MOBILE COMPUTING

THIRD EDITION

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Features of

Mobile Communication: An Overview

CHAPTER 1

LEARNING OBJECTIVES

This chapter serves as an introduction to mobile communication. The following concepts are discussed in detail in this chapter:

- Basic concepts of wireless transmission—ranges of frequencies, which are used for transmitting signals and propagation of signals by antennae
- Modulating and shift-keying of amplitude, frequency, and phase before transmission of signals
- Multiplexing of signals from multiple sources as a function of space, time, frequency, and code (SDMA, TDMA, FDMA, CDMA)
- Spread spectrum techniques
- Circuit- and packet-switching techniques
- Introduction to common technologies used for mobile communication: 2G, 2.5G, 3G, 3G+, and 4G

Learning Objectives The chapters begin with a set of learning objectives that provide a broad overview of the content discussed

Figures and Tables The chapters comprise numerous figures and tables to support the text

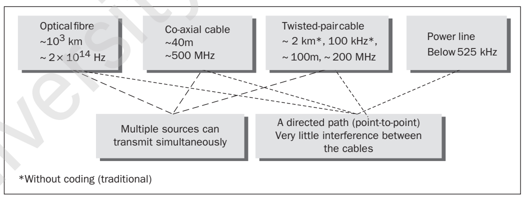

Fig. 1.1 Fibre- and wire-based transmissions and their ranges (without using repeater), frequencies, and properties

Table 1.6 WCDMA enhancements in 3G standards

WCDMA Enhancement	Features
HSDPA	3GPP WCDMA enhancement Supports downlink data rates of 7.2 Mbps, 14 Mbps, 21 Mbps, 28 Mbps, and 42 Mbps for high-performance packet data applications Short TTI and significantly reduced latency Fast link adaptation and scheduling Fast hybrid Automatic Repeat reQuest (ARQ) for good error correction performance
HSUPA	3GPP Release 6 Supports uplink data rates of 1.9 Mbps and 5.8 Mbps Fast link adaptation and scheduling Fast hybrid automatic repeat request (ARQ)
HSPA	HSDPA and HSUPA for mobile phones with new protocol for mobile phone and base station

Sample Code 8.1 This code is for a database ‘Contacts’ designed in XML. Here, we are using search, `Allnames`, `name_record`, `address`, and `telnumber` as tags. The tags and attributes function as primary and secondary keys for the given XML database. Let us use the attribute `first_character` with the tag `<Allnames>`. All names with `first_ character = R` are grouped together between the tag and the end tag for it

```
</Allnames>.
<search>
<Allnames first_character = “R”>
<name_record> Raj Kamal
<address> ABC Street, …. </address> <telnumber>
9876543210 </telnumber> </name_record>
</Allnames>
<Allnames first_character = “S”>
.
.
</search>
```

Sample Codes Samples codes are added to help build successful mobile applications

the Book

Examples Several solved examples are interspersed with the text to help students apply the concepts learnt

Example 5.2

Assume that a digital signal is represented by four symbols, S_0, S_1, S_2, and S_3. Let S_0 be 0000, S_1 = 0100, S_2 = 1000, and S_3 = 1100. Also assume that a symbol changes every 31.25 μs. and that a sequence of four symbols is S_0, S_1, S_0, and S_3 during a transmission interval of 125 μs. Therefore, the successive sequences are S_0, S_1, S_0, S_3, S_0, S_1, S_0, S_3, S_0, S_1, S_0, S_3, S_0, S_1, S_0, and S_3 in 500 μs (in four successive cycles).

(a) What is the rate at which the digital symbols are being transmitted?
(b) What is the rate at which the bits are being transmitted?
(c) What are the alternative sequences during the cycles of 125 μs each?
(d) Assume that a sequence of 48 symbols is $S_0S_1S_2S_3S_0S_1S_3S_2S_1S_0S_2S_3S_1S_0S_3S_2S_1S_2S_0\ S_3S_1S_2S_3S_0S_2S_1S_0S_3S_2\ S_1S_3S_0S_2S_3S_0S_1S_2S_3S_1S_0S_3S_2S_0S_1S_3S_2S_1S_0$ in each cycle and symbols are transmitted in a cycle at symbol rate of 6M symbols/s. (M stands for million)
  (i) What is the interval for a symbol present in the signal?
  (ii) What is the frequency?
  (iii) What is the bit transfer rate?

Solution:

(a) Since a symbol changes every (500 μs /16) = (1000 μs /32) = 31.25 μs/Symbol (= 0.03125 ms/S), the symbols transmit at (32 S/1000 μs) = 32 kSps. (1 kSps = 1 kSps.)
(b) Each symbol consists of 4 bits; thus, bit transfer rate is 32 k × 4 = 128 kbps
(c) $S_0S_1S_2S_3$, $S_0S_1S_3S_2$, $S_1S_0S_2S_3$, $S_1S_0S_3S_2$, $S_1S_2S_0S_3$, $S_1S_2S_3S_0$, $S_2S_1S_0S_3$, $S_2S_1S_3S_0$, $S_2S_3S_0S_1$, $S_2S_3S_1S_0$, $S_3S_2S_0S_1$, and $S_3S_2S_1S_0$ are 12 possible sequences during the cycle for 4 symbols of 125 μs each.
(d) (i) Symbol rate is 6 MS/s. Therefore, each symbol interval = 1/6 s = 166.6 ns.
  (ii) Given that 48 symbols are present in one cycle, the frequency is 1/48 of signal transmission rate. Therefore, frequency = (6/48) MHz = 125 kHz.
  (iii) Each symbol has 4 bits. Bit transfer rate is 4 times of symbols rate. Bit transfer rate = 6M × 4 = 24 Mbps.

KEYWORDS

ACID rules Rules for *a*tomicity, *c*onsistency, *i*solation, and *d*urability criteria in the transactions.
Adapter Software for adapting to the computing system; for example, converting data, which is in one format (or by a given protocol) into another format (or by another protocol).
Asynchronous When the transmission of bits or actions does not occur at predefined periods, intervals, or phase differences.
Atomic transaction A transaction, which cannot be done in parts, which cannot be undone once completed, and which must be undone (rolled back) if not completed.
Atomic An action or process, which must be completed if initiated, which cannot occur in parts, and which, once completed, cannot be undone.
Business logic A logical way in which transactions are carried out between two ends, for example, between database client (application) and database server or between an API and a database.
Cache A list or database consisting of saved items or records at the device, which the device saved for faster computing systems after the system has performed the required computations.
Client–server computing A computing structure in which a client requests for computations and data, and the client receives the requested data or responses after necessary computations. It is a computing structure in which the client caches or accesses the data record(s) after computations at a server. The access may be either on client request or on broadcasts or distribution from the server. The client and the server can be on the same computing system or on different computing systems.
Connectivity protocol A protocol with API(s), which has predefined methods to handle various data access functions.
Context A set of interrelated conditions on which the existence, action(s), and result of operations(s) depend.
Data invalidation A mechanism by which a cached or stored data item or record is declared as invalid and, thus, unusable. The reason for this could be modifica-

Keywords Important terms discussed in the chapters are listed at the end of each chapter

Exercises Exercises consist of objective type and review questions for students to test their understanding of the concepts

EXERCISES

Objective Type Questions

Choose the correct or most appropriate statement among the choices given:

1. The connectivity protocol is used for interchange of data sets between the database server (for sending data sets to clients) and database for the data sets. It describes:
   (a) The network connection headers.
   (b) The relations between various data sets.
   (c) The transaction model for connecting various data sets.
   (d) An API with predefined methods to handle various data access functions.

   (c) No access latency and delay in retrieving the queried record from the server.
   (d) Synchronization of server database with the mobile device database.
3. A stored data invalidation mechanism is a:
   (a) Server-initiated mechanism for informing mobile devices that data sent previously is invalid.
   (b) Server-initiated mechanism of sending invalidation report(s) of a data record to the device in order to synchronize two records and maintain cache consistency.

Review Questions

1. How does data stored in a file differ from a database? Explain the function of the database connectivity protocol.
2. Explain the database transaction models and the ACID rules.
3. Explain the query processing architecture for processing a query using distributed databases.
4. Explain the situations in which a database can crash. How does a database recover using a recovery manager? What is the role of logged entries in updating transactions?

of stateless and stateful cache invalidation. What are the advantages and disadvantages of asynchronous and synchronous cache invalidation?

8. Show a client–server computing architecture in which the database is at the application tier. How does this architecture differ if the application server fetches the data from the enterprise server tier?
9. Draw and explain the four-tier architecture. How do multimedia databases serve a mobile device

Preface to the Third Edition

The basic principle of mobile computing is transfer of voice, data, images, videos, files, or web pages and transfer of data for transactions, such as e-payment or e-commerce transactions between two or more terminal devices out of which at least one using the wireless is mobile and without deploying any guided physical medium consisting of wire or fibres.

Demand for high quality content at higher speeds supported by new-age mobile devices has led to leapfrog changes in the technology used to transmit voice and data over mobile networks. Technologies such as 3G, 4G, and LTE are used to transmit unimaginable amount of data at breathtaking speeds. Lately 5G networks are used. The developments are too fast. Robust mobile network along with global Internet and lately cloud infrastructure are providing new mobile computing applications, never imagined before.

The scope of mobile computing is not limited to personal communication but is now used in almost all aspects of life, be it e-learning, e-books, reading novels, calling a cab, booking movie tickets, taking an examination test, or for banking and financial transactions. Everything is now in easy reach, almost at finger tips with the help of mobile applications and mobile devices, such as smart phone, tablet and Kindle reader.

New device emulators, application development tools, and operating systems have now become widely popular development platforms. Mobiles use new advanced OSs such as iOS 8, 10.1.1 and 11 and Android 7. Cloud is turning into storage, computing, and services medium. New markup language HTML 5 along with XML is now gaining importance. Therefore, the third edition of the book has now become a necessity due to significant technological advancements after the publication of the second edition. The third edition provides insight into these new technologies and incorporates a set of new topics and updates for the readers.

The earlier editions of *Mobile Computing* have been received very well by students as well as faculty and have also been adopted by a large number of universities and institutes in their syllabi. This edition takes into account the feedback we receive from students and learned professors.

About the Book

The third edition of *Mobile Computing* is a comprehensive text that covers the technical aspects of mobile computing environment and recent technical advancements in this area. Designed to serve as a textbook for undergraduate students of CSE, IT, and ECE and those pursuing MCA, and for reference book for trainees in mobile App development. It offers an insight into the fundamental principles behind different access technologies as well as their service and application aspects.

New to the Third Edition

The third edition includes a host of new topics and chapters based on the technological advancements in the area of mobile computing in the past few years. The most notable features of this edition are as follows:

- Updated coverage of the methods of using application development architecture, virtual enterprise-server and cloud computing platform. This inclusion ensures an exhaustive coverage of the syllabi.
- Extensive coverage of developments in mobile and Web application languages such as XML, HTML, and HTML5, and mobile computing languages such as Java, JME, Python, and .Net framework.
- Dedicated chapters on mobile application development platforms and chapter on OSs and advanced mobile OSs such as iOS and Android and development tools. The new chapters will help students get more technical insight about advanced mobile applications, devices, and OSs.
- Numerous solved examples and self-explanatory figures for better understanding of fundamental concepts.

Content and Structure

This book contains 16 chapters, which provide comprehensive discussions on various aspects of mobile communication and computing.

- *Chapter 1* now exclusively provides an overview of mobile communication from the perspective of the students of CSE and IT to facilitate an easy understanding of wireless communication. Introduction to access technologies in 1G, 2G, 3G, 4G, and 5G and their comparison are highlights of this chapter.
- *Chapter 2* focuses exclusively on the overview of mobile computing applications, mobile computing architecture, client–server architecture, limitations, security, synchronization and mobility management, and mobile Internet.
- *Chapter 3* provides an overview of mobile devices and systems, and includes features of latest smartphones and tablets.
- *Chapter 4* covers 2G GSM and GPRS wireless communication and network architectures. The chapter now includes SMS and its applications.
- *Chapter 5* includes easy-to-understand examples to help students comprehend topics related to wireless MAC, spread spectrum, CDMA, OFDM, 3G networks, HSPA, WiMax, HSOPA, LTE, 4G, and the upcoming 5G networks.
- *Chapters 6* and *7* discuss mobile IP and mobile TCP. Chapter 6 now includes cellular IP and mobile IP with IPv6.
- *Chapter 8* describes data organization in mobile devices, databases, transactions, adaptation, Client–Server Computing, adaptation, query processing using databases, data recovery, and quality of service aspects. Data dissemination and synchronization are not covered in a separate chapter but in sections describing the relevant computing aspects.
- *Chapter 9* covers MANETs, ad-hoc networks and wireless sensor networks. Chapter 9 now adds additional topics in wireless sensor networks.
- *Chapter 10* covers WLANs and Bluetooth, and ZigBee personal area networks.
- *Chapter 11* describes service discovery, and now includes wireless enterprise and virtual and mobile cloud networks.

