The Road to 3G

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Abstract - *This paper provides a high level overview of 2G and 3G wireless cellular technologies and the expected evolutionary path between them. The technical aspects of each technology are discussed with an emphasis on understanding key characteristics of each specification. Technologies including PDC, cdmaOne (IS-95), TDMA (IS-54, IS-136), GSM, GPRS, EDGE, cdma2000 (IS-2000), cdma2000 1xEV-DO (IS-856), and W-CDMA (UMTS FDD) are discussed. Less widely deployed technologies such as cdma2000 1xEV-DV, DECT+, UMTS TDD, and TD-SCDMA are mentioned briefly with limited discussion due to their expected limited use.*

INTRODUCTION

Cellular systems have become enormously popular. As of early 2001, one out of ten people in the world (680 million) used a cellular phone. Once thought of as a luxury, cell phones are now more appropriately referred to as a necessity and lifeline in time of emergency. As the cellular market matures and becomes saturated, service providers see new data applications as the next step in providing customers with new products and services. Current technology offers the nomadic user data services such as email, but higher data rates will provide far more sophisticated applications. The limiting factor to providing these new services is the transmission data rate. It has taken a decade to bring reasonable speeds to the desktop using ISDN, DSL, and cable modems. Providing similar speeds to the mobile user is more difficult due to limited bandwidth and the harsh RF environment that is plagued by deep fades, diversity, and high bit error rates.

In many ways, the cellular system is a victim of its own success. The increase in subscribers and demand for additional services requires more bandwidth, a precious and limited resource. For this reason spectral efficiency is an important cornerstone of all new technologies. By using advanced digital control systems and high-level modulation techniques, new technologies can supply high data rates in limited bandwidth.

The selection of the "air interface" for a wireless system is a seminal decision for a service provider. The air interface for first generation (1G) analog systems, second generation (2G) digital systems, enhanced second generation (2.5G) systems, and third generation (3G) advanced digital cellular systems are discussed with emphasis on understanding the key characteristics of each air interface technology and the factors that go into making that decision.

1G

The idea of using cells for communication can be traced back to Bell Laboratories in 1947, but it was not until 1979 that such a system was first deployed in Japan. The United States followed with a system in Chicago in 1983.

1G is referred to as an analog technology since the RF carrier is modulated using frequency modulation (FM), a simple analog modulation technique. By today's standard, 1G is archaic. It suffers from poor voice quality, poor battery life, large phone size, no security, frequent call drops, limited capacity, and poor handoff reliability between cells. But no one can deny its importance in the evolution of wireless cellular communication. It proved there was a huge demand and despite its limitations, 1G was a huge success. Although such systems are still operational in many portions of North America, they are slowly being replaced by 2G and in the near future, 3G wireless networks.

2G

Digital 2G networks provided improvements to system capacity, security, performance, and voice quality. 2G makes heavy use of digital technology through the use of digital vocoders, Forward Error Correction (FEC), high-level digital modulation, and greater use of computer technology to improve voice quality, security, and call reliability.

1G used simple Frequency Division Multiple Access (FDMA) to support multiple users simultaneously. But it was not until 2G that more advanced multiple access technologies such as Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) were made available to make more efficient use of frequency spectrum. Given the popularity of cellular communication and limited bandwidth, multiple access technology is a necessity for market expansion. Although each method has the same goal, they take significantly different paths to achieving it. 1G FDMA provided multiple access by separating users by RF frequency. TDMA achieves the goal by allocating time slots among users, while CDMA uses an elegant coding scheme to allow all users simultaneous access to the available bandwidth, and separates users by codes.

For technical reasons (e.g., frequency allocation and reuse, bandwidth) and non-technical reasons (e.g., economic, political, historical, patents) several 2G standards have evolved. The technologies fall primarily along geographic boundaries. GSM is widely deployed in Europe. cdmaOne and TDMA are widely available in North America, Korea, and South America while PDC is limited to Japan. An early goal of 3G was to attempt to consolidate technologies and develop a unifying global technology, but various factors have led to continuation of competing offerings.

