14 Mbps close to the cell tower and about 4 Mbps at the cell edge. The eHSPA standard also introduces an optional all-IP architecture for the network where base stations are directly connected to the operator's edge routers using Internet Protocol (IP) backhaul connections. The technology also delivers significant battery life improvements and dramatically quicker wake-from-idle time—delivering a true always-on connection.

For many operators, the cost to evolve a UMTS network to HSPA and Evolved HSPA should be significantly less than the cost of deploying an entire new 4G network. This is particularly true if the operator only upgrades the existing HSPA air interface. Upgrading to all-IP networks also significantly increases upgrade costs and has other cost implications for the operators to consider. In December 2008, Telstra and Ericsson teamed together to announce the first eHSPA deployment in Australia, and demonstrated the first data call at 21 Mbps downlink speed. How many more operators will choose to extend the life of their 3G networks with Evolved HSPA?

CDMA2000 1x

The CDMA2000 1x wireless air interface standard is known by many terms: 1x, 1xRTT, IS-2000. The designation "1xRTT" (1 times Radio Transmission Technology) is the nomenclature used to identify the version of CDMA2000 radio technology that operates in a single 1.25 MHz bandwidth channel. The new 3G standard more than doubles the voice capacity when compared to second generation CDMA networks. Capable of higher data rates than cdmaOne, CDMA2000 1x has a peak data rate of 153 kbps, with a realistic data throughput on a loaded network of 70-90 kbps; about the same user data speed as GPRS and EDGE. The CDMA2000 standards are maintained by the 3rd Generation Partnership Project 2 (3GPP2) and are available online at **3gpp2.org**.

The early radio configurations of CDMA2000 used the same radio access technology as IS-95, which made 3G upgrades simpler for 2G CDMA operators. They did not have to deploy an entire new 3G access network as GSM operators did, because CDMA2000 was truly backward compatible with IS-95. This accelerated the upgrades to 3G for many cdmaOne operators. While CDMA2000 1x officially qualifies as 3G technology per the ITU definition described earlier, 1xRTT has also been deployed in 2G spectrum in some countries that limit 3G systems

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to certain frequency bands. CDMA2000 1x and 1xEV-DO are currently deployed by both Verizon and Sprint in the United States.

By the end of 2006, there were over 180 deployed commercially operating networks providing service with cdmaOne and CDMA2000 systems supporting over 300 million subscribers globally. Earlier in this decade, CDMA2000 had a big edge over WCDMA in terms of 3G deployments and subscriber numbers. This was largely due to the fact that it was an easier 3G upgrade for cdmaOne operators. However, CDMA2000 growth has slowed significantly at the end of this decade, and WCDMA continues to take a greater portion of the 3G market.

CDMA2000 1x Evolution-Data Optimized (1xEV-DO) Release 0

Abbreviated as 1xEV-DO, EV-DO, or Rel 0, this wireless packet data standard has been adopted by many CDMA service providers throughout the world over the past decade. The air interface standard is also developed and maintained by 3GPP2 as part of the CDMA2000 family of standards. The initial design of 1xEV-DO was developed by Qualcomm in 1999 to exceed 3G requirements for a 2 Mbps downlink data rate during stationary communications.

Compared to the 1xRTT networks, or the GPRS and EDGE networks still employed by their GSM competitors, 1xEV-DO Release 0 is significantly faster, providing mobile devices with downlink air interface data speeds of up to 2.4 Mbps. More practically, users on loaded networks can obtain average mobile broadband speeds of 400-600 kbps, according to published field data. EV-DO was designed for downlink data-intensive and delay-tolerant applications such as web browsing and email. Note that the uplink performance in Release 0 is only 153 kbps, the same peak data rate offered in 1x.