- *Chapter 12* explains database management issues, mobility, wireless communication and portability, data replication methods, multi-hopping and clustering of mobile nodes, and mobile file system—CODA and disconnected operation.
- *Chapter 13* describes smart client architecture in a mobile computing architecture and usages of additional layers—user interface and DataStore. This chapter also covers application-servers, gateways, and enterprise and cloud data servers.
- *Chapter 14* now describes markup languages—XML, HTML, XHTML, and HTML5 for building mobile Internet applications.
- *Chapter 15* describes the mobile application development languages such as Java, JME, Python, and .Net framework.
- *Chapter 16* contains fresh sections on new mobile application development platforms and new-generation OSs—iOS and Android.

Online Resources

The third edition includes the following online resources available at: india.oup.com/orcs/9780199455416.

For Instructors

- Chapter-wise Lecture PPTs
- Chapter-wise Solutions Manual

For Students

- Model Question Papers (based on University Examination)
- Additional Quiz Questions (with Solutions)
- Additional Reading Material

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I am grateful to Dr Davis Jain, Vice Chairman, and Dr Suresh Jain Director, P.I.E.M.R. for providing me a platform to learn and continue research and teaching in new, exciting as well as challenging areas of engineering and technology.

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I am grateful to Oxford University Press for bringing out the new edition in time and in a very elegant format.

The readers are most welcome to share their valuable suggestions and feedback at dr_rajkamal@hotmail.com or at author's website www.rajkamal.org/.

Raj Kamal

Preface to the First Edition

Mobile computing has revolutionised the way in which we work, connect, and communicate to the world. Applications of mobile computing are uncountable. It offers mobility with computing power and facilitates a large number of applications on a single device. The earliest mobile communication devices in the true sense were the portable radio transmitters introduced during the Second World War for military deployment. Popularly known as walkie-talkies, these backpacked (and handheld) transmitters launched by Motorola used vacuum tubes and high-voltage dry cell batteries.

The latter half of the twentieth century saw exponential development in the field of wireless communication and computing technology so much so that from the multitude of electronic gadgets that came and went, arose the star player—the do-it-all mobile phone. Known as Smartphones in technical jargon, the present-day mobile phones offer amalgamated functionalities of PocketPCs, palmtops, camera, media players, radios, and even TVs. There is a plethora of mobile devices available, besides mobile phones, which perform numerous complex functions. But the most revolutionary and spectacular prototype of mobile devices remains the ever versatile cellular phone.

Advances in cellular communication networks and mobile device technology have unearthed the twin concepts of pervasive computing and ubiquitous computing. The future is looking towards smart devices, smart appliances, and increasing capabilities of artificial intelligence. The day is not far when computing systems will pervade our everyday lives and simplify complex tasks.

About the Book

In the present context, mobile computing and its offshoots are the most important players in the computing arena. *Mobile Computing* attempts to comprehensively introduce the reader to the various aspects of computing in mobile environments. Primarily designed to serve as a textbook for undergraduate students enrolled in the disciplines of computer science, electronics, and communications engineering, this book will also prove to be a useful reference for postgraduate students and research scholars.

Undergraduate students of engineering need a text which covers 2G and 3G communication systems, databases in mobile systems, methods of data dissemination and synchronization, and programming languages and operating systems used in mobile devices. Written in a lucid, student-friendly manner, the book includes detailed discussions on all the relevant topics. Simplicity of style and language, and many examples spread through the text allow the reader to grasp the concepts easily. A special attempt has been made to include topics which are a part of curricula of courses offered by a large cross-section of educational establishments.

Each chapter is divided into independent sections. Suitable figures are provided in all chapters to enable easy understanding of the important concepts. Important concepts are explained with the help of tables and flowcharts. A large number of examples and illustrations are interspersed through the text. Sample program segments have been provided to assist the reader in understanding the coding procedures of XML and related languages. Key terms introduced in each chapter are listed at the end of the chapter along with their definitions. End-chapter exercises include review questions and objective type questions, which comprehensively test student's understanding of the concepts discussed. The appendices on mobile satellite communication networks and Java programs presented towards the end of the book are useful supplements to the text. A Select Bibliography is provided at the end of the book for those interested in further reading.

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I am immensely grateful to my teachers at the Indian Institute of Technology Delhi (1966–72) and the University of Upsala, Sweden (1978–79, 1984) for teaching me the importance of self-learning and the essence of keeping up with emerging technology. I would like to thank Prof. M.S. Sodha, F.N.A., for his support and blessings throughout my academic life. I acknowledge my colleagues—Dr P.C. Sharma, Dr P.K. Chande, Dr Sanjeev Tokekar, Mrs Vrinda Tokekar, Dr A.K. Ramani, Dr M.K. Sahu, Dr Maya Ingle, Mr Sanjay Tanwani, Dr Preeti Saxena, Mrs Shraddha Masih, Ms Aparna Dev, and Ms Vasanti G. Parulkar—for their constant encouragement and appreciation. I am thankful to the editorial team at Oxford University Press India for their reviews and suggestions. Finally, I would like to acknowledge my wife Sushil Mittal and my family members—Needhi Mittal, Dr Atul Kondaskar, Dr Shilpi Kondaskar, and Arushi Kondaskar—for their love, understanding, and support during the writing of this book.

Any suggestions, comments, and feedback for further improvement of the text are welcome. A link for the purpose can be found on the author's website at www.rajkamal.org.

Raj Kamal

Brief Contents

Detailed Contents

CHAPTER 1

Mobile Communication: An Overview

LEARNING OBJECTIVES

This chapter serves as an introduction to mobile communication. The following concepts are discussed in detail in this chapter:

- Basic concepts of wireless transmission—ranges of frequencies, which are used for transmitting signals and propagation of signals by antennae
- Modulating and shift-keying of amplitude, frequency, and phase before transmission of signals
- Multiplexing of signals from multiple sources as a function of space, time, frequency, and code (SDMA, TDMA, FDMA, CDMA)
- Spread spectrum techniques
- Circuit- and packet-switching techniques
- Introduction to common technologies used for mobile communication: 2G, 2.5G, 3G, 3G+, and 4G

INTRODUCTION

Three landmark inventions that laid the foundation of the wireless world are as follows:

1. Faraday (1831) demonstrated the phenomenon of electromagnetic (EM) induction;
2. Maxwell (1864) gave the theory of EM fields and the famous wave equations; and
3. Hertz (1886) experimentally demonstrated the transmission and reception of EM waves between two points a few metres apart.

Transmission of long-wavelength EM waves over long distances (transatlantic) started at the beginning of the 20th century. The operating frequency was 1 MHz (=0.3 km). Radio propagation using short waves (50 m to 10 m equivalent to frequencies between 6 MHz and 30 MHz) started in 1920. The waves used a new concept of reflections of transmitted waves. The reflections occur by the upper-atmospheric ionised layers, and, thus, the waves could reach up to the radio receivers at very long distances. The short waves enabled intercontinental communication. (*Radio* stands for radiation through ionosphere, a set of ionised layers with spherical surfaces.)

Mobile telephony started in 1946. The first generation of mobile communication (1G) used voice-oriented analog signals and generally used the concept of cells. The cellular communication used a base station in each cell. Second-generation mobile telephony (2G) started around 1979, which deployed digital signals and the cellular concept for the mobile communication. It deploys multiplexing of signals in space, frequency bands, and time slots and also code division multiplexing and other technologies like spread spectrum.

Third-generation mobile communication (3G) deploys wideband spectrum. 3G enables high data-rate mobile communication up to 100 million bits per second (Mbps). Fourth generation (4G) employs data rates much higher than 100 Mbps. Very high rate enables high-speed file transfer and high-definition mobile TV.

The following sections of the chapter provide an overview of mobile communication technology. Chapter 2 will describe the cellular technology and mobile computing concepts. Chapter 3 will describe the mobile devices. Chapter 4 will describe 2G communication GSM, GPRS, and others protocols. Chapter 5 will describe 3G communication protocols, CDMA, OFDM, and others, and will introduce the 4G- and satellite-based mobile communication technologies.

1.1 MOBILE COMMUNICATION

Mobile communication entails transmission of data to and from mobile devices. Out of the two or more communicating devices, at least one is hand-held or mobile. The location of the device can vary either locally or globally. Communication takes place through a wireless, distributed, or diversified network.

Communication is a two-way transmission and reception of data streams. Voice, data, or multimedia streams are transmitted as signals, which are received by a receiver. Signals from a system can be transmitted through optical fibre, wire, or wireless medium.

During the transmission process, the transmitter sends the signals according to defined regulations, recommended standards, and protocols.

1.1.1 Signals

A signal means an action that intends to convey a particular message by varying an amplitude [instantaneous value of (i) electrical potential difference in Volt or (ii) electric current], frequency, or phase angle of an electric wave. A signal is communicated by a variation of electrical voltage v or current i through a path between two points in a circuit. The values of v or i vary as a function of time t at the circuit.

Example 1.1

(i) What is the meaning of the term *frequency of a signal*?
(ii) What do you mean by *sinusoidal signal*?
(iii) How is a time-varying signal represented?
(iv) What is the meaning of the phase *angle of a signal*?
(v) How can non-sinusoidal but periodic with wave amplitudes be represented as sum of a fundamental frequency sine wave and harmonics of sine frequencies, which are integral multiples of the f in case the wave repeats at successive intervals of $T = f^{-1}$.

Take 1 GHz signal as an example to explain. (Unit of EM wave frequency is Hertz (Hz) after the name of the inventor of the transmission and detection of EM waves.)

Solution:

(i) Suppose voltage v (instantaneous value of electrical potential difference) is varying in such a manner that 10^9 times in 1 s it attains its maximum value. This also means that the voltage v or current i oscillates 10^9 times per second between its maximum and minimum values. Then the electrical signals are considered to have a frequency $f = 10^9$ Hz (called 1 GHz).

(ii) The oscillations are like oscillations in a pendulum. Sine of an angle varies between 0° and 360° (sin 0° = 0, sin 90° = 1, sin 180° = 0, sin 270° = –1, and sin 360° = sin 0° = 0). The similar is the variation of amplitude during the oscillations. Therefore, amplitude can be represented by a pure sinusoidal function (mathematical equation). (Pure means no other superimposing sine components.)

(iii) The simplest representation of a signal v or i is s where s varies as a pure sinusoidal function of time. Consider the instantaneous change in the value of the amplitude of a signal represented by s(t), which means s at the instant t.

(iv) Consider signal s(t) as a function of t, and $s(t)$ varies analogous to sine of an angle. Therefore, s(t) varies from 0 to maximum $+s_o$, then to 0, then to minimum $-s_o$ value, and then to 0 during a cycle. Phase of the signal is represented by an angle called *phase angle* or simply the *phase*. When $s(t)$ varies, one can say the phase varies with time.

The signal s(t), at an instant t, is given using a classic sinusoidal equation:

$$s(t) = s_o \sin [(2\pi \times f \times t) + \phi_{\text{to}}] \tag{1.1}$$

where s_o is the peak amplitude during one cycle of sinusoidal variation, ϕ_{to} is a constant phase angle, and $2\pi \times f \times t$ is variable part of phase angle at an instant t; ϕ_{to} is taken into consideration when at instant $t = 0$, the s(t) has a non-zero finite value.

If f = 1 GHz, then s(t) will reach the maximum positive value 10^9 times in 1 s, minimum negative value 10^9 times in 1 s, and 0 value 2×10^9 times in 1 s. In addition, one can say that phase angle ϕ is changing 10^9 times per second between 0 and 2π radian (= 360°). If f = 1 GHz, then the angular frequency ω is $2\pi \times 10^9$ rad/s (1 radian = 360°/π). [Angular frequency means number of times angle changes by 1 rad in 1 s.]

