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## Introduction

### 1.1 The Evolution of Mobile Radio Systems

For several decades now, the mobile communications sector has been the fastest growing market segment in telecommunications. At present, we are still in the early stages of a global growth trend in mobile communications, which will most likely continue for many years to come. In trying to define the reasons for this development, one can readily identify a broad range of factors. We have seen the international liberalization of telecommunications services, the opening and deregulation of major world markets, the extension of the frequency range around and beyond 1 GHz, improved modulation and coding techniques, as well as impressive progress in semiconductor technology (e.g., by using VLSI<sup>1</sup> circuits based on FPGA<sup>2</sup>-, CMOS<sup>3</sup>-, and GaAs<sup>4</sup>-technologies), and, last but not least, greater knowledge of the propagation characteristics of electromagnetic waves in an extraordinarily complex environment have undoubtedly contributed to the stellar success of the telecommunications sector worldwide. The beginning of the success story of mobile communications can be traced back by more than 50 years — a period of half a century that spans over four generations of mobile communication systems.

**First generation (1G) mobile communication systems** were introduced in the early 1980s. They were based entirely on analog transmission techniques. The objective of 1G mobile communication systems was to offer voice services over mobile radio channels. The technology employed was based on analog frequency modulation (FM) and frequency division multiple access (FDMA) schemes. 1G systems were strictly limited in their subscriber capacity and their accessibility. Moreover, they suffered from an inherently inefficient use of the frequency spectrum.

A variety of 1G analog cellular mobile radio standards has been developed in Europe, the United States, and Japan. In Europe, the first 1G standard was the Nordic Mobile Telephone (NMT) standard, which was developed jointly in Sweden, Norway, Denmark, Finland, and

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<sup>1</sup> VLSI: very large scale integration.

<sup>2</sup> FPGA: field programmable gate arrays.

<sup>3</sup> CMOS: complementary metal oxide semiconductor.

<sup>4</sup> GaAs: gallium arsenide.

Iceland. The first fully operational NMT systems were inaugurated in Sweden and Norway in 1981, in Denmark and Finland in 1982, and in Iceland in 1986. This system operated originally in the 450 MHz frequency band (NMT-450) and later, from 1986, also in the 900 MHz frequency band (NMT-900). In Germany, the first cellular mobile radio system was called randomly A-Net. It was in service between 1958 and 1977. The A-Net was based on manual switching techniques, so that human operators were required to connect calls. Direct dialing first became possible with the B-Net, which was in service from 1972 until 1994. The capacity limit of 27 000 subscribers was reached fairly quickly. In order to reach a subscriber, the calling party had to know the location of the called party, because the handset required knowledge of the local area code of the base station serving it. Handover was not possible, but roaming calls could be made between neighbouring countries (Austria, The Netherlands, and Luxembourg) that had also implemented the B-Net standard. The B-Net was taken out of service on 31 December 1994. Automatic localization of the mobile subscriber and handover to the next cell was first made possible with the technically superior cellular C-Net, which was officially put into operation on May 1, 1985. It operated in the 450 MHz frequency band and had a Germany-wide accessibility. The C-Net service reached a peak of around 800 000 subscribers in the early 1990s. The C-Net service was shut down in most parts of Germany on 31 December 2000. Other important 1G analog systems developed in Europe include the Total Access Communication System (TACS), which was largely used in the United Kingdom and Ireland, as well as the NMT-F and RadioCom 2000 systems used in France, and the Radio Telephone Mobile (RTM) system that operated in Italy in the 450 MHz frequency band. In the United States, the Advanced Mobile Phone System (AMPS) standard developed by the Bell labs was officially introduced in 1983. The AMPS systems operated in the 800 MHz frequency band. In Japan, the first commercial 1G service was provided by the Nippon Telephone and Telegraph (NTT) Public Corporation (NTTPC) in 1979.

Today, 1G analogue mobile systems are not in use anymore. Many countries have reallocated the frequency resources to other mobile system standards. The mobile market in the 1G era was fragmented in the sense that an efficient harmonization and interoperability/roaming was either a non-issue or at best a very complicated process. This was especially seen as a huge problem in Europe. Hence, one of the requirements for the next generation mobile was the use of common standards and the creation of a single market for mobile services. Another main requirement for the new standards was an improved utilization of the frequency resources. This requirement has been fulfilled by selecting digital technology as the foundation for the next standards.

**Second generation (2G) mobile communication systems** were developed in the early 1990s. These systems differ from the previous generation in their use of digital transmission techniques instead of analog techniques. The primary objectives of 2G mobile communication systems were to facilitate pan-European roaming, to improve the transmission quality, and to offer both voice services and data services over mobile radio channels. The new system uses digital modulation techniques and provides higher voice quality and improved spectral efficiency at lower costs to consumers.

The Global System for Mobile Communications (GSM<sup>5</sup>) standard is generally recognized as the most elaborate 2G standard worldwide. In 1982, the Conference of European Postal

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<sup>5</sup> Formerly, the acronym GSM stood for “Groupe Spécial Mobile”. As the original pan-European GSM standard became more global, the meaning of the acronym GSM was changed to its present meaning.

and Telecommunications Administrations (CEPT) established a working group called Groupe Spécial Mobile with the mandate to define standards for future pan-European cellular radio systems. Later, in 1989, GSM was taken over by the European Telecommunications Standards Institute (ETSI), which finalized the GSM standard in 1990. GSM uses a combination of time division multiple access (TDMA) and FDMA techniques. It supports voice calls and data services with possible data rates of 2.4, 4.8, and 9.6 kbit/s, together with the transmission of short message services (SMS) [1]. In Germany, the so-called D-Net, which is based on the GSM standard, was brought into service in 1992. It operates in the 900 MHz frequency band and offers all subscribers Europe-wide coverage. In addition, the E-Net (Digital Cellular System, DCS 1800) operating in the 1800 MHz frequency band has been running in parallel to the D-Net since 1994. These two GSM networks differ mainly in their respective frequency range. In Great Britain, the DCS 1800 is known as the Personal Communications Network (PCN). In the United States and Canada, GSM operates in the 850 MHz and 1900 MHz frequency bands. The original European GSM standard has become in the meantime a worldwide mobile communication standard that had been adopted by 222 (210) countries by the end of 2009 (2005). In 2009, the network operators altogether ran worldwide 1050 GSM networks with over 3.8 billion GSM subscribers. This means that approximately 55 per cent of the world's population use GSM services.

