Mobile communications—an overview

S.R. Subramanya and Byung K. Yi

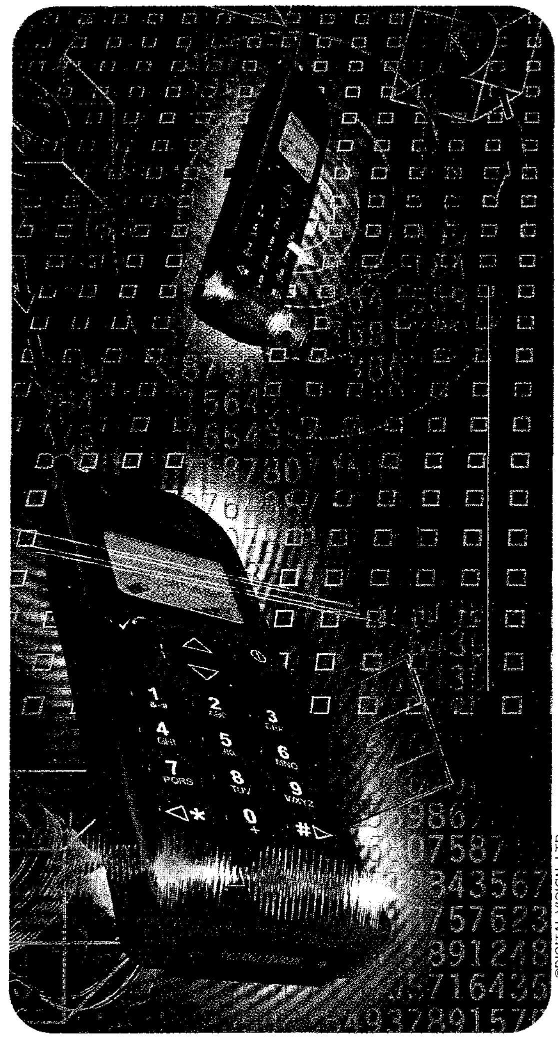
Wireless electrical transmission of information dates back to over 100 years ago, when Marconi transmitted trans-Atlantic radio signals in 1896. In the beginning, wireless radio transmissions were predominantly used for telegraphy and radio. Later they were used in broadcast radio and television. In the recent past, wireless communication has taken two distinct routes: one involving predominantly voice communication using mobile phones, commonly referred to as a *mobile* or *cellular* communication system, and the other involving primarily data communications using laptop computers and personal digital assistants (PDA), commonly referred to as a *wireless* communication system. These two systems use totally different protocols, techniques, and standards. This article focuses only on voice communications using mobile (cell) phones over mobile/cellular networks.

Only recently, with the advances in processors, memory, signal processing, communication technologies, and several related techniques, personal mobile communications has witnessed tremendous growth. More recently, there have been trends of convergence of voice telephony and data transmissions over mobile communication networks. In the future, rich multimedia data consisting of combinations of voice, images, video, audio, text, and animation are expected to be increasingly used in mobile networks. This article presents a very broad overview of key technologies and techniques involved in mobile communications and some details of how the actual communications take place. It also briefly describes the short messaging service (SMS) and major issues in handoff and power control.

Basic steps in communications

Three basic steps in communications are: 1) *modulation*, where the signal corresponding to the information to be transmitted is piggybacked on radio-frequency (RF) waves, which consist of a small portion of the electromagnetic spectrum; 2) *transmission*, where the modulated RF waves are sent—depending upon the frequency and the transmission power, RF waves could be transmitted for distances ranging from a few miles to thousands of miles; 3) *demodulation*, where the original information is recovered from received modulated RF waves. The very basic difference between mobile/wireless communication and fixed-line (wireline) communication is that, in the former, the transmission of the modulated signal takes place in the air, while in the latter, it is done over wires (twisted pair, coaxial cable, fiber optic, etc.).

RF occupies a small portion of electromagnetic spectrum, in the range of approximately 3 KHz–30 GHz. The lower frequency waves have a farther range while the higher frequency waves have a shorter range. Table 1 summarizes the division of the RF spectrum into various bands and their typical applications.