GSM (2G)

GSM (Global System for Mobile communication) was the first digital wireless technology; it is also the most popular. In 2001, it enjoyed a 60% market share. In addition to voice, it supports low rates for data services (9.6 Kbps) and Short Message Services (SMS).

A two-level digital FM modulation method, called Gaussian Minimum Shift Keying (GMSK) was developed specifically for GSM. It uses Minimum Shift Keying with Gaussian filtering. The filtering smoothes rapid transitions and reduces bandwidth. GMSK was developed as a compromise between conflicting goals including the need to reduce susceptibility to radio noise, reduce bandwidth, and limit power to increase battery life for mobile users. These characteristics result in several highly desirable characteristics such as: increased frequency reuse (ability to support more users), lower distortion (better voice quality), and higher data rates. To support multiple accesses by users, GSM uses a combination of FDMA and TDMA.

cdmaOne, IS-95 (2G)

cdmaOne is the branding name for the first generation of CDMA. It is an international standard, specified as IS-95. It was originally designed for voice, but changes specified in IS-95A allowed packet data rates up to 14.4 Kbps.

The major difference between CDMA and other 2G technologies is the modulation scheme. CDMA uses spread spectrum technology that spreads a signal across a wide frequency (1.25 MHz) channel. All mobiles use the same channel and are separated through orthogonal sequences called Walsh codes. Standard CDMA specifies 64 Walsh codes, which supports approximately 60 simultaneous users. Some Walsh codes are predefined such as the pilot channel that uses Walsh code 0 and the synchronization channel, which uses Walsh code 32. Up to 7 Walsh codes are used to support paging channels.

CDMA uses a sophisticated RF power control mechanism to increase capacity. Mobiles near the base station are instructed to lower power, while users far from the base station increase power. This is commonly referred to as the "near far" problem. Additional benefits of power control are the reduction in interference between users and lengthening battery life.

When a mobile moves between cells, it undergoes a "handoff". 1G systems were plagued by interruptions during this period, commonly referred to as a hard handoff. CDMA uses a soft handoff scheme that insures the mobile has completed the transition to the next cell before disconnecting from the previous cell. During this transition period, the mobile communicates with both cells, resulting in diversity, which makes the connection more efficient and robust.

CDMA also fosters deployment of efficient wireless networks since it provides for full frequency reuse as compared to TDMA systems where adjacent cells must be allocated different frequencies to insure they do not interfere with each other.

Perhaps the greatest advantage of CDMA over other technologies is its spectral efficiency. In real world terms this translates to increased system capacity (users in a cell). Capacity is a key component for a service provider to consider. More capacity reduces the need for costly equipment to support additional users.

TDMA, IS-54, IS-136 (2G)

Time Division Multiple Access (TDMA) was originally specified as IS-54. Further improvement to the specification led to IS-136 that supports short message services (SMS), user groups, wireless PBX, and sleep modes to reduce mobile power consumption and therefore extend battery life.

Unlike CDMA that separates users by codes, TDMA separates users by time. User information is encoded, transmitted, and decoded in a fraction of the time required to produce it. Each user is given a small slice of air time (time slot), which allows all users to share the available bandwidth.

TDMA uses the same frequency band and channels as 1G systems, but provides increased capacity and improved performance. By using digital voice signals, TDMA is able to provide three times the capacity of a standard 1G Advanced Mobile Phone System (AMPS) 30 KHz channel.

The upgrade path from 1G AMPS to 2G TDMA is eased by the use of dual mode cellular phones that support both. However, the evolutionary path to 3G is less clear. One can make a strong argument for moving to IS-95 CDMA with a straightforward evolution to 3G using 1X technology. However, some wireless operators have opted to move to GSM and eventually to WCDMA.

PDC (2G)

PDC (Personal Digital Cellular / Pacific Digital Cellular) is used primarily in Japan. It is similar to IS-54/IS-136. The major difference is the channel spacing (25 KHz vs. 30 KHz) and voice codec (VSELP 6.7 kbps vs. 7.95 kbps). The modulation scheme, voice frame size, TDMA frame duration, and interleaving remain the same.