In addition to the GSM standard, a new standard for cordless telephones, named the Digital European Cordless Telephone (DECT) standard, was introduced by ETSI. The DECT standard allows subscribers moving at a fair pace by using cordless telephones within a maximum range of about 300 m. Other important 2G standards include the Interim Standard 95 (IS-95), IS-54, IS-136, as well as the Personal Digital Cellular (PDC) standard. The brand name for IS-95 is cdmaOne, which was the first digital cellular standard developed by Qualcomm. IS-95 systems are based on code division multiple access (CDMA) techniques. They are widely used in America, particularly in the United States and Canada, and parts of Asia. IS-54 and IS-136 are also known as Digital Advanced Mobile Phone Service (D-AMPS), which is the digital version of the 1G analog cellular phone standard AMPS. D-AMPS uses digital TDMA techniques and operates in the 800 and 1900 MHz frequency bands. D-AMPS systems were once widely used in the United States and Canada, but today they are considered end-of-life, and existing networks have mostly been replaced by GSM or CDMA2000 networks. The PDC standard was defined in Japan in April 1991 and launched by NTT DoCoMo in March 1993. PDC systems are TDMA-based and used exclusively in Japan. Although 2G mobile communication systems are still widely in use in many parts of the world, their underlying technology has been superseded by newer technologies, such as 2.5G, 2.75G, 3G, and 4G.

**Third generation (3G) mobile communication systems** were developed in the early 2000s. The prime objective of 3G mobile systems is to achieve a fully integrated digital mobile terrestrial (satellite) communication network that offers voice, data, and multimedia services (mobile Internet) at anytime and anywhere in the world with seamless global roaming. The key factors of 3G systems include worldwide usage, global coverage by integration of satellite and terrestrial systems, and high spectrum efficiency. 3G systems provide a wide range of telecommunications services (voice, data, multimedia, Internet), and they are able to operate in all radio environments (cellular, satellite, cordless, and LAN<sup>6</sup>). In addition, they support both packet-switched and circuit-switched data transmissions. Depending on the environment,

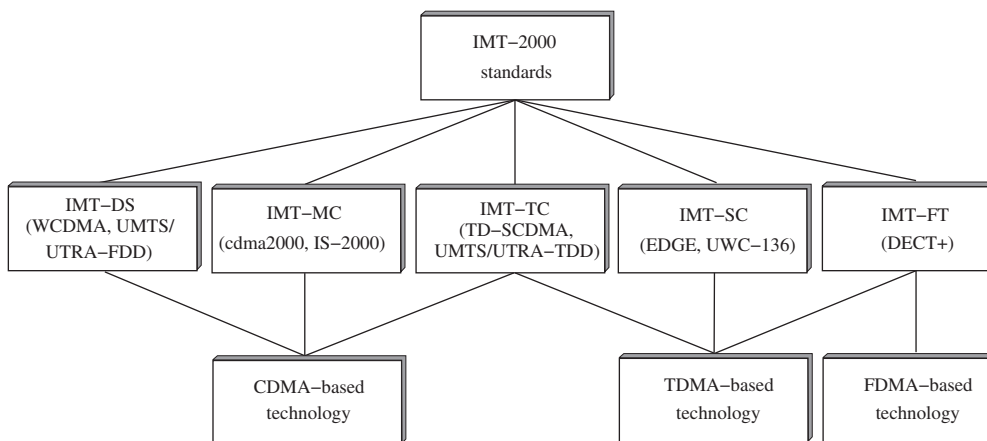
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<sup>6</sup>LAN: local area network.

3G wireless systems offer a wide range of data rates, ranging from 9.6 kbit/s for satellite users over 144 kbit/s for vehicular users (high mobility) and 384 kbit/s for pedestrian users (restricted mobility) up to a maximum data rate of 2.048 Mbit/s for users in stationary indoor office environments. The first commercial 3G system was launched by NTT DoCoMo in Japan in October 2001. Its technology was based on wideband CDMA (WCDMA).

In Europe, 3G mobile communication systems are usually referred to as Universal Mobile Telecommunications System (UMTS). With UMTS, one is aiming at integrating the various services offered by 2G systems into one universal system. An individual subscriber can be called at anytime, from any place (car, train, aircraft, etc.) and is able to use mobile Internet services via a universal terminal. Apart from that, UMTS also provides a variety of application services that were not previously available to 2G mobile phone users, such as mobile TV, video on demand, video conferencing, telemedicine, and location-based services.

Originally it was the intention to have only one common global standard for 3G systems. For the first time, this would enable worldwide roaming with a single handset. But unfortunately, during the standardization process led by the International Telecommunications Union (ITU<sup>7</sup>), it became clear that for both technical and political reasons, the ITU was not in a position to enforce a single unified worldwide standard. Instead, a set of globally harmonized standards fulfilling the specifications set by the ITU has been specified under the umbrella known as International Mobile Telecommunications 2000 (IMT-2000<sup>8</sup>). IMT-2000 operates in the frequency bands 1885–2025 MHz and 2110–2200 MHz, which were assigned to 3G systems by the World Administration Radio Conference (WARC) in March 1992 for worldwide use. At the 18th ITU Task Group 8/1 meeting held in Helsinki from 25 October to 5 November 1999, a set of five terrestrial and satellite radio interface standards was approved for IMT-2000. The IMT-2000 family of standards accommodates the following five terrestrial radio interface standards (see Figure 1.1):



**Figure 1.1** The IMT-2000 family of standards for terrestrial radio interfaces.

<sup>7</sup> The ITU is the leading United Nations agency for information and communication technology issues.