(v) Assume a wave is non-sinusoidal but periodic with wave amplitudes repeating at successive intervals of $T = f^{-1}$, where f is frequency. Such periodic signal amplitudes as a function of time, s(t), according to Fourier theorem, can be defined by another classic equation, called the *Fourier equation*:

$$S(t) = \Sigma a_n \times \sin [(2\pi \times n \times f \times t) + \phi_{\text{to}}] + \Sigma b_n \times \cos [(2\pi \times n \times f \times t) + \phi_{\text{to}}] + 0.5a_0 \tag{1.2}$$

where a_0 is the constant part of the signal amplitude (dc part), and n is an integer varying from 1, 2, 3, …, ∞. It can be derived from the Fourier equation (1.2) that any signal (sinusoidal or non-sinusoidal), which repeats itself every interval of $T = f^{-1}$, can be considered to be consisting of sum of (a) a sinusoidal signal of fundamental frequency f (which means n = 1) of amplitude given by constants a_1 and b_1 and (b) the harmonics (sinusoidal signals) of frequencies $n \times f$.

The harmonics are the sinusoidal signal of frequencies, which are the integral multiples $\boldsymbol{f}(= n \times f)$, where n = 2, 3, …, ∞. The amplitude of each frequency component (fundamental or harmonic) is given by constants a_n and b_n.

Equation (1.1) for a sinusoidal wave is a special case, when $a_1 \neq b_1$; a_0, a_2, a_3, …, and b_2, b_3, … = 0s.

1.1.2 Guided Transmission

Metal wires and optical fibres are used in guided or wired transmission of data. Figure 1.1 shows the frequencies used in fibre- and wire-based communication and the main properties of guided mode of transmission.

Guided transmission of electrical signals takes place using four types of cables:

1. optical fibre for pulses of wavelength 1.35 to 1.5 μm,
2. co-axial cable for electrical signals of frequencies up to 500 MHz and up to a range of about 40 m,
3. twisted wire pairs for conventional (without coding) electrical signals of up to 100 kHz and up to a range of 2 km, or for coded signals of frequencies up to 200 MHz and a range of about 100 m, and
4. power lines, a relatively recent advent in communication technology, are used for long-range transmission of frequencies between 10 kHz and 525 kHz.

The major advantages of cable-based transmission are as follows:

- Transmission is along a directed path from one point to another.
- There is practically no interference in transmission from any external source or path.
- Using multiplexing and coding, a large number of signal sources can be simultaneously transmitted along an optical fibre, a co-axial cable, or a twisted-pair cable.

Signal transmitter and receiver are fixed (immobile). Hence, there is no mobility of transmission and reception points.

The number of transmitter and receiver systems limit the total number of possible interconnections.

1.1.3 Wireless Transmission (Unguided Transmission)

Wireless or unguided transmission is carried out through radiated EM energy.

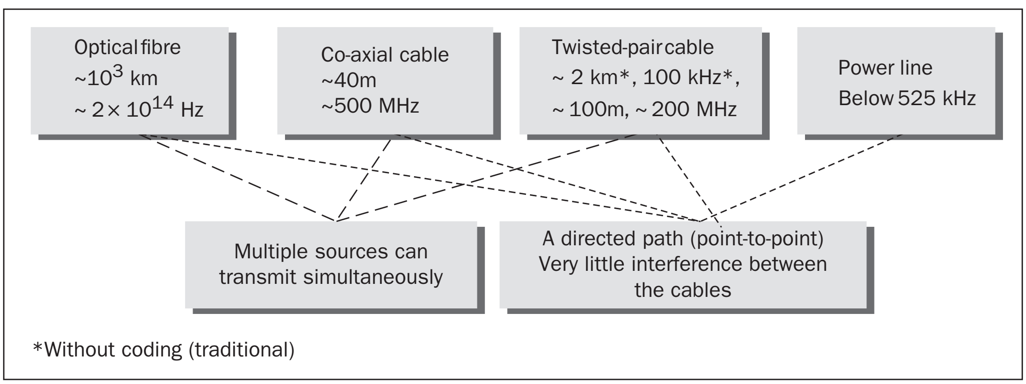

Fig. 1.1 Fibre- and wire-based transmissions and their ranges (without using repeater), frequencies, and properties

When electric charges flow, that means current flows. An electric charge creates electric field. When an electric current passes through a conductor, it creates a magnetic field. This electric field varies with variation in current. When the current varying with time (e.g., sinusoidal varying current) flow through an antenna, it generates the time-varying EM field. The strength of the EM field primarily depends on the distance from the source for a given frequency. The EM signals are said to radiate in free space in this case.

A receiver antenna generates the time-varying electric currents by EM induction in the presence of time-varying EM fields due to a radiating source. Wireless transmission is communication of messages, voice, or data using EM radiation. It enables mobility of sources and receivers.

1.2 FREQUENCIES FOR SIGNAL PROPAGATION

Electrical signals are transmitted after being converted into EM radiation. These radiations are transmitted via antenna that radiates EM signals. There are various frequency bands within the EM spectrum, and all have different transmission requirements. Figure 1.2 shows very high frequency (VHF) and ultra high frequency (UHF) for wireless transmission and their transmission properties. Frequency, f, in MHz and wavelength, λ, in metres of EM radiation are related by a classic formula:

$$f = c/\lambda = (300/\lambda) \tag{1.3}$$

Here, the velocity of signal propagation, c, is 300×10^6 m/s (this is the velocity of EM waves in vacuum or air; for other media, such as water, this velocity will be reduced and different, depending on the dielectric constant). The frequencies, and thus wavelengths, of transmitters for various ranges are as follows:

1. Long-wavelength radio, very low frequency (LW): 30 kHz to 1 MHz (10,000 to 300 m).
2. Medium-wavelength radio, medium frequency (MW): 0.5 to 2 MHz (600 to 150 m).
3. Short-wavelength radio, high frequency (SW): 6 to 30 MHz (50 to 10 m).
4. FM radio band frequency (FM): 87.5 to 108 MHz (3.4 to 2.8 m), maximum range 50 km.
5. VHF: 50 to 250 MHz (6 to 1.2 m) [digital audio broadcasting (DAB) band III VHF 174 to 240 MHz, 226 ± 4 MHz, maximum range 50 km, TV VHF channels—174 to 230 MHz, maximum range 50 km]. Figure 1.2 shows the properties of VHF communication. Voice and data cellular network service providers deploy VHF/UHF frequencies.
6. UHF: 200 to 2000 MHz (≡2 GHz; 1.5 to 0.15 m) [DAB radio at frequencies 1.452 to 1.492 GHz, TV UHF channels—470 to 790 MHz, maximum range 10 km, digital video broadcasting (DVB) TV UHF band IV/V 470 to 830 MHz mobile TV band IV—554 MHz, mobile communication frequencies GSM 900, GSM 1800, GPRS, HSCSD, DECT, 3G CDMA, maximum range ~5 km, Bluetooth 2.4 GHz].
7. UHF propagates in line of sight. Range of UHF signals is thus less than 50 km. The effect of earth's surface curvature is not insignificant beyond this range. Figure 1.2 shows the properties of UHF communication.

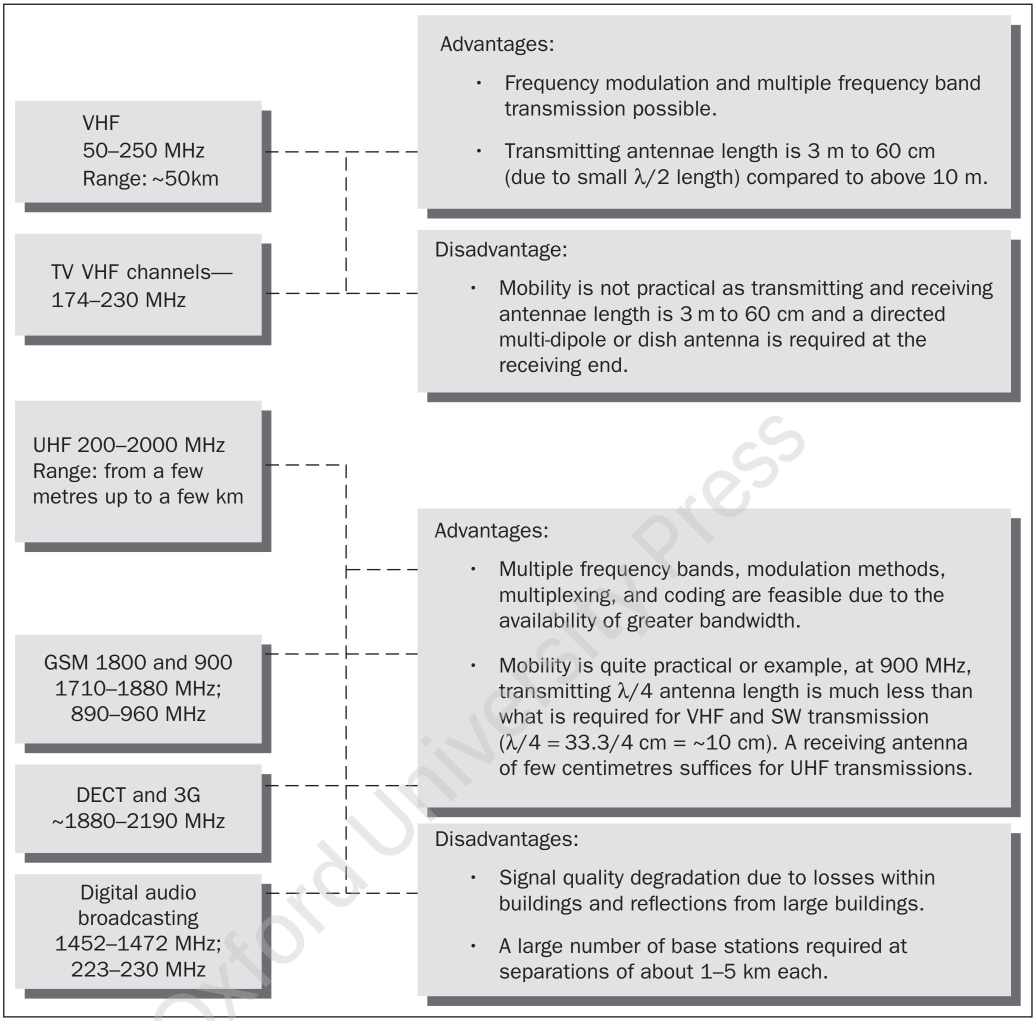

Fig. 1.2 Wireless transmission in VHF and UHF ranges: frequencies and properties will be reduced and different, depending on the dielectric constant).

8. Super high microwave frequency (SHF): 2 to 40 GHz (–15 to 0.75 cm) (microwave bands and satellite signal bands).
9. Extreme high frequency (EHF): Above 40 GHz to 10^{14} Hz (0.75 cm to 3 μm).
10. Optical and IR wavelengths: (i) Far infrared between 1.0 μm and 2.0 μm and [(1.5 to 3) × 10^{14} Hz (0.15–0.3 THz)], (ii) Infrared: 0.90 to 0.85 μm in wavelength and ~(3.3 to 3.5) × 10^{14} Hz (~350 to 330 THz), (iii) Visible light: 0.70 μm to 0.40 μm in wavelength and ~(4.3 to 7.5) × 10^{14} Hz = (~430 to 750 THz). Far IR, IR, and visible EM wave ranges depend on source intensity and divergence angle of emitting source. Transmission is line of sight. When using optical fibres, the range is more than 1000 km.
11. Ultraviolet (UV): <0.40 μm in wavelength (>750 THz). UV ranges depend on source intensity.

1.3 ANTENNAE

Antennae are devices that transmit and receive EM signals. Most antennae function efficiently for relatively narrow frequency ranges. If an antenna is not properly tuned to the frequency band in which the transmitting system connected to it operates, the transmitted or received signals may be impaired. The types of antennae used are chiefly determined by the frequency ranges they operate in and can vary from a single piece of wire to a parabolic dish. Figure 1.3 (a) shows a simple antenna design. It is a $\lambda/2$-long antenna for wireless transmission of waves of wavelength λ. It is also called a *dipole antenna* because at any given instant, at both the ends A and B, the signals are 180° out of phase.

Example 1.2

A 200 MHz to 2000 MHz UHF signal is to be transmitted wirelessly. Calculate the length of the dipole antenna required for transmission.

Solution:

Length of the dipole antenna = $\lambda/2$

$\lambda = 300/f$ (Here, λ is in m and f is in MHz)

Therefore, λ = [300/(200 to 2000)] m

= 1.5 to 0.15 m = 150 to 15 cm

$\lambda/2$ = 75 to 7.5 cm

Therefore, the length of the required antenna will be 75 cm down to 7.5 cm.