2.5G

Customer demand for digital services is the major impetus for 3G. However, there is a huge technical jump from 2G to 3G. New technologies and standards take years to develop and deploy. 2.5G (a.k.a. "two and a half G") is essentially a "bridge" technology that allows service providers to smoothly transition from 2G to 3G systems and to provide customers limited 3G features before 3G is fully available.

2.5G systems use improved digital radio and packet-based technology with new modulation techniques to increase data rates, system efficiency, and overall performance. Their greatest advantage is that despite changes, they remain compatible with 2G systems. An added benefit is the low cost of the changes as compared to moving to totally new 3G systems.

From a user's standpoint the transition from 2G to 3G is transparent; services provided by 2G are also provided by 3G. However, from the service provider's viewpoint, the migration to 3G is difficult, risky, and costly. Most 2G equipment must be replaced to support 3G. It also requires more frequency spectrum, which is particularly scarce and costly. For this reason deploying interim 2.5G systems makes sense. It provides significant improvements over 2G but does not require large investments.

cdmaOne, IS-95B (2.5G)

IS-95B builds on IS-95A technology to provide higher data rates. By combining CDMA code channels, rates of 64 Kbps are possible. This is significantly above data rates provided by 2G systems, but not yet sufficient to be labeled 3G.

The migration path from IS-95A, a 2G technology, to IS-95B is straightforward. Virtually all investments made by service providers remains. Some hardware modifications are required, but the greatest change is to the system software.

EDGE (2.5G)

Enhanced Data Rates for GSM Evolution (EDGE) is an improved version of GSM. Like GSM, it supports voice, but provides significant data rate improvements. Using enhanced 8-level phase shift keying (8PSK) modulation, a three-fold data rate increase over standard 2-level GMSK modulation, used in first generation GSM, is possible. Specifically, EDGE provides 69.2 kbps/slot throughput vs. 22.8 kbps/slot of a standard GSM carrier. Throughputs can be further increased to approximately 474 kbps by using multiple slots.

It is important to note that improved data rates are not free. In the case of EDGE, 8PSK provides higher data rates at the cost of requiring higher signal to noise ratios, which typically means higher RF power requirements. A mobile terminal can save power by supporting 8PSK only when RF signal conditions are favorable. cdma2000 1xEV-DO, a data optimized 3G technology discussed later in this paper, uses this technique extensively. As signal conditions change, the modulation and rates are changed dynamically to accommodate current RF conditions. Another consequence of 8PSK modulation is the need for increased linearity of costly RF power amplifiers.

The major advantage of EDGE is that by modifying the GSM air interface slightly, EDGE modulation can be time inserted on a slot-by-slot basis. This allows EDGE systems to coexist with GSM systems. First generation GSM cellular phones will ignore EDGE time slots since they cannot be demodulated or decoded. The evolutionary path from GSM to EDGE has minimal impact on the existing network architecture and the ability to reuse installed equipment is a big advantage. Changes to support EDGE are limited to the radio portion of the network (e.g., base station); all other network interfaces remain largely unchanged.

HSCSD (2.5G)

High-Speed Circuit Switched Data (HSCSD) is based on GSM and overcomes the 9.6 kbps barrier. HSCSD is a practical rather than elegant solution to higher data rates. Higher rates are achieved by combining traffic channels. This has the disadvantage of reducing network voice capacity, since it removes channels from service that would normally be used to support voice calls. Since the user requires more system resources, the cost of the connection can be significantly higher than a normal voice call. Nevertheless, this enhancement does allow GSM systems to support higher data rates. Multi-slot raw transfer rates as high as 64 kbps (uncompressed) are achievable which results in user data rates of 38.4 kbps. When two time slots are used, data rates of 19.2 kbps are achievable.

