GSM – Architecture, Protocols and Services

Third Edition

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Preface

The GSM family (GSM, GPRS, EDGE) has become one of the most successful technical innovations in history. As of June 2008, more than 2.9 billion subscribers were using GSM, corresponding to a market share of more than 81%, and its story continues, even now, despite the introduction and development of next-generation systems such as IMT-2000 or UMTS (3G) and even systems beyond 3G, dubbed IMT-Advanced.

At the same time, wireless local area networks have substantially expanded the wireless market, sometimes drawing market share from GPRS and 3G (e.g. in public WiFi hotspots), sometimes coexisting (e.g. in UMTS home routers used as a replacement for fixed wire connections). However, these are used typically for low mobility applications. Mobile communication with all of its features and stability has become increasingly important: cellular and GSM technology, plus, of course, lately 3G, GSMs sister technology, so-to-say.

Another impressive trend has emerged since our last edition: the permanent evolution in the handheld market, producing fancy mobile phones with cameras, large memory, MP3 players, Email clients and even satellite navigation. These features enable numerous nonvoice or multimedia applications, from which, of course, only a subset is or will be successful on the market.

In this third edition, we concentrate again on the architecture, protocols and operation of the GSM network and outline and explain the innovations introduced in recent years. The main novelties in this book are the presentation of capacity enhancement methods such as sectorization, the application of adaptive antennas for Spatial Filtering for Interference Reduction (SFIR) and Space Division Multiple Access (SDMA), a detailed introduction to HSCSD and EDGE for higher data rates, and an update of the available GSM services, specifically introducing the Multimedia Messaging Service (MMS).

We are happy to have received, over the past few years, many constructive comments, and a lot of praise and encouragement. The book has obviously been successfully used by professionals (especially people beginning careers in the cellular network business) but also by students including our own who use it as a textbook enhancing their course material.

Our author team has been enlarged with the addition of Dr. Christian Hartmann, an assistant professor at Technische Universität München, who took most of the load for this edition.

We thank all of the involved staff from Wiley who convinced us to prepare this updated version of a book that will hopefully be as successful over the next few years as in the past.

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1

Introduction

1.1 The idea of unbounded communication

Communication everywhere, with everybody, and at any time – that was the dream and goal of researchers, engineers and users, since the advent of the first wireless communication systems. Today it feels like we have almost reached that goal. Digitalization of communication systems, enormous progress in microelectronics, computers and software technology, the invention of efficient algorithms and procedures for compression, security and processing of all kinds of signals, as well as the development of flexible communication protocols have all been important prerequisites for this progress. Today, technologies are available that enable the realization of high-performance and cost-effective communication systems for many application areas.

Using current wireless communication systems, the most popular of which is GSM (Global System for Mobile Communication), we see that we have the freedom to not only roam within a network, but also between different networks, and that we can in fact communicate (almost) everywhere (unless we are in one of the rare spots still without GSM coverage today), with (almost) everybody (unless our desired communication partner is in one of the rare spots mentioned above or chooses not to be reachable), and at (almost) any time (unless we forgot to pay our last phone bill and the operator decides to lock us out). If there is one major aspect still missing in order to make our wireless experience flawless, it is the large (albeit diminishing) gap between data rates available through wireless services and those available through wired services, such as Digital Subscriber Line (xDSL). This and the limited capability of data representation at the mobile terminal (mostly due to the limited size of mobile phones) is one of the main challenges for future developments in wireless communication.

Let us now briefly take a look at the functionalities, which enable us to move and roam so freely in GSM systems: terminal mobility and personal mobility.

In the case of terminal mobility, the subscriber is connected to the network in a wireless way – via radio- or light-waves – and can move with their terminal freely, even during a

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communication connection. The degree of mobility depends on the type of mobile radio network. The requirements for a cordless in-house telephone are much less critical than for a mobile telephone that can be used in a car or train. If mobility is to be supported across the whole network (or country) or even beyond the network (or national) boundaries, additional switching technology and administrative functions are required, to enable the subscribers to communicate in wireless mode outside of their home areas.

Such extended network functions are also needed to realize personal mobility and universal reachability. This is understood to comprise the possibility of location-independent use of all kinds of telecommunication services, including fixed and wireless networks. The user identifies themselves (the person), e.g. by using a chip card, at the place where they are currently staying and have access to the network. There, the same communication services can be used as at home, limited only by the properties of the local network or terminal used. A worldwide unique and uniform addressing system is an important requirement for personal mobility.

In the digital mobile communication system GSM, which is the subject of this book, terminal mobility is the predominant issue. Wireless communication has become possible with GSM in any town, any country and even on any continent.

GSM technology contains the essential intelligent functions for the support of personal mobility, especially with regards to user identification and authentication, and for the localization and administration of mobile users. Here it is often overlooked that in mobile communication networks by far the largest part of the communication occurs over the fixed network part, which interconnects the radio stations (base stations). Therefore, it is no surprise that in the course of further development and evolution of the telecommunication networks, a lot of thought has been given to the convergence of fixed and mobile networks.