<sup>8</sup> IMT-2000 was formally known as Future Public Land Mobile Telecommunications System (FPLMTS).

- **IMT-DS:** This terrestrial radio interface standard is based on direct sequence CDMA (DS-SS) technology. The frequency division duplex (FDD) mode is used for symmetrical applications requiring the same amount of radio resources in the uplink as in the downlink. IMT-DS is also known as wideband CDMA (WCDMA), WCDMA-FDD, and UMTS/UTRA<sup>9</sup>-FDD. This standard is suitable for applications in public macrocell and microcell environments. IMT-DS is supported by the GSM network operators and vendors as well as by Japan's Association of Radio Industries and Businesses (ARIB).
- **IMT-MC:** This terrestrial radio interface standard falls under the multi-carrier CDMA (MC-SS) category, which is based mainly on FDD frameworks. IMT-MC is also known as cdma2000 and IS-2000. The cdma2000 standard is an evolutionary outgrowth of cdmaOne, which is supported by US cellular network operators and vendors.
- **IMT-TC:** This standard is based on a combination of TDMA and WCDMA technologies. IMT-TC is also known as UMTS/UTRA-TDD, TD-SS, and TD-SS-SS. UMTS/UTRA-TDD is an evolutionary outgrowth of the TDMA-based GSM standard. TD-SS-SS is proposed by China. The IMT-TC standard is optimized for symmetrical and asymmetrical applications with high data rates. It aims to provide 3G services in public microcell and picocell environments.
- **IMT-SC:** This standard falls under the TDMA single-carrier category. IMT-SC is also known as EDGE (Enhanced Data Rates for GSM Evolution) and UWC-136 (Universal Wireless Communications 136). IMT-SC is an evolutionary outgrowth of GSM and TDMA-136, which is achieved by building upon enhanced versions of GSM and TDMA-136. Many EDGE physical layer parameters are identical to those of GSM, including GSM's TDMA frame structure and carrier spacing. EDGE was developed to enable operators to offer multimedia and other IP-based services at speeds of up to 472 kbits/s in wide area networks when all eight time slots are used.
- **IMT-FT:** This standard falls into both the FDMA and the TDMA category. IMT-FT is also well known in Europe as DECT+, which is an evolution of the DECT standard. IMT-FT is used mainly to provide 3G services in indoor environments.

IMT-2000 provides smooth evolution paths from the various widely deployed existing 2G to 3G mobile networks. The trend is currently that people are moving rapidly from 2G to 3G networks, in both developed and developing countries [2]. The ITU estimates that at the end of 2010 there will be 940 million mobile subscriptions to 3G services worldwide, which corresponds to 18 per cent of the total number of subscriptions. In 2010, 143 countries were offering 3G services commercially, compared to 95 in 2007 [2]. Some countries, including Sweden, Norway, Ukraine, and the United States, are already moving to 4G.

Mobile satellites systems are an integral part of UMTS/IMT-2000. The advantages of mobile satellite systems are that they provide global coverage and offer cost-effective services in large areas with low user density and limited traffic density. Their role is not to compete with terrestrial mobile communication systems, but to complement them in a geographical sense (cost-effective coverage of remote areas) and in a service sense (cost effective for broadcast/multicast services). Satellite communication systems can be classified into geostationary earth orbit (GEO) and non-geostationary earth orbit (NGEO) satellite systems. GEO satellites are placed in an equatorial orbit approximately 36 000 km above the earth such that the

<sup>9</sup> UTRA: UMTS Terrestrial Radio Access.

satellites orbit synchronously with the rotating earth and seem to be fixed in the sky [3]. Global coverage can be reached by just three geostationary satellites, but their high altitude results in large propagation delays and causes a very high signal attenuation. N GEO satellite systems include low earth orbit (LEO), medium earth orbit (MEO), and highly elliptical orbit (HEO) satellite systems. LEO satellites (700–1000 km altitude) have relatively short propagation delays and low signal attenuations, but require a large number of satellites to cover the earth's surface. A compromise is provided by MEO satellites (6000–20 000 km altitude), which avoid both the large propagation delays and the high signal attenuation of geostationary satellites, while still providing global coverage with a comparatively small number of about 10 satellites. A thorough survey on mobile satellite systems is provided in [4].

Typical representatives of GEO satellite systems are Inmarsat, Thuraya, and the Asian Cellular System (ACeS). Inmarsat operates currently three global constellations of 11 GEO telecommunications satellites. They provide seamless mobile voice and data communications around the world, enabling users to make phone calls or connect to the Internet on land, at sea or in the air. In addition, Inmarsat offers global maritime distress and safety services to ships and aircraft for free. Thuraya runs two active communications satellites (Thuraya-2 and Thuraya-3) and provides GSM-compatible mobile telephone services to over 140 countries around the world. Its coverage area encompasses the Middle East, North and Central Africa, Europe, Central Asia, and the Indian subcontinent. ACeS is a regional satellite telecommunications company that operates one GEO satellite (Garuda 1), which was launched in 2000. It offers GSM-like satellite telephony services to the Asian market. The coverage area includes South East Asia, Japan, China, and some parts of India.

The first global LEO satellite system was Iridium, which was launched on 1 November 1998 to provide handheld telephone and paging satellite services. The Iridium system consists of 66 satellites covering 100 per cent of the globe and circulating the earth in six polar LEO planes at a height of 781 km. Iridium plans to replace its current satellite constellation by Iridium NEXT, the world's largest LEO satellite system, which is expected to begin launching in 2015. Iridium NEXT will offer truly global mobile communication services on land, at sea, and in the sky. Other representatives of LEO satellite systems include Globalstar (48 satellites, 1414 km altitude)<sup>10</sup> and Teledesic (288 satellites, 1400 km altitude)<sup>11</sup> [5].

