MOBILE COMMUNICATION

The desire for mobility and for communication with others is deeply ingrained in human nature. The need to develop an efficient public mobile communication system has been driving a lot of researchers since the late nineteenth century. It is generally accepted that mobile communication (precisely speaking, mobile radio communication) was born in 1897, when Guglielmo Marconi gained a patent for his wireless telegraph. Since then, mobile communications have gone from the early stages at the beginning of the twentieth century, when mobile communication was widely used in navigation and in maintaining contacts with remotely traveling ships and airplanes, through infancy of the 1950s and the 1960s, to maturity at the end of the twentieth century, when public mobile telephony, paging, and other mobile services are commonplace. There are several comprehensive readings available on each of those specific services (1–4), and this article does not pretend to cover all topics related to mobile communication. Rather, we concentrate on some specific issues that, in our opinion, allow the reader to understand major differences between mobile and stationary or fixed communications.

HISTORY

Mobile communication has always been used by people, particularly during military struggles, when commanders needed to pass their orders to remote troops in the middle of a battle. Several methods have been used, with horns and drums among the most popular. Different optical "mobile communication" systems based on so-called signal flags have also been used for maritime applications. All of those methods have been, however, of a limited range and small capacity. There were no major improvements in mobile communication until the birth of electromagnetic theory.

In the late nineteenth century, after the theoretical predictions made by Maxwell in his treatise on electricity and magnetism and Rudolf Hertz's experimental work on the transmission and reception of electromagnetic waves, Guglielmo Marconi and some other researchers started to look into possible applications of electromagnetic radiation for communication purposes. Since then, radio communications have been used to save lives, win battles, generate new businesses, maximize opportunities, and so forth. From the introduction of public mobile cellular telephony in the 1980s, mobile communications have become elements of mass communication with the objective of providing a broad range of services similar to,

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

and in some instances exceeding, those offered by the public switched telephone network (PSTN). The level of penetration for mobile phones varies among different countries, but in some countries it is already high.

Before the 1970s, numerous private mobile radio networks—citizen band (CB) radio, ham operator mobile radio, and portable home radio telephones—used different types of equipment utilizing diverse fragments of radio spectrum located in the frequency band from about 30 MHz to 3 GHz. Standardization started to take place in the 1970s with the development of the Nordic Mobile Telephone (NMT) system by Ericsson and the Advanced Mobile Phone Services (AMPS) by AT&T. Both systems have become de facto and de jure the technical standards for the analog mobile telephony as the so-called first-generation systems. Soon after the deployment of those first-generation systems, second generation, fully digital mobile cellular systems appeared on drawing boards throughout the world. The Groupe Spécial Mobile (GSM), pan-European, fully digital cellular telephony standard was developed in late 1980s. After its successful deployment, it began to be accepted as a standard for the second-generation mobile radio not only in Europe but also in other parts of the world. The main competition for the GSM monopoly in digital mobile telephony has come from code division multiple access (CDMA) spread spectrum technology, developed primarily for military applications. The CDMA-based IS-95 systems, and time division multiple access (TDMA)–based GSM systems have their powerful supporters and vigorous opponents, and it is not clear yet which approach is going to be adopted in the development of the third generation of mobile telephony or the future public land mobile telecommunication system (FPLMTS), which recently has been renamed International Mobile Telecommunications—2000 (IMT-2000).

OVERVIEW OF CONCEPTS

A typical mobile communication system consists of mobile terminals, base stations, mobile switching centers, and telecommunication channels. Those telecommunication channels are either of a fixed nature (cables or dedicated radio links), to provide connections between base stations and the mobile switching center, or mobile radio channels between mobile terminals and base stations servicing those terminals.

Unlike fixed telecommunication channels, the mobile radio channels are nonstationary and exhibit a high level of unpredictability with regard to channel characteristics. In addition, due to the nature of radio communication and low directivity of antennas used, there is always a possibility of strong interference from other users of the radio spectrum. All these factors need to be carefully taken into account while calculating a power budget for a mobile radio channel.

One of the specific features of mobile communication systems is the need to assign a free radio channel to the user requiring the connection. This is done during setup of the connection. This setup, combined with the limited frequency spectrum available for mobile services, means that the number of simultaneous calls within the coverage area of a single base station is highly limited. Therefore, before introduction of the cellular concept (which is explained later in the section on spectrum management), the number of simultaneous calls within a system covering sometimes a huge area was very low. For example, the single base station mobile system in New York City in the 1970s could only support a maximum of 12 simultaneous calls over one thousand square miles (5). The concept of such a cellular system is illustrated in Fig. 1.

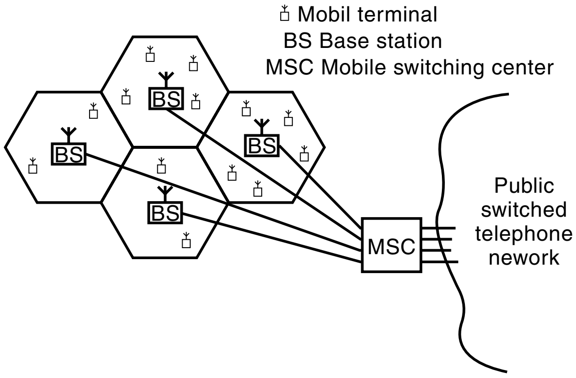

Figure 1. Configuration of a cellular system.

There are generally four different types of channels that are used for communication between the base station and mobiles: (1) forward voice channels (FVC), used for voice transmission from the base station to mobiles; (2) reverse voice channels (RVC), used for voice transmission from mobiles to the base station; (3) forward control channels (FCC), used for transmission of signaling data from the base station to mobiles; and (4) reverse control channels (RCC), used for transmission of signaling data from mobiles to the base station. The control channels transmit and receive data necessary to set up a call, moving it to an unused voice channel, and to manage the handovers between base stations. They are also used for constant monitoring of the system and for synchronization purposes.

The base station serves as a bridge between all mobile users in its coverage area and the mobile switching center (MSC). The MSC acts as a central switching point, closing the traffic among the connected base stations, and serves as a gateway to the PSTN. It also coordinates all activities of the base stations and accommodates all billing and maintenance functions. A typical MSC handles 100,000 cellular subscribers and 5000 simultaneous conversations (6).