In the beginning, GSM was used almost exclusively for speech communication; however, the Short Message Service (SMS) soon became extremely popular with GSM users: several billion text messages are being exchanged between mobile users each month. In the mean time, additional data services have been realized, most notably the High Speed Circuit Switched Data (HSCSD) and the General Packet Radio Service (GPRS), which enable improved data rate performance by allowing for more than one GSM timeslot to be used by a terminal for a service at a time. The driving factor for new (and higher bandwidth) data services obviously is wireless access to the Internet. To this end, the Wireless Application Protocol (WAP) is also explained in this book. These additions are already working towards closing the gap between wireless and fixed networks that we discussed above.

A further step was the introduction of third-generation (3G) mobile communication networks. The 3G networks, known as the Universal Mobile Telecommunication System (UMTS) in Europe and as the International Mobile Telecommunication System 2000 (IMT-2000) worldwide, have already been introduced. However, the implementation of such 3G wireless technologies has not so far stretched much beyond busy city centers. In fact, GSM is still the major technology for providing full coverage, while 3G technology is applied to cover hot-spot areas, mainly those with very high user densities. Thanks to multi-mode terminals, which can handle both standards (GSM and UMTS), wireless network users usually do not even realize which technology they are currently using while making a call or using other wireless services. Regarding the relevance of GSM technology, it is important to note that most network providers who have implemented UMTS are using basically the same fixed backbone infrastructure architecture as used for GSM and GPRS together.

1.2 The success of GSM

GSM is now in more countries than McDonalds.

(*Mike Short, Chairman MoU Association 1995–1996*)

The relevance of the GSM standard today becomes obvious when we take a brief look at the success story of GSM so far and keeping in mind that many countries are still working towards full wireless coverage, mainly by deploying GSM. GSM was initially designed as a pan-European mobile communication network, but shortly after the successful start of the first commercial networks in Europe, GSM systems were also deployed on other continents (e.g. in Australia, Hong Kong and New Zealand). In the meantime, as of May 2008, 670 networks in 208 countries are in operation according to GSM world.

In addition to GSM networks that operate in the 900 MHz frequency band, other so-called Personal Communication Networks (PCNs) and Personal Communication Systems (PCSs) are in operation. They use frequencies around 1800 MHz, or around 1900 MHz in North America. Apart from the peculiarities that result from the different frequency range, PCNs/PCSs are full GSM networks without any restrictions, in particular with respect to services and signaling protocols. International roaming among these networks is possible based on the standardized interface between mobile equipment and the Subscriber Identity Module (SIM) card, which enables personalization of equipment operating in different frequency ranges (SIM card roaming). Now that UMTS technology has been integrated by most wireless providers into their networks, roaming not only between providers but also between different technologies is already state of the art. To this end, multi-band and multi-standard terminals have been developed and are considered commonplace today. Users of state-of-the-art terminals with a SIM card from one of the major providers in Europe can use their terminals in different frequency ranges as well as in GSM and UMTS networks, without having to configure or select anything. The terminals roam between different networks and technologies automatically.

1.3 Classification of mobile communication systems

This book deals almost exclusively with GSM; however, GSM is only one of many facets of modern mobile communication.

For the bidirectional – and hence genuine – communication systems, the simplest variant is the cordless telephone with very limited mobility (particularly the Digital Enhanced Cordless Telecommunications (DECT) standard in Europe). This technology is also employed for the expansion of digital Private Branch Exchanges (PBXs) with mobile extensions.

Local Area Networks (LANs) have also been augmented with mobility functions: Wireless LANs (WLANs) have been standardized and are now offered by several companies. WLANs offer Internet Protocol (IP)-based, wireless data communication with very high bit rates but limited mobility. WLANs have been installed, for example, in office environments and airports, as a supplement or alternative to wired LANs, but also in universities, cafes, restaurants, etc. WLAN access points, however, are also very popular in private homes as access technology. In fact, in urban areas the coverage of IEEE 802.11 type access points is impressive and could theoretically be used for roaming while using WLAN by applying

Mobile IP enhanced routing for mobility support. This, however, is hindered by the fact that each WLAN cell is typically managed by someone else, in effect making it impossible to form a large network. Another aspect is that most WLAN cells are of course encrypted and cannot therefore be used by just anyone. A little different are campus-type WLAN networks, operated by companies or universities, for instance. The IEEE 802.11 type WLAN standards are continuously being amended. The IEEE 802.11n standard for high data rates enables data rates in the 100 Mbit/s range by applying multiple antennas and using multiple in multiple out (MIMO) technology. Even though standardization is not complete for IEEE 802.11n, so-called draft-n devices are already commercially available and promise data rates close to 100 Mbit/s.

Another emerging class of wireless networks are being used for short-range communication. Bluetooth, for example, replaces cables by enabling direct wireless information exchange between electronic devices (e.g. between cellular phones, Personal Digital Assistants (PDAs), computers and peripherals). These networks are also called Body Area Networks or Personal Area Networks. Unlike the mobile technologies mentioned above, they are not based on a fixed network infrastructure (e.g. base stations). The possibility of building up such networks in a spontaneous and fast way gave them the name *ad hoc* networks. WLAN technologies also include the capability for peer-to-peer *ad hoc* communication (in addition to the classical client-to-base station transmission modus).