The performance enhancements in EV-DO are similar to those in HSDPA in that they both significantly improve downlink packet data performance without improving the uplink data rate. Both air interfaces replace the fixed-rate, dedicated-downlink power-controlled user channel, with a time shared channel. The network adapts the channel throughput of the shared channel for each user as their link quality changes. When deployed with a 1x voice network, 1xEV-DO requires that the operator set up a completely separate EV-DO radio channel of 1.25 MHz. This is different from the HSPA approach were the existing Release 99 radio channels can be modified to add HSPA operation on the same radio channel.

1xEV-DO Revision A and B

The successor to the initial release of the EV-DO standard is called Revision A, which has been commercially deployed in the United States by Sprint and Verizon Wireless since 2006. Revision A offers fast packet session establishment on both the downlink and uplink, along with air interface enhancements that reduce latency and improve data rates. In addition to the slight increase in the maximum downlink data rate from 2.4 to 3.1 Mbps, Rev A has a 12x improvement in the maximum uplink data rate over Release 0, from 153 kbps to 1.8 Mbps.

In many ways, the uplink and latency performance improvements in Rev A are similar to those in HSUPA. EV-DO Rev A supports low latency services (as low as 50 milliseconds) including Voice over Internet Protocol (VoIP) and Video Telephony on the same carrier using traditional IP data services. Today there are more than 160 commercial EV-DO networks deployed in over 50 countries with over 110 million subscribers worldwide. About 100 of these deployments are Release 0 networks.

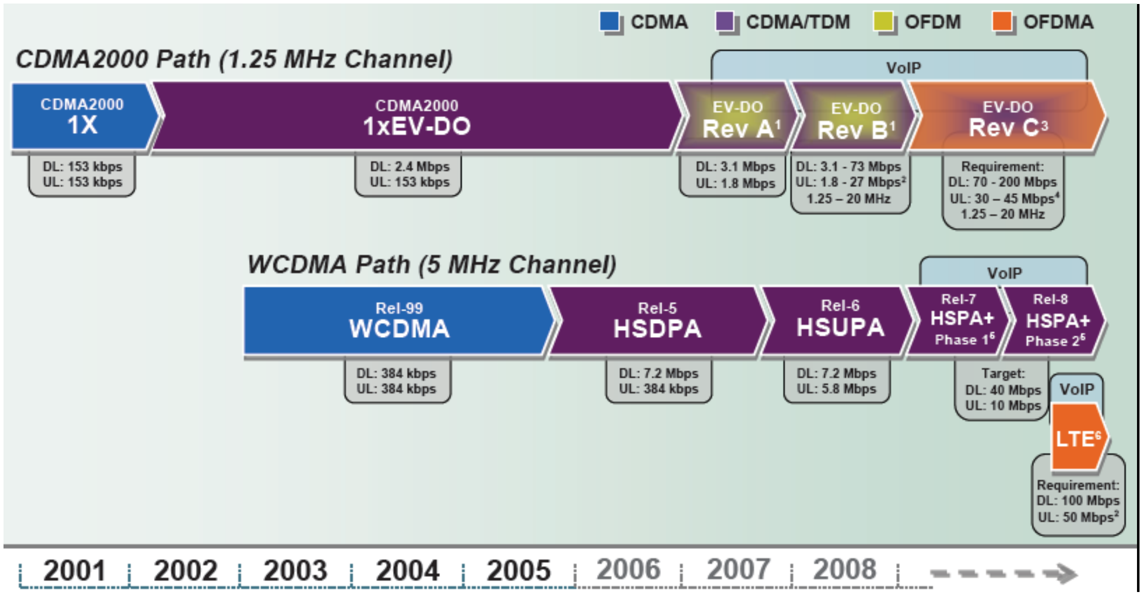
1xEV-DO Revision B is the future evolutionary path for 1xEV-DO Rev A. This second revision of the Release 0 standard increases the throughput of the radio link by allowing aggregation of the radio channels in 1xEV-DO Rev A. Initial implementation aggregates three radio channels (1.25 MHz each) using a software upgrade. Further improvements in data rate and user capacity can be achieved with a hardware upgrade that enables interference cancellation and higher order modulation such as 64 QAM. Even though Rev B aggregates the Rev A channels, it still allows existing Rev A and Rel 0 devices to use the network, and hence is backward compatible with existing user handsets.