Satellite phones are no longer big and expensive. Around the millennium, the price of a satellite phone was about \$3000, and the cost of making voice calls was about \$7 per minute. Ten years later, satellite phones are available for around \$500 to \$1200, calling plans can fall under \$1 per minute, and the handset weight came down from 400 g to only 130 g [6].

The Mobile Broadband System (MBS) has been considered as a necessary step towards the next generation of mobile communication systems [7]. The research on MBS was initiated by the Research and Development in Advanced Communications Technologies in Europe (RACE II) program. MBS plans mobile broadband services up to a data rate of 155 Mbit/s in the 40 and 60 GHz frequency bands. Services of MBS include voice, video, and high demanding data applications, such as the wireless transmission of high-quality digital TV and video

<sup>10</sup> Globalstar's second generation satellite constellation will consist of 32 LEO satellites.

<sup>11</sup> Teledesic had originally planned in 1995 to operate 924 satellites (840 active satellites plus 84 on-orbit spares) circling around the earth in 21 orbits at an altitude between 695 and 705 km. In 2002, Teledesic has officially suspended its work on satellite construction.

conferencing signals. MBS can be considered as a wireless extension of the wired B-ISDN<sup>12</sup> system. It provides radio coverage restricted to small indoor and outdoor areas (e.g., sports arenas, factory halls, television studios) and supports the wireless communication between MBS terminals and terminals directly connected to the B-ISDN network. The underlying technology of MBS is IP-based.

**Fourth generation (4G) mobile communication systems** are currently under development. They are often referred to as IMT-Advanced (International Mobile Telecommunications Advanced) systems, whose requirements have been stated in the ITU-R report [8]. The prime objective of 4G mobile systems is to achieve a fully integrated digital mobile terrestrial (satellite) communication network that offers voice, data, and next generation multimedia services (mobile Internet) at anytime and anywhere in the world with seamless global roaming. 4G systems will offer enhanced peak data rates of 100 Mbit/s for high mobility devices and 1 Gbit/s for low mobility devices. Some other requirements and features that have been identified for 4G systems are increased spectral efficiency, interworking with other radio access systems, compatibility of services, smooth handovers across heterogeneous networks, and the ability to offer high quality of service for multimedia support. The principal technologies used in 4G systems include multiple-input multiple-output (MIMO) techniques, turbo coding techniques, adaptive modulation and error-correcting coding schemes, orthogonal frequency division multiple access (OFDMA) techniques, as well as fixed relaying and cooperative relaying networks. Proper candidates for 4G standards are LTE-Advanced (Long Term Evolution Advanced) and IEEE 802.16m. The present LTE [9] and WiMAX<sup>13</sup> [10] systems are widely considered as pre-4G systems, as they do not fully comply with the LTE-Advanced requirements regarding the peak data rates of 100 Mbit/s for high mobility devices and 1 Gbit/s for low mobility devices.

Before the introduction of newly developed mobile communication systems, a large number of theoretical and experimental investigations have to be made. These help to answer open questions, such as how existing resources (energy, frequency range, labour, ground, capital) can be used economically with a growing number of subscribers and how reliable secure data transmission can be provided for the user as cheap and as simple to handle as possible. Also included are estimates of environmental and health risks that almost inevitably exist when mass-market technologies are introduced and that are only to a certain extent tolerated by a public that is becoming more and more critical. Another boundary condition growing in importance during the development of new transmission techniques is often the demand for compatibility with existing systems. To solve the technical problems related to these boundary conditions, it is necessary to have a firm knowledge of the specific characteristics of the mobile radio channel. The term mobile radio channel in this context is the physical medium that is used to send the signal from the transmitter to the receiver [11]. However, when the channel is modelled, the characteristics of the transmitting and the receiving antenna are in general included in the channel model. The basic characteristics of mobile radio channels are explained subsequently. The thermal noise is not taken into consideration in the following and has to be added separately to the output signal of the mobile radio channel, if necessary.

<sup>12</sup> B-ISDN: Broadband Integrated Services Digital Network.

<sup>13</sup> WiMAX: Worldwide Interoperability for Microwave Access.

## 1.2 Basic Knowledge of Mobile Radio Channels

The three basic propagation phenomena are known as *reflection*, *diffraction*, and *scattering*. Reflection occurs when a plane wave encounters an object with size  $A$  that is very large compared to the wavelength  $\lambda_0$ , i.e.,  $A \gg \lambda_0$ . According to the law of reflection, the direction of the incident plane wave and the direction of the reflected plane wave make the same angle  $\alpha$  with respect to the surface normal. Diffraction arises when a plane wave strikes an object with size  $A$  that is in the order of the wavelength  $\lambda_0$ , i.e.,  $A \approx \lambda_0$ . According to Huygens' principle, the interaction of a plane wave with a diffracting object generates secondary waves behind the object. Scattering occurs when a plane wave incidents on an object with size  $A$  that is very small compared to the wavelength  $\lambda_0$ , i.e.,  $A \ll \lambda_0$ . A scattering object redirects the energy of the incident plane wave in many directions. The three basic propagation phenomena are illustrated in Figure 1.2.