GSM and UMTS belong to the class of cellular networks that are used predominantly for public mass communication. These had an early success with analog systems such as the Advanced Mobile Phone System (AMPS) in America, the Nordic Mobile Telephone (NMT) in Scandinavia, or the *C-Netz* in Germany. Founded on the digital system GSM (with its variants for 900, 1800 and 1900 MHz), a market with millions of subscribers worldwide was generated, and it represents an important economic force. A strongly contributing factor to this rapid development of markets and technologies has been the deregulation of the telecommunication markets, which allowed the establishment of new network operators.

Another competing or supplementary technology is satellite communication based on Low Earth Orbiting (LEO) or Medium Earth Orbiting (MEO) satellites, which also offer global, and in the long term even broadband, communication services. Trunked radio systems – in digital form with the European standard *Trans European Trunked Radio* (TETRA) – are used for business applications such as fleet control. They offer private services that are only accessible by closed user groups.

In addition to bidirectional communication systems, there also exists a variety of unidirectional systems, where subscribers can only receive but not send data. With unidirectional message systems (paging systems) users may receive short text messages. A couple of years ago, paging systems were very popular, since they offered a cost-effective reachability with wide-area coverage. Today, the SMS in GSM has basically replaced the function of paging systems. Some billion SMS messages are being exchanged between mobile GSM users each month. Digital broadcast systems, such as Digital Audio Broadcast (DAB) and Digital Video Broadcast (DVB), are very interesting for wireless transmission of radio and television stations as well as for audio- and video-on-demand and broadband transmission of Internet pages.

GSM and its enhancements (including UMTS air interfaces), however, will remain the technological base for mobile communication for many years, and will continue to open up new application areas.

1.4 Some history and statistics of GSM

In 1982 the development of a pan-European standard for digital cellular mobile radio was started by the Groupe Spécial Mobile of the CEPT (Conférence Européenne des Administrations des Postes et des Télécommunications) (see Table 1.1). Initially, the acronym GSM was derived from the name of this group. After the founding of the European standardization institute ETSI (European Telecommunication Standards Institute), the GSM group became a technical committee of ETSI in 1989. After the rapid worldwide proliferation of GSM networks, the name has been reinterpreted as Global System for Mobile Communication.

After a series of incompatible analog networks had been introduced in parallel in Europe, e.g. Total Access Communication System (TACS) in the UK, NMT in Scandinavia and the *C-Netz* in Germany, work on the definition of a European-wide standard for digital mobile radio was started in the early 1980s. The GSM was founded, which developed a set of technical recommendations and presented them to ETSI for approval. These proposals were produced by the Special Mobile Group (SMG) in working groups called Sub Technical Committees (STCs), with the following division of tasks: service aspects (SMG 01), radio aspects (SMG 02), network aspects (SMG 03), data services (SMG 04) and network operation and maintenance (SMG 06). Further working groups were mobile station testing (SMG 07), integrated circuit card aspects (SMG 09), security (SMG 10), speech aspects (SMG 11) and system architecture (SMG 12) (ETSI, 2008). SMG 05 dealt with future networks and was responsible for the initial standardization phase of the next generation of the European mobile radio system, the UMTS. Later, SMG 05 was closed, and UMTS became an independent project and technical body of ETSI. The Third Generation Partnership Project (3GPP) has been founded in cooperation with other standardization committees worldwide. Its goal was the composition of the technical specifications for UMTS. Finally, in July 2000, ETSI announced the closure of the SMG which has been responsible for setting GSM standards for the last 18 years. Their remaining and further work has been transferred to groups inside and outside ETSI; most of the ongoing work has been handed over to the 3GPP.

After the official start of the GSM networks during the summer of 1992, the number of subscribers increased rapidly such that during the fall of 1993 already more than one million subscribers had made calls in GSM networks, more than 80% of them in Germany. On a global scale, the GSM standard also received very fast recognition, as evident from the fact that at the end of 1993 several commercial GSM networks started operating outside Europe, in Australia, Hong Kong and New Zealand. Afterwards, GSM was introduced in Brunei, Cameroon, Iran, South Africa, Syria, Thailand, USA and United Arab Emirates. Whereas the majority of the GSM networks operate in the 900 MHz band (GSM900), there are also networks operating in the 1800 MHz band (GSM1800) – PCN and Digital Communication System (DCS1800) – and in the United States in the 1900 MHz band (GSM1900) – PCS. These networks use almost completely identical technology and architecture; they differ essentially only in the radio frequencies used and the pertinent high-frequency technology, such that synergy effects can be taken advantage of, and the mobile exchanges can be constructed with standard components.

In parallel to the standardization efforts of ETSI, in 1987 the then existing prospective GSM network operators and the national administrations formed a group whose members signed a common Memorandum of Understanding (MoU). The MoU Association was supposed to form a base for allowing the transnational operation of mobile stations using

Table 1.1 Time history – milestones in the evolution of GSM.

