Three generations of cellular wireless systems

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Over the past decade, wireless technology has undergone enormous growth. Surveys have shown that a new wireless subscriber signs up every 2.5 seconds. The number of cellular and personal communication system (PCS) users in the US has surpassed 100 million.

However, wireless is not a recent technology. As early as 1793, wireless messages were transmitted in France using the optical telegraph. Stations consisting of a telescope and a set of semaphore flags capable of encoding multiple messages were placed on adjacent hills. France was entirely linked by 566 such

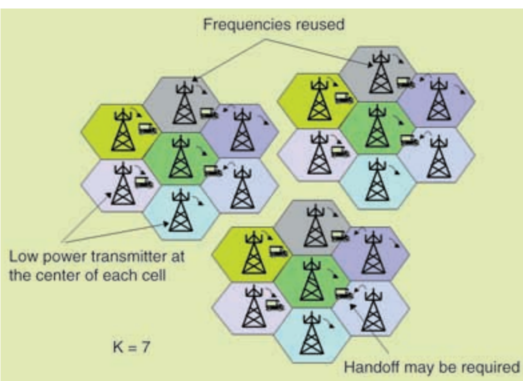

Fig. 1 Cellular concept/frequency reuse

stations. A message could be sent from Paris to the border in about an hour.

The first wireless electrical communication devices emerged in the late 19th century. The original application of wireless was to communicate—where wires could not go—with ships at sea. The first wireless

transatlantic communication occurred in 1901. Throughout that century, great advances were made in wireless communication technology.

Predecessors to cellular

A major milestone was reached in 1946 with the development of the radiotelephone in the US by AT&T. This allowed mobile users to be connected to the public switched telephone network (PSTN). This service, named the Mobile Telephone Service (MTS), used FM at a carrier frequency of 150 MHz. But it offered only one to three channels per city at 120 kHz per channel. Because it was a non-trunked system, each mobile unit was permanently assigned a specific frequency from a pool of possible frequencies. Thus, a mobile user could not place a call if another user was communicating at the same frequency, even if other channels were available.

Although MTS was successful in providing basic wireless telephony, it had many shortcomings. Because it used a high power transmitter placed at high elevation to encompass a large area, it was prone to interference. Also, since MTS did not support handoff, calls were dropped when a mobile unit crossed the boundary of one service area to the next.

Some of these problems were addressed with the Improved Mobile Telephone Service (IMTS) in 1965. IMTS supported full-duplex signaling, which allowed two-way communication over two separate frequencies. Technological improvements allowed the required channel bandwidth to decrease from 120 kHz to 60 kHz in 1950, and from 60 kHz to 30 kHz in 1965. Thus, the number of concurrent calls was doubled in 1950 and then doubled again in 1965.

The introduction of automatic trunking in 1965 enabled a dynamic assignment of channel frequencies to each mobile unit. Now a mobile could place a call on any open channel. Thus, the blocking probability was reduced, and the number of supported subscribers could be increased.

Although IMTS was a significant improvement over MTS, it did not incorporate any handoff mechanism and experienced a 50% probability of blocked calls. The capacity, in terms of the ratio of the number of channels to subscribers, was not sufficient. For instance in 1976, only 12 trunked channels were available for the entire New York City market of approximately ten million people. (A trunk is a telelphone circuit connectiongto or more telephone company central offices.) The system could only support 543 paying customers. The waiting list exceeded 3,700.

The birth of cellular

The congestion in the radio spectrum made it clear that a whole new approach was necessary. During the 1960s, the concept of cellular telephony was pioneered in the US at AT&T Bell Laboratories. In 1968, AT&T proposed the concept of cellular telephony to the Federal Communications Commission (FCC).

The idea behind cellular telephony is to break each market into small coverage regions, or *cells*, as shown in Fig. 1. Each area is approximated with a hexagonal cell. A base station is located at the center of each cell. Each cell is assigned a fraction of the total available radio spectrum. Since transmitted power drops with distance, cells located far apart can be assigned the same spectrum. With this ability to reuse spectrum, cellular accommodates many more customers.

Moreover, since the coverage area of each base station is greatly reduced, low power transmitters at each base station are sufficient to cover the entire cell. The handoff mechanism, in which a mobile unit is transferred between cells as it moves out of a cell's coverage area, is incorporated. This takes place without the user's knowledge, permitting long and uninterrupted calls to be placed.

Figure 1 illustrates clusters of cells with a frequency reuse factor (K) equal to 7 (i.e., the complete spectrum is shared by a cluster of K=7 cells). It also depicts a typical situation where a handoff may be required.