In mobile radio communications, the emitted electromagnetic waves often do not reach the receiving antenna directly because of obstacles blocking the line-of-sight path. In fact, the received waves are a superposition of waves coming from many different directions due to reflection, diffraction, and scattering caused by buildings, trees, and other obstacles. This effect is known as *multipath propagation*. A typical scenario for the terrestrial mobile radio channel is shown in Figure 1.3. Without loss of generality, we assume in the following that the base station acts as the transmitter, while the mobile station is the receiver. Due to multipath propagation, the received signal is composed of an infinite sum of attenuated, delayed, and phase-shifted replicas of the transmitted signal, each influencing each other. Depending on the phase constellations of the received plane waves, the superposition can be constructive or destructive. A constructive (destructive) superposition of the received wave components corresponds to a high (low) received signal level. Apart from that, when transmitting digital signals, the form of the transmitted impulse can be distorted during transmission and often several individually distinguishable impulses occur at the receiver due to multipath propagation. This effect is known as the *impulse dispersion*. The size of the impulse dispersion depends on the propagation delay differences and the amplitude relations of the plane waves. We will see later on that

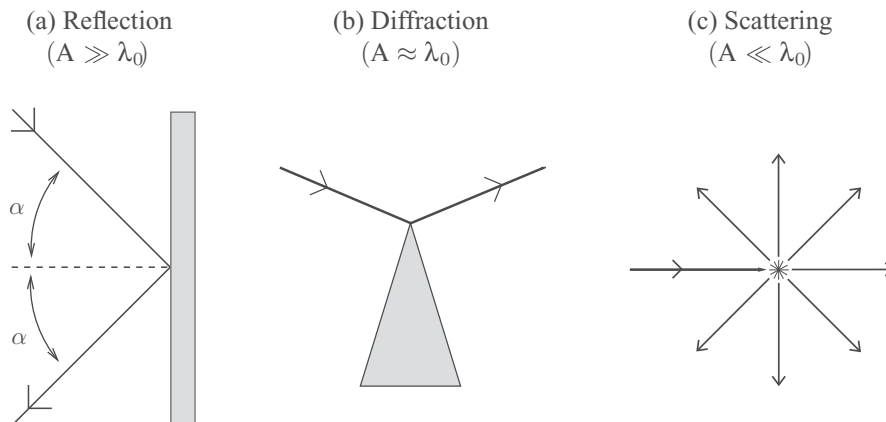
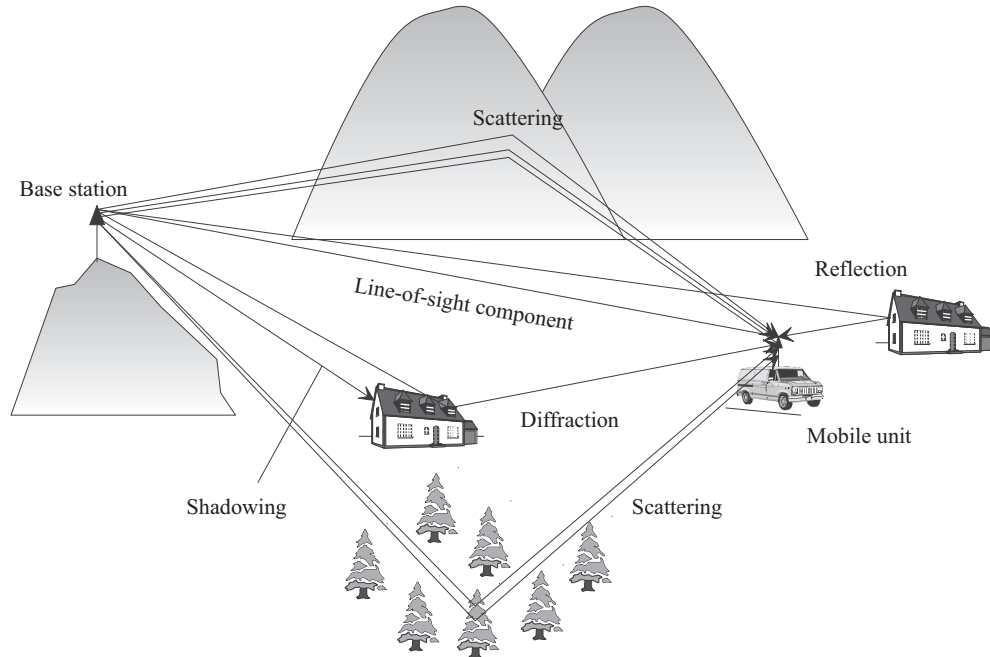


Figure 1.2 The three basic propagation phenomena: (a) reflection, (b) diffraction, and (c) scattering.



**Figure 1.3** A typical mobile radio scenario illustrating the effect of multipath propagation due to reflection, diffraction, and scattering in a terrestrial mobile radio environment.

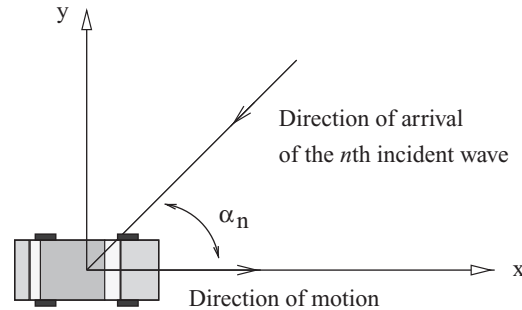
multipath propagation manifests itself in the frequency domain in a non-ideal frequency response of the transfer function of the mobile radio channel. As a consequence, the channel distorts the frequency response characteristic of the transmitted signal. This effect can generally be neglected in narrowband wireless systems, but not in wideband wireless systems, where the impulse dispersion of multipath channels results in *intersymbol interferences*. The distortions caused by multipath propagation are linear and have to be compensated in wideband wireless systems in the receiver, for example, by using equalization techniques.