Year	Event
1982	Groupe Spécial Mobile established by the CEPT.
1986	Reservation of the 900 MHz spectrum band for GSM agreed in the EC Telecommunications Council. Trials of different digital radio transmission schemes and different speech codes in several countries.
1987	Basic parameters of the GSM standard agreed in February.
1988	Completion of first set of detailed GSM specifications for infrastructure.
1989	Groupe Spéciale Mobile (transferred to an ETSI technical committee) defines the GSM standard as the internationally accepted digital cellular telephony standard.
1990	GSM adaptation work started for the DCS1800 band.
1991	First GSM call made by Radiolinja in Finland.
1992	First international roaming agreement signed between Telecom Finland and Vodafone (UK). First SMS sent.
1993	Telstra Australia becomes the first non-European operator. Worlds first DCS1800 (later GSM1800) network opened in the UK.
1994	GSM Phase 2 data/fax bearer services launched. GSM MoU membership surpasses 100 operators. GSM subscribers hit one million.
1995	117 GSM networks on air. The number of GSM subscribers worldwide exceeds 10 million. Fax, data and SMS services started, video over GSM demonstrated. The first North American PCS 1900 (now GSM 1900) network opened.
1996	First GSM networks in Russia and China go live. Number of GSM subscribers hits 50 million.
1997	First tri-band handsets launched.
1998	Number of GSM subscribers worldwide over 100 million.
1999	WAP trials begin in France and Italy.
2000	First commercial GPRS services launched. First GPRS handsets enter the market. Five billion SMS messages sent in one month.
2001	First 3GSM (W-CDMA) network goes live. Number of GSM subscribers exceed 500 million worldwide.
2003	First EDGE networks go live. Membership of GSM Association breaks through 200-country barrier. Over half a billion handsets produced in a year.
2008	GSM surpasses three billion customer threshold.

internationally standardized interfaces. As of April 2008, the GSM MoU has 747 members which operates 670 GSM networks in 200 countries.

1.5 Overview of the book

The remainder of this book is organized as follows. In Chapter 2, we give an introduction to radio channel characteristics and the cellular principle. The understanding of duplex and multiple access schemes serves as the basis for understanding GSM technology. We also describe some measures to increase the capacity in GSM systems, sectorization, as applied by most GSM networks already today, and Spacial Filtering for Interference Reduction (SFIR). Chapter 3 introduces the GSM system architecture and addressing. It explains the basic structure and elements of a GSM system and their interfaces as well as the identifiers of users, equipment and system areas. Next, Chapter 4 deals with the physical layer at the air interface (how are speech and data transmitted over the radio channel?). Among other things, it describes GSM modulation, multiple access, duplexing, frequency hopping, the logical channels and synchronization. Also we discuss GSM coding (source coding, speech processing and channel coding). In Chapter 5, the entire protocol architecture of GSM (payload transport and signaling) is covered. For example, communication protocols for radio resource management, mobility management, connection management at the air interface are explained as well as mechanisms for authentication and encryption. Chapter 6 describes in detail three main principles that are needed for roaming and switching: location registration and update (i.e. how does the network keep track of the user and find them when there is an incoming call?), connection establishment and termination and handover (i.e. how is a call transferred between cells?). Chapter 8 is on enhanced data services in GSM. It explains in detail GPRS which can be used for wireless Internet access. In addition this chapter includes HSCSD and Enhanced Date Rates for Global Evolution (EDGE). Chapter 7 contains the major GSM services and, finally, Chapter 9 gives a brief outlook on future mobile network developments. Appendix A covers basic GSM data services and Appendix B describes network operation and management.

2

The mobile radio channel and the cellular principle

Many measures, functions and protocols in digital mobile radio networks are based on the properties of the radio channel and its specific qualities, in contrast to information transmission through guided media. For the understanding of digital mobile radio networks it is therefore helpful to know a few related basic principles. For this reason, the most important fundamentals of the radio channel and of cellular and transmission technology are presented and briefly explained in the following. For a more detailed treatment, see, for example, Bertsekas and Gallager (1987), Lee (1989), Proakis (1995) and Steele and Hanzo (1999).

2.1 Characteristics of the mobile radio channel

The electromagnetic wave of the radio signal propagates under ideal conditions in free space in a radial-symmetric pattern. The received power P_r decreases with the square of the distance L from the transmitter. Specifically, the received power P_r can be described according to the free-space model as a function of the transmit power P_t, the distance L and the wavelength of the radio signal λ as

$$P_\mathrm{r} = P_\mathrm{t} \cdot g_\mathrm{t} \cdot g_\mathrm{r} \cdot \left(\frac{\lambda}{4\pi L} \right)^2, \tag{2.1}$$

where g_t and g_r are the transmit and receive antenna gains, respectively. While this model is appropriate, for instance, for inter-satellite as well as for Earth-to-satellite communication, it does not capture the effects of terrestrial radio propagation, where the signal is scattered and reflected by obstacles such as buildings, mountains, vegetation, the ground and water surfaces. At the receiver, direct and – potentially many – reflected signal components are superimposed. In effect, we can describe P_r as a linear function of P_t, g_t, g_r, and an overall channel gain g_c:

$$P_\mathrm{r} = g_\mathrm{c} \cdot g_\mathrm{t} \cdot g_\mathrm{r} \cdot P_\mathrm{t}. \tag{2.2}$$

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The channel gain g_{c} can be split into three components

$$g_{\mathrm{c}} = g_{\mathrm{d}}(L) \cdot g_{\mathrm{s}} \cdot g_{\mathrm{m}} \tag{2.3}$$

each capturing one of the main propagation effects.