Generations of mobile communications

Three generations have been identified in cellular/mobile systems. The first-generation mobile systems consisted of phones supporting voice (speech) communications in analog form. This system was known as advanced mobile phone service (AMPS). The second-generation systems support predominantly voice communications in digital form. A sizable percentage of the phones and mobile-communication systems currently in use would belong to this generation. All second-generation systems have error detection and correction, giving clear voice reception. They also provide encryption to prevent eavesdropping. The second-generation systems allow channels to be dynamically shared by a number of users. The recently emerging generation is referred to as 2.5 generation (2.5G). The mobile devices of this generation support both voice and data and some limited multimedia capability. The next-generation systems are referred to as the third-generation (3G) systems, which are expected to support high-quality voice transmission, messaging [FAX, SMS, multimedia messaging service (MMS), chat, etc.], streaming multimedia (music, videos, films, TV, animations, graphics, etc.), and Internet access (Web surfing, e-mail, etc.)

Cells and channels

The geographic area covered by a mobile communication system is divided into small regions called "cells" (the terms "cell phones," and "cellular communications" are related to the term "cell" in this context). Each cell denotes the area covered by a particular base station (BS), which acts as a relay of the signals it receives (the details of the BS are given later). Each cell is

0278-6648/05/$20.00 © 2005 IEEE

(approximately) a circle, but represented as a hexagon (to avoid overlaps) for analytical purposes.

Each cell has a limited number of about 10 to 50 allotted frequencies called *channels*. Each cell phone within a cell is given a channel on which it communicates. Adjacent cells are assigned different frequencies to avoid interference or crosstalk. Frequencies are reused in cells that are a sufficient distance apart (so that a signal from one cell completely fades before it reaches the other cell). Cellular/mobile communication systems use multiple low-power transmitters (each about 100 W or less). Transmission power is controlled to limit power at that frequency from escaping to adjacent cells. One of the main issues is to determine how many cells must intervene between two cells using the same frequency.

The channels are divided into four categories:

1) *control channel* (base to mobile) to manage the system

2) *paging channel* (base to mobile) to alert users to calls for them

3) *access channel* (bidirectional) for call setup and channel assignment

4) *communication channel* (bidirectional) for voice, fax, or data.

The cell capacity refers to the number of cell phones that can be supported by a cell. There are several situations where increased cell capacity is desirable, such as in congested areas, large public buildings, etc., to support a large number of users in a small area. There are several ways of increasing the capacity of a cell. The major ones are:

- adding new channels
- frequency borrowing—frequencies are borrowed by congested cells from adjacent cells
- cell splitting—dividing cells in areas of high usage into smaller cells
- cell sectoring—dividing cells into a number of wedge-shaped sectors, each with their own set of channels
- use of microcells—using smaller cells with reduced power levels.

There have been several digital cellular communication standards. Among these, the global system for mobile communications (GSM) and the code division multiple access (CDMA) system have been the most popular ones. The GSM system has been more predominant (over 1 billion users). It was developed in Europe and adopted in 1992. GSM uses time division multiple access (TDMA) for communications. It operates in different frequency bands (450, 900, 1,800, and 1,900 MHz). The personal communication system (PCS) based on GSM operates at 1,900 MHz.

Major entities in a mobile/cellular communication network

A typical mobile communication network is shown in Fig. 1. It consists of:

- mobile devices (cell phones)
- BSs
- mobile switching centers (MSC)
- gateway mobile switching centers (GMSC).

A call originates at a mobile device, goes to the (nearest) BS, then onto a mobile switching center. The GMSC routes calls from MSCs. The call then goes through (possibly) several BSs and then reaches the destination device.

The main components and functionalities of the above entities are given below.

A call originates and terminates at a cell phone. The major components of a cell phone [also called mobile subscriber unit (MSU) or mobile device] are

- a microprocessor, which performs the core control operations
- a digital signal processor (DSP), which performs compression/decompression, modulation/demodulation, and error detection/correction of signals
- A/D (analog/digital) and D/A (digital/analog) conversion chips
- ROM and flash memory storage for telephone operating system and for other data
- amplifier
- microphone and speaker
- keyboard
- display
- battery.

Some of the key data pertaining to the cell phone are stored in the subscriber identity module (SIM) card. These are

Table 1.