Besides the multipath propagation, the *Doppler effect* also has a negative impact on the performance of mobile radio communication systems. Due to the movement of the mobile station, the Doppler effect causes a frequency shift of each of the incident plane waves. The *angle-of-arrival*  $\alpha_n$ , which is defined by the direction of arrival of the  $n$ th incident wave and the direction of motion of the mobile station, as shown in Figure 1.4, determines the *Doppler frequency* (or *Doppler shift*) of the  $n$ th incident plane wave according to the relation

$$f_n := f_{\max} \cos \alpha_n, \quad (1.1)$$

where  $f_{\max}$  denotes the *maximum Doppler frequency*. The maximum Doppler frequency  $f_{\max}$  is related to the speed  $v$  of the mobile station, the speed of light  $c_0$ , and the carrier frequency  $f_0$  through the equation

$$f_{\max} = \frac{v}{c_0} f_0. \quad (1.2)$$

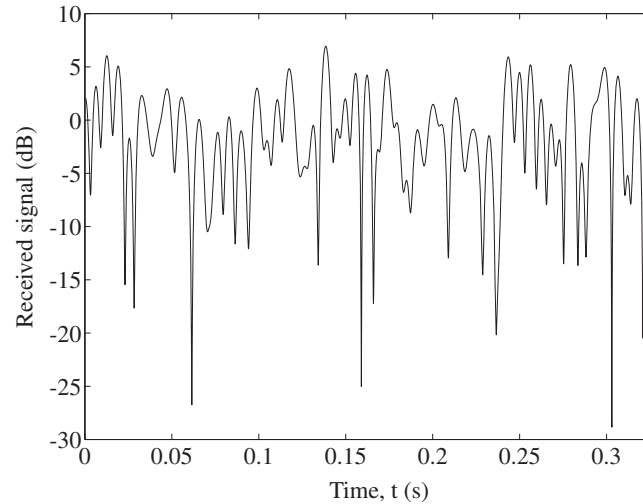


**Figure 1.4** Angle-of-arrival  $\alpha_n$  of the  $n$ th incident wave illustrating the Doppler effect.

Note that the maximum Doppler frequency  $f_{\max}$  increases linearly with the mobile speed  $v$  and the carrier frequency  $f_0$ . The  $n$ th incident plane wave experiences the maximum (minimum) Doppler shift if  $\alpha_n = 0$  ( $\alpha_n = \pm\pi$ ), i.e.,  $f_n = f_{\max}$  ( $f_n = -f_{\max}$ ). The Doppler shift is zero ( $f_n = 0$ ) if  $\alpha_n = \pi/2$  or  $\alpha_n = 3\pi/2$ . Due to the Doppler effect, the spectrum of the transmitted signal undergoes a frequency expansion during transmission. This effect is called the *frequency dispersion*. The size of the frequency dispersion mainly depends on the maximum Doppler frequency and the amplitudes of the received plane waves. In the time domain, the Doppler effect implicates that the impulse response of the channel becomes time-variant. One can easily show that mobile radio channels fulfil the principle of superposition [12], and therefore they are linear systems. Due to the time-variant behaviour of the impulse response, mobile radio channels fall generally into the class of linear time-variant systems.

Multipath propagation in connection with the movement of the receiver and/or the transmitter leads to drastic and random fluctuations of the received signal. Fades of 30 to 40 dB and more below the mean value of the received signal level can occur several times per second, depending on the speed of the mobile station and the carrier frequency [13]. A typical example of the behaviour of the received signal in mobile communications is shown in Figure 1.5. In this case, the speed of the mobile unit is  $v = 110$  km/h and the carrier frequency is  $f_0 = 900$  MHz. According to (1.2), this corresponds to a maximum Doppler frequency of  $f_{\max} = 91$  Hz. In the present example, the distance covered by the mobile station during the chosen period of time from 0 to 0.327 s is equal to 10 m.

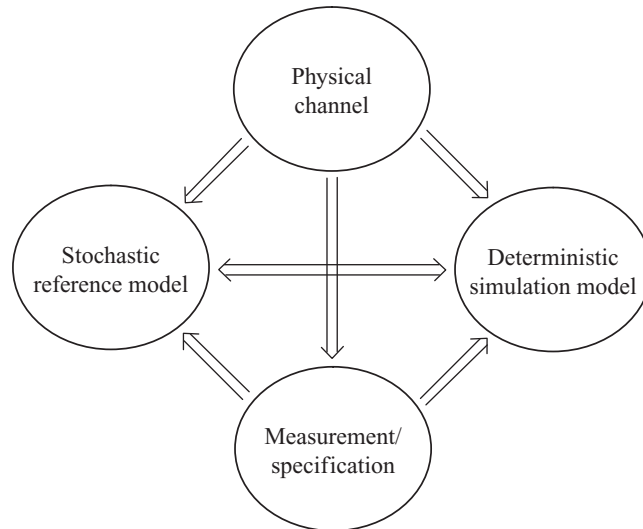
In digital data transmission, the fading of the received signal causes *burst errors* or *error bursts*. A burst error of length  $t_e$  is a sequence of  $t_e$  symbols, the first and the last of which are in error [14]. A fading interval produces burst errors, where the burst length  $t_e$  is closely related to the duration of the fading interval for which the term *duration of fades* has been coined [15]. Corresponding to this, a *connecting interval* produces a symbol sequence almost free of errors. Its length depends on the duration of the connecting interval, which is known as the *connecting time interval* [15]. As suitable measures for error protection and error correction, high-performance channel coding schemes with burst-error-correcting capabilities are called in to help. The development of error correction schemes requires detailed knowledge of the statistical distribution of the duration of fades as well as of the connecting time intervals. The tasks of channel modelling now are to identify, to analyze, and to model the main characteristic



**Figure 1.5** Typical behaviour of the received signal in mobile communications.

properties of the channel and to thus create a basis for the development, optimization, and test of digital transmission systems.

Classical methods of modelling the fading behaviour of mobile radio channels are characterized by the modelling of the transmission link between a base station and a mobile station. In the early stage of channel modelling, the aim was to characterize the statistical properties of real-world channels mainly with respect to the probability density function (first order statistics) of the channel's envelope. The time characteristics, and later the frequency characteristics of the mobile radio channel, have been included in the design procedure only to a limited degree. Modern methods of channel modelling aim to characterize the envelope fading regarding the first order statistics and the second order statistics, which includes the level-crossing rate and the average duration of fades. They also try to capture accurately the space-time-frequency characteristic of the mobile radio channel in a variety of environments. Questions connected to this theme will be treated in detail in this book. Mainly, two goals are aimed at. The first is to find proper stochastic processes, which are suitable for the modelling of the temporal, frequency, and spatial characteristics of mobile radio channels. In this context, we will refer to channel models described by ideal (non-realizable) stochastic processes as *reference models* or as *analytical models*. The second goal is to provide fundamental methods for the design of efficient simulation models enabling the simulation of a huge class of mobile radio channels on a software or hardware platform. The simulation model is usually derived from the underlying reference model or directly from measurements of a physical (real-world) channel. The usefulness and the importance of a reference model and the corresponding simulation model are ultimately judged on how well their statistical properties can be matched to the statistical properties of specified or measured channels. Following these primary goals, Figure 1.6 illustrates the relationships between the physical channel, the stochastic reference model, and the simulation model derived therefrom. These relationships will accompany us throughout the book.