- **Distance-dependent path gain $g_{\mathrm{d}}(L)$**: This part of the channel gain is usually modeled as a deterministic function of the distance L between the transmitter and the receiver, such that $g_{\mathrm{d}}(L) \cdot P_{\mathrm{t}}$ gives the mean received power at distance L from the transmitter (assuming $g_{\mathrm{t}} = g_{\mathrm{r}} = 1$). A common model for the path gain is given by

  $$g_{\mathrm{d}}(L) = \left(\frac{\lambda}{4\pi L}\right)^2 \left(\frac{L_0}{L}\right)^{\gamma-2} \sim L^{-\gamma}, \tag{2.4}$$

  where L_0 is a reference distance and $\gamma \geq 2$ is the attenuation exponent, depending on the propagation environment (Rappaport, 2002). Typical values for γ are between 3 and 5. In addition to the described model, specifically for modeling and planning of GSM networks, measurement-based models are available, such as the Okumura–Hata model (Hata, 1980; Okumura, 1968) for GSM900 networks and the COST-231 Hata model (Damosso, 1999) for GSM1800 networks. Those models are parameterized by the heights of transmit and receive antennas as well as by the propagation environment (rural, sub-urban or urban).

- **Shadowing gain g_{s}**: Shadowing describes the effect of fluctuations of the received power around the main value, as it is caused by obstacles such as buildings and vegetation. The severeness of the shadowing effect depends on the number and properties of obstacles between the transmitter and receiver. Changes in shadowing occur in the order of meters, e.g. when a user turns around a corner during a phone call. In accordance with measurement data, the most commonly used model for shadowing is a statistical model, describing the shadowing gain g_{s} as a log-normal distributed random variable. Therefore, the shadowing gain in decibels, i.e. $\chi = 10 \log_{10}(g_{\mathrm{s}})$, is distributed according to a Gaussian distribution given by

  $$f_\chi(\chi) = \frac{1}{\sqrt{2\pi}\sigma} \cdot \mathrm{e}^{-\chi^2/2\sigma^2}. \tag{2.5}$$

  The standard deviation σ defines the severeness of the shadowing and depends on the environment to be modeled. According to measurements, typical values for σ are between 5 and 10 dB (Geng and Wiesbeck, 1998).

- **Multipath fading gain g_{m}**: Another source of received power fluctuations around the mean value is caused by multipath propagation. In urban environments, in particular, multiple copies of the transmitted signal arrive at the receiver through different propagation paths. The superposition of many such copies of the transmitted signal, arriving at the receiver from different directions and with different delays, causes a wave field around the receiver. The received signal strength within this wave field changes severely in the order of the signal wavelength between places where destructive and constructive superposition occurs. The resulting amplitude variations

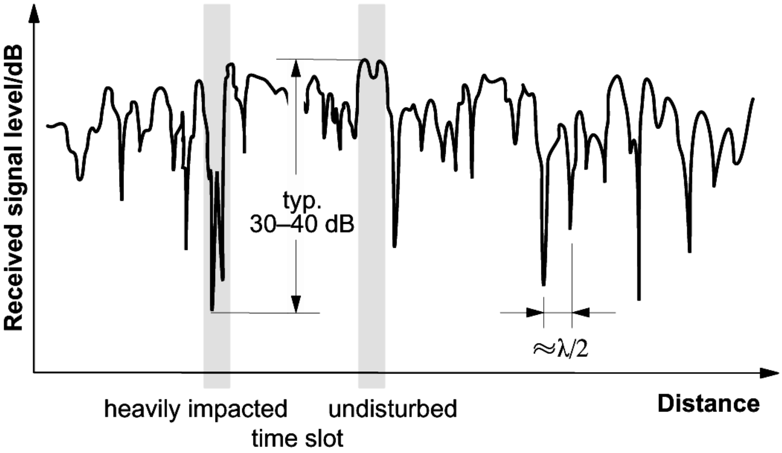

Figure 2.1 Typical signal in a channel with Rayleigh fading.

are modeled by a random variable a, such that

$$g_{\mathrm{m}} = a^2. \tag{2.6}$$

The distribution of the random variable a depends on the propagation environment. If no direct line of sight between sender and receiver is present, a is assumed to be Rayleigh distributed, while an additional line of sight can be taken into consideration if a Rice distribution is applied. Figure 2.1 shows typical channel fluctuations according to Rayleigh fading for a receiver traveling through the wave field. It can be shown that if a is Rayleigh distributed, the multipath fading gain $g_{\mathrm{m}} = a^2$ will be exponentially distributed (Schwartz, 2005).