HSCSD lessens the financial impact of providing users with higher data rates since it is primarily a software upgrade. Some hardware is required in the form of gateway equipment to connect the system to data networks (e.g., the Internet), but this is minimal and easy to implement.

GPRS (2.5G)

General Packet Radio Service (GPRS) builds on current GSM technology to provide higher data rates. It differs from HSCSD by achieving improved transfer speeds by dynamically assigning time slots on GSM radio channels. Data transmission speeds as high as 171.2 kbps are possible. To connect to a data network, a serving GPRS support node and a GPRS backbone network with a gateway GPRS support node is required.

The goals of GPRS are to efficiently service data sources and to provide a packet-switched service that can share GSM resources. The physical layer (air interface) of GPRS is the same as GSM. The challenge of GPRS is maintaining compatibility with the circuit-switched GSM network and the packet-switched Internet system. It uses the same GSM modulation scheme, frames, and multiple-access method.

3G

The term 3G was coined by the global cellular community to represent the next generation of mobile services. In 1992, the World Administrative Radio Conference (WARC) defined the frequency spectrum for the third generation of wireless communication to support advanced services, particularly data services. IMT-2000 (International Mobile Telecommunications-2000) is the International Telecommunications Union's (ITU) effort to develop a rigorous definition. Minimum IMT-2000 requirements include:

- **High-speed data transmissions**: 3G will bring an order of magnitude improvement to data communications enabling the use of bandwidth hungry multimedia applications. Although the use of email and web browsing is skyrocketing, they are not the killer applications that justify the huge investment in 3G. Multimedia and video conferencing are the services that are expected to justify the new infrastructure. 3G data rates fall into three categories:
  - 2 Mbps to stationary users (i.e., fixed location)
  - 384 Kbps to pedestrian users (~3 m/hr)
  - 144 Kbps to vehicular users (~60 m/hr)
- **Symmetrical and asymmetrical data transmission support**: Email and web browsing is predominately asymmetrical. For example, data transmitted to the user is much greater than that transmitted by the user. However, services such as video conferencing are symmetrical resulting in equal data transmission in both directions.
- **Improved voice quality**: Provide voice quality comparable to that of wire-line telephony.
- **Greater capacity**: With the explosion in cellular phone usage, the need to efficiently use frequency spectrum is imperative.
- **Multiple simultaneous services**: This allows a user to download an MP3 audio file while talking on the same cell phone.
- **Global roaming across networks**: 3G is expected to support international roaming. Currently roaming between international networks requires a different cellular phone for each network.
- **Improved security**: Users will be able to communicate and conduct business in a secure environment. This will ultimately foster additional commercial services.
- **Service flexibility:** Both circuit-switched (e.g., voice, real-time video) and packet-switched services (e.g., Internet Protocol) shall be supported.

Developing the 3G specification required participation from many companies and agencies throughout the world to assure the standard was globally accepted. The 3GPP (third generation partnership project) was tasked with overall coordination responsibilities.

The original intent of the Universal Mobile Telecommunications System (UMTS) was to develop a single worldwide standard, but the realities of economics, competition, and other factors forced the development of competing and incompatible systems. The 3GPP developed the UMTS FDD and UMTS TDD specifications. The 3GPP2 produced 1xEV-DO (IS-856) that is a part of the larger CDMA2000 specification. Other technologies such as DECT+ come under the 3G umbrella, but are not expected to be widely deployed.

WCDMA (3G)

WCDMA also referred to as the Universal Mobile Telecommunications System (UMTS), gets its name from its 5 MHz wide bandwidth requirement. The large bandwidth of WCDMA stems from the direct sequence chip rate of 3.84 Mcps. This is much larger than the 1.2288 Mcps rate of cdmaOne and cdma2000 1xRTT (1 time IS-95 Radio Telephone Technology) that requires 1.25 MHz, and the 3.6864 Mcps rate of cdma2000 3X multicarrier (3X MC). The chip rate is the primary difference between the two technologies and a major reason for their incompatibility.