Cellular service has proven to be extremely successful. The exponential growth in customer demand has caused cellular networks in large metropolitan areas to become extremely congested. In theory, cellular has the potential to provide service to all who desire it by making the cells smaller and smaller via a process called cell-splitting. However, there are practical and economic factors that limit just how much a cell can be shrunk. Each cell must be serviced by a centrally located base station. These stations are expensive and utilize unsightly antenna towers. Many local governments block the placement of base station towers. In addition, having more cells increases the rate at which calls are handed over from one cell to another,

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which in turn complicates the network architecture.

The first generation

The first operational cellular system in the world was fielded in Tokyo, Japan by Nippon Telephone and Telegraph (NTT), in 1979. It used 600 FM duplex channels in the 800 MHz band with a channel bandwidth of 25 kHz.

This was followed in Europe in 1981 by the Nordic Mobile Telephone (NMT 450) system developed by Ericsson that began operation in Scandinavia. It used the 450 MHz frequency band with 25 kHz channels. Total Access Communications System (TACS) was introduced in the United Kingdom in 1982 and the Extended Total Access Cellular System (ETACS) was deployed in 1985. The total number of ETACS channels was 1000 with a channel bandwidth of 25 kHz. Subsequently, in Germany, the C-450 (450 MHz frequency band) cellular system was introduced in September 1985. Another system called Radicom 2000 was introduced in 1985 in France and operated at 200 MHz. Thus, at the end of the ’80s, cellular service in Europe had a multitude of systems that were not interoperable.

The situation in the United States was different. In the US, there was initially only a single analog cellular standard called Advanced Mobile Phone System (AMPS). The company, Ameritech, first placed it in service in 1983 in Chicago. AMPS uses FM in the 800 MHz frequency band with each channel having a bandwidth of 30 kHz.

The FCC initially allocated 40 MHz of bandwidth for AMPS cellular in 1981.

To ensure some competition, the FCC insisted on a duopoly by mandating that two and only two cellular providers serve each market. Each provider was designated as either “A-side” or “B-side.” A-side providers were upstart companies that did not originate in the traditional telephone business. They were called non-wireline carriers. B-side providers had a base in telecommunication services and were called wireline carriers. Each provider had access to 20 MHz of bandwidth offering 666 full duplex channels in each of the 734 markets. In 1986, the FCC allocated another 10 MHz leading to an increase in the number of channels to 832.

The second generation

By the late 1980s, it was clear that the first generation cellular systems—based on analog signaling techniques—were becoming obsolete. Advances in integrated circuit (IC) technology had made digital communications not only practical, but, actually, more economical than analog technology.

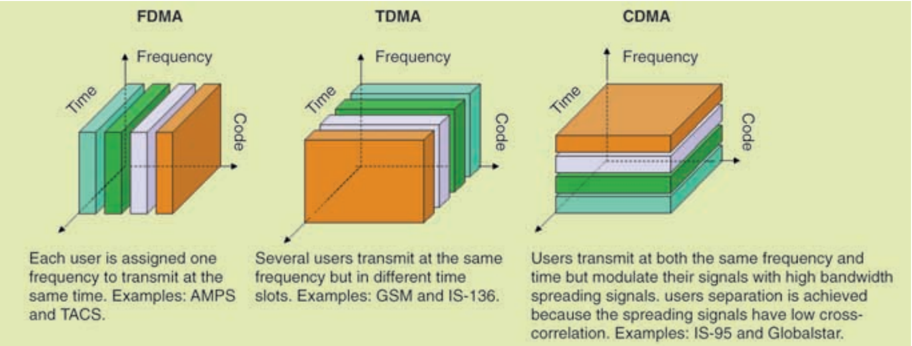

Fig. 2 Multiple access techniques

Digital communication enables advanced source coding techniques to be utilized. This allows the spectrum to be used much more efficiently and, thereby, reduces the amount of bandwidth required for voice and video. In addition, we can use error correction coding to provide a degree of resistance to interference and fading that plagues analog systems, and to allow a lower transmit power. Also, with digital systems, control information is more efficiently handled, which facilitates network control.

Second generation digital systems can be classified by their multiple access techniques as either Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) or Code Division Multiple Access (CDMA) as illustrated in Fig. 2. In FDMA, the radio spectrum is divided into a set of frequency slots and each user is assigned a separate frequency to transmit. In TDMA, several users transmit at the same frequency but in different time slots. CDMA uses the principle of direct sequence spread-spectrum: the signals are modulated with high bandwidth spreading waveforms called signature waveforms or codes. Although the users transmit at both the same frequency and time, separation of signals is achieved because the signature waveforms have very low cross correlation.