CLASSIFICATION

Mobile communication systems are classified into generations in accordance with evolution of systems in time. Indicators for a generation are involved transmission techniques, supported services, and status of unification. First-generation systems were introduced in the early 1980s and used analog techniques basically for speech services. Second generation systems evolved in the late 1980s and are now in a mature form. They utilize digital techniques, and, apart from speech, they support some low-rate data services. Second-generation systems may be further classified into cellular, cordless, and professional radio systems. Due to the wide range of second-generation systems and their immense complexity, we only summarize some air interface parameters of selected digital cellular systems in Table 1. Standards for third-generation systems are currently being developed to provide mobile multimedia telecommunications and universal coverage. In the

Table 1. Characteristics of Selected Second-Generation Systems

Mobile System	GSM	DCS-1800	DECT	IS-95
Frequency band				
MS → BS	890–915 MHz	1710–1785 MHz	1880–1900 MHz	824–849 MHz
BS → MS	935–960 MHz	1805–1880 MHz	1880–1900 MHz	869–894 MHz
Carrier spacing	200 kHz	200 kHz	1728 kHz	1250 kHz
Duplex spacing	45 MHz	95 MHz	0 Hz	45 MHz
No. of carriers	125	375	10	20
System bandwidth	2 × 25 MHz	2 × 75 MHz	20 MHz	2 × 25 MHz
Speech coder				
Full rate	13 kb/s RPE-LTP	13 kb/s RPE-LTP	32 kb/s ADPCM	8, 4, 2, 1 kb/s QCELP
Half rate	5.6 kb/s VSELP	4.5 kb/s VSELP		
Multiple access	TDMA	TDMA	TDMA	CDMA
Duplexing method	FDD	FDD	TDD	FDD
Modulation	GMSK ($BT^a = 0.3$)	GMSK ($BT^a = 0.3$)	GMSK ($BT^a = 0.5$)	QPSK/BPSK
Frame bit rate	271 kbit/s	271 kbit/s	1.152 Mbit/s	1.288 Mbit/s
Frame length	4.615 ms	4.615 ms	10 ms	20 ms

[a] *BT:* 3 dB-bandwidth and bit-duration product of the Gaussian filter.

following subsections, we will give a concise overview of mobile communication systems and refer to the literature for details.

First-Generation Systems

The first-generation cellular systems use analog frequency modulation (FM) for traffic channels, digital frequency shift keying (FSK) for signaling channels, and a frequency division duplex (FDD) method. In addition, frequency division multiple access (FDMA) is employed to share the transmission medium. In the beginning, businesspeople were the main customers, but later acceptance in residential markets started to increase immensely. In 1981, the Scandinavian countries introduced the Nordic Mobile Telephone standard NMT-450 (7) and in 1986 the NMT-900 standard, where the numbers in the acronyms indicate the utilized frequency band in MHz. The AMPS system (8) was developed in the United States, and service opened in 1983. AMPS has been adapted by many countries, such as Canada and Australia. A variant of AMPS is the Total Access Communication System (TACS) deployed in 1985 in the United Kingdom, which basically uses a smaller channel spacing than AMPS. In 1986, the C-450 system (9) opened its service in Germany.

Second-Generation Systems

Cellular Systems

Global System for Mobile Communication. Though mobile communication in most European countries was well covered by their individual analog cellular systems, incompatible standards made it impossible to interwork among systems or share equipment. To overcome this deficiency, the Conférence Européenne des Postes et Télécommunications (CEPT) established in 1982 the Groupe Spécial Mobile to develop a pan-European standard. The outcome was the GSM system (10), which now stands for global system for mobile communication. The standard specifies a digital cellular system on the basis of a dedicated pan-European frequency band allocated at 900 MHz. GSM supports a variety of speech and low-rate data services. In 1991, the first GSM system opened and since then it has experienced tremendous popularity worldwide, as indicated by the more than 65 countries that have already adopted GSM. An extension of GSM is the Digital Cellular System—1800 (DCS-1800) standard allocated in the 1.8 GHz band. DCS-1800 has been designed to meet the requirements of personal communication networks (PCN).

Interim Standard 54 (IS-54). During the 1980s, increasing demand on cellular services was observed in the United States, approaching traffic capacity limits of analog AMPS. To satisfy the enormous capacity requirements, the Cellular Telecommunication Industry Association asked for a digital standard. As a result, IS-54 (11) has been developed and is also known as United States Digital Cellular (USDC). IS-54 is designed to coexist with analog AMPS in the same frequency band but to replace the analog system step by step. For that reason, IS-54 has to be upward compatible to AMPS and hence is sometimes referred to as digital AMPS (D-AMPS). With the used digital techniques and planned employment of a half-rate codec, IS-54 is expected to provide six times the traffic capacity than AMPS.

Interim Standard 95 (IS-95). Development of IS-95 was launched in 1991 after Qualcomm successfully demonstrated a CDMA digital cellular validation system. The IS-95 standard (12) specifies a direct sequence CDMA digital cellular system. This wideband digital cellular standard employs a set of spreading sequences that are assigned to users. All users in the cellular system transmit in the same radio channel but using different sequences. Therefore, frequency planning is not required and can be thought of as replaced by planning how to allocate spreading sequences in different cells.

Personal Digital Cellular (PDC). The Japanese effort to increase capacity over analog systems is documented in a PDC air interface standard (13), which was issued in 1991. This digital cellular system has been allocated a different frequency band than the analog system. It supports speech, data, and short message services.

Cordless Systems

Cordless Telephony (CT2). The initial goal of cordless telephony was to provide wireless pay phone services with low-cost equipment but no support of incoming calls. These systems cover only a single cell with a radius of about 300 m outdoor and 50 m indoor. Most manufactures in Europe agreed on a common air interface (CAI), which become the

CT2/CAI standard (14). It uses digital techniques and replaces analog cordless telephony, which offered only a small number of channels. In Canada, CT2+ was developed to support incoming calls as well. By dedicating more carriers for signaling purposes, location management was practicable.