**Figure 1.6** Relationships between the physical channel, the stochastic reference model, the deterministic simulation model, and the measurement or specification.

### 1.3 Structure of this Book

This book provides both fundamental and advanced topics in the area of mobile radio channel modelling. It serves as a basic introduction to concepts indispensable in the fascinating world of channel modelling and guides the reader step by step to the forefront of research. To this end, the book is split into ten chapters. A brief synopsis of each chapter is given in the following.

**Chapter 2** outlines the basics of statistics and systems theory, which provide powerful tools for active research scientists as well as for engineers in practice. The main objective of this chapter is to provide a sound platform upon which a deeper understanding of mobile radio channels can be developed. Therefore, the most important definitions, terms, and formulas often referred to in the following chapters will be introduced. As a sideline, Chapter 2 makes the reader familiar with the nomenclature used consistently throughout the book.

**Chapter 3** builds on the terms introduced in the previous chapter and introduces Rayleigh and Rice processes as reference models for characterizing frequency-nonselctive mobile radio channels. This chapter opens with a system theoretical analysis of multipath fading channels. It continues with a formal description of Rayleigh and Rice channels. Then, their correlation properties and spectral characteristics are studied in detail. The most frequently used Doppler power spectral densities, known as the Jakes (or Clarke) power spectral density and the Gaussian power spectral density, are discussed and their characteristic quantities, such as the mean Doppler shift and the Doppler spread, are presented. This chapter elaborates further on the statistical analysis of Rayleigh and Rice processes by deriving their first order statistical properties (probability density function of the envelope and phase) as well as their second order statistical properties (level-crossing rate and average duration of fades). The last

topic of this chapter is devoted to the analysis of the distribution of the fading intervals of Rayleigh channels.

**Chapter 4** presents an introduction to sum-of-sinusoids channel models. From the systems developer's point of view, Rayleigh and Rice channels represent to a certain extent, like many other analytical channel models, non-realizable reference models. An important task in channel modelling is to find a flexible simulation model with low realization complexity that has approximately the same statistical properties as a given reference model. To solve this problem, various stochastic and deterministic methods have been proposed in the literature. The core of many methods is based on the well-known fact that filtered Gaussian random processes can be approximated by a finite sum of weighted sinusoids. This procedure can be traced back to the seminal work of S. O. Rice [16,17]. Starting from the original Rice method, the principle of deterministic channel modelling is developed at the beginning of Chapter 4. It follows a study of the elementary properties of sum-of-sinusoids processes, including the autocorrelation function, power spectral density, and Doppler spread. The analysis of the elementary properties of sum-of-sinusoids processes is performed by applying concepts of systems theory and signal theory. This is in contrast to the analysis of their statistical properties for which we will refer to concepts of probability theory and statistics. Of interest are both the first and the second order statistical properties. An overview of the various classes of sum-of-sinusoids processes is given and their stationary and ergodic properties are briefly described. Another substantial part of this chapter deals with processes comprising a sum of complex-valued sinusoids (cisoids). A sum-of-cisoids process allows a simple physical interpretation as a wave propagation model, which makes such processes very attractive for the development of mobile radio channel models. In this regard, the relationship and the main differences between sum-of-sinusoids and sum-of-cisoids processes are highlighted. Finally, the most important quality criteria for the performance evaluation of fading channel simulators are presented. The application of these criteria will turn out to be useful in subsequent chapters for the development of high-performance channel simulators.

**Chapter 5** treats the parametrization of sum-of-sinusoids processes. It provides a comprehensive description and analysis of the most important procedures presently known for computing the model parameters of sum-of-sinusoids processes. The model parameters of sum-of-sinusoids processes are the gains, frequencies, and phases. Depending on the underlying philosophy of the parameter computation methods, they can be classified in deterministic and stochastic methods. Deterministic methods provide constant values for all model parameters, while stochastic methods result in random variables for at least one type of model parameters (gains, frequencies, phases). Deterministic (stochastic) parameter computation methods result in deterministic (stochastic) sum-of-sinusoids processes. The performance of each parameter computation method will be assessed with the help of the quality criteria introduced in the previous chapter. This chapter strives to fairly compare the performance of the proposed methods and highlights their individual advantages and disadvantages. This chapter also analyzes the duration of fades of Rayleigh fading channel simulators designed by using deterministic and stochastic sum-of-sinusoids processes. Chapter 5 ends with solutions to the parametrization problem of sum-of-cisoids processes, which unfold their full potential when modelling and simulating temporally and spatially correlated mobile radio channels in non-isotropic scattering environments.