cdma2000 and WCDMA take different approaches to using the available bandwidth. Three IS-95 or cdma2000 channels fit in the same bandwidth that one WCDMA channel requires. The fact that cdmaOne and cdma2000 use the same bandwidth explains why the evolution between the technologies is graceful as compared the transition from GSM to WCDMA that requires new frequency spectrum. This and other factors make the transition from GSM to WCDMA revolutionary rather than evolutionary.

cdma2000, IS-2000 (3G)

cdma2000 is formally documented as IS-2000 and builds on its predecessor cdmaOne (IS-95). It has much in common with the 2G version of CDMA. It uses similar modulation techniques and Walsh codes but enhancements give greater flexibility and performance.

One major improvement of cdma2000 is its ability to support higher data rates. Peak data rates of 153 kbps are possible with low-end phones and rates as high as 307 kbps are possible with high end phones and devices. Additional changes to the IS-95 specification nearly doubles voice capacity and the addition of a 5 ms frame supports "quick paging" which improves battery life.

While cdmaOne offered some security predominantly by the sheer complexity of its design, cdma2000 offers complex scrambling to support privacy.

IS-2000 also supports smart antenna technology that significantly improves system capacity. Smart antennas can be steered electronically, allowing RF power to be concentrated to a mobile subscriber rather than spreading the RF energy over a wide area that dilutes the signal, causes interference, and ultimately lowers capacity.

The evolutionary path from cdmaOne to cdma2000 is flexible and will have minimal impact due predominately to the similarities of the two technologies.

cdma2000 1xEV-D0, IS-856 (3G)

1xEV-DO (a.k.a. High Data Rate) is a data service technology that is formally specified as IS-856. The 1x prefix stems from its use of 1x (1 times) the 1.2288 Mcps spreading rate of a standard IS-95 CDMA channel. EV signifies that it is an Evolutionary technology built on the IS-95 standard. What differentiates it from other 3G technologies is that it supports Data Only (DO), voice services are not provided. By optimizing the system for packet data, it is not limited by voice timing requirements that are significantly different from data requirements. 1xEV-DO provides an always-on connection, which provides seamless Internet connectivity.

IS-856 can provide peak data rates of 2.4 Mbps in a 1.25 MHz IS-95 CDMA channel. It is also spectrally efficient. Given the cost of frequency spectrum, the importance of this characteristic cannot be overstated. Simulations with fixed and mobile users show a spectral efficiency of 1bit/sec/Hz is achievable. The high spectral efficiency is accomplished by a combination of adaptive rate/modulation coding, Turbo code, a multi-user diversity scheduler, and hybrid-ARQ.

cdma2000 1xEV-DV should not be confused with cdma2000 1xEV-DO, they are very different. 1xEV-DV supports both data and voice (DV). This technology is currently being standardized.

CONCLUSION

Analog 1G wireless cellular systems had many weaknesses, but their importance cannot be overstated. 1G showed there was a huge worldwide market for mobile communication. Digital 2G technology solved many of the weaknesses of 1G, added services, and saw the beginning of low speed data communication. Advanced digital 3G technology represents a quantum leap in technology from 2G and is expected to support many new applications and services.

Arthur C. Clark, the farther of satellite communication, known to most as the author of, "2001 A Space Odyssey", said, "Any sufficiently advanced technology is indistinguishable from magic". The complexity of 3G is certainly advanced, time will tell if it is magic.