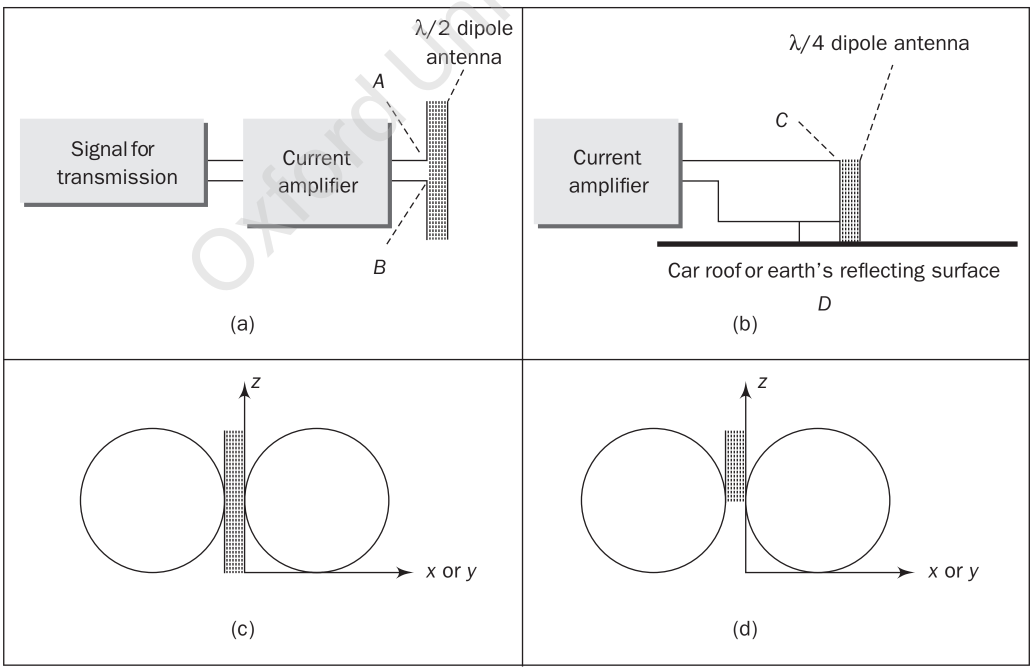

Fig. 1.3 (a) $\lambda/2$ dipole antenna, (b) $\lambda/4$ dipole antenna, (c) Radiation pattern in *z-y* and *x-z* planes for $\lambda/2$ dipole, and (d) Radiation pattern in *y-z* and *x-z* planes for $\lambda/4$ dipole of wavelength λ. It is also called a *dipole antenna* because at any given instant, at both the ends A and B, the signals are 180° out of phase.

Figure 1.3(b) shows an antenna that functionally is equivalent to the $\lambda/2$ antenna. When an antenna of length $\lambda/4$ mounts on a long conducting surface, for example, the roof of a car or a moist ground surface, then at any given instant, the signals at the end C and surface D are 180° out of phase. This is because D is reflector for the waves. Reflection means 180° phase change in the waves. The original and reflected waves thus superimpose and create the same electrical effects as the waves at two ends in the $\lambda/2$ antenna. The length of a $\lambda/4$ antenna for the 200–2000 MHz UHF transmission of Example 1.2 is just 37.5 cm down to 3.75 cm. In general, the length of an antenna is directly proportional to the wavelength and, therefore [using the formula λ = (300/f MHz) m], inversely proportional to frequency of the transmitted signal. Hence, the required antenna length is smaller at higher frequencies and vice versa.

Example 1.3

A dipole antenna is to be mounted on a conducting surface. Calculate the length of the required antenna for transmitting a GSM signal of frequency 900 MHz.

Solution:

Length of antenna to be mounted on a conducting surface = $\lambda/4$

Using the classic formula, $f = (300/\lambda)$, for f in MHz and λ in m,

we get λ = (300/900) m = 33.3 cm

Thus, $\lambda/4$ = 8.1 cm.

Radiation Pattern The radiation pattern of a given antenna defines a path on which each point will have identical signal strength at any given instant t. A pattern represents the surface along which the radiation intensities are identical.

Figure 1.3(c) shows a radiation pattern that consists of two circles in *z*–*x* plane. Same will be the pattern in *z*–*y* plane. Z is the axis of the dipole. The circles touch each other and are symmetrical. It means radiation intensity along the *x*-axis at distance *d* from the antenna centre will be the same as at a distance –*d*. It also means identical to *x*-axis, same is the behaviour of radiation intensities along *y*-axis.

The strengths of the radiations along the circumference show symmetry in the *x*–*z* and *y*–*z* planes for a $\lambda/2$ dipole, assuming the *z*-axis to be the dipole longitudinal axis.

The radiation pattern shows that the signal amplitude at an instant is identical along the circles when the antenna's axis (*z*-axis) is perpendicular to the plane of the circle, and the antenna axis is a tangent to both the circles (circles directed along the *x* and –*x* axes or the *y* and –*y* axes). The radiation pattern in the *x*–*y* plane (perpendicular to both *x*–*z* and *y*–*z* planes) will be a single circle with the *z*-axis passing through its centre and perpendicular to the plane it lies in.

Figure 1.3(d) shows that a $\lambda/4$ dipole mounted on a conducting surface will also have an identical radiation pattern. The radiation patterns in the *x*–*y*, *y*–*z*, and *x*–*z* planes are identical to the one shown in Fig. 1.3(c).

The radiation pattern is an important feature of an antenna. Circular patterns mean that radiated energy and, thus, signal strength distribute equally in all directions in the plane.

Radiation Pattern of a Directional Antenna A directed radiation pattern is required between mobile users and the base station. One of the methods of forming a directed antenna is placing multiple directing re-radiating antennae parallel to the dipole time carrying the varying currents. The directors are equidistant from each other.

Assume that dipole and directors lie parallel to dipole axis z. Assume that the radiation strength is required to be the highest along u. The directivity is along direction u when u is perpendicular to z-axis, and u lies either in z–x or z–y plane.

Figure 1.4(a) shows the case when u is either along axis x or y. The figure shows the directed antenna pattern. The pattern is similar to an inflated balloon. Assume that u is along the x-axis. The rate of decrease in signal strength along x is the least, because strength at the farthest point along x-axis is the same as strength at shorter distances but along directions inclined from x-axis in the x–z plane.

Figure 1.4(b) shows the radiation pattern along x–y plane.

1.3.1 Antennae for Multiple Input and Multiple Output

Consider two sources that are physically separated by a distance. Assume a red light beam from a source and a red or green light beam from another source reaching a same point. The beams are using different paths. Because phase of a signal depends on time and hence on distance travelled, the colour that is visible after superimposition of the signals of two sources will be different from the colour when only one source is used. This is because the radiations from both sources follow a slightly different path. The colour intensity difference between the sources will determine the resultant intensity at the receiving end. (Difference in intensities of each colour is present due the path difference.) The spacing between the sources and the phase differences between the two source signals will thus determine the end resultant colours and intensities after the superimposition of two signals of two beams.

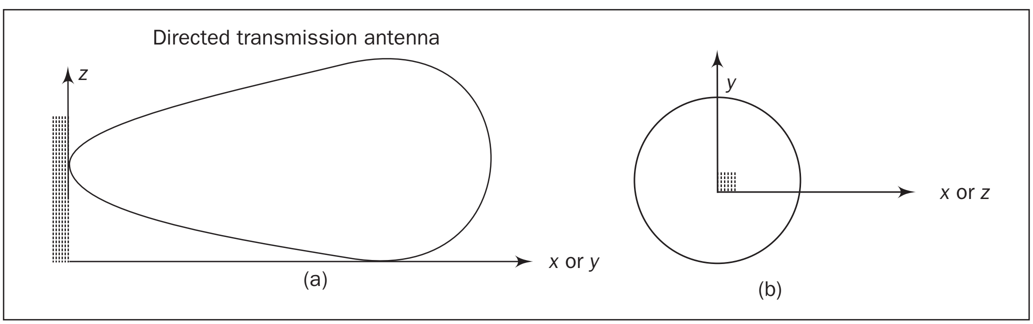

Fig. 1.4 (a) Radiation pattern along the z–y and z–x planes in a directed transmission case antenna (e.g., between a base station and mobile phone) (b) Radiation pattern of the same antenna along the x–y plane

Multiple input and multiple output (MIMO) communication technology involves usage of more than one or multiple, physically spaced antennae at the outputs from transmission end as well as the inputs at the receiving end. The multiple antennae outputs are used for transmission, analogous to the use of two light sources in the earlier example. Each antenna output is pre-coded distinctly before the transmission, analogous to the use of two different colour sources in Example 1.3.

The paths to the end points for each output (beam) will differ for each antenna output. The two or more antennae that are appropriately spaced are used to communicate with two or more sources' signal along these different paths, and their frequencies and phase angles are, then, also appropriately selected at the receiver ends in MIMO.

Let us assume that one antenna radiating in the direction of the receiver is placed in the vicinity of another antenna, also radiating in the direction of the receiver. Appropriate separation between the antennas can cause constructive interference between the radiations from them. The receiver will get superimposed signals. This fact can be used to increase the wireless link range. This fact can also be used to code the signals for a channel and increase the transmitted spectral efficiency (Mbps per MHz bandwidth).

A receiver has 1 or m separate appropriately spaced antennae. The distance between the receiver antennae cannot be large and is kept small. However, a special design is used. Each i^{th} receiver (i = 1,…, m) will receive signals from n transmitting antennas through n paths. Signal propagates through a matrix of $n \times m$ paths. This arrangement is called MIMO.

MIMO results in the increase in throughput. More Mbps per MHz bandwidth can be transmitted and received. MIMO improves the range of communication between a transmitter and a receiver.

The latest wireless communication standards deploy antennae systems with MIMO in 4G, 3GPP long-term evolution (LTE), IEEE 802.11n (Wi-Fi), WiMAX, and HSPA+ (Chapter 5).

1.4 PROPAGATION OF SIGNALS

Wireless propagation of signals faces many complications. Mobile communication renders reliable wireless transmission much more difficult than communication between fixed antennae. The antenna height and size at mobile terminals are generally quite small and internally hosted in the mobile device. Therefore, obstacles in the vicinity of the antenna have a significant influence on the propagated signal. To minimize such impairing effects on the signal, propagation routes have to be specially designed and calculated taking into account the various types of propagation losses. Also, the propagation properties vary with place and, for a mobile terminal, with time. Nowadays, statistical propagation models are used whereby no specific data paths are considered; rather, the channel parameters are modelled as stochastic variables (probability-based random variables). The following are some of the properties of propagation:

- *Line-of-sight propagation* is transmission of signals without refraction, diffraction, or scattering between the transmitter and the receiver. However, even in such an ideal scenario, transmission losses do occur [refer horizontal dotted lines in Fig. 1.5 (a) to (c) between the transmitter and the receiver]. Signal strength in free space decreases as the square of the distance from the transmitter. This is because at larger distances, the radiated power is distributed over a larger spherical surface area.

Example 1.4

A transmitter sends a signal that has the strength of 9 μW/cm^2 at a distance of 500 m. Assuming free-space propagation in line of sight, calculate the signal strength at 1500 m.

Solution:

The strength of the transmitted signal is inversely proportional to the square of the distance from the transmitter.

Therefore, the strength of the signal at 1500 m = $(500/1500)^2 \times 9$ μW/cm^2 = 1 μW/cm^2.