Digital European Cordless Telecommunications (DECT). The DECT standard (14) was developed by the European Telecommunications Standards Institute (ETSI) and has been allocated a guaranteed pan-European frequency. It is designed as a flexible interface based on open system interconnection (OSI) and was finalized in 1992. The system provides mobility in picocells with very high capacity. Speech and data services are supported where incoming and outgoing calls can be managed. Initially, DECT was intended for interworking with private automatic branch exchange (PABX) to provide mobility within the area of a PABX. Its application-independent interface allows also interworking with PSTN, integrated services digital network (ISDN), or even GSM. For operators of public networks, DECT can be employed to span the last mile to subscribers by radio local loop (RLL).

Personal Handy Phone Systems (PHS). In 1989, the Japanese Ministry of Posts and Telecommunications initiated the standardization process for another cordless system, which become the PHS standard (15). Among other things, the standard defines the air interface, voice services, and data services. The system is designed for small cells, and it maintains incoming as well as outgoing calls. A special feature of PHS is that mobiles that are close enough may bypass the base station and communicate directly with each other.

Professional Mobile Radio. Besides cellular and cordless systems, a variety of professional mobile radio (PMR) systems have been designed for professional and private users. In 1988, the European Commission and ETSI initiated standardization of a PMR system known as trans-European trunked radio (TETRA). Applications include group calls within a fleet of users and fleet management as required by police, safety organizations, or taxi companies. Similarly, in the United States the so-called Associated Public Safety Communications Officers Project 25 (APCO 25) is specifically concerned with public safety radio services. There are a number of other PMR systems, such as European radio message (ERMES), digital short-range radio (DSSR), and terrestrial flight telephone system (TFTS), to mention only a few.

Third-Generation Systems

At present, mobile communications is realized by many kinds of competitive and incompatible standards, systems, and services. On the other hand, unification of cellular, paging, cordless, and professional mobile radio is desirable to manage limited physical resources, improve system quality, and keep up with the great demand for mobile services. Third-generation systems aim to provide unification and worldwide coverage.

Universal Mobile Telecommunication System. The European effort to support the same type of services anywhere and anytime is known as the Universal Mobile Telecommunication System (UMTS) and is described in Ref. 16. It is based on GSM, DCS-1800, and DECT. Standardization is concerned with air interface and protocol issues aiming for global coverage for speech, low-to-medium bit rate services, and multimedia capabilities. A major challenge is to achieve higher data rates, up to 2 Mbit/s. In 1987, the European Union launched a program called Research and Development in Advanced Communications Technologies in Europe (RACE). RACE was supposed to investigate advanced options for mobile communications and in that way assist ETSI in standardization of UMTS. Several subprojects within RACE were concerned with advanced topics, as the following examples indicate. The advanced TDMA (ATDMA) project investigated antenna systems and equalization issues. An approach to increase data rate was undertaken in the Code Division Testbed (CODIT) project. Recently, an agreement was reached among European companies on the radio interface for UMTS based on wideband CDMA (W-CDMA) and time division CDMA (TD-CDMA) technologies (17). Operation of UMTS is expected to commence in the beginning of the twenty-first century.

International Mobile Telecommunications—2000. In the mid-1980s, the International Telecommunications Union (ITU) began its studies of future public land mobile telecommunication systems, the goal of which is to support mobile communication anywhere, anytime. The goals are similar to those intended to be reached by UMTS, but under a worldwide perspective. The ITU approach is now called International Mobile Telecommunications—2000 (IMT-2000) (18), the former FPLMTS (the attached 2000 indicates the frequency band of operation in MHz as well as the year in which service is planned to open). At the World Administrative Radio Conference in 1992 (WARC-92), a bandwidth of 230 MHz in the 2 GHz frequency band was allocated worldwide to IMT-2000. A major objective of IMT-2000 is to offer users a small, inexpensive pocket communicator and provide for seamless roaming of a mobile terminal across various networks. Services range from voice to data and mobile multimedia applications or even Internet access. These services will be offered for a wide range of operating environments, such as indoor, outdoor, terrestrial, and satellite networks. ITM-2000 will utilize technologies like the asynchronous transfer mode (ATM) to provide broadband transport services.

Other Systems

Wireless Local Area Networks (WLAN). Mobile data of second-generation systems offers only low bit rate wireless data transmission but with wide area mobility and roaming. UMTS and IMT-2000 are supposed to increase the bit rate to some 2 Mbit/s. On the other hand, for in-house and on-premises networking there is substantial demand for higher bit rates in the range of 20 Mbit/s, whereas mobility is required only in a restricted area. WLAN systems for such local networking are planned to complement third-generation systems and are considered a flexible and cost-effective alternative to cable-based LANs. Since proprietory solutions are typically customized and rely on products of a particular equipment supplier, standardization of WLAN systems has been undertaken as follows. The high-performance radio local area network (HIPERLAN) standard (19) was developed by ETSI. HIPERLAN achieves a bit rate of 20 Mbit/s and can be used to extend wired LANs such as Ethernet. Spectrum has been recommended in the 5 GHz and 17 GHz bands. Access to the shared transmission channel is gained by a contention-based and collision avoidance strategy. All time critical services are supported by best effort and, in principle, may achieve the same access priority. The Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard (20) represents the first approach for WLAN products from an internationally recognized, independent organization. It defines the protocol for two types of networks—namely, adhoc and client/server networks. IEEE 802.11 operates in the industrial, scientific, and medical (ISM) band at 2.4 GHz using spread spectrum modulation. The medium access control (MAC) uses a collision avoidance mechanism. The third major effort in the area of WLANs is known as wireless ATM (WATM) (21,22). With ATM being a widely accepted standard for broadband networking, it is natural to extend this technology into the wireless domain. Accordingly, the ATM Forum is working toward a WATM standard. A WATM system will provide bandwidth on demand for low- and high-priority services, hence providing real support of time critical multimedia services. Furthermore, a WATM system will interwork seamlessly with wired ATM networks and can be expected to cooperate very well with IMT-2000.