The signal level observed at a specific location is determined by the phase shift of the multipath signal components. This phase shift depends on the wavelength of the signal, and thus the signal level at a fixed location is also dependent on the transmission frequency. Therefore, the fading phenomena in radio communication are also frequency specific. If the bandwidth of the mobile radio channel is small (narrowband signal), then the whole frequency band of this channel is subject to the same propagation conditions, and the mobile radio channel is considered frequency-nonselective. On the other hand, if the bandwidth of a channel is large (broadband signal), the individual frequencies suffer from different degrees of fading (Figure 2.2) in which case we speak of a frequency-selective channel (David and Benkner, 1996; Steele, 1992). Signal breaks because of frequency-selective fading along a signal path are much less frequent for a broadband signal than for a narrowband signal, because the fading holes only shift within the band and the received total signal energy remains relatively constant (Bossert, 1991).

In addition to frequency-selective fading, the different propagation times of the individual multipath components also cause time dispersion on their propagation paths. Therefore, signal distortions can occur due to interference of one symbol with its neighboring symbols (‘intersymbol interference’). These distortions depend first on the spread experienced by a

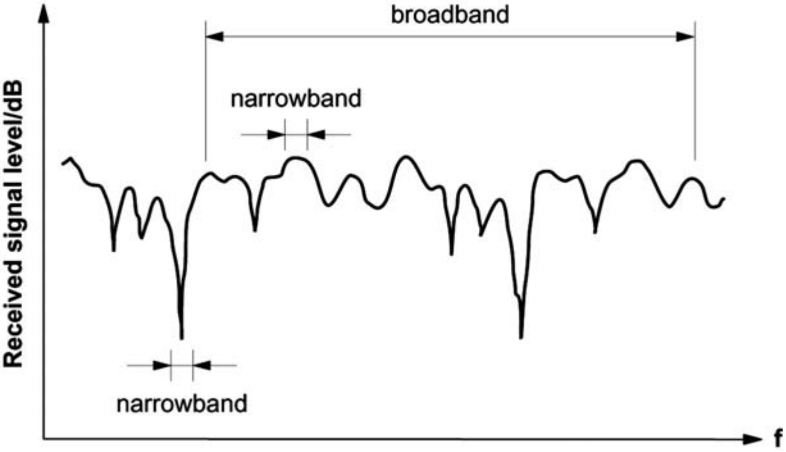

Figure 2.2 Frequency selectivity of a mobile radio channel.

pulse on the mobile channel, and second on the duration of the symbol or of the interval between symbols. Typical multipath channel delays range from 0.5 μs in urban areas to about 16 to 20 μs in hilly terrain, i.e. a transmitted pulse generates several echoes which reach the receiver with delays of up to 20 μs. In digital mobile radio systems with typical symbol durations of a few microseconds, this can lead to smearing of individual pulses over several symbol durations.

Owing to the described effects of the wireless channel, mobile information transport requires additional, often very extensive measures, which compensate for the effects of multipath propagation. First, an equalizer is required, which attempts to eliminate the signal distortions caused by intersymbol interference. The operational principle of such an equalizer for mobile radio is based on the estimation of the channel pulse response to periodically transmitted, well-known bit patterns, known as the training sequences (Bertsekas and Gallager, 1987; Watson, 1993). This allows the time dispersion of the channel and its compensation to be determined. The performance of the equalizer has a significant effect on the quality of the digital transmission. On the other hand, for efficient transmission in digital mobile radio, channel coding measures are indispensable, such as forward error correction with error-correcting codes, which allows the effective bit error ratio to be reduced to a tolerable value (about 10^{-5} to 10^{-6}). Further important measures are transmitter power control and algorithms for the compensation of signal interruptions in fading, which may be of such a short duration that a disconnection of the call would not be appropriate.

2.2 Separation of directions and duplex transmission

The most frequent form of communication is the bidirectional communication which allows simultaneous transmitting and receiving. A system capable of doing this is called full-duplex. One can also achieve full-duplex capability if sending and receiving do not occur simultaneously but switching between both phases is done so fast that it is not noticed by the user, i.e. both directions can be used quasi-simultaneously. Modern digital mobile radio systems are always full-duplex capable. Essentially, two basic duplex procedures are employed: Frequency Division Duplex (FDD) using different frequency bands in each direction, and Time Division Duplex (TDD) which periodically switches the direction of transmission.

2.2.1 Frequency Division Duplex

The frequency duplex procedure has been used already in analog mobile radio systems and is also used in digital systems. For communication between a mobile and a base station, the available frequency band is split into two partial bands, to enable simultaneous sending and receiving. One partial band is assigned for *uplink* (from mobile to base station) transmissions and the other partial band is assigned for *downlink* (from base station to mobile) transmissions.

- Uplink band: transmission band of the mobile *and* receiving band of the base station.
- Downlink band: receiving band of the mobile *and* transmission band of the base station.

To achieve good separation of both directions, the partial bands must be a sufficient frequency distance apart, i.e. the frequency pairs of a connection assigned to uplink and downlink must have this distance band between them. Usually, the same antenna is used for sending and receiving. A duplexing unit is then used for the directional separation, consisting essentially of two narrowband filters with steep flanks (Figure 2.3). These filters, however, cannot be integrated, so pure frequency duplexing is not appropriate for systems with small compact equipment (David and Benkner, 1996).