**Chapter 6** is concerned with the development of frequency-nonselective channel models. It is well known that the first and second order statistics of Rayleigh and Rice channels can only be controlled by a small number of parameters. On the one hand, this simplifies considerably the mathematical description of these models, but on the other, it restricts severely their flexibility in the sense that their main statistical properties (probability density function, level-crossing rate, and average duration of fades) can only be varied in a very limited range. A consequence of the small number of available parameters is that the statistical properties of real-world channels can only roughly be modelled by Rayleigh and Rice processes. To achieve a better fit to real-world channels, one therefore calls for more flexible stochastic model processes. Chapter 6 presents sophisticated combined stochastic processes for the modelling of frequency-nonselective mobile radio channels. The so-called extended Suzuki processes of Type I and Type II as well as the generalized Rice and Suzuki processes are derived and their statistical properties are analyzed. Apart from that, a modified version of the Loo model is introduced, containing the classical Loo model as a special case. To demonstrate the usefulness of all channel models suggested in this chapter, the statistical properties of each channel model in terms of the probability density function of the channel envelope, level-crossing rate, and average duration of fades are fitted to measurement results available in the literature. Starting from each underlying reference channel model, the corresponding simulation model is derived by using the concept of deterministic channel modelling, which provides us with the ability to confirm all theoretical results by simulations. The final part of this chapter delves into the modelling of nonstationary land mobile satellite channels. It includes an approach for the modelling and simulation of nonstationary real-world land mobile satellite channels.

**Chapter 7** is dedicated to the development, analysis, and simulation of frequency-selective channel models. This chapter begins with a review of the ellipse model introduced originally by Parsons and Bajwa for describing the path geometry of multipath fading channels. It follows a system theoretical analysis of linear time-variant systems. With the help of systems theory, four important system functions are introduced allowing for a description of the input-output relationship of linear time-variant systems in alternative forms. The core of Chapter 7 is devoted to Bello's theory of linear time-variant stochastic systems going back to 1963 [18]. In this connection, all relevant stochastic system functions and the related characteristic quantities of frequency-selective stochastic channel models will be derived. Special attention will be paid to the so-called wide-sense stationary uncorrelated scattering (WSSUS) model. For typical propagation environments, the COST 207<sup>14</sup> channel models, specified by the European working group COST 207 [19], and the HIPERLAN/2<sup>15</sup> channel models according to ETSI<sup>16</sup> BRAN<sup>17</sup> [20] are presented. Another substantial part of Chapter 7 is devoted to the design and analysis of frequency-selective sum-of-sinusoids channel models enabling the simulation of wideband channels. In addition, this chapter includes an overview of methods for the modelling of given power delay profiles. The last part of Chapter 7

<sup>14</sup> COST: European Cooperation in the Field of Scientific and Technical Research.

<sup>15</sup> HIPERLAN/2: High Performance Radio Local Area Network Type 2.

<sup>16</sup> ETSI: European Telecommunications Standards Institute.

<sup>17</sup> BRAN: Broadband Radio Access Networks.

presents a general method for the modelling and simulation of measured wideband mobile radio channels.

**Chapter 8** focusses on the modelling, analysis, and simulation of multiple-input multiple-output (MIMO) fading channels. A MIMO mobile system employs multiple antennas at the transmitter side and the receiver side, and a MIMO channel is the wireless link between the multiple transmitter and the multiple receiver antennas. MIMO channel models are important for the optimization, test, and performance evaluation of space-time coding schemes [21] as well as space-time processing techniques [22]. The main focus in this chapter is on geometry-based MIMO channel models. Starting from specific geometrical scattering models, a universal technique is presented for the derivation of stochastic reference MIMO channel models under the assumption of isotropic and non-isotropic scattering. By way of example, we apply the technique to the most important geometrical models, which are known as the one-ring model, the two-ring model, and the elliptical model. For all presented geometry-based MIMO channel models, the complex channel gains of the reference models are derived starting from a wave propagation model. The statistical properties of the derived MIMO channel models are studied in detail. General analytical solutions are provided for the three-dimensional (3D) space-time cross-correlation function from which other important correlation functions, such as the 2D space cross-correlation function and the time autocorrelation function, can easily be derived. Furthermore, from the non-realizable reference models, stochastic and deterministic simulation models are derived using a limited number of complex-valued sinusoids (cisoids). It is shown how the parameters of the simulation models can be determined for any given distribution of the angle-of-departure and the angle-of-arrival. In the case of isotropic scattering, closed-form solutions are presented for the parameter computation problem. The principal theoretical results for the designed reference and simulation models are illustrated and validated by simulations. The proposed procedure provides an important framework for designers of advanced mobile communication systems to verify new transmission concepts employing MIMO techniques under realistic propagation conditions.

**Chapter 9** deals with the derivation, analysis, and realization of high-speed channel simulators. For the derivation of high-speed channel simulators, the periodicity of sinusoidal functions is exploited. It is shown how alternative structures for the simulation of sum-of-sinusoids processes can be derived. In particular, for complex Gaussian random processes, it is extraordinarily easy to develop simulation models by just using adders, storage elements, and simple address generators. During the actual simulation of the complex-valued channel envelope, not only time-consuming trigonometric operations but even multiplications can be avoided. This results in high-speed channel simulators, which are suitable for all kinds of channel models presented in previous chapters. Since the proposed principle can be generalized easily, we will restrict our attention to the derivation of high-speed channel simulators for Rayleigh channels. Therefore, we employ exclusively the discrete-time representation. At the beginning of Chapter 9, we introduce so-called discrete-time deterministic processes. These processes open up new possibilities for indirect realization forms. The three most important of them will be introduced in the second part of Chapter 9. In the third part, the elementary and statistical properties of discrete-time deterministic processes are examined. The second to last part deals with the analysis of the required realization complexity and with the measurement of the simulation speed of the designed high-speed

channel simulators. Finally, Chapter 9 ends with a comparison of the Rice method and the filter method.

**Chapter 10** concludes the book with an outline of three selected topics in mobile radio channel modelling. The first topic addresses the problem of designing multiple uncorrelated Rayleigh fading waveforms. After a short problem description, the reader will find a class of parameter computation methods, which enables him to design theoretically an infinite number of uncorrelated Rayleigh fading waveforms under the assumption of isotropic scattering conditions. The second topic is devoted to spatial channel models for shadow fading. Several correlation models for shadow fading are described, including the Gudmundson correlation model, the Gaussian correlation model, the Butterworth correlation model, and a measurement-based correlation model. Finally, the third and last topic elaborates on the modelling of frequency hopping mobile radio channels with applications to typical frequency hopping scenarios in GSM.