Satellite Systems. Further improvement of coverage can be provided by satellite systems (23), which are a component of future generation mobile systems. Low earth orbit (LEO) satellite systems typically operate on orbits at an altitude of 700 km to 1400 km, whereas medium earth orbit (MEO) satellite systems have their orbits at about 10,000 km. Compared to geostationary satellite systems, LEO and MEO systems allow low-power handhelds and smaller antennas and offer a smaller round-trip delay between earth and satellite. Both LEO and MEO systems employ a number of satellites that form a satellite network and offer worldwide coverage. Satellite systems can be used to cover remote areas that are out of range of a terrestrial cellular system or where a telephony system does not exist. The first generation of satellite personal communications networks (S-PCN) will basically support voice, data, facsimile, and paging. Promising candidates of LEO/MEO systems are Intermediate Circular Orbit (ICO) satellite cellular telephone systems, formerly known as Inmarsat-P, Odyssey, Globalstar, and Iridium. The second generation of S-PCN systems, such as the Teledesic approach, will evolve toward multimedia services and employ ATM technology as well.

MOBILE RADIO CHANNELS

Mobile radio channels considered to be a complex and severe transmission medium. Path loss often exceeds that of free space by several tens of decibels. Reflection, diffraction, scattering, and shadowing lead to fading and multipath reception (Fig. 2). Mobile radio channels are time variant, where signals fluctuate randomly as the receiver moves over irregular terrain and among buildings. Understanding channel behavior and development of channel models for a specific band is always vital for efficient system design.

Large-Scale Propagation Models

Propagation models that predict the average signal strength of a received signal at a given distance from the transmitter are called large-scale propagation models. These models are concerned with loss along the wave propagation path between the mobile and base stations. Extensive measurement campaigns have been undertaken to develop models for some typical environments. We distinguish roughly between rural, suburban, and urban environments.

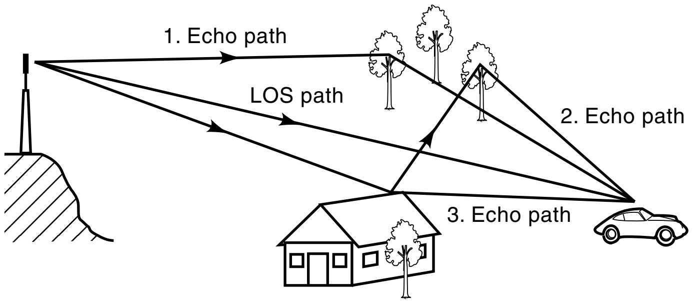

Figure 2. Illustration of multipath propagation typically experienced in a mobile radio environment. Signals between transmitter and receiver propagate along a line-of-sight (LOS) path and are scattered through several echo paths.

Free-Space Model. The ideal large-scale model is free-space propagation, assuming that no objects or obstacles influence propagation. Free-space path loss is given by (24)

$$L_{\mathrm{F}} = 10\log G_{\mathrm{t}} + 10\log G_{\mathrm{r}} - 20\log f_{\mathrm{c}} - 20\log d - 32.44\,\mathrm{dB} \tag{1}$$

where G_t and G_r are the transmitter and receiver antenna gain compared to an isotropic antenna, f_c is the carrier frequency in MHz, and d is the distance between the transmitter and receiver in km.

Okumura and Hata Model. Okumura (25) presented a graphical method to predict the median attenuation relative to free space for a quasi-smooth terrain. The model consists of a set of curves developed from measurements and is valid for a particular set of system parameters in terms of carrier frequency, antenna height, and so forth. After the free-space path loss has been computed, the median attenuation, as given by Okumura's curves, has to be added. Additional correction factors apply for different terrains. Later, Hata (26) transformed Okumura's graphical method into an analytical framework. The Hata model for urban areas is given by the empirical formula

$$\begin{aligned} L_{50,\mathrm{urban}} = {} & 69.55\mathrm{dB} + 26.16\log f_{\mathrm{c}} - 13.82\log h_{\mathrm{t}} - a(h_{\mathrm{r}}) \\ & + (44.9 - 6.55\log h_{\mathrm{t}})\log d \end{aligned} \tag{2}$$

where $L_{50,\mathrm{urban}}$ is the median path loss in dB. Equation (2) is valid for carrier frequencies f_c in the range from 150 MHz to 1500 MHz, mobile antenna height h_r from 1 m to 10 m, and base station antenna height ranging from 30 m to 200 m. The distance d between mobile and base is supposed to be within 1 km to 20 km. The correction factor $a(h_r)$ for mobile antenna height h_r for a small- or medium-sized city is given by

$$a(h_{\mathrm{r}}) = (1.1\log f_{\mathrm{c}} - 0.7)h_{\mathrm{r}} - (1.56\log f_{\mathrm{c}}) - 0.8\,\mathrm{dB} \tag{3}$$

and for a large city it is given by

$$a(h_{\mathrm{r}}) = \begin{cases} 8.29\,[\log(1.54h_{\mathrm{r}})]^2 - 1.1\,\mathrm{dB} & \text{for } f_{\mathrm{c}} \le 300\,\mathrm{MHz} \\ 3.2\,[\log(11.75h_{\mathrm{r}})]^2 - 4.97\,\mathrm{dB} & \text{for } f_{\mathrm{c}} \ge 300\,\mathrm{MHz} \end{cases} \tag{4}$$

Equation (2) serves as the standard formula in urban areas and has to be modified for suburban areas:

$$L_{50,\text{suburban}} = L_{50,\text{urban}} - 2[\log(f_c/28)]^2 - 5.4\,\text{dB} \tag{5}$$

For rural areas, we have to use

$$L_{50,\text{rural}} = L_{50,\text{urban}} - 4.78(\log f_c)^2 - 18.33\log f_c - 40.94\,\text{dB} \tag{6}$$

A uniform extension of these formulas for carrier the frequency range 1500 MHz $\leq f_c \leq$ 2000 MHz and small cells, such as those of personal communications systems, is specified by the European Co-operative for Scientific and Technical research (COST-231) recommendation (27).

Wideband Characterization

To model the time and frequency dispersion of a mobile radio channel with respect to wideband transmission, a system theory approach can be utilized (28). This approach is concerned with fading and multipath in the vicinity of a small area. A set of system functions provides a description in either the time or frequency domain. Due to the random nature of the radio channel, system functions describe stochastic processes.