- Signal strength also decreases due to attenuation when obstacles in the path of the signal are greater in size than the wavelength of the signal. A few examples of attenuation of signals are as follows: (a) If an FM radio transmitter sends out a 90-MHz (λ = 3.3 m) FM band signal, then the signal will be attenuated by objects of size 10 m and above (size much greater than λ); (b) if a transmitter sends a GSM 900-MHz (λ = 33 cm) signal, then it will face attenuation in objects of size 1 m and above (size much greater than 33 cm).
- A signal scatters when it encounters an obstacle of size equal to or less than the wavelength. For example, a GSM signal, about 33 cm in wavelength, is scattered by an object of 30 cm or less. Figure 1.5(a) shows the scattering of a transmitted signal. Only a small part of the scattered signal reaches the receiver.
- A signal bends as a result of diffraction from the edges of an obstacle of size equal to or less than the wavelength. For example, a GSM signal of wavelength 33 cm will diffract from an object of 33 cm or less. Figure 1.5(b) shows a diffracted signal. A diffracted signal may or may not reach its destination; it depends on the geometry of the obstacle and the separation between the object, the receiver, and the transmitter.
- The signal may also be reflected from the surface of an obstacle, the earth's surface, or a water body of size greater than the wavelength of the signal. For example, if a transmitter sends out a GSM 900 MHz (λ = 33 cm) signal, then the transmitter signal reflects from an object of size 10 m and above (much greater than λ). The reflected signal suffers a delay in reaching its destination. Figure 1.5(c) shows the reflection and the delay. The delay is more pronounced in case of multi-hop paths. Delayed signals have distorted waveforms and cause misrepresentation of information encoded in the signal. There are digital signal processing (DSP) techniques to eliminate the distortions due to delays from direct and multiple paths so that the original signal can be recovered. The delay in the reflected signal with respect to the original direct signal is given as follows:

$$\text{Delay} = \text{Additional path travelled in metres}/(t_{\text{indirect}} - t_{\text{direct}}) = 3 \times 10^8\,\text{m}\,\text{s}^{-1} \tag{1.4}$$

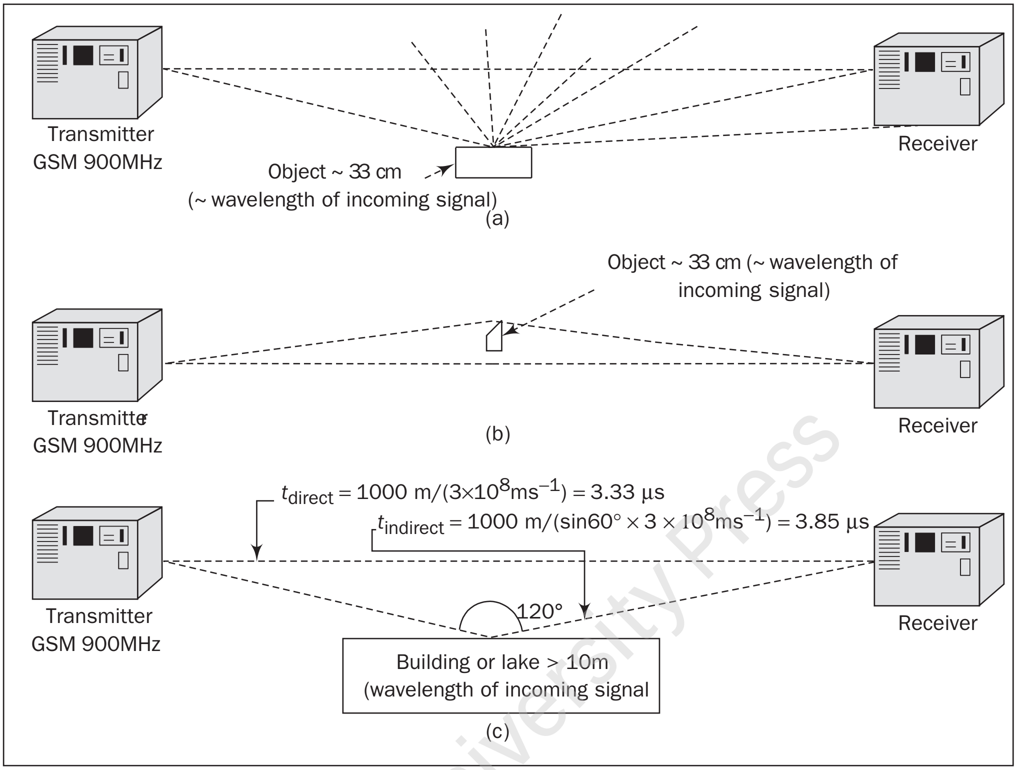

Fig. 1.5 (a) Scattering of signal, (b) Diffraction of signal, and (c) Reflected and direct signals from a 900 MHz transmitter and calculation of delay

Example 1.5

A receiver receives two signals, one directly in line-of-sight and the other after a reflection of 120° from a transmitter at a distance of 1000 m [Fig. 1.5(c)]. Calculate the delay in the reflected signal with respect to the direct signal.

Solution:

Direct path time, $t_{direct} = \dfrac{1000\text{ m}}{3 \times 10^8\text{ ms}^{-1}} = 3.33\ \mu\text{s}$

Reflected path time, $t_{indirect} = \dfrac{1000\text{ m}}{\sin(120°/2) \times (3\times10^8)\text{ms}^{-1}} = 3.85\ \mu\text{s}$

Delay in reflected signal w.r.t. direct signal = $t_{indirect} - t_{direct}$

$= 3.85–3.33\ \mu\text{s} = 0.52\ \mu\text{s}$

A transmitter can simultaneously transmit a signal $s(t)$ and a reference signal $s_{ref}(t)$. Reference signal means a transmitted signal of known sequences of bit frames in given time intervals.

The receiver receives superimposed signals after each signal propagates along two or more paths, one direct and the other reflected. Receiver receives superimposed multipath path signal $s(t)$ and superimposed reference multipath path signal, $s'_{ref}(t)$ simultaneously.

The receiver analyses $s'_{ref}(t)$ using a signal processor. It recover $s_{ref}(t)$ from $s'_{ref}(t)$. Using these results, the processor can determine the delay parameters at the reflected paths. Now the signal processor can find $s(t)$ (the direct path expected signal) from $s'(t)$ using these parameters. The processors can even recover original $s(t)$ from the superimposed signals from five paths having significant radiation strengths at the receiver.

1.4.1 Signal Processing

Mobile systems process the signals for voice, music, images, and sensors. Physical analog signals are represented by digital signals for the analog values of varying current or voltage. Signals are processed by coding, interleaving, modulation, multiplexing, filtering, equalization, digitization, smoothening, de-blurring, compression, extracting the features (e.g., text to speech or speech to text conversion), adaptive filtering, and so on.

Signals are reconstructed in mobile receivers by adding signals from multiple paths after taking into account the delays (phase angle changes) and echoes. [Echoes also result in delayed (phase angle changed) signals.] Multi-path signals and echoes help in reconstruction. The processor compensates for the phase angle change in signals by advancing further the phase angle changes of each to 360°.

Processing of signals involves many operations and use of special algorithms. ['Signal Processing for Communication with Application Examples' by Paolo Prandoni and Martin Vetterbi at the site http:www.sp4comm.org/.]

Figure 1.5(a) to (c) showed how reflection, scattering, and diffraction may help a signal reach the points not reachable by the line-of-sight path on one hand. The multi-path signals cause degradation (distortion) of signal quality on the other hand. DSP at the receiver is used for compensating the distortions, but it may or may not be able to completely compensate for the distortion of signal quality.

The compensation depends upon the signal-to-noise ratio in the received signals. [Noise refers to the unwanted, randomly varying signals of other sources, which are received along with the original signal due to interference.]

1.5 MODULATION

Modulation means modification to original action so that the modification in the action is clearly represented. For example, a professor's voice is modulated and reflects her command over the subject. Similarly, electrical signals [Eqns (1.1) or (1.2)] are modulated with information or electrical signals, which are then communicated over long distances.

The size of antennae required for wireless transmission is inversely proportional to the frequencies of transmitted signals. This means that low frequency signals need very large antennae for their transmission. For example, voice signals have frequencies between 0.1 kHz and 8 kHz. Music-signal frequencies lie between 0.1 kHz and 16 kHz. These ranges are unsuitable for wireless transmission due to the requirement of abnormally large-sized antennae. Moreover, due to the properties of the signal-propagating medium (air or vacuum), ultra low frequency signals cannot be transmitted across long distances without a significant loss of signal strength. In addition, video-signal frequencies lie in the range 10 kHz to 2 MHz. However, this range of frequencies is reserved for medium wave (MW) and short wave (SW) radio broadcasts. Therefore, independent (without modulation) wireless transmission of voice, music, video, or data signals is not very practical. Modulation is compulsorily required to make wireless transmission practical by increasing the compatibility of the transmitted signal and the medium of transmission.

Modulation is the process of varying one signal, called the *carrier*, according to the pattern of another signal (modulating signal). The carrier is usually an analog signal selected to match the characteristics of a particular transmission system. Analog signal modulation is as follows:

The amplitude, frequency, or phase angle of a carrier wave is varied in proportion to the variation in the amplitude of the modulating wave (message signal). Digital modulation is as follows: The amplitude, frequency, or phase angle of a carrier wave is varied (shifted) in proportion to the variation of logic state 1 or 0, variation of pair or set of logic states in the modulating signal (message signal).

1.5.1 Modulation Examples

Let us look back at Eqn (1.1) for the instantaneous change in the value of the amplitude of a signal:

$$s_{\mathrm{m}}(t) = s_{\mathrm{m0}} \sin\,[(2\pi \times f_{\mathrm{m}} \times t) + \phi_{\mathrm{to}}] \tag{1.5}$$

where f_{m} is the frequency of signal to be modulated, s_{m0} is peak amplitude, and ϕ_{to} is phase angle at $t = 0$.

Assume f_{m} is of the order of 4 kHz. Modulation is done to enable its propagation in free space using appropriate antenna. Consider that a carrier frequency, f_{c}, is used to modulate a signal for its wireless transmission. Assume f_{c} is of the order of 4 MHz. Assume that the carrier amplitude and its instantaneous amplitude, $s_{\mathrm{c}}(t)$, are as per Eqn (1.1):

$$s(t) = s(t) = s_{\mathrm{c0}} \sin\,[(2\pi \times f_{\mathrm{c}} \times t) + \phi_{\mathrm{cto}}] \tag{1.6}$$

The carrier signal parameters are as follows: peak amplitude = s_{c0}, phase angle = ϕ_{cto}, when $t = 0$.

Analog Signal Modulation

Now, modulation is a technique by which carrier frequency f_{c} or a set of carrier frequencies is used for wireless transmission such that peak amplitude, s_{c0}, frequency, f_{c}, phase angle, ϕ_{cto}, or some other parameter varies with t in proportion to the peak amplitude of the modulating signal $s_{\mathrm{m}}(t)$, which is the voice or data signal to be communicated. The modulation is referred to as amplitude, frequency, or phase modulation, depending upon which parameter of the carrier is varied.

Digital Signal Modulation

Signal $s_{\mathrm{m}}(t)$ can be digital, varying as 1 and 0 as a function of time. Assume $s_{\mathrm{m}}(t)$ = 10010011. [1 corresponds to some value of v, i, or *f*; 0 corresponds to some another value of v or i.] It means

$$s_{\mathrm{m}}(t) = 1 \text{ at } t \text{ between } 0 \text{ and } T,\ 3T \text{ and } 4T,\ 6T \text{ and } 7T, \text{ and } 7T \text{ and } 8T, \text{ and} \tag{1.7}$$

$$s_{\mathrm{m}}(t) = 0 \text{ at } t \text{ between } T \text{ and } 2T,\ 3T \text{ and } 3T,\ 4T \text{ and } 5T, \text{ and } 5T \text{ and } 6T, \tag{1.8}$$

where T is the periodic interval between successive bits. T = reciprocal of frequency $f_m = f_m^{-1}$.

Signal $s_m(t)$ can also be digital such that pair of bits varies as 00, 01, 10, and 11 as a function of time. Signal $s_m(t)$ can be digital such that the set of bits varies between 2^n possible bit patterns as a function of time.

Digital modulation is a technique by which amplitude s_{c0}, frequency f_c, or phase angle ϕ_{cto} parameters of carrier or sub-carrier frequencies are varied (shifted between one and another) according to the variation (shift) in the modulating signal. The modulation is then called amplitude, frequency, or phase-shift keying (ASK, FSK, or PSK) modulation of the carrier, respectively.

Amplitude Modulation

The equation for an amplitude-modulated signal $s_{am}(t)$ after modulation with a sine wave of modulating frequency f_m is as follows:

$$s_{am}(t) = s_{c0} \sin [(2\pi \times f_c \times t) + \phi_{cto}] \tag{1.9}$$

where $$s_{c0} = k_{am} \times s_m(t) = k_{am} \times s_{mo} \sin [(2\pi \times f_m \times t) + \phi_{mto}] \tag{1.10}$$

where k_{am} is a constant, called *modulation index*, s_{mo} is modulating signal peak amplitude, f_m is modulating signal frequency, and ϕ_{mto} is the phase angle at $t = 0$. The modulated signal $s_{am}(t)$ of Eqn (1.9) can be analysed mathematically to show that the transmitted signal frequency consists of three sinusoidal components of frequencies, $f_c - f_m$, f_c, and $f_c + f_m$.

Figure 1.6 (a) shows an amplitude-modulated signal. Each vertical line represents a sinusoidal component. The components $f_c - f_m$ and $f_c + f_m$ are known as *lower and upper sidebands of* f_c. If sinusoidal wave f_c = 4 MHz, sinusoidal wave f_m = 4 kHz, then $s_{am}(t)$ will have three sinusoidal components of frequency 3.996 MHz, 4 MHz, and 4.006 MHz.

Example 1.6

A SW transmitter sends out a 6.000 MHz carrier signal after amplitude modulation of frequency 5 kHz at an instant. What are the three sinusoidal components in the transmitter at that instant? Calculate the bandwidth of the transmitted signal.