READ MORE ABOUT IT

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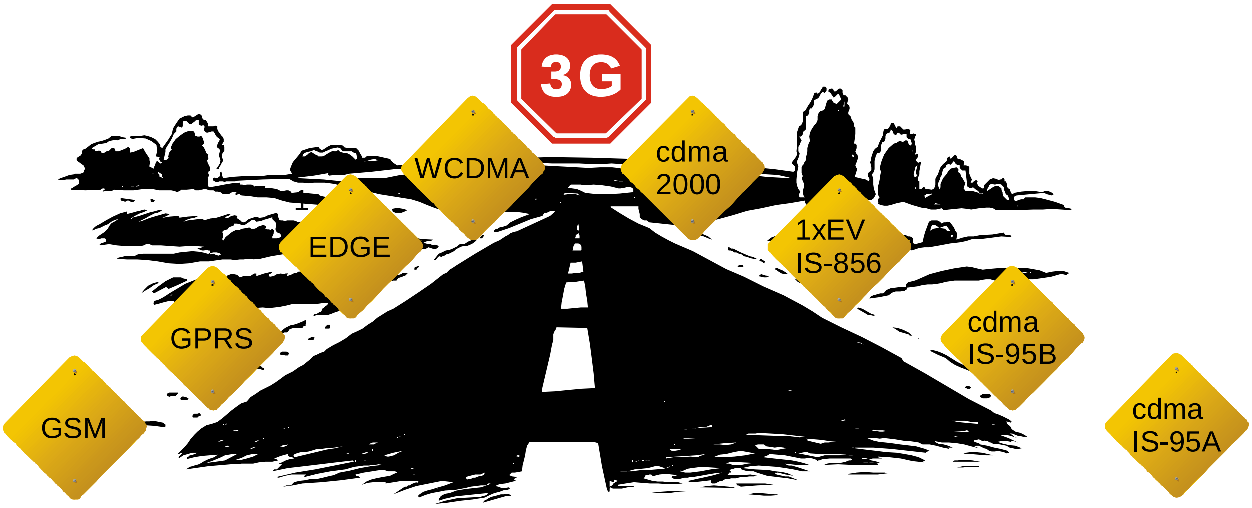

Figure 1. The road to 3G is complex, expensive, and financially risky. Several competing and incompatible technologies have been developed to meet 3G requirements.