Time-Variant Impulse Response and Autocorrelation Function. Bello (28) showed that a radio channel may be regarded as a linear time-variant system. He introduced a set of continuous-time and continuous-frequency system functions, each of which completely describes the channel and can be transformed into any of the remaining functions. For the sake of clarity, we assume hereinafter that signal spectra are narrow compared with carrier frequency and channel bandwidth. Thus, we can use a complex lowpass equivalent to represent a bandpass system (29). In doing so, let us focus on the time domain and consider the input delay spread function $h(t, \tau)$, defined by

$$y(t) = \int_{-\infty}^{\infty} x(t-\tau)h(t,\tau)\,d\tau \tag{7}$$

where $x(t)$ and $y(t)$ denote the complex envelope of the transmitted and received signals, respectively. The input delay spread function $h(t, \tau)$ can be thought of as time-variant impulse response of the lowpass equivalent channel at time t due to unit input impulse applied in the past at time $t - \tau$.

Correlation functions provide significant insight into stochastic processes and are often used to avoid specification of multidimensional probability density functions. In this context, the autocorrelation function of the channel impulse response is given by (28)

$$R_h(t_1, t_2, \tau_1, \tau_2) = \overline{h(t_1, \tau_1)h^*(t_2, \tau_2)} \tag{8}$$

where $h(t, \tau)$ is assumed to be a random process without deterministic component, $\overline{h(\cdot)}$ denotes the ensemble average of $h(\cdot)$, and $*$ indicates a conjugate complex. Variables t_1 and t_2 denote time instants, whereas τ_1 and τ_2 denote delays. For many mobile radio channels Eq. (8) does not depend on absolute time but on time difference. In addition, scatterers may be regarded as uncorrelated. Such a channel is called a wide-sense stationary uncorrelated scattering (WSSUS) channel, and its autocorrelation function simplifies to (28)

$$R_h(t_1, t_2; \tau_1, \tau_2) = P_h(\Delta t; \tau_2)\delta(\tau_2 - \tau_1) \tag{9}$$

where $P_h(\Delta t; \tau_2)$ is a cross-power spectral density, $\Delta t = t_2 - t_1$ indicates time difference, and $\delta(\tau)$ denotes a unit impulse at time $\tau = \tau_2 - \tau_1$.

Time and Frequency Dispersion Parameters. In practice, a set of typical channel parameters is used to characterize the dispersive behavior of a mobile radio channel in the time and frequency domain. Similar to Bello's system approach of corresponding functions, time and frequency dispersion parameters possess dual representations in the frequency and time domain, respectively. These parameters can be obtained from measurements and employed for channel classification.

Delay Spread and Coherence Bandwidth. Because of multipath propagation, the impulse response of a mobile radio channel appears as a series of pulses rather than a single delayed pulse. A received signal suffers spreading in time compared to the transmitted signal. Delay spread can range from a few hundred nanoseconds inside buildings up to some microseconds in urban areas. Delay-related parameters can be obtained from the power delay profile $P_h(\tau)$ (29), which is defined as the power spectral density for $\Delta t = 0$; that is,

$$P_h(\tau) = P_h(\Delta t, \tau)|_{\Delta t=0} \tag{10}$$

Maximum excess delay is defined as the period between the time of the first arriving signal and the maximum time at which a multipath signal exceeds a given threshold. The first moment of a power delay profile is called mean excess delay, m_τ, and is defined by

$$m_\tau = \frac{\int_0^\infty \tau P_h(\tau)\,d\tau}{\int_0^\infty P_h(\tau)\,d\tau} \tag{11}$$

The square root of the second central moment of the power delay profile is referred to as root mean square (rms) delay spread, σ_τ, and is defined by

$$\sigma_\tau = \sqrt{\frac{\int_0^\infty [\tau - m_\tau]^2 P_h(\tau)\,d\tau}{\int_0^\infty P_h(\tau)\,d\tau}} \tag{12}$$

The coherence bandwidth B_c translates time dispersion into the language of the frequency domain. It specifies the frequency range over which a channel affects the signal spectrum nearly in the same way, causing an approximately constant attenuation and linear change in phase. Coherence bandwidth is inversely proportional to rms delay spread:

$$B_c \propto \frac{1}{\sigma_\tau} \tag{13}$$

Doppler Spread and Coherence Time. Movement of a mobile station relative to a base station or movement of objects within the channel causes the received frequency at the mobile station to differ from the transmitted frequency due to Doppler shift. In a multipath environment, a mobile station receives signals from different paths. Its relative movement with respect to each path differs, which results in a range of Doppler shifts. The bandwidth over which dispersion of the transmitted frequency occurs is referred to as the Doppler spread, B_d. The time domain equivalent to Doppler spread B_d is called coherence time, T_c. It specifies a period over which the channel impulse response $h(t, \tau)$ is nearly time invariant. Coherence time is inversely proportional to Doppler spread:

$$T_c \propto \frac{1}{B_d} \tag{14}$$

Classification of Multipath Channels

Flat Fading. This type of fading is related to delay spread. It occurs when the signal symbol period is much larger than rms delay spread. As a result, intersymbol interference (ISI) almost vanishes. In the dual domain, the signal bandwidth is narrow compared to the coherence bandwidth. The channel has a flat transfer function with almost linear phase, thus affecting all spectral components of the signal similarly.

Frequency Selective Fading. If the signal symbol period is much lower than rms delay spread, the receiver is able to resolve multipath components, and ISI impairs transmission. In that case, the bandwidth of the signal exceeds the coherence bandwidth, and various spectrum components may be affected differently. Frequency selective fading is also caused by delay spread.

Fast Fading. This type of fading is caused by motion in a mobile environment and hence relates to Doppler spread. Fast fading can be observed when significant changes in the channel impulse response occur within the signal symbol period. In other words, the bandwidth of the Doppler spectrum is wide compared with the signal bandwidth, which then causes significant signal distortion.

Slow Fading. In the case when the channel impulse response is almost time invariant for the duration of a signal symbol period, we observe a slow fading and only a minor signal distortion. The Doppler spread is then narrow compared to the signal bandwidth.