2.2.2 Time Division Duplex

Time duplexing is therefore a good alternative, especially in digital systems with time division multiple access. In this case, the transmitter and receiver operate only quasi-simultaneously at different points in time, i.e. the directional separation is achieved by switching in time between transmission and reception, and thus no duplexing unit is required. Switching occurs frequently enough that the communication appears to be over a quasi-simultaneous full-duplex connection. However, out of the periodic interval T available for the transmission of a time slot only a small part can be used, so that a time duplex system requires more than twice the bit rate of a frequency duplex system.

2.3 Multiple access

The radio channel is a communication medium shared by many subscribers in one cell. Mobile stations compete with one another for the frequency resource to transmit their information streams. Without any other measures to control simultaneous access of several users, collisions can occur (multiple access problem). Since collisions are very undesirable for a connection-oriented communication like mobile telephony, the individual subscribers/mobile stations must be assigned dedicated channels on demand. In order to divide the available physical resources of a mobile system, i.e. the frequency bands, into voice channels, special multiple access procedures are used which are presented in the following (Figure 2.4).

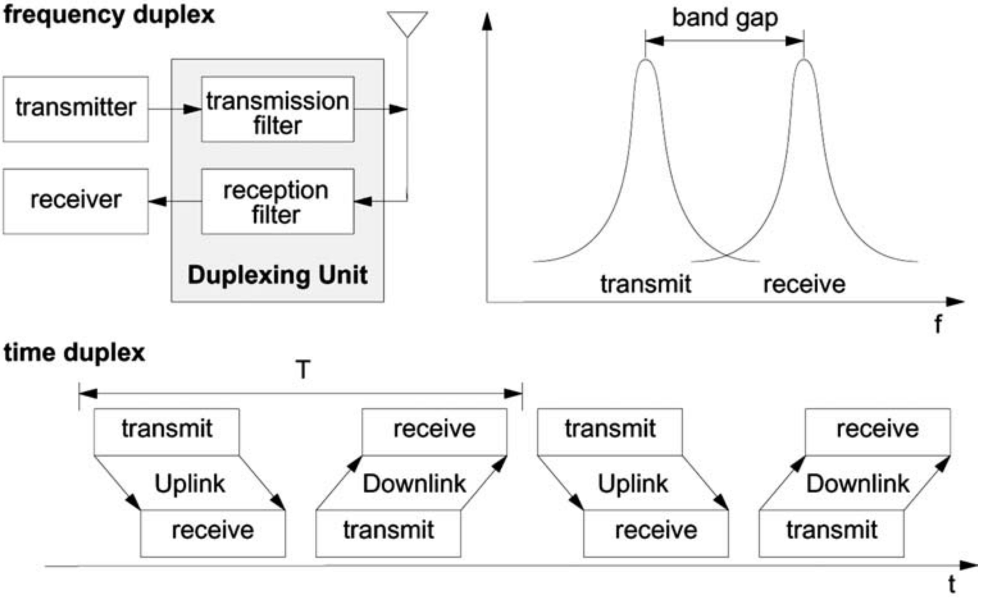

Figure 2.3 Frequency and time duplex.

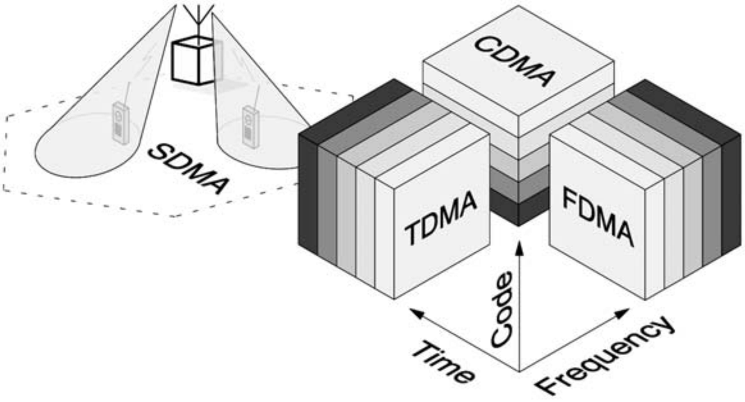

Figure 2.4 Multiple access procedures.

2.3.1 Frequency Division Multiple Access

Frequency Division Multiple Access (FDMA) is one of the most common multiple access procedures. The frequency band is divided into channels of certain bandwidth such that each conversation is carried on a different frequency (Figure 2.5). The effort in the base station to realize an FDMA system is very high. Even though the required hardware components are

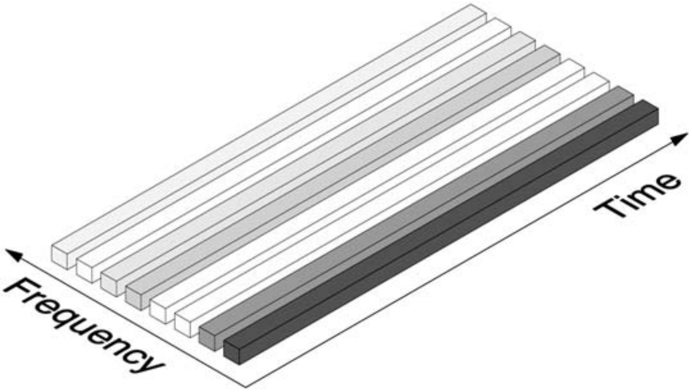

Figure 2.5 Channels of an FDMA system.