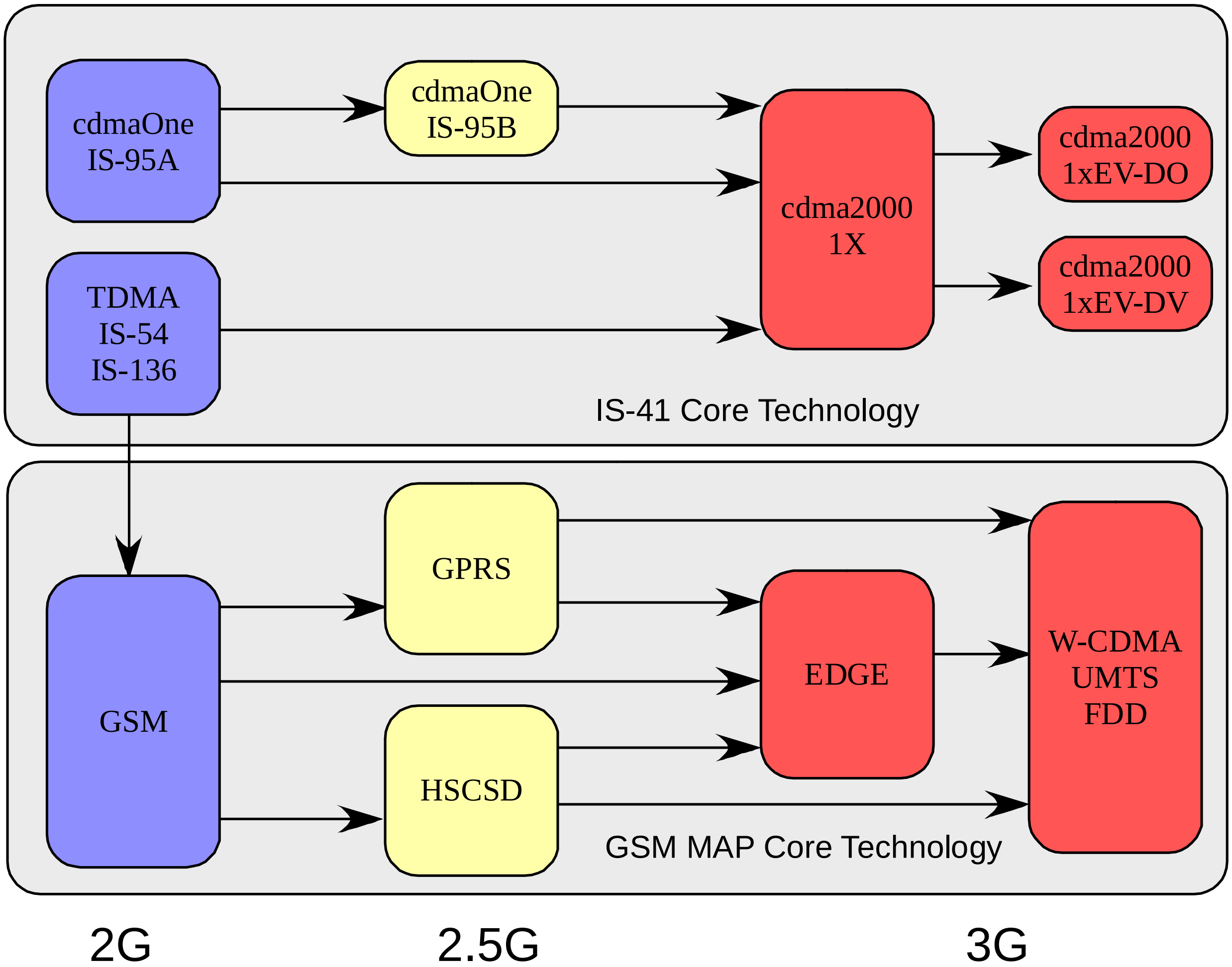

Figure 2. The evolutionary path shown by the arrows represent the logical and expected path to 3G. Carriers can select any technology to reach 3G, but current infrastructure investments play a major role in the decision making process.

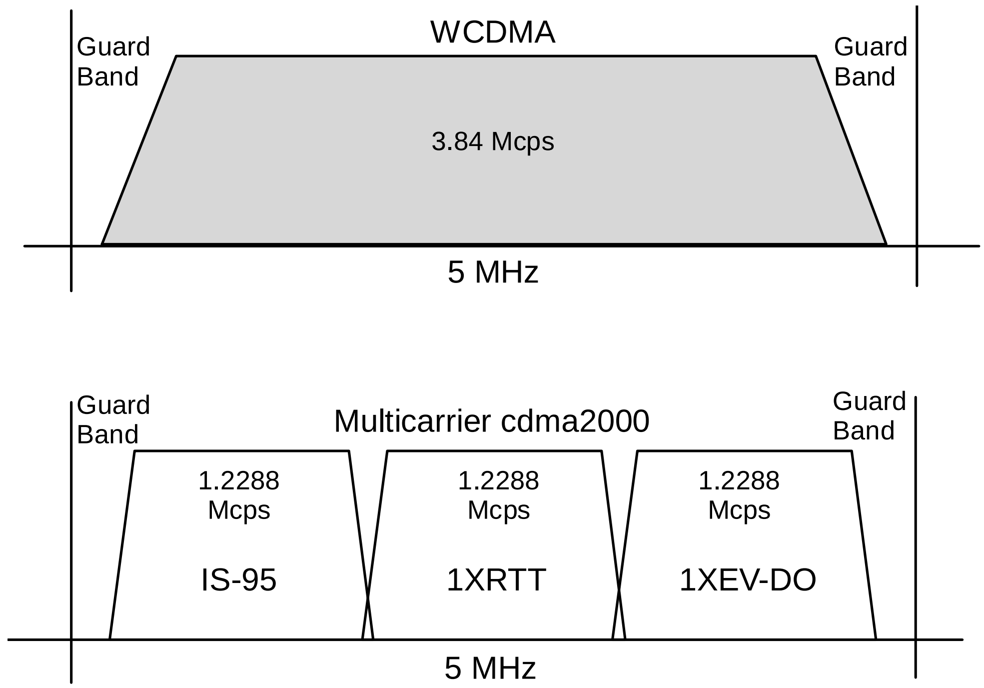

Figure 3. WCDMA uses 5 MHz of bandwidth to provide both voice and data services. It requires new spectrum that explains why the evolutionary path is more difficult. CDMA allows network architects flexibility in assigning combinations of 1X or one 3X Multicarrier channel to use the available bandwidth.