Narrowband Characteristics

We consider an unmodulated sinusoidal waveform being transmitted at carrier frequency f_c and described in complex notation by $x(t) = \exp(j2\pi f_c t)$, where $j = \sqrt{-1}$. The equivalent lowpass signal at the receiver can be written as (29)

$$y(t) = y_I(t) + jy_Q(t) = \sum_{i=-\infty}^{\infty} a_i(t) \cdot \exp[j2\pi f_{d,i}t - j2\pi f_c \tau_i(t)] \tag{15}$$

where $y_I(t)$ and $y_Q(t)$ denote, respectively, inphase and quadrature components of the complex-valued signal $y(t)$, $a_i(t)$ is complex amplitude, $f_{d,i}$ is Doppler frequency, and $\tau_i(t)$ is delay of the ith multipath component.

Fading Distributions

Rayleigh Fading. Suppose there is no dominant path between transmitter and receiver, and all multipath components are multiply reflected to build a diffuse received signal. In that case, complex amplitude $a_i(t)$, Doppler frequency $f_{d,i}$, and delay $\tau_i(t)$ can be considered statistically independent of each other. The probability density function of the received signal envelope $r(t) = |y(t)| = \sqrt{y_I^2(t) + y_Q^2(t)}$ leads to a Rayleigh distribution given by (24)

$$p_{\text{Rayleigh}}(r) = \frac{r}{\sigma_y^2} \exp\left(-\frac{r^2}{2\sigma_y^2}\right) \tag{16}$$

where $r \geq 0$ is the received signal envelope and $\sigma_y^2 = E\{y_I^2(t)\} = E\{y_Q^2(t)\}$ is the variance of the zero-mean and normally distributed processes, describing $y_I(t)$ and $y_Q(t)$. Mean m_r and variance σ_r of $r(t)$ are given by $m_r = E\{r(t)\} = \sqrt{\pi/2} \cdot \sigma_y$ and $\sigma_r^2 = (2 - \pi/2) \cdot \sigma_y^2$, respectively.

Rice Fading. Let the received signal contain a dominant component that might be caused by a line-of-sight (LOS) path or single reflected multipath components. In terms of an equivalent lowpass signal, we have to add a constant r_0 to the real part of $y(t)$ and thus $y(t) = [r_0 + y_I(t)] + jy_Q(t)$. The corresponding probability distribution function of the signal envelope $r(t) = \sqrt{[r_0 + y_I(t)]^2 + y_Q^2(t)}$ leads to a Rician distribution (24)

$$p_{\text{Rice}}(r) = \frac{r}{\sigma_y^2} \exp\left(-\frac{r^2 + r_0^2}{2\sigma_y^2}\right) I_0\left(\frac{r \cdot r_0}{\sigma_y^2}\right) \tag{17}$$

where $r_0 \geq 0$ is the peak amplitude of the dominant component and $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind.

Log-Normal Fading. When a mobile station moves within an area about the base station, the local-mean power P_r of the received signal varies about the area-mean power P_s due to shadowing effects. Measurements have shown that the logarithmic value $L_r = 10\log(P_r)$ in dB of the local-mean power P_r is normal distributed about the logarithmic value $L_s = 10\log(P_s)$ in dB of the area-mean power P_s. This gives rise to the call P_r being log-normal distributed, and the corresponding probability density function is given by (30)

$$p_{\text{Log-normal}}(P_r) = \frac{10\log(e)}{P_r} \cdot \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left\{-\frac{[10\log(P_r) - L_s]^2}{2\sigma_s^2}\right\} \tag{18}$$

where standard deviation σ_s in dB characterizes the shadowing effect.

SPECTRUM MANAGEMENT

The radio frequency spectrum is a limited resource that has to be shared in some way among the communication community. With the increasing demand for mobile radio communication, regulations and methods for efficient spectrum usage are required. Frequency authorities such as the ITU and the Federal Communications Commission (FCC) play a vital part in allocating frequency bands to new systems and in worldwide coordination of the radio spectrum. Once a frequency band has been licensed, the cellular concept enables spectrum efficiency by reusing frequency in spatial by distant areas. Bandwidth-efficient modulation schemes can be used to increase further the total number of available channels in a system.

Frequency Licensing

Spectrum planning is a hierarchical process that starts at the highest international level at the ITU and is covered by the WARC. This international framework is a base for national frequency planning and allocation. From the start of a licensing process to actual frequency allocation with specified services, often several years ellapse. On the other hand, today's main requirements of licensing procedures are speed, transparency, fairness, efficiency, and conformity with government objectives. As a response, several national regulatory methods for licensing of frequency bands have been applied and are still used, depending on the local situation (31).

Over-the-Counter Allocation. This is the traditional method, which can be regarded as a first come, first served principle. Obviously, with this method there will be unsatisfied demand. In addition, there is no guarantee that those who apply first will be those who value the spectrum most highly or whose service is of greatest importance to the community. In cases where demand does not exceed supply (e.g., for many military applications), this approach is still favored.

Comparative Assessment. In this approach governments and regulators assess the relative merits of different applicants for a frequency band. The criteria are varied—for example, anticipated consumer benefits, the technology applied, or the perceived overall social worth of the service to be supplied. A regulator must be able to make judgments about the most valued use of a frequency band. Apparently, comparative assessment is neither transparent nor fast or even fair and should only be used when a decision can be easily reached (e.g., if there is no competition between providers due to a monopolistic market).

Lotteries. Lotteries involve a random distribution of licenses to different applicants of the same frequency band. Lotteries are quick and fair as long as all participants have the same weight and do not circumvent this by submitting multiple entries under different names. Even then lotteries might not be effective because the value of the service cannot be accounted for.

Tenders. Applicants provide sealed bid tenders for a desired frequency band. The advantages of this method are its fairness and transparency. The problem is that it is not effective in the sense that the most valued service will be gained by the company with the highest financial resources. This may lead to proprietary services if the final service in that band is not completely defined in advance. Otherwise, if the service is already defined, this approach is better than those previously mentioned. One major disadvantage still remains: the high possibility of overvaluing the asset because the bids of others are not known.