In practice, the TDMA and CDMA schemes are combined with FDMA. Thus the term “TDMA” is used to describe systems that first divide the channel into frequency slots and then divide each frequency slot into multiple time slots. Similarly, CDMA is actually a hybrid of CDMA and FDMA where the channel is first divided into frequency slots. Each slot is shared by multiple users who each use a different code.

In the early 1990s, second generation (i.e., digital) cellular systems began to be deployed throughout the world. Europe led the way in 1990 with the development of GSM (Global System for Mobile communications), the Pan-European digital cellular standard. The purpose of GSM was twofold: to upgrade transmission technology and to provide a single, unified standard in Europe. Because there were so many different first generation systems, it was necessary to allocate a new frequency band for GSM, over the range 890-960 MHz. GSM uses the TDMA multiple access scheme.

In the US, there was but a single standard, AMPS. Since there was just one standard, there was no need to set aside new spectrum. However, the AMPS standard was becoming outdated. New technology would be required in congested markets.

The industry’s response was to introduce several new, but incompatible bandwidth efficient standards. In 1992, the TR45.3 technical subcommittee of the Telecommunications Industry Association (TIA) introduced the IS-54 (North American TDMA Digital Cellular or United States Digital Cellular) standard

Table 1 Comparison of various cellular standards

NAME	AMPS	GSM/DCS -1900	IS-136 USDC	IS-95	cdma2000	WCDMA/ UTRA
Generation	1	2	2	2	3	3
Year introduced & origin	1983 US	1992/1994 Germany	1996 US	1993 US	2002 US	2002 Europe
Region of Coverage	US	Europe, India, US (PCS)	US	US, Hong Kong, Middle-East, Korea	US	Europe
Frequency Band Uplink (MHz) Downlink (MHz)	824-849 869-894	Cellular /PCS 890-915/ 1850-1910 935-960/ 1930-1990	Cellular/PCS 824-849/ 1850-1910 869-894/ 1930-1990	Cellular/PCS 824-849/ 1850-1910 869-894/ 1930-1990	PCS 1850- 1910 1930- 1990	1920 - 1980 2110 - 2170
Multiple Access Scheme	FDMA	TDMA	TDMA	CDMA	CDMA	CDMA
Bandwidth per Channel	30 kHz	200 kHz	30 kHz	1.25 MHz	1.25, 3.75, 7.5, 11.25, 15 MHz	5, 10, 20 MHz
Modulation type	FM	GMSK	π/4 - DPSK	QPSK and OQPSK	QPSK and BPSK	QPSK and BPSK
Max. output power Base: Mobile:	20 W 4 W	320 W 8 W	20W 4 W	1.64 kW** 6.3 W	1.64 kW** 2 W	Unspecified 1 W
Users/Channel	3	8	3	Up to 63	Up to 253	Up to 250
Data Rate	19.2 kbps*	22.8 kbps	13 kbps	19.2 kbps	1.5 kbps to 2.0736 Mbps	100 bps to 2.048 Mbps

* Using Cellular Digital Packet Data (CDPD). ** Total Effective Isotropic Radiated Power (EIRP) for all the carriers within the channel bandwidth.

based on TDMA. It provides a three-fold increase in the system capacity over AMPS. IS-136, a new version of IS-54, was introduced in 1996 and supports additional services.

The IS-95 CDMA standard, known as cdmaOne, was introduced by the TR45.5 subcommittee of the TIA in 1993. Since CDMA is used, the system is very flexible and supports wideband signaling, and offers increased capacity. Both IS-136 and IS-95 operate in the same band as AMPS and are specified to be dual-mode systems. The dual-mode nature of these systems allows for a gradual transition from AMPS to the newer digital systems.

Satellite telephony side note

Satellite telephony is similar to cellular telephony except that the base stations are satellites in orbit around the earth. The goal of satellite systems is to extend cellular access to people in remote and rural areas where conventional fixed phone or terrestrial cellular service do not exist. Global roaming enables users subscribed to a satellite system to communicate worldwide. Satellite telephony systems can be categorized according to the height of the orbit as either LEO (Low earth-orbit), MEO (Medium earth-orbit), or GEO (Geosynchronous earth-orbit). Typical heights above the earth's equator are 500-1500 Km for LEO satellites, 5000-12,000 Km for MEO satellites and 35,800 Km for GEO satellites.

GEO systems have been used for many years to relay television signals. GEO telephony systems, such as INMARSAT, allow communications to and from remote locations, with the primary application being ship-to-shore communications. With, GEO systems, global coverage up to 75 degrees latitude can be provided with just 3 satellites. The disadvantage of GEO systems is a long round-trip propagation delay of about 250 msec and a high transmit power required by both the mobile unit and the satellite.