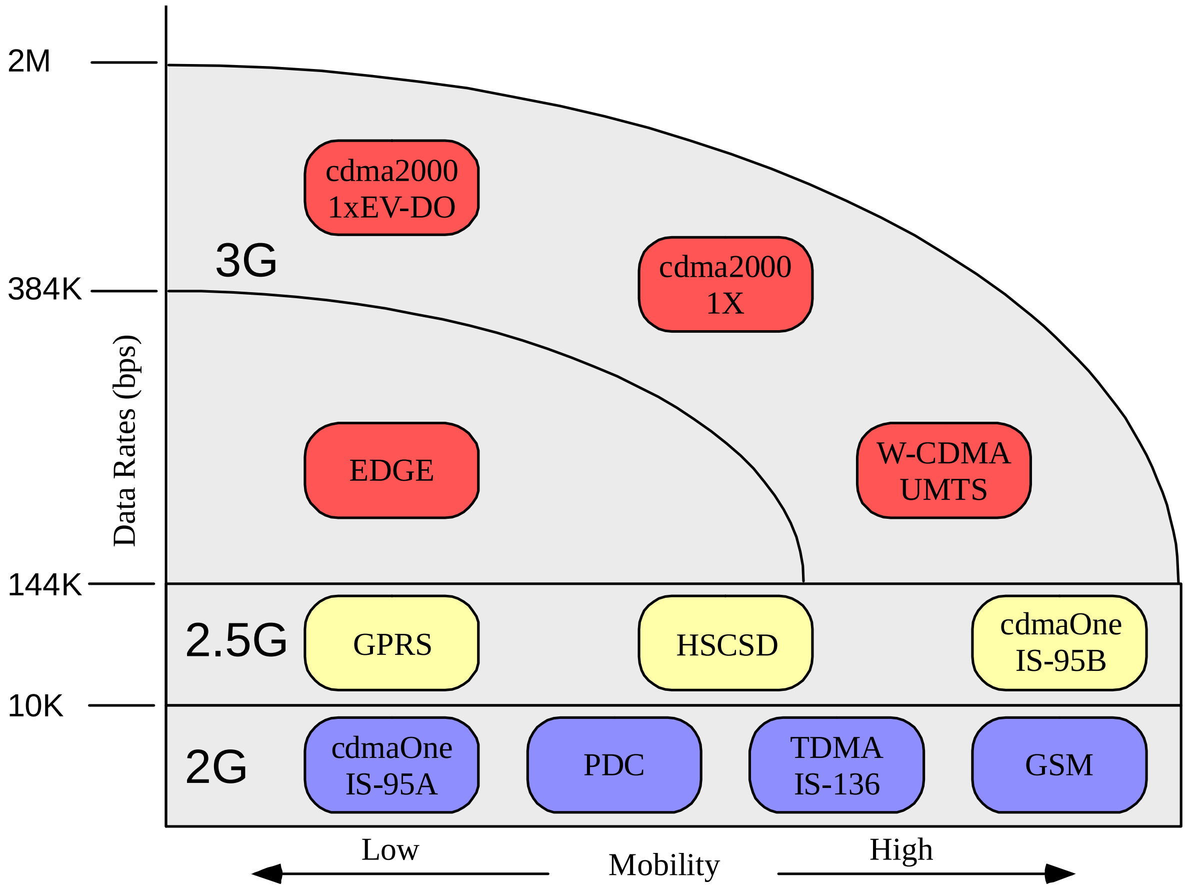

Figure 4.The data rate provided to a user is determined by the technology and mobility. As mobility of the subscriber increases (e.g., fixed, pedestrian, vehicular) the ability to achieve the highest data rates decreases.