Rev B multi-carrier EV-DO supports significantly higher per-user throughput by multiplexing traffic across multiple radio channels. Such multi-carrier multiplexing delivers a significant reduction in data latency when compared to Rev A systems serving the same users on the same carriers. After a Rev B software upgrade to an existing 1xEV-DO Rev A radio network, operators can launch services utilizing peak speeds of 9.3 Mbps on the downlink and 5.4 Mbps on the uplink, using three 1.25 MHz-wide carriers. This represents a 3x improvement over Rev A in peak data rate, which will significantly improve the end user experience when running multimedia applications such as high definition video streaming and music downloads.

3G Evolutionary Paths - CDMA2000 versus UMTS/WCDMA

Figure 6 graphically depicts the two primary evolutionary paths that have emerged in 3G: CDMA2000 and UMTS/WCDMA. Both paths provide a relatively seamless transition from 2G to 3G technologies by ensuring backward compatibility or interoperability. Both the CDMA2000 and WCDMA evolutionary paths strive to provide an efficient solution for wireless service providers, with support for mobile high speed packet data.

In Figure 6, notice how the current 3G technologies evolve from CDMA to OFDMA (we will discuss OFDMA shortly).



Note: timeline depicts initial commercial availability of each technology. Those introduced beyond 2008 are under standardization and are subject to variability

[1] EV-DO Rev A and Rev B incorporate OFDM for multicasting
[2] Data rates of 73 Mbps for the DL and 27 Mbps for the UL figures are based on a 2 x 20 MHz allocation.
[3] May have multiple modes, with at least one mode being backwards compatible with EV-DO (all versions); will likely utilize CDMA/OFDM or a combination of OFDMA; MIMO/SDMA; leverages EV-DO protocol stack.
[4] Data rate dependant on level of mobility. Data rates of 73 Mbps for the DL and 27 Mbps for the UL figures are based on a 2 x 20 MHz allocation.
[5] Release 7 and Release 8 introduce enhancements such as MIMO and VoIP.
[6] Utilizes OFDMA on the DL and SC-FDMA on the UL; MIMO.

Figure 6. 3G Evolutionary Paths - CDMA2000 versus UMTS/WCDMA

Current CDMA2000 networks employ a combination of CDMA2000 1X—primarily for voice services—and EV-DO for high speed data. As deployments of 1xEV-DO Release 0 and Rev A continue, the big challenge for the CDMA2000 operators is to choose their future evolution path. Because 1xEV-DO Rev C technology development has been abandoned, the question then becomes, will these operators decide to migrate to Rev B, or will they decide to upgrade their networks to 4G?

WCDMA networks followed a similar evolution. These networks employ a combination of GSM/GPRS/EDGE and WCDMA, supporting voice over circuit switched networks as well as packet data. As these networks are upgraded to HSDPA and HSUPA, packet data rates will significantly increase. These networks will in turn evolve to HSPA+ and LTE networks in the future, providing more efficient voice services via VoIP, as well as very high data rates.

Fourth Generation (4G)

Fourth-generation (4G) wireless is the stage of broadband mobile communications that will supersede the third generation. Neither standards bodies nor carriers have specified or agreed upon what exactly 4G will be, but fourth generation networks are likely to use a combination of WiMAX and LTE radio standards. What most distinguishes 4G technologies from their 3G predecessors is the use of OFDMA, a new radio interface technology to replace third generation CDMA, and the use of multiple input multiple output (MIMO) antenna technology. Another important goal in 4G is to eliminate circuit switched core network elements and implement a packet core network based on Internet Protocol (IP).

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a radio technology that distributes data over a large number of closely spaced narrowband carriers, or *subcarriers*.