Solution:

The three sinusoidal components are as follows:

$f_c - f_m$ = 5.995 MHz,
f_c = 6.000 MHz, and
$f_c + f_m$ = 6.005 MHz.

Bandwidth of the transmitted signal = 6.005 MHz – 5.995 MHz = 10 kHz

Amplitude Shift Keying

The equations for ASK of a sine wave of frequency f_c, after modulating with signals of 0s and 1s, are as follows:

$$s_{ask}(t) = 0 \text{ when } s_m(t) = 0 \tag{1.11}$$

$$s_{ask}(t) = s_{s0} \sin[[(2\pi \times f_s \times t) + \phi_{sto}] \text{when } s_m(t) = 1 \times s_{m0}] \tag{1.12}$$

where s_{m0} is a constant and is the constant (dc) amplitude of modulating signal when logic state is 1, f_s is the shifted frequency of the ASK modulated signal with peak amplitude, s_{s0}. The modulated signal propagated is given by Eqns (1.11) and (1.12). When analysed mathematically, the equations show that the transmitted signal frequency consists of two components—a dc component and a sinusoidal component of frequency, f_s. Figure 1.6(b) shows the result of ASK.

Example 1.7

How do 1s and 0s transmit from the antenna in a smart card?

Solution:

A smart card transmits an ASK signal of 13.56 MHz. The transmitter signals represent 1 when output is 13.56 MHz and represent 0 when output amplitude is negligibly small. When the stream of 1s and 0s occurs at the rate of 1 Mbps, the frequencies in the transmitter will be 13.56 MHz to 14.56 MHz with a bandwidth of 1 MHz. Negligibly small amplitude represents 0 and a finite large amplitude represents 1 at any instant, *t*. [A card hosts a plated metal rectangular stripe. It functions as antenna as the distance between the receiver and transmitter is just an mm or so.]

Frequency Modulation

The equations for a frequency modulated signal, $s(t)$, after modulating with a sine wave of modulating frequency, f_m, are as follows:

$$s_{fm}(t) = s_{c0}\sin[(2\pi \times f_s \times t) + \phi_{cto}] \tag{1.13}$$

$$f_s = f_c + k_{fm} \times s_m(t) = f_c + k_{fm} \times s_{mo} \sin[(2\pi \times f_{m0} \times t + \phi_{mto}] \tag{1.14}$$

where k_{fm} is a constant, called FM *modulation index*, s_{m0} is modulating signal peak amplitude, f_{m0} is modulating signal frequency, and ϕ_{mto} is phase angle at $t = 0$. The modulated signal of Eqn (1.13) can be mathematically analysed to show that the transmitted signal frequency consists of many sinusoidal components of frequencies: f_c, $f_c - f_m$, $f_c - 2f_m$, $f_c - 3f_m$, …, and $f_c + f_m$, $f_c + 2f_m$, $f_c + 3f_m$, …. Figure 1.6 (c) shows frequency components of frequency-modulated waves. Each vertical line represents a sinusoidal component. Conventionally, we consider up to five sidebands. Therefore, only 10 components are shown.

Example 1.8

An FM transmitter sends a 90 MHz signal and is frequency modulated with 5 kHz modulating signal. Consider one carrier, and five lower and five upper sidebands. What are the 11 sinusoidal components in the transmitter? Calculate the bandwidth of the signal. What will be the bandwidth for a voice-signal frequency modulation of 8 kHz?

Solution:

The 11 sinusoidal components in the transmitter at that instant are as follows:

Lower sidebands—$f_c - 5f_m = 89.975$ MHz, $f_c - 4f_m = 89.980$ MHz, $f_c - 3f_m = 89.985$ MHz, $f_c - 2f_m = 89.990$ MHz, and $f_c - f_m = 89.995$ MHz

Carrier frequency—$f_c = 90.000$ MHz
Upper sidebands—$f_c + f_m = 90.005$ MHz, $f_c + 2f_m = 90.010$ MHz, $f_c + 3f_m = 90.015$ MHz, $f_c + 4f_m = 90.020$ MHz, and $f_c + 5f_m = 90.025$ MHz

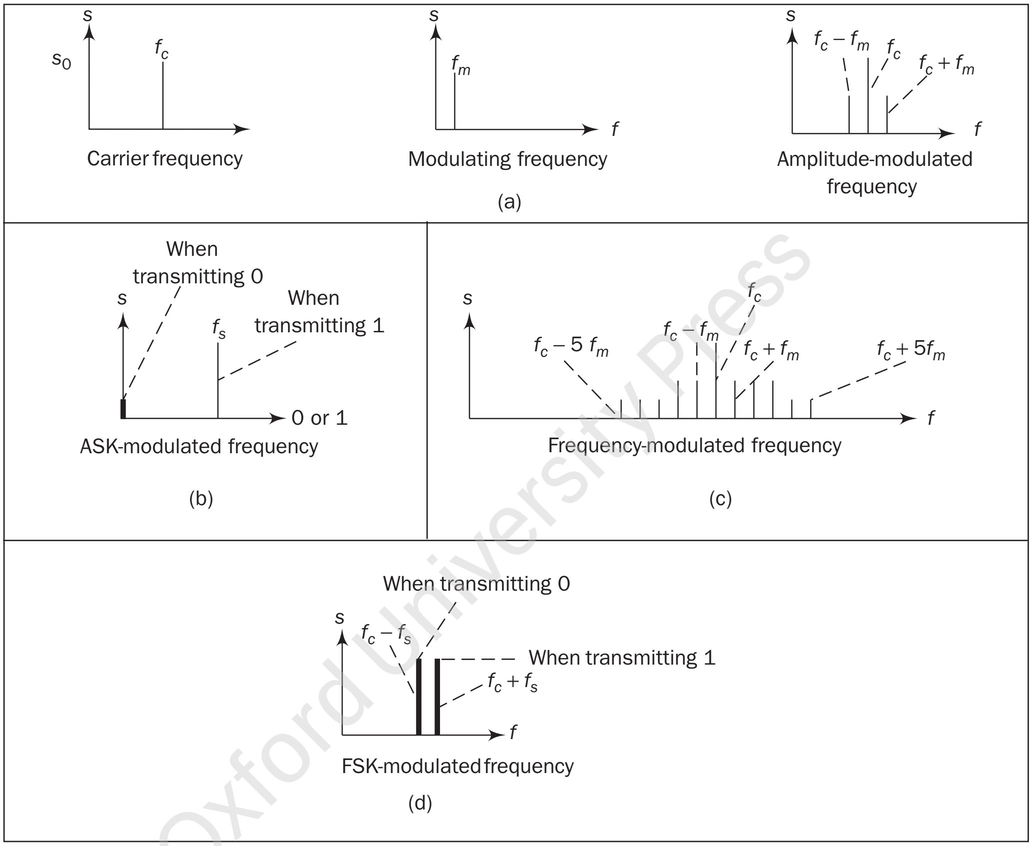

Fig. 1.6 (a) AM signal, (b) ASK signal, (c) FM signal, and (d) FSK signal (all plots are shown in the frequency domain, each vertical line represents a sine wave of Eqn (1.1). The x-axis depicts the frequency and the y-axis the peak amplitude.)

Bandwidth of the transmitted signal = 90.025 MHz – 89.975 MHz = 50 kHz
For an 8 kHz voice-signal frequency modulation, the bandwidth = 10 × 8 kHz = 80 kHz.

Frequency Shift Keying

FSK is a digital modulation technique in which data is transmitted by shifting the frequency of modulation of the carrier wave. The equations for FSK of a sine wave with modulating signal of 0s and 1s are as follows:

$$s_{\mathrm{fsk}}(t) = s_{s0}\,\sin[\{2\pi \times (f_c - f_s) \times t\} + \phi_{\mathrm{to}}] \text{ when } s_m(t) = 0 \tag{1.15}$$

$$s_{\mathrm{fsk}}(t) = s_{s0}\,\sin[\{2\pi \times (f_c + f_s) \times t\} + \phi_{\mathrm{to}}] \text{ when } s_m(t) = 1 \times s_{\mathrm{mo}} \tag{1.16}$$

where s_{m0} is a constant that represents peak amplitude of the modulating signal when logic output state is 1, and f_s is shifting frequency of the modulated signal with peak amplitude, s_{s0}. The modulated signal given by Eqns (1.15) and (1.16) can be analysed to show that the transmitted signal frequency consists of a component of frequency ($f_c - f_s$) and one sinusoidal component of frequency ($f_c + f_s$), both having identical amplitudes. Figure 1.6 (d) displays the result of FSK.

Example 1.9

How do 1s and 0s modulate in FSK-modulation modem? Assume 902.000 MHz carrier and 64 kHz modulated signal bandwidth.

Solution:

A wireless modem transmits an FSK 902.000 MHz signal, then the transmitter signals 1 when output is 902.032 MHz and signals 0 when output is 901.968 MHz signal. When the stream of 1s and 0s occurs at a rate of 64 kbps, the frequencies in the transmitter will be 901.968 MHz to 902.032 MHz with a bandwidth of 64 kHz.

Phase Modulation

The equations for a phase-modulated signal, $s_{pm}(t)$, with a modulating sine wave of modulating frequency, f_m, are as follows:

$$s_{pm}(t) = s_{c0} \sin [(2\pi \times f_c \times t) + \phi_{st0}] \tag{1.17}$$

$$\phi_{st0} = k_{pm} \times s_m(t) = k_{pm} \times \sin[(2\pi \times f_m \times t) + \phi_{mt0}] \tag{1.18}$$

where k_{pm} is a constant, s_{m0} is modulating signal peak amplitude, f_m is modulating signal frequency, and ϕ_{mt0} is the phase angle at $t = 0$. The modulated signal of Eqn (1.17) is then propagated and can be analysed mathematically to show that the transmitted signal frequency consists of many sinusoidal components of frequencies: $f_c, f_c - f_m, f_c - 2f_m, f_c - 3f_m, f_c - 4f_m, \ldots,$ and $f_c + f_m, f_c + 2f_m, f_c + 3f_m, f_c + 4f_m, \ldots$

Phase Shift Keying

PSK is a digital modulation technique in which data is transmitted by varying or modulating the phase of the carrier wave. There are various types of PSK techniques, each using a finite number of phases. Each of these phases corresponds to a unique binary number or sequence of bits. The different methods for PSK are described as follows.

Binary Phase Shift Keying

The transmitted signal frequency phase advances or decreases by 180° at the instant when 1 changes to 0 or 0 changes to 1. The sinusoidal components have identical amplitudes. The modulated signal is given as follows:

$$s_{bpsk}(t) = s_{s0} \sin[(2\pi f_c\, t) + \phi_{t0} - \pi/2] \text{ when } s_m(t) = 0 \tag{1.19}$$

$$s_{bpsk}(t) = s_{s0} \sin[(2\pi f_c\, t) + \phi_{t0} + \pi/2] \text{ when } s_m(t) = 1 \times s_m 0 \tag{1.20}$$

where s_{m0} is a constant and the amplitude of the modulating signal.

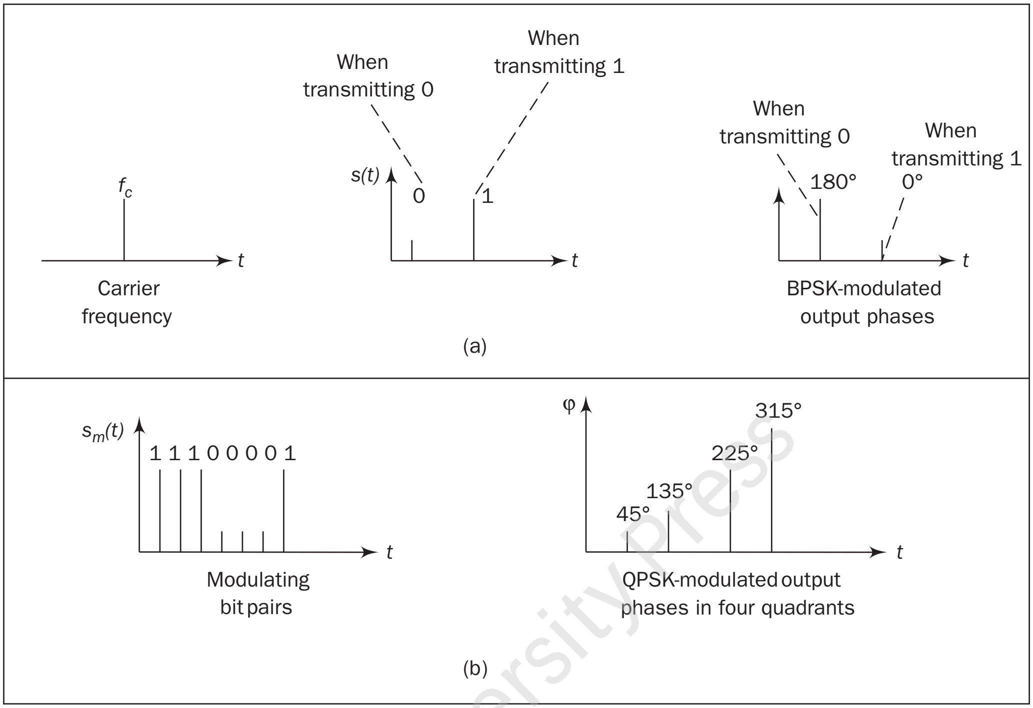

Fig. 1.7 (a) BPSK signal for transmitting the bits (01) (b) QPSK signal for transmitting four bit pairs 11100001

When the logic output state is 0, there is a phase shift of 180° with respect to the phase when 1 in the modulated signal, and the peak amplitude is $-s_{m0}$ and when 1, then s_{m0}. Figure 1.7(a) shows the BPSK output phases when the modulating signal is (01).