With LEO systems, both the propagation time and the power requirements are greatly reduced, allowing for more cost-effective satellites and mobile units. The main disadvantage of LEO systems stem from the smaller footprint and high speed of the satellites (more satellites are required and handoff frequently occurs as satellites enter and leave the field of view). A secondary disadvantage of LEO systems is a shorter life span of 5-8 years (compared to 12-15 in GEO systems) due to the increased amount of radiation in low earth orbit.

MEO systems represent a compromise between LEO systems and GEO systems, balancing the advantages and disadvantages of each. Examples of LEO systems include Iridium (66 satellites, 1998 startup), Globalstar (48 satellites, 1999 startup), Ellipso (14 satellites, 2000 start up), Teledesic (288 satellites, 2002 startup), and Orbcomm (35 satellites, 1999 startup). Examples of MEO systems include ICO (10 satellites, 2000 start up), and Odyssey (12 satellites, 1998 startup).—*NC & MCV*

At the same time, the 900 MHz band was being transitioned from AMPS to the new cellular standards, the FCC auctioned a new block of spectrum in the 1.9 Ghz band. The systems that occupy this band are collectively known as Personal Communications Systems (PCS). The intention was for PCS to offer a slightly different range of coverage and services than cellular. Although in practice, PCS is almost identical to cellular only at a higher frequency. Examples of PCS systems include J-STD-008 (upbanded CDMA), DCS-1900 (upbanded GSM) and J-STD-011 (upbanded USDC).

The third generation

Mobile communications by 1999 was characterized by a diverse set of applications using many incompatible standards around the world. For today's mobile communications to become truly personal communications, it will be necessary to consolidate the standards and applications into a single unifying framework. The eventual goal is to define a global third generation mobile radio standard. It was initially called the Future Public Land Mobile Telecommunications System (FPLMTS). Last year, it was renamed IMT-2000 for International Mobile Telecommunications. It would offer services like wireless voice, video, e-mail, web browsing, videoconferencing, multimedia and e-commerce, at any time and from anywhere.

With this goal in mind, the International Telecommunications Union (ITU) is evaluating several proposals submitted by standards committees in

Europe, the United States, Japan, South Korea and China. The committees have, by and large, embraced the wide-bandwidth CDMA technology. However, each committee has proposed its own distinct standard.

The European Telecommunications Standards Institute (ETSI) in Europe, the Association of Radio Industries and Business (ARIB) in Japan, and the Telecommunications Technology Association (TTA) in South Korea have all developed standards based on a common technology known as Wideband CDMA (WCDMA). However, the Telecommunications Industry Association (TIA) in the United States has proposed a standard called cdma2000. WCDMA and cdma2000 have many similar features. However, a major difference is that WCDMA is backward compatible with GSM networks, while cdma2000 is backward compatible with IS-95 networks. A recent agreement between Ericsson and Qualcomm, the proponents of the WCDMA and cdma2000 standards respectively, has brought about an opportunity for the two standards to converge into a single third generation standard.

The final standard or standards will take a multi-tiered approach, with cells of a variety of sizes. Small cells would be used for low mobility applications, such as cordless telephony, and for high data rate services, such as Wireless Local Area Networks (WLANs). Larger cells will overlay the small cells and serve high mobility applications such as the vehicular communications served by today's cellular systems. Ideally, all services would be unified into a single standard and global roaming would finally become possible.

Conclusion

Advances in cellular communication technology have resulted in improved capacity, higher data rates and better quality of service. Many first and second-generation systems have been deployed and currently offer a range of predominantly voice-oriented services. Third generation cellular systems have been proposed with the goal of providing a seamless integration of mobile multimedia services into a single global network infrastructure. These systems are all summarized in Table 1. However, a fourth generation of cellular systems may be required before truly seamless global roaming is finally possible.

Read more about it

• D.J. Goodman, *Wireless Personal Communication Systems*, Addison Wesley, 1997.

• B. Miller, "Satellites Free the Mobile Phone," *IEEE Spectrum*, vol. 35, no. 3, Mar. 1998, pp. 26-35.

• M.W. Oliphant, "The mobile phone meets the Internet," *IEEE Spectrum*, vol. 36, no. 8, Aug. 1999, pp. 20-28.

• K. Pahlavan and A.H. Levesque, *Wireless Information Networks*, Wiley, 1995.

• T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall, 1996.

• M. Zeng, A. Annamalai, and V.K. Bhargava, "Recent Advances in Cellular Wireless Communications," *IEEE Communications Magazine*, vol. 37, no. 9, Sept. 1999, pp. 128-138.

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