In a conventional frequency division multiplexing system, the frequency spacing between carriers (channels) includes a guard band to ensure that interference is minimized and can be removed. In OFDM, however, the carriers are packed much closer together as shown in Figure 7, thus increasing spectral efficiency and data rate performance. Notice that in OFDM, the adjacent subcarrier power is zero at the center of each subcarrier, which minimizes interference between the subcarriers.

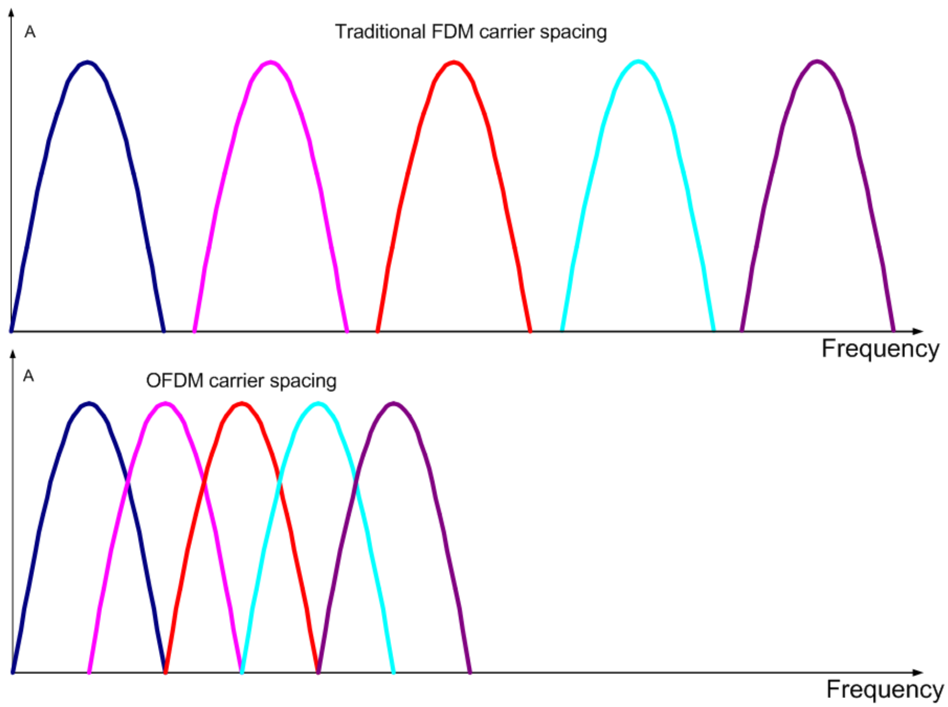


Figure 7. Traditional FDM versus OFDM Carrier Spacing

Another key feature of OFDM is its resistance to multipath fading. OFDM functions by sending a high rate data stream over many low rate subcarriers. This is different from CDMA where the transmitted information is coded and spread across a single high rate carrier.

Orthogonal Frequency Division Multiple Access (OFDMA) is a technique that allows users to share an OFDM channel by assigning users to different tones or subcarriers at different time slots. The OFDMA concept depicted in Figure 8 shows how the different subcarriers are reallocated to different users (represented as different colors) over time. Based on both user demand and channel conditions, different users can be given different groups of subcarriers during each time slot. Users avoid interfering with one another within the same cell by using different subcarriers at different times to send their data.