Gaussian Minimum Shift Keying

During transmission by BPSK, the carrier frequency abruptly advances or retards the phase by 180° when 0 follows 1 or 1 follows 0, respectively. These abrupt changes bring about high-frequency components in $s(t)$. [Refer to the Fourier equation, Eqn (1.2).] The periodically varying abrupt changes induce the higher harmonics in the transmitted frequency. Using minimising techniques and DSP-based Gaussian low pass filter, these components can be filtered out so that changes at the transitions 1 to 0 and 0 to 1 are smoothened out. Such a BPSK signal is called *Gaussian minimum shift keying* (*GMSK*).

Quadrature Phase Shift Keying

Quadrature phase shift keying (QPSK) is a modulation technique in which the phase angle of the carrier is shifted in one of the four quadrants between 0° and 360°. The shift depends on whether the pair of bits in modulating signal bit pattern is (1, 0), (0, 1), (0, 0), or (1, 1). QPSK is also known as *4-phase shifted keying* (*4-PSK*).

Example 1.10

How do eight bits, 10 00 01 11 transmit after QPSK modulation of the carrier frequency? How much will the change be in bit transfer rate compared to BPSK?

Solution: Let us consider the case where each pair of bits 0 and 1 is being transmitted in period = T, each bit transmits in period $T/2$. Rate of bit-pair per second = T^{-1}. Assume that 8 bits in the modulating signal are 10 00 01 11. The phase angle of the transmitted signal $s_{qpsk}(t)$ will be $3\pi/4$, $-3\pi/4$, $-\pi/4$, and $+\pi/4$, after each successive time interval T. The frequency of the signal remains f_c and peak amplitude s_{s0}.

Bit transfer rate will be double due to QPSK modulation of the carrier compared to BPSK.

The equations for QPSK of a sine wave of modulating signal of 0s and 1s at a frequency f are as follows:

$$s_{qpsk}(t) = s_{s0} \sin[(2\pi f_c t) + \phi_{t0} + 3\pi/4] \text{ when } s_m(t) = 1 \text{ and } s_m(t + T/2) = 0 \quad (1.21)$$

$$s_{qpsk}(t) = s_{s0} \sin[(2\pi f_c t) + \phi_{t0} - \pi/4] \text{ when } s_m(t) = 0 \text{ and } s_m(t + T/2) = 1 \quad (1.22)$$

$$s_{qpsk}(t) = s_{s0} \sin[(2\pi f_c t) + \phi_{t0} - 3\pi/4] \text{ when } s_m(t) = 0 \text{ and } s_m(t + T/2) = 0 \quad (1.23)$$

$$s_{qpsk}(t) = s_{s0} \sin[(2\pi f_c t) + \phi_{t0} + \pi/4] \text{ when } s_m(t) = 1 \text{ and } s_m(t + T/2) = 1 \quad (1.24)$$

Modulating signal = 1 means s_{m0} and 0 means 0 or $-s_{m0}$. Figure 1.7(b) shows the QPSK signal output phases when the modulating signal is 11100001.

Eight Phase Shift Keying

The phase angles of a carrier frequency can be one of the eight different angles corresponding to one of the eight combinations of a set of three consecutive bits (000, 001, …, 111) in the 8-phase shift keying (8-PSK) modulation technique. The triplets of bits are thus transmitted in varying phases so that triplet combinations can be simultaneously transmitted in wave period T, in place of one bit at a time in period T in BPSK and 2 bits in QPSK. For example, let us assume that a triplet of bits is being transmitted at rate T^{-1}. Bit pattern is 101 000 110 011 100 111. The phase angle of the transmitted signal $s(t)$ will be $-5\pi/8$, $\pi/8$, $-3\pi/8$, $7\pi/8$, $-7\pi/8$, and $-\pi/8$, after each successive time interval of T. The frequency of signal remains f_c and peak amplitude, s_{s0}.

Let us assume that the carrier is a sine wave of frequency, f_c, and it modulates a signal of 0s and 1s (binary signal). Then the 8 equations for 8-PSK are as follows:

$$s_{8psk}(t) = s_{s0} \sin[(2\pi f_c t) + \phi_{t0} + \phi] \quad (1.25)$$

where $\phi = \pi/8$, $3\pi/8$, $5\pi/8$, $7\pi/8$, $-7\pi/8$, $-5\pi/8$, $-3\pi/8$, and $-\pi/8$ corresponding to the triplets of bits 000, 001, 010, …, and 111. The triplet $(n_1 n_2 n_3)$ can represent these combinations where n_1, n_2, and n_3 each takes value 0 or 1. When $s_m(t) = n_1$, then $s_m(t + T/3) = n_2$, and then $s_m(t + 2T/3) = n_3$.

Quadrature Amplitude Modulation

Quadrature amplitude modulation uses QPSK (4-PSK) with three- or four-stage amplitude modulation. The 16-PSK, 3-stage amplitude modulation can be defined by 16 equations. It is popularly known as *16-quadrature amplitude modulation* (*16-QAM*). The 16-QAM modulation technique uses QPSK modulation. There are 16 distinct quadruplets each of which has a phase angle in one of the four quadrants. A quadruplet has one of three possible peak amplitudes, A_1, A_2, or A_3. Four quadruplets have amplitude A_1, eight have A_2, and the remaining four have A_3. Each quadruplet is in one of the four quadrants between 0° and 360° according to one of the 16 combinations of 4 bits from 0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111, 10000, 1001, 1010, 1011, 1100, 1101, 1110, and 0111.

Let n_1, n_2 specify a quadrant, and n_3, n_4 specify a phase angle in that quadrant. The equations for the 16 quadruplets in QAM are given as follows:

$$s_{\text{qam}}(t) = s_{s0}\,(t)\,\sin[(2\pi f_c t) + \phi_{t0} + \phi] \tag{1.26}$$

Phase angle $\phi = \pi/4$, $3\pi/4$, $-3\pi/4$, and $-\pi/4$ and $s_{s0} = A_1$ correspond to the quadruplets 1111, 1011, 0011, and 0111 [in general $(n_1n_2n_3n_4)$], respectively, when

$$s_m(t) = n_1;\ s_m(t + T/4) = n_2;\ s_m(t + T/2) = n_3;\ \text{and}\ s_m\,(t + 3T/4) = n_4 \tag{1.27}$$

Phase angle $\phi = \pi/8$, $3\pi/8$, $5\pi/8$, $7\pi/8$, $-7\pi/8$, $-5\pi/8$, $-3\pi/8$, $-\pi/8$, and $s_{s0} = A_2$ for the quadruplets 1100, 1110, 1000, 1010, 0000, 0010, 0100, and 0110 [in general $(n_1n_2n_3n_4)$], respectively, when

$$s_m(t) = n_1;\ s_m(t + T/4) = n_2;\ s_m(t + T/2) = n_3;\ \text{and}\ s_m(t + 3T/4) = n_4 \tag{1.28}$$

Phase angle $\phi = \pi/4$, $3\pi/4$, $-3\pi/4$, and $-\pi/4$ and $s_{s0} = A_3$ for the $(n_1n_2n_3n_4)$ quadruplets of bits 1101, 1001, 0001, and 0101, respectively, when

$$s_m(t) = n_1;\ s_m(t + T/4) = n_2;\ s_m(t + T/2) = n_3;\ \text{and}\ s_m(t + 3T/4) = n_4 \tag{1.29}$$

64-Quadrature Amplitude Modulation

64-quadrature amplitude modulation (64-QAM) is a higher-order modulation combining ASK and PSK. It is a modulation technique in which there is 8-PSK modulation with 64 distinct octets. Each octet has its phase angle in one of the eight phase angles and has one of the eight combinations of possible peak amplitudes A_1, A_2, A_3, and A_4.

1.6 MULTIPLEXING (SDMA, TDMA, FDMA, AND CDMA) AND EXAMPLES

Multiplexing means that different channels, users, or sources can share a common space, time, and frequency, or can use distinct codes for transmitting data. Section 4.3 will explain the sharing of a common space, time, or frequency using space division multiple access (SDMA), time division multiple access (TDMA), or frequency division multiple access (FDMA) in detail. Figures 4.4 to 4.7 will show diagrammatically how sharing takes place in a common space, time, or frequency using SDMA, TDMA, and FDMA by taking examples. The following is an overview of multiplexing techniques:

Space Division Multiplexing

When using the identical set of frequencies in identical time instances, the different sources of transmitting signals can transmit along the distinct paths.

SDMA means division of the available space so that multiple sources can access the medium at the same time. SDMA is a technique in which a wireless transmitter transmits the modulated signals and accesses a space slot, and another transmitter accesses another space slot such that signals from both can propagate in two separate spaces in the medium without affecting each other and can operate in the same frequency band.

Example 1.11

How do eight groups, A, B, C, D, E, F, G, and H of mobile users and eight different regional space slots, $R_1, \ldots, R_8$ transmit?

Solution: Assume that a directed antenna A_{n1} radiates in the direction north and uses region R_1 between A and the receiver. Assume that another directed antenna A_{n2} uses region R_2 and radiates in the direction north-west. Similarly, six antennae, A_{n3}, A_{n4}, A_{n5}, A_{n6}, A_{n7}, and A_8 transmit in six distinct directions.

The space used is such that there is no interference of signals from the group of users when Group A uses $R_1, \ldots,$ and H uses R_8 for transmitting and receiving signals to and from a base station. This is space division multiplexing of eight sources of transmission of modulated signals.

Time Division Multiplexing

Different vehicles on a road share a common lane. They can pass through same point in different time slots. Similarly, different source-transmitting signals along the identical path using identical band of frequencies can transmit in successive time slices. TDMA entails different sources using successive time slices for transmission of signals along same space and using same frequency band.

TDMA is an access method in which multiple users, data services, or sources are allotted different time slices to access the same channel (identical band of frequencies). The available time slice divides among multiple sources of modulated signals. These sources use the same medium, the same set of frequencies, and the same channel for transmission of data.

Example 1.12

How do eight radio carriers (e.g., mobile phones) C_1, C_2, C_3, C_4, C_5, C_6, C_7, and C_8 transmitting signals in a GSM channel transmit?

Solution: The GSM channel provides for eight TDMA time slices—one for each radio carrier. Radio interfaces of carrier waves in eight phones can simultaneously transmit in the same frequency band (channel). The time slice allotted to each is 577 µs. C_1 transmits in the first time slice t_1 = 0 to 577 µs, C_s in the second t_2 = 578 to 1144 µs, and so on. Therefore, each transmitter uses the channel after time intervals of (577 × 8) µs or 4.615 ms.

Frequency Division Multiplexing

Different colours can be used to identify different objects. Similarly, different source-transmitting signals along the identical path in same time instances can transmit using distinct band of frequencies. Frequency multiplexing requires a separation of frequency bands used for transmission by different channels. The available frequency range is divided into bands, which are used by multiple sources or channels at the same time and space. Various channels are allotted distinct frequency bands for transmission. *FDMA* is an access method that entails assignment of different frequency slices to different users for accessing the same carrier.

Example 1.13

How do 124 radio channels operating at frequencies fch1 ± 100 kHz, fch2 ± 100 kHz, …, fch123 ± 100 kHz, fch124 ± 100 kHz transmit? Assume GSM900 services for 890–915 MHz uplink from users to the base station and a 935–960 MHz downlink from the base to the users.

Solution: A ± 100 kHz channel bandwidth = 200 kHz. Therefore, 124 channels for uplink need 200 kHz × 124 = 24.8 MHz in the 890–915 MHz uplink range. Similarly, the 124 channels for downlink require 200 kHz × 124 = 24.8 MHz in the 935–960 MHz.