Auctions. Auctioning of frequency bands combines the advantages of the tender approach with information about the bids of the other applicants. In addition, government interests concerning enhanced competition can be taken into account by restricting the occupied amount of frequency bands for an applicant to a certain percentage. Sometimes the fairness of this approach is criticized because similar lots could be sold for very different prices. Furthermore, collisions may happen at auctions. To offer multiple frequency bands at the same time, the simultaneous multiple-round auction was developed. It seems that the latter method is one of the best for efficient and fair spectrum management. It fulfills most of the requirements mentioned previously and returns the pressure from the regulators back to the applicants. Thus, it is going to be applied in future licensing procedures in which an excess of demand over supply can be forecast (e.g., for third-generation mobile systems).

Frequency Reuse

The concept of frequency reuse is a core element of all cellular mobile radio systems (1,6). It significantly increases system capacity, which may be indicated by the total number of available duplex channels. The frequency band allocated to a cellular system is organized into a finite number of frequency channels, each of which can be simultaneously reused in different geographic locations (so-called cells). In that way, a cellular system can serve more customers compared with the case when the whole system area is covered by just a single base station. On the other hand, reuse of frequency channels causes interference between those cells that use the same channel (this is called co-channel interference). It is a major task of cellular system design to maximize capacity and to minimize interference. Since capacity can be increased by using smaller cells and interference decreases with larger cells, a compromise is required.

In cellular system design, some idealized assumptions are made that ease the complex task of capacity and interference analysis. First, a hexagonal cell shape is normally proposed as a model to approximate the actual footprint of a base station. Thus, the whole coverage area of a cellular system can be represented by a homogeneous grid of hexagons. Because of this geometry, the number of cells in a cluster or cluster size can only take certain values and is given by

$$N = I^2 + IJ + J^2 \tag{19}$$

where the shift parameters I and J are nonnegative integers. Figure 3 shows the frequency reuse concept for a seven-cell cluster in which each letter denotes a set of frequencies. A certain cell is surrounded by adjacent channel neighbors. The nearest co-channel neighbor (say, to cell G) can be found by moving along a chain of $I = 2$ hexagons, turning 60° counter-

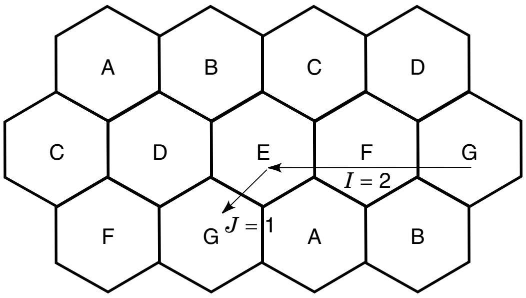

Figure 3. Illustration of the cellular concept by means of a seven-cell cluster. The seven frequencies reused in the system are labeled A through G. Shift parameters are $I = 2$ and $J = 1$.

clockwise, and finally moving in that new direction along $J = 1$ cells.

Here, we consider a homogeneous hexagonal cellular system in which cells are roughly of equal size. It turns out that co-channel interference does not depend on transmission power but on the ratio between distance D of a cell to the center of the nearest co-channel cell and the radius R of a cell (Fig. 4). This parameter is called the co-channel reuse ratio and is given by

$$Q = D/R = \sqrt{3N} \tag{20}$$

A large co-channel reuse ratio means that transmission quality is high, since co-channel interference is kept low due to a reasonable spatial separation of co-channel neighbors. Large capacity can be obtained when the cluster size and correspondingly the co-channel reuse ratio is small.

Usually, co-channel interference can be quantified by computing the signal-to-interference ratio (SIR). For that purpose, let γ denote the path loss exponent and assume γ to be constant over the whole coverage area of the cellular system. In a mobile radio environment, γ typically ranges between two and four. In addition, assume that all base stations transmit the same power. Then the SIR at a mobile station can be estimated by

$$\frac{S}{I} = \frac{R^{-\gamma}}{\Sigma_{i=1}^{i_0} D_i^{-\gamma}} \tag{21}$$

where i_0 is the number of co-channel interfering cells. Let us now consider co-channel interfering cells from the first tier only and assume that all those base stations are at a distance D from the desired base station. Then the SIR can be approximated as

$$\frac{S}{I} = \frac{Q^{\gamma}}{i_0} = \frac{(D/R)^{\gamma}}{i_0} = \frac{(\sqrt{3N})^{\gamma}}{i_0} \tag{22}$$

Finally, in the worst-case scenario, in which the mobile station is located at the cell boundaries, the SIR can be approximated as

$$\frac{S}{I} = \frac{1}{2(Q-1)^{-\gamma} + 2Q^{-\gamma} + 2(Q+1)^{-\gamma}} \tag{23}$$

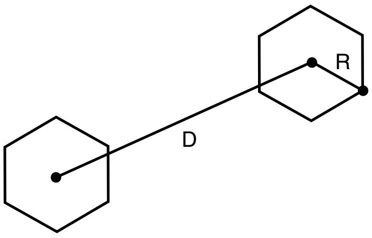

Figure 4. Interference geometry between two co-channel cells used to compute the signal-to-interference ratio assuming an idealized hexagonal cell shape. Cells are of radius R and have distance D from each other.

Table 2. Signal-to-Interference Ratio for Various Cluster Sizes

				S/I in dB	
I	J	N	Q	Eq. (22)	Eq. (23)
1	1	3	3.00	11.30	8.03
2	1	7	4.58	18.65	17.26
3	0	9	5.19	20.84	19.74
2	2	12	6.00	23.34	22.57

Table 2 shows SIR values for some typical cluster sizes. The pass loss exponent is taken as $\gamma = 4$, and the number i_0 of co-channel interfering cells in a fully developed system is about six. Subjective tests undertaken for voice services have shown that an $S/I = 18$ dB gives satisfactory quality. In a homogeneous hexagonal system, this requires a cluster size of at least seven.

Apart from frequency reuse, there are some other techniques to improve the capacity of a cellular system. Improved capacity is often required to adapt the initial system to an increasing demand on services or to better cover congested areas. Sectoring is such a technique and replaces omnidirectional antennas at a base station by several sector antennas. Most common is an arrangement of three or six sectors whereby a 120° or 60° directional antenna radiates within a certain sector. Due to less cochannel interferers in the first tier of a sectorized system, this approach decreases the signal-to-interference ratio and thus allows for a smaller cluster size (i.e., higher capacity). A second technique is called cell splitting, which basically reduces the cell sizes. In that way, more cells fit within an area, resulting in more available channels per area.