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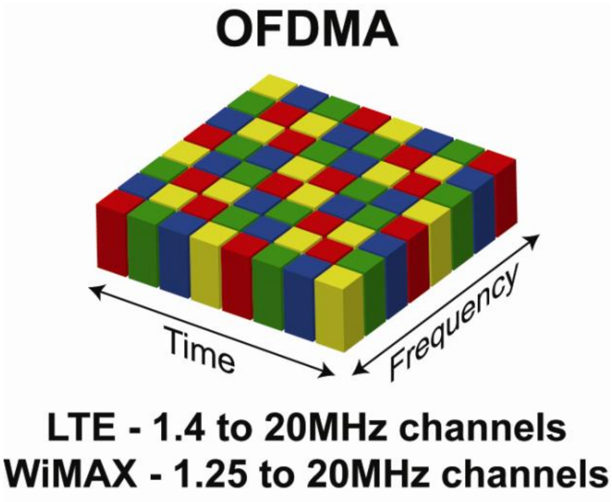

Figure 8. OFDMA Concept

OFDMA and CDMA Compared

CDMA and OFDMA technologies share the radio channel in different ways. CDMA spreads the user information over a wider bandwidth than the information rate. This technique works well for voice service data rates (~10 kbps) and packet data rates (~1 Mbps) for radio channels up to 5 MHz of bandwidth. For wider radio channels, beyond 5 MHz, an OFDMA multicarrier approach offers a more flexible implementation and improved spectral efficiency. Because OFDMA tightly packs many subcarriers into a channel, portions of the entire radio channel bandwidth can be allocated to users differently over time. In addition, OFDMA radio channels can be easily scaled to wider bandwidths.

OFDMA is being implemented in 4G radio technologies that will be deployed in parallel with the current CDMA2000 and UMTS 3G radio networks. For this reason, CDMA and OFDMA will coexist for the next several years as 4G broadband technologies like WiMAX and LTE become widely deployed. The future of CDMA depends on the lifetime of CDMA air interface standards such as WCDMA and CDMA2000. Considering the planned performance enhancements available with CDMA2000 and eHSPA, one can expect CDMA to remain widely deployed in the coming decade.

MIMO

Multiple-Input and Multiple-Output, or MIMO, is the use of multiple antennas at both the transmitter and receiver to improve communication performance. An example of the MIMO approach is shown in Figure 9. MIMO technology has become more prevalent in evolved HSPA and fourth generation wireless communications, because it offers significant increases in data throughput and link reliability without additional bandwidth. MIMO achieves this by exploiting the multiple communication channel paths between multiple transmitters and receivers. The result is higher throughput in a given channel bandwidth and better resistance to fading in the communication channel.

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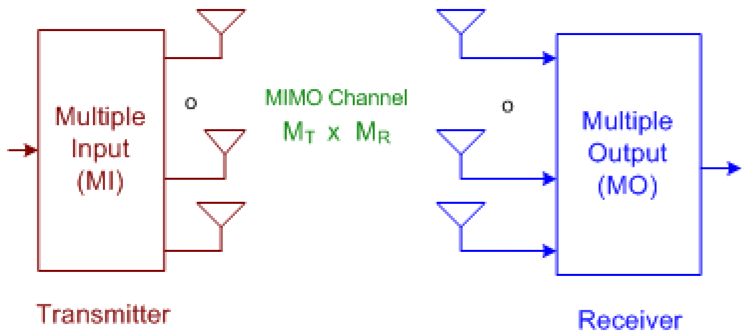

Figure 9. MIMO Concept

1xEV-DO Revision C

Also known as Ultra Mobile Broadband (UMB), this third revision of 1xEV-DO can deliver higher data rates and lower latency than previous 3G EV-DO systems. In 20 MHz of bandwidth, UMB can increase the peak rates up to 200 Mbps in the downlink. Revision C supports flexible and dynamic channel bandwidth scalability from 1.25 MHz up to 20 MHz and is backward compatible with Revisions A and B. The standard uses OFDMA and MIMO antenna systems to improve performance over previous EV-DO revisions. Like LTE, the UMB system is based on Internet Protocol (IP) networking technologies running over a next-generation radio system. Early versions of the standard were published in 2007.