Because the frequency slice allotted to each is 200 kHz, Channel 1 transmits in the 890.1 MHz ± 100 kHz range, Channel 2 in the 890.3 MHz ± 100 kHz range, and so on. Channel 1 receives in the 935.1 MHz ± 100 kHz range, Channel 2 in the 935.3 MHz ± 100 kHz range, and so on.

Code Division Multiplexing

Code division multiplexing (*CDMA*) requires a specific *n*-bit code sequence of 1s and 0s used for coding the *n* frequency bands used for transmission by a channel. Each channel uses a distinct sequence of 1s and 0s. The distinct codes are used by multiple sources or channels at the same set of *n* frequency bands time and space. The following section elaborates it further.

1.7 USES OF SPREAD SPECTRUM

All the seven colours can be used but different pattern of colours in coloring an object can be used to identify different objects. Similarly, transmission using CDMA is by a wide range of frequencies, called *spread spectrum*. Spread spectrum has a distinct set of equally separated frequencies.

1.7.1 Code Division Multiple Access (CDMA)

Different source-transmitting signals along the identical path in the same time slices in a second using spread spectrum frequencies can do so using distinct codes. There are two methods using which a given spread spectrum frequency can be coded. Sections 5.7 and 5.8 will describe two methods called *direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS)*.

Direct Sequence Spread Spectrum Method

Let us assume n equally spaced frequencies, f_0, f_1, …, f_{n-2}, and f_{n-1}. These are used for transmission during successive n instances, and n frequencies are used in direct sequence but according to a code. The time interval of n instances is called *chipping interval* and is denoted by t_{chip}. Frequencies are called the *chipping frequencies*.

Example 1.14

How can 4 equally spaced chipping frequencies, f_1, f_2, f_3, and f_4 be used for transmission during four successive chipping instances per chipping interval t_{chip} in direct sequences according to a 4-bit code?

Solution: Assume that a 4-bit code is 1000. Then, in one chip interval, f_1 is used after coding with 1 at an instance. In the next instance, f_2 is used after coding with 0. In the next instance, in transmission chip uses f_3 after coding with 0, and next to next instance uses f_4 after coding with 0.

Assume another 4-bit code is 1010 in each chip interval. Then, f_1 is used after coding with 1. In the next instance, f_2 is used after coding with 0. Next instance, f_3 is used after coding with 1; and next instance, f_4 used after coding with 0. [Coding with 1 means advancing of phase angle ϕ_0 (=90°) and with 0 means reducing the phase angle ϕ_0 (= –90°) of the transmitted signal s(t) given by Eqn (1.1).] Assume BPSK modulation, Eqns (1.19) and (1.20) gave the phase angles for 1s and 0s.

There are a group of code sets that can be used and another group of code sets that cannot be used. For example, 0000 and 1111 cannot be used.

Frequency Hopping Sequence

Different hopping sequences of colours can be used to identify different objects. Let us assume n equally spaced sequence of frequencies, f_0, f_1, …, f_{n-2}, and f_{n-1}. These are used for transmission during successive n intervals, and n frequencies are used in a hopping sequence according to a code. The intervals are called *hopping intervals*. Frequencies are called the *hopping frequencies*.

Example 1.15

How can four frequencies, f_1, f_2, f_3, and f_4 hop in frequency hopping of the sequences?

Solution: Let us assume hopping between the frequencies according to some code. For example, choose one code as 2,1,3,4. This means transmission is using $f2$ in the first instance, $f1$ next, $f3$ third, and $f4$ in the fourth instance. The interval between two instances is called *hopping interval*.

Let us choose another code as 4,1,2,3. This means transmission is using $f4$ in the first instance, $f1$ next, $f2$ in the third, and $f3$ in the fourth instance.

$4 \times 3 \times 2 \times 1 = 24$ codes are possible when deploying a group of 4 frequencies for hopping within an interval. The interval is called hopping interval.

Code Division Multiple Access

CDMA is an access method in which multiple users are allotted different codes to access the same channel (set of frequencies) for transmitting the symbols. [A symbol is a bit (0 or 1), which is transmitted after encoding and processing a set of bits for the data or text, voice, pictures, or video.] Sections 5.6 and 5.7 will discuss CDMA and spread spectrum techniques in greater detail. The following is an overview:

One of the methods for the CDMA is DSSS. Each code is uniquely made up of n bits. The code is used for transmitting a signal using a sequence of frequencies f_{c0}, $f_{c0} + f_s$, $f_{c0} + 2.f_s$, …, $f_{c0} + (n - 2).f_s$, $f_{c0} + (n - 1).f_s$ by the same spectrum. These n frequencies are also called *chipping frequencies* when DSSS method is used. Assume that $n = 16$ and the code is 1110000111100001 during the 16 timing instances in one chip interval, t_{chip} [t_{chip} is reciprocal of chipping rate (frequency) multiplied by number of chipping frequencies, f_s used].

Consider symbol S being transmitted is 1. Assume spread factor = 1 and $n = 16$. [Each Symbol transmits in period t_S. The ratio of t_S and t_{chip} is called spread factor.] It means that symbol S = 1 during the period spread factor × 16× f_s^{-1}. Then output is 0001111000011110 during the period $16 \times f_s^{-1}$ due to XORing of 1110000111100001 with 1111111111111111 during sixteen instances during a t_{chip}.

When the symbol S to be transmitted is 0 during the period t_S = spread factor × t_{chip}, then output is 1110000111100001 during each chip interval (= the period $16 \times f_s^{-1}$) due to XORing of 1110000111100001 with 0000000000000000.

Table 1.1 XORing of the chipping and modulating signals

Chipping signal (A)	Modulating signal symbol (B)	Modulated carrier (A XOR B)
0	0	0
0	1	1
1	0	1
1	1	0

XORing of the modulating symbols and chipping frequencies can be explained in terms of the resultant modulated carrier frequency, amplitude, and phase s(t) representing output 1 or 0. The possible XOR combinations of the modulating symbols B and chipping signals A and their XORed output (A XOR B) are listed in Table 1.1.

The rate at which the chips after XORs with symbols generate the modulating signal is called the *chipping rate* and is equal to the reciprocal of f_s. Each chipping frequency is separated in integral multiples of f_s.

When symbol S to be transmitted is 1 and assumed spread factor = 64, it means that symbol S remains 1 during the period $64 \times 16 \times f_s^{-1}$. Then, the output is 0001111000011110 during the period t_{chip}, and this output repeats 64 times.

When the symbol S to be transmitted is 0 during the period $64 \times t_{chip}$, then output is 1110000111100001 during the period t_{chip} due to XORing of 1110000111100001 with 0000000000000000, and this repeats 64 times.

It is clear from Table 1.1 that if the modulating symbol and chipping signals are 1–1 or 0–0, then modulated output is 0, but when the modulating and chipping signals are dissimilar (0–1 or 1–0), then the modulated output is 1. Multiple channels can transmit at the same set of chipping frequencies (using the same f_{c0} and f_s values), but they must transmit via each chipping sequence carriers with distinct set of codes. The transmitter performs the XOR operation between the chipping signals (carrier) and the modulating symbols at any given instant *t*. The distinct codes are assigned to each source, channel, or radio carrier (mobile).

Example 1.16

How does a 16-bit code (1110000111100001) transmit by XORing in a set of sequences when a symbol $S = 1$ and 0 in the modulating signals? Assume 16 chipping frequencies f_{ch0}, $f_{ch1} \pm f_s$, $f_{ch2} \pm 2f_s$, …, $f_{ch14} \pm 14f_s$, $f_{ch15} \pm 15f_s$.

Solution: Assume that the symbol $S = 1$ or 0 is transmitted as a sequence of 0s and 1s. The amplitude in the carrier signal is 0 when the code bit is 0 and is finite and constant when the symbol is 1. The bandwidth of the channel is $16.f_s$. Figure 1.8 shows the carrier signal chipping frequencies when the code (1110000111100001) is transmitted and symbol $S = 0$.

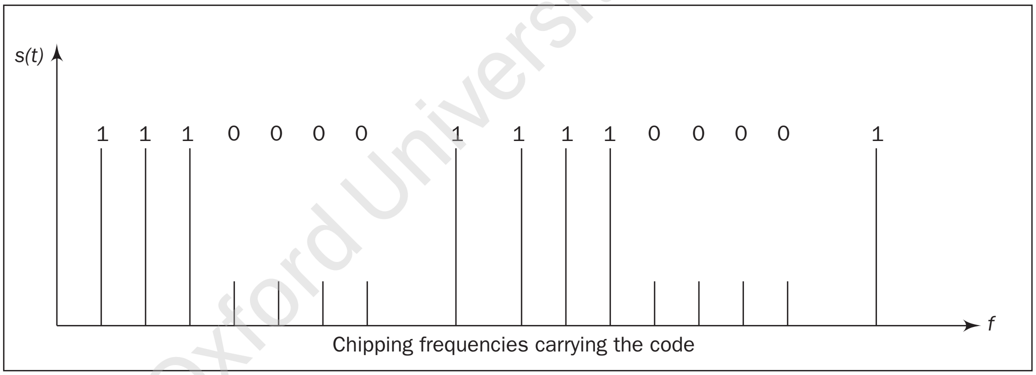

Fig. 1.8 Carrier signal frequencies in spread spectrum when 1110000111100001 coded 16 chipping frequencies XORed with the symbol $S = 0$ () during a chipping interval of transmission

1.7.2 Orthogonal Frequency Division Multiple Access (OFDMA) Using Orthogonal Codes

Orthogonal frequency division multiple access [OFDMA; also called code OFDM (COFDM)] is a multi-carrier, multi-tone access method for transmitting multiple carriers for a set of modulating signal symbols. Each carrier transmits a distinct set of sub-carriers, and each set of sub-carriers is assigned a code, which is orthogonal to another. An OFDM transmitter can transmit N/n_{sc} symbols in 1s deploying each sub-carrier (n_{sc} = 3, 4, or 8).

Two frequency signals, $s_1(t)$ and $s_2(t)$, are said to be orthogonal if $s_1(t)$ has 1 [maximum amplitude s_{c0} at the instant when $s_2(t)$ has 0 (minimum amplitude $-s_{c0}$) and vice versa]. To elucidate, if at an instant $t = t'$, $s_1(t')$ is 1, and $s_2(t')$ is 0, and at $t = t''$, $s_2(t'')$ has 1, and the amplitude of $s_1(t'')$ is 0, then $s_1(t)$ and $s_2(t)$ are orthogonal.

Example 1.17

How does a COFDM transmitter transmit using three sub-carriers of frequency sets of f_{c0}, f_{c1}, and f_{c2} in a second 3 times more number of modulating signal symbols? Assume three sets of sub-carrier frequencies (f_{c0}, f_{c1}, f_{c2}) are chipping with $[f_{c0} + f_s, f_{c1} + f_s, f_{c2} + f_s],[(f_{c0} + 2.f_s, f_{c1} + 2.f_s, f_{c2} + 2.f_s], \ldots,[f_{c0} + (m - 1).f_s, f_{c1} + (m - 1).f_s, f_{c2} + (m - 1).f_s]$.

Solution: A CDMA transmitter transmits using a carrier frequency f_{c0} for N modulating symbols in a second. The successive symbols transmit by frequencies f_{c0}, $f_{c0} + f_s$, $f_{c0} + 2.f_s, \ldots, f_{c0} + (m - 1).f_s$, f_{c1}, $f_{c1} + f_s$, $f_{c1} + 2.f_s, \ldots,$. Here, *m* is the number of chipping frequencies used for coding. Assume that three successive symbols transmit at the same instance in each chipping instance. Here, 3 is the number of different set of sub-carriers used for coding instead of a single carrier frequency, f_{c0}, transmitting all the symbols. Orthogonal codes are used for each set of sub-carriers.

COFDMA is an access method in which the adjacent sets of sub-carriers are carrying a subset of symbols and are orthogonal. Each subset of symbols and carrier is allotted a different set of sub-carriers, and each adjacent set of sub-carriers satisfies the orthogonality condition for the code. Section 5.14 will describe OFDM in detail.

1.8 CIRCUIT AND PACKET SWITCHING NETWORKS

Switching means establishing a communication channel between a source and a destination so that data can transmit till the switch is disconnected. Let us assume *m* symbol groups transmission with each group having between *k* and l symbols.

One way is to establish a path for transmission and transmit till all symbol groups complete the transmission or till the disconnection. Each transmitter transmitting symbols at an instant assigns to distinct path, called a *circuit*. The network of transmitter and receivers is called *circuit switched network*.

The second way is to divide all symbols into *m* packets with each packet having