Frequency Bands	Frequency Ranges	Typical Applications
Extremely low frequency (ELF)	below 3 kHz	Submarine communications
Very low frequency (VLF)	3–30 KHz	Maritime communications
Low frequency (LF)	20–300 kHz	AM radio broadcast
Medium frequency (MF)	300 kHz–3 MHz	AM radio broadcast
High frequency (HF)	3–30 MHz	AM broadcast, amateur radio
Very high frequency (VHF)	30–300 MHz	FM radio, TV
Ultra high frequency (UHF)	300 MHz–3 GHz	TV broadcast, Cellular phones
Super high frequency (SHF)	3–30 GHz	Fixed wireless, Satellite
Extremely high frequency (EHF)	30–300 GHz	Satellites, radar

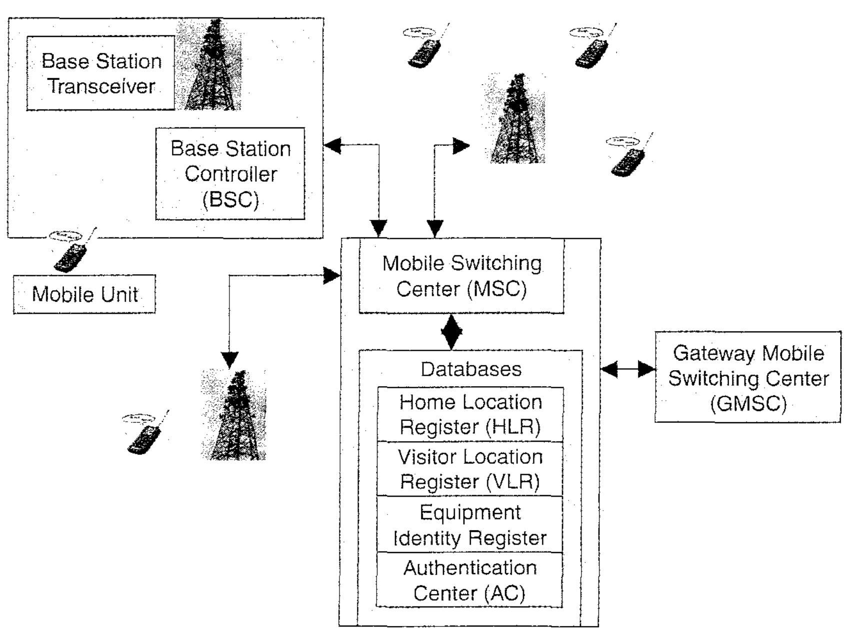


Fig. 1 Major entities in a mobile/cellular network

• mobile identification number (MIN), which is the phone number

• system ID (SID), a number identifying the cell phone system it works with

• the electronic serial number (ESN), which identifies the phone and guards against fraud

• information about subscribed features.

The BS [also called base transceiver station (BTS)], consists of an antenna, a BS controller (BSC), and a number of transceivers. The BSC reserves RFs (channels), takes part in the handoff of the mobile unit from one cell to another, and controls paging.

MSCs [also called Mobile Telephone Exchange (MTX) or Mobile Telephone Switching office (MTSO)], are the "brains" of cellular networks. These are responsible for providing the link between the cellular network and public switched telecommunications networks, connecting calls between mobile units, controlling handoffs between cells, authenticating users and validating accounts, and enabling worldwide roaming of mobile users. The GMSC routes calls from MSCs to final destinations.

The mobile switching center maintains several databases. The major ones are: 1) the home location register (HLR), which stores information about each subscriber that belongs to it; 2) the visitor location register (VLR), which maintains information about subscribers who are currently physically in the region; 3) the authentication center (AC), which authenticates activities and holds encryption keys; and 4) the equipment identity register (EIR), which keeps a list of the types of mobile devices.

Call processing

The fundamental operations in cell phone communications are:

• cell phones connect to mobile/cellular communication networks

• cell phones initiate calls

• calls are routed in cellular networks

• calls are received by cell phones.

Cell phones communicate wirelessly with BSs. Base stations communicate with MSCs on fiber-optic cables or microwave links (1.544 Mb/s). The details of the above operations are described below.

How cell phones connect to a network

The major steps involved in a cell phone connection to a mobile network are illustrated in Fig. 2.

1) When a cell phone is turned on, it listens to *overhead signals* from BSs which contain SIDs.