Digital Modulation Techniques for Mobile Communication

A modulation scheme for a mobile communication system should utilize the allocated frequency band and power as efficiently as possible. With regard to second-generation systems and the intended application of data services in future wireless systems, digital modulation techniques are a natural choice. Selection of an appropriate digital modulation scheme can be made on the basis of the following characteristics. The power density spectrum is defined as the relative power in a modulated signal versus frequency. It consists of a main lobe and several side lobes, which indicate interference into adjacent channels. A modulation scheme can be further assessed by its robustness against interference and channel impairments, which is indicated by a low bit error rate. Bandwidth efficiency measures the bit rate that can be transmitted per unit of frequency bandwidth and is expressed as the number of bits per second per hertz (b/s/Hz). Apart from that, implementation complexity and costs have to be considered as well. A desirable modulation scheme should achieve high bandwidth efficiency at a given bit error rate and simultaneously offer a narrow power density spectrum. Digital modulation schemes currently being used in second generation systems can be classified into phase shift keying (PSK) and continuous phase modulation (CPM).

The family of PSK schemes belongs to the class of linear modulation techniques (29); that is, a modulating digital signal is used to vary linearly the amplitude of a transmitted signal. The most popular schemes within this family include quaternary phase shift keying (QPSK), offset QPSK (OQPSK), $\pi/4$ phase shift QPSK ($\pi/4$-QPSK), and differentially encoded $\pi/4$-QPSK, called $\pi/4$-DQPSK. QPSK splits the baseband data signal into two pulse streams (namely, inphase and quadrature components), which reduces the data rate to half that of the baseband signal. The phase of the carrier takes one of four values (say, 0°, 90°, 180°, or 270° or an equally spaced but rotated constellation of these). Side lobes in the power density spectrum of a QPSK modulated signal are usually suppressed by passing the signal through a front-end filter, but then the signal envelope will no longer have a constant envelope. When the filtered signal experiences a 180° shift in carrier phase, the envelope fluctuates significantly and even goes through zero. Such an envelope fluctuation will cause reappearance of side lobes every time the filtered QPSK modulated signal passes a nonlinearity (e.g., a nonlinear amplifier). An improvement over QPSK offers the OQPSK modulation scheme, in which a shift of one bit delay is introduced to the quadrature component. As a result, inphase and quadrature components have signal transitions at separate time instants, and thus shifts in carrier phase are limited to a maximum of ±90°. Because 180° phase shifts have been removed, the envelope cannot go through zero any longer. Envelope fluctuations are less severe, and nonlinear amplification can be applied. Finally, $\pi/4$-QPSK can be regarded as a compromise between QPSK and OQPSK, which limits the maximum phase shift to ±135. $\pi/4$-QPSK can be differentially encoded and is then called $\pi/4$-DQPSK. The $\pi/4$-DQPSK technique uses the phase shifts in the carrier instead of the phase to transmit information. It can be noncoherently detected, which is one of the reasons that $\pi/4$-DQPSK has been employed in many digital mobile communication systems, such as IS-54, PDC, and PHS.

Improvement of OQPSK in terms of out-of-band radiation can be obtained from the CPM technique (32), which continuously varies the carrier phase and thus completely avoids discontinuous phase transitions. Further, all CPM schemes have constant carrier envelopes and hence allow for nonlinear amplification. Among the most popular CPM schemes are minimum shift keying (MSK) and Gaussian minimum shift keying (GMSK). MSK can be regarded as a special case of OQPSK in which the baseband signal uses half-sinusoidal pulses instead of a rectangular pulse shape (this produces the desired smooth phase transitions). Unfortunately, MSK does not have a power density spectrum as compact as desirable for mobile radio. A tighter spectrum can be achieved by passing the modulating signal through a premodulating pulse-shaping filter. Following this concept, GMSK uses a filter with a Gaussian or bell-shaped transfer function. The compact power density spectrum of GMSK is gained at the expense of an increased irreducible bit error rate due to intersymbol interference. GMSK has been adopted for GSM, DECT, and CT-2.

Table 3. Spectral Efficiency of Second-Generation Systems

System	Modulation Technique	Data Rate (kbit/s)	Channel Spacing (kHz)	Efficiency (b/s/Hz)
GSM	GMSK (BT[a] = 0.3)	270.8	200	1.35
IS-54	$\pi/4$-DQPSK	48.6	30	1.62
IS-95	QPSK/BPSK	1288	1250	1.03
PDC	$\pi/4$-DQPSK	42	25	1.68
CT-2	GMSK (BT[a] = 0.5)	72	100	0.72
DECT	GMSK (BT[a] = 0.5)	1152	1728	0.67
PHPS	$\pi/4$-DQPSK	384	300	1.28
TETRA	$\pi/4$-DQPSK	36	25	1.44

[a] BT = 3 dB-bandwidth and bit-duration product of the Gaussian filter.

Table 3 summarizes modulation techniques used in second-generation systems along with the achieved bandwidth efficiency. The most popular schemes are $\pi/4$-DQPSK and GMSK. Note that the employed GMSK schemes differ in the 3 dB bandwidth and bit-duration product BT of the Gaussian filter.

CONCLUSION

Mobile communication has already become an integral part of modern life and is one of the driving forces of telecommunications. Wireless access to global telecommunication can be expected to change the face of telecommunication even further. Apart from traditional voice services and low-rate data, future mobile communication will provide for multimedia services that are a mixture of voice, data, text, graphic, and video. Land mobile, maritime, aeronautic, and satellite systems will not just coexist but will establish a global mobile system allowing users to communicate at any time and from anywhere in the world. Before this vision of a global mobile system can become reality, several technical challenges have to be resolved. Such resolution will require support from all areas of communication engineering, such as source and channel coding, bandwidth-efficient modulation, multiple access control, and protocol and security issues.

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MOBILE COMMUNICATION ANTENNA ARRAYS. See ANTENNA ARRAYS FOR MOBILE COMMUNICATIONS.

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