To provide compatibility with the systems it was intended to replace, UMB is designed to support handoffs with earlier 3GPP2 technologies, including existing CDMA2000 1x and 1xEV-DO systems. However, 3GPP added this functionality to LTE, allowing LTE to become the single upgrade path for all wireless networks. Since the Revision C standard was published, no carriers have announced plans to adopt UMB, and most CDMA carriers in Australia, USA, Canada, China, Japan and Korea have already announced plans to adopt either WiMAX or LTE as their 4G technology.

In November 2008, UMB's lead sponsor, Qualcomm, announced it was ending development of the technology.

Future of CDMA2000 - 1x Advanced

With no major supporters for continuing the evolution of EV-DO Rev C, the future of CDMA2000 depends, to a large extent, on the success of LTE and WiMAX. To offer alternative network upgrades to CDMA2000 operators, enhancements to CDMA2000 1xRTT and 1xEV-DO have been proposed. These enhancements are often marketed as "1x Advanced" or "DO Advanced."

The idea behind 1x advanced is to improve network utilization of the existing CDMA2000 infrastructure. This allows operators to improve the capacity of existing 3G networks as they upgrade to 4G technologies such as LTE and WiMAX.

In CDMA2000 1xRTT, advancements focus on improving circuit switched voice capacity, by improving the voice coder efficiency and using interference cancellation techniques. Initially, 1x plans to increase voice capacity from 35 to 55 calls per 1.25 MHz radio channel, using a new codec (EVRC-B) and handset interference cancellation. Future upgrades more than double capacity to 70 calls per channel.

In 1xEV-DO, advancements focus on improving Rev B peak data rates to approximately 35 Mbps in 5 MHz of spectrum. To achieve this, several improvements are proposed, such as implementing higher order modulation and MIMO to allow greater spectral efficiency, thus increasing the throughput of each radio carrier in both directions. Scalable spectrum allocation allows different non-contiguous radio channels to be aggregated in scalable fashion, giving operators more flexibility in spectrum usage. In addition, further improvement in terminal chipsets reduces the power consumption and increases access terminal standby times.

Worldwide Interoperability for Microwave Access (WiMAX)

The name "WiMAX" was created by the WiMAX Forum, which promotes the conformity and interoperability of the standard. The technology is based on the IEEE 802.16 standard, also called Broadband Wireless Access. There many versions of the 802.16 standard and early versions did not support mobility. Mobile WiMAX is designed to offer data speeds up to 15 Mbps; fixed WiMAX offers data speeds up to 70 Mbps as an alternative to wireline broadband networks. Mobile WiMAX defines an end-to-end solution including air interface radio technology 802.16e and an all-IP network architecture. The solution is based on standards that allow interoperability among operators. While WiMAX does not define a specific spectrum range, it can support a wide range of frequency allocations around the world.

WiMAX had its inception in 2001. The 802.16 standard, which started as an alternative to fixed microwave access, has evolved in a different direction. The 802.16 group was initially tasked with developing fixed Line of Sight (LoS) technology operating at higher spectrum ranges (10 to 66 GHz) for metropolitan access. The 802.16 group then created 802.16-2004 (aka 802.16 a/d), a solution for fixed broadband wireless networks. 802.16-2004 is based on OFDM technology. Fixed WiMAX offers a Non Line of Sight (NLOS) version that operates in a spectrum range between 2 GHz and 11 GHz, which is where most fixed broadband wireless networks operate.

The next step in WiMAX's evolution was the addition of mobility to the air interface standard, 802.16e-2005, based on scalable OFDMA technology. 802.16e typically operates in spectrum ranges between 2 GHz and 6 GHz, The WiMAX Forum is investigating deploying below 2 GHz where most cellular networks operate today.

In mid-2006, Sprint Nextel announced that it would invest about $5 billion in a WiMAX technology build-out over the next few years. Since that time, Sprint Nextel has experienced setbacks resulting in billions of revenue losses, which has delayed this investment. In 2008, Sprint, Google, Intel, Comcast, and Time Warner announced a pooling of an average of 120 MHz of spectrum and formation of a new company that will take the name Clearwire.