2) The cell phone sends its SID (and other related information) to the BTS.

3) The BTS relays this information to the BSC.

4) The BSC determines the appropriate BS with strongest signal for the cell phone and notifies the BS and cell phone.

5) The cell phone then tunes to the specified BS and sends its MIN and ESN to the BTS, which in turn relays these to the BSC.

6) The BSC sends the above information to the MSC.

7) The MSC consults the appropriate databases and authenticates the cell phone. It also updates the databases with the received information. The MSC determines the location of the cell phone and the BS it is communicating with, and uses this to route calls.

The first four steps are repeated every few minutes. If the SID stored in cell phone matches the SID in the strongest overhead signal, the cell phone is in its home network; otherwise it goes into roaming mode.

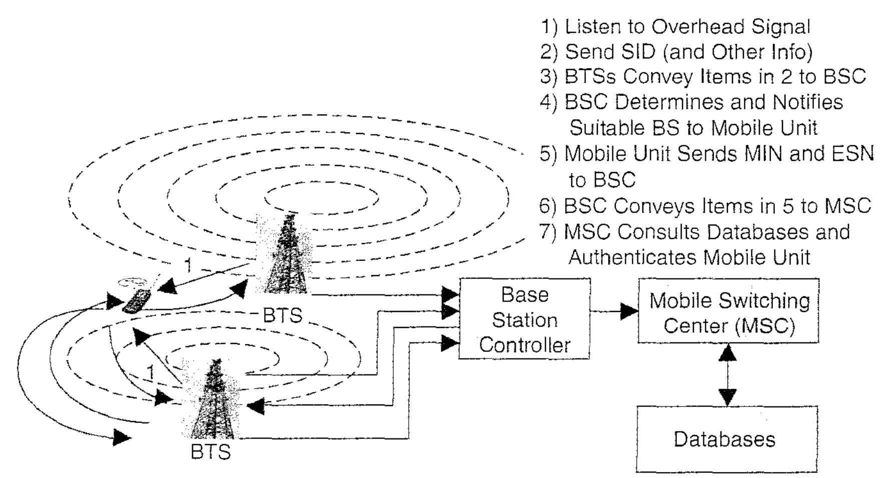


Fig. 2 Major steps in a cell phone connecting to a mobile/cellular network

How a call goes through in a mobile/cellular network

The major steps involved in a call going through a mobile network are illustrated in Fig. 3.

1) After making connection to a BS (as explained above), a cell phone sends the destination number to a BS.

2) The above information is relayed by the BS to a MSC.

3) The MSC (after verifying the authenticity of the cell phone) routes the information to a GMSC.

4) The GMSC exchanges signaling tones with the destination GMSC (or MSC). This is to ensure that the network is up and running at the destination.

5) The ringing signal is sent to the calling phone.

Receiving a call

6) The call request from the caller is sent by the GMSC to the GMSC (or MSC) on the destination network.

7) The destination MSC determines the appropriate base BS based on the location of the destination cell phone by consulting its databases. It then sends the call request to the BS.

8) The BS sends a request to the cell phone using the overhead signal.

9) The cell phone receives the call request and then informs BS to send the call.

10) The BS conveys this to the MSC, which, in turn, conveys it to the GMSC.

11) The destination GMSC (MSC) exchanges signaling tones with the calling-side GMSC (MSC) to ensure that the network is in order, in which case the call goes through.

12) The ringing signal is sent to the called phone.

Also shown in Fig. 3 is a portion of the wire-line network. If the call originates at a cell phone and is destined for a wire-line phone, the GMSC makes contact with the appropriate wire-line telephone switching office on the destination side and exchanges signaling tones to ensure that the network is in order. The wire-line telephone switching office contacts the destination phone, and, if it is in order (and not busy), it informs the GMSC and sends a ringing signal to the telephone. The other scenario of a call from a wire-line telephone to a cell phone is similar and easy to see from the figure.