relatively simple, each channel needs its own transceiving unit. Furthermore, the tolerance requirements for the high-frequency networks and the linearity of the amplifiers in the transmitter stages of the base station are quite high, since a large number of channels need to be amplified and transmitted together (David and Benkner, 1996; Steele, 1992). One also needs a duplexing unit with filters for the transmitter and receiver units to enable full-duplex operation, which makes it hard to build small, compact mobile stations, since the required narrowband filters can hardly be realized with integrated circuits.

2.3.2 Time Division Multiple Access

Time Division Multiple Access (TDMA) is used in digital mobile radio systems. The individual mobile stations are cyclically assigned a frequency for exclusive use only for the duration of a time slot, which obviously requires frame synchronization between transmitter and receiver. Furthermore, in most cases the whole system bandwidth for a time slot is not assigned to one station, but the system frequency range is subdivided into subbands, and TDMA is used for multiple access to each subband. The subbands are known as carrier frequencies, and the mobile systems using this technique are designated as multicarrier systems (not to be confused with multicarrier modulation). GSM employs such a combination of FDMA and TDMA; it is a multicarrier TDMA system. The available frequency range is divided into frequency channels of 200 kHz bandwidth each (with guard bands between to ease filtering), with each of these frequency channels containing eight TDMA conversation channels.

Thus, the sequence of time slots assigned to a mobile station represents the physical channels of a TDMA system. In each time slot, the mobile station transmits a data burst. The period assigned to a time slot for a mobile station thus also determines the number of TDMA channels on a carrier frequency. The time slots of one period are combined into a so-called TDMA frame. Figure 2.6 shows five channels in a TDMA system with a period of four time slots and three carrier frequencies.

The TDMA signal transmitted on a carrier frequency in general requires more bandwidth than an FDMA signal; this is because with multiple time use, the gross data rate has to be

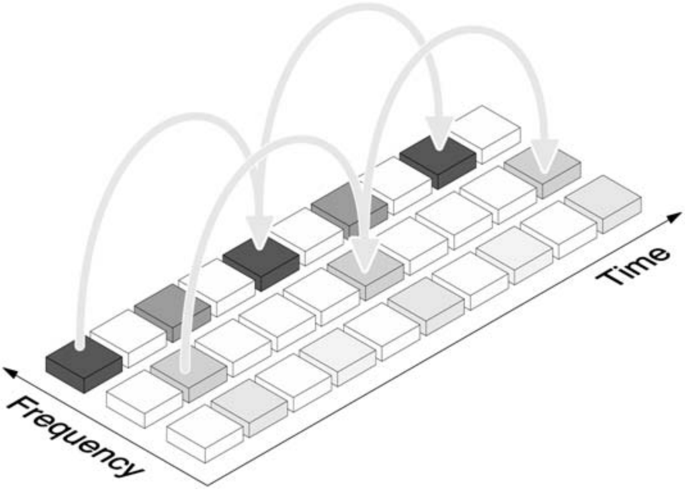

Figure 2.6 TDMA channels on multiple carrier frequencies.

correspondingly higher. For example, GSM systems employ a gross data rate (modulation data rate) of 271 kbit/s on a subband of 200 kHz, which amounts to 33.9 kbit/s for each of the eight time slots.

Narrowband systems are particularly susceptible to frequency-selective fading (Figures 2.1 and 2.2) as already mentioned, such that a single channel might be in a deep fade while switching to another channel might result in a significantly better reception. Furthermore, there are also frequency-selective co-channel interferences, which can contribute to the deterioration of the transmission quality. To this end a TDMA system offers very good opportunities to attack and drastically reduce such frequency-selective interference by introducing a frequency hopping technique. With this technique, each burst of a TDMA channel is transmitted on a different frequency (Figure 2.7).

In this technique, selective interference on one frequency at worst hits only every i_{th} time slot, if there are i frequencies available for hopping. Thus, the signal transmitted by a frequency hopping technique uses frequency diversity. Of course, the hopping sequences must be orthogonal, i.e. one must ascertain that two stations transmitting in the same time slot do not use the same frequency. Since the duration of a hopping period is long compared with the duration of a symbol, this technique is called slow frequency hopping. With fast frequency hopping, the hopping period is shorter than a time slot and is of the order of a single symbol duration or even less. This technique belongs to the family of spread spectrum techniques. As mentioned above, for TDMA, synchronization between a mobile and base station is necessary. This synchronization becomes even more complex due to the mobility of the subscribers, because they can stay at varying distances from the base station and their signals thus incur varying propagation times. First, the basic problem is determining the exact moment when to transmit. This is typically achieved by using one of the signals as a time reference, such as the signal from the base station (downlink, Figure 2.8). On receiving the TDMA frame from the base station, the mobile can synchronize and transmit a time slot