The new company hopes to benefit from combined services offerings and network resources. The cable companies will provide media services to other partners while gaining access to the wireless network as a Mobile Virtual Network Operator (MVNO). Google will contribute Android handset device development and applications and will receive revenue share for advertising and other services they provide. Sprint and Clearwire gain a majority stock ownership in the new venture and ability to access both the new Clearwire and Sprint 3G networks.

Market statistics on WiMAX deployments and subscriber numbers are still sporadic because WiMAX is in the early stages of development and deployment. Deployment maps, available at the WiMAX Forum web site at **wimaxforum.org**, show that fixed WiMAX networks still make

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up the majority of the deployments worldwide. According to these maps, the U.S. currently has six mobile WiMAX deployments in service in the 2.5 GHz frequency range; most are confined to small geographical areas such as a city.

Clearwire's new CEO, William Morrow, recently said they still plan to cover 120 million Americans across 80 markets by 2010. However, Morrow also emphasized that their broadband strategy did not depend on a nation-wide footprint and that the business model of WiMAX enabled a good return on investment even with lower penetration of markets. Clearwire's first commercial launch recently occurred in Baltimore. Coverage maps of the "XOHM" service, available at **xohm.com**, currently show Baltimore as the only U.S. city with commercial WiMAX service. A full commercial launch in Portland is planned later in 2009, followed by previously announced markets in Atlanta, Las Vegas, Dallas, and Chicago. Most WiMAX deployments are still in the 3.5 GHz spectrum internationally and the technology is most widely used in Europe.

Long Term Evolution (LTE)

LTE is the evolution of 3GPP's UMTS Terrestrial Radio Access (E-UTRA) technology. The LTE project develops standards for the Evolved Packet System (EPS), which is the evolution of the complete 3GPP UMTS Radio Access and Packet Core networks and their integration into legacy networks. The EPS includes the radio access part of the network—the Evolved UTRA Network (E-UTRAN)—and also the system architecture portion—the Evolved Packet Core (EPC). LTE and E-UTRAN are often used interchangeably and mean the same thing.

The LTE air interface uses OFDMA and MIMO antenna technology and allows an operator to deploy scalable transmission bandwidths from 1.4 to 20 MHz. The goal is to improve downlink spectrum efficiency by 2-4x HSDPA, and uplink efficiency by 2-3x HSUPA. As a result, LTE expects to double average user throughputs to over 1 Mbps on the uplink and downlink. Cell coverage up to 5 km is targeted with slight degradation allowed out to 30 km. While mobility is optimized for low speeds (< 15 km/h), it should support users moving up to 350 km/h.

Another important goal in the EPS is the inter-working with existing UMTS networks and non-3GPP systems such as CDMA2000 1x and 1xEV-DO. The interruption time of a user's services during handovers between E-UTRAN and UTRAN shall be less than half a second.

As we approach the end of another decade, most major operators like Vodaphone, Verizon, and AT&T have announced their intent to deploy LTE networks. According to the GSA website, there are now 31 operator commitments to LTE deployments worldwide. LTE has gained much more operator and vendor support recently than WIMAX. Progress in LTE's development, trials and testing is monitored by the LTE/SAE Trial Initiative (LSTI). The initiative was started by a group of leading telecommunication vendors and service providers to promote the industrialization of LTE/SAE and demonstrate its performance capabilities. The forum will also validate key functionalities and interoperability of LTE network components. More information about the forum, and early LTE test results, is available at their website, **lstiforum.org**.

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Conclusion

Only time will tell how well 4G technology is accepted by the wireless communications industry as whole, and how quickly it evolves from 3G technology. The radio access technology has matured four times over these past three decades, yet most voice traffic is still carried over the older circuit switched telephone networks, just as AMPS did in the 1980s. While the transition to the all-IP core networks did not happen in 3G, WiMAX and LTE's evolved packet core aim to do just that.

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