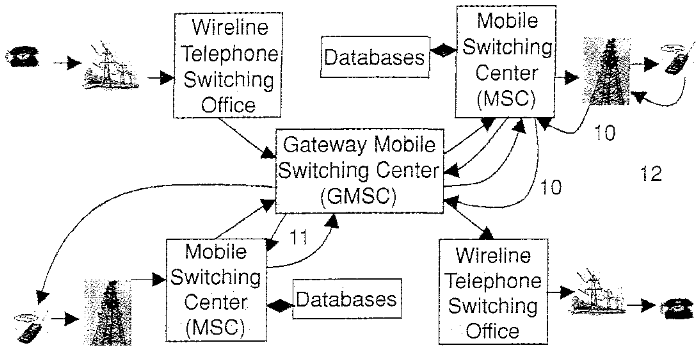
Short message service (SMS)

SMS allows text messages (instead of voice) to be sent from cell phone to cell phone. The most commonly used limit on message size is 160 B (characters). The basic procedure of SMS is as follows. The text message from a cell phone (which has been keyed in) is sent to the MSC via the BS. The MSC routes the message to the messaging center (MC) for storage. At the messaging center, there are mailboxes associated with cell phones. The message-switching center determines the BS, which is in the cell closest to the destination mobile device (recipient). It then sends a signal over the control channel to that BS notifying about the intended message. The BS relays this to the destination mobile device. The cell phone (mobile device) then tunes to the channel where the message will be sent. The MSC sends the message to cell phone via the BS over the control channel. After receipt of the message, the receiving cell phone sends an acknowledgement to the MSC, which then informs the message center to delete the message.

Handoff procedure

When a cell phone moves from one cell to another, the handoff procedure ensures continuous communication of the cell phone with a BS by suitably associating the mobile device with a BS which has the strongest signal with respect to the location of the mobile device. The MSC continuously monitors power levels of the cell phone and BS and determines the handoff suitably. The handoff procedure is initiated when a mobile unit physically leaves a cell or when the BS notices a fading signal. The BS then communicates with the surrounding BSs to determine the signal power from the mobile unit. It then transfers ownership of the mobile device to the BS (cell) with the strongest signal, and informs mobile unit of the new BS. This process takes about 300 ms.

There are two broad types of handoff—*soft handoff* and *hard handoff*. In *soft handoff*, the mobile unit is acquired by a new BS before the current one signs off. Thus, there is no loss of continuity. However, the mobile unit must be capable of tuning to two different frequencies at the same time. This type of handoff is not available in first-generation systems. In hard handoff, the current (old) BS drops the mobile unit before the new BS acquires it. Thus, there is a discontinuity in service. If the new BS is unable to acquire the mobile device (due to unavailability of channels), the call gets disconnected.



1) Cell Phone Sends Destination Number to BST. 2) BST Relays it to MSC. 3) MSC Sends It to GMSC. 4) GMSC Exchanges Signaling Tones with Destination MSC (or GMSC). 5) Ringing Tone Sent to Caller. 6) GMSC Routes Call to Appropriate GMSC/MSC. 7) Destination MSC Sends Request to Appropriate BS. 8) BS Sends Request to Called Cell Phone. 9) Cell Phone Responds to BS to Send Call. 10) BS Conveys This to MSC onto GMSC. 11) GMSC Exchanges Signaling Tones with Caller MSC. 12) Ringing Signal Sent to Called Phone.

Fig. 3 Major steps indicating how a call goes through a mobile/cellular network

Handoff performance metrics

It is desirable for the handoff procedure to be smooth (without discontinuity in communication), transparent (without the user noticing he change), and as quick as possible. There are several measures that determine the quality of handoff. The major ones are:

- call blocking probability, which is the probability of a new call being blocked
- call dropping probability, which is the probability that an existing call is terminated due to a handoff
- handoff probability, which is the probability that a handoff occurs before call termination
- rate of handoff, which is the number of handoffs per unit time
- interruption duration, which is the duration of time during a handoff in which a mobile unit is not connected to either BS
- handoff delay, which is the distance the mobile moves from the point at which the handoff should occur to the point at which it does occur.

Power control

The signal strength must be strong enough between the BS and mobile unit to ensure good signal quality at the receiver. At the same time, it must not be so strong as to create too much interference with channels in another cell using the same frequency band. Due to several reasons, signals may fade and result in disruption of communication or cause other errors. To ensure the received power is sufficiently above the background noise for effective communication, while at the same time minimizing the power in the transmitted signal from the mobile device, *power control schemes* are employed.

There are two major types of power control: open loop and closed loop. Open-loop power control depends solely on a mobile unit, and there is no feedback from BS. It is not as accurate as closed loop but can react quicker to fluctuations in signal strength. Closed-loop power control adjusts the signal strength based on some metrics of performance such as the probability that call request is blocked, average delay, and the capacity needed to achieve a certain average delay. The BS makes power adjustment decisions and communicates them to the mobile device on the control channel.

Enhanced messaging service (EMS) is an evolution of SMS, which supports richer content options such as still pictures, short animations, melodies, graphics, fonts, and formatted text. Similar to SMS, EMS uses the store-and-forward mechanism and the control channels to send messages. A more recent extension is the MMS which allows messages to be multimedia—combinations of text, images (GIF, JPEG formats), audio (MP3, MIDI formats), video (MPEG format), graphics, and animations. MMS requires special protocols, supporting 2.5G and 3G networks and devices.

3G system capabilities

The International Telecommunications Union's (ITU) view of 3G mobile system capabilities are

- voice quality comparable to the public switched telephone network
- 144 kb/s data rate available to users in high-speed motor vehicles over large areas
- 384 kb/s available to pedestrians standing or moving slowly over small areas
- support for 2.048 Mb/s for office use
- symmetrical/asymmetrical data transmission rates
- support for both packet- and circuit-switched data services
- an adaptive interface to the Internet to reflect efficiently the common asymmetry between inbound and outbound traffic
- more efficient use of the available spectrum in general
- support for a wide variety of mobile equipment
- flexibility to allow the introduction of new services and technologies.

There have been a few different variants of 3G deployments. The most popular ones are:

- The universal mobile telephone system (UMTS), which is based on wideband CDMA (W-CDMA), which is widely deployed in Europe
- FOMA, launched by NTT DoCoMo in Japan
- CDMA2000, the outgrowth of IS-95 (2G CDMA standard) is deployed in the Americas, Japan, and Korea.

The fourth-generation (4G) systems are in the works. Their general characterizations are:

- higher data rates
- rich multimedia services and personalization
- location-based services
- better use of spectrum
- more coverage
- seamless interoperability of different 4G technologies.

Summary

The proliferation of mobile/cellular communications has been phenomenal in the past few years, thanks to the maturity of several key technologies. They are expected to provide improved and enhanced services in the near future. This article presented an overview of mobile/cellular communication systems and how calls are handled.

Table 2 lists some of the most commonly used acronyms in the context of mobile communications.

Table 2.

Acronym	Expansion
AC	Authentication center
BS	Base station
BTS	Base station transceiver subsystem
BSC	Base station controller
EIR	Equipment identity register
ESN	Electronic serial number
GMSC	Gateway mobile switching center
HLR	Home location register
MIN	Mobile device identification number
SID	System ID
SIM	Subscriber identity module
VLR	Visitor location register

Read more about it

- J. Schiller, *Mobile Communications*. 2nd ed. Reading, MA: Addison-Wesley, 2004.
- V.J. Duuren, F.C. Schoute, and P. Kasjelein, *Fixed and Mobile Telecommunications: Networks, Systems and Services*, 2nd ed. Reading, MA: Addison-Wesley, 1996.
- U. Black, *Emerging Communications Technologies*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 1997.
- W. Lee, *Wireless and Cellular Communications*. New York: McGraw-Hill, 2005.
- N. Muller, *Wireless A to Z*. New York: McGraw-Hill, 2003.

About the authors

S.R. Subramanya obtained his Ph.D. in computer science from George Washington University. He is currently a senior research scientist at LGE Mobile Research in San Diego, California. His current research interests include mobile multimedia services and content management. He has over 70 publications in refereed conferences and journals. He has served as program committee member, as session chair, and as reviewer for several international conferences. He has also served as a reviewer for several journals and research grant proposals. He is a Senior Member of the IEEE. He may be reached at <subra@umr.edu>.

Byung K. Yi obtained his Ph.D. in electrical engineering from George Washington University in Washington, D.C. He is currently senior executive vice president of LG Electronics in San Diego, California. One of his papers won the JCN 2000 best paper award. He has several U.S. patents to his credit. He has also been a reviewer for several journals, conferences, and grant proposals. He is a Senior Member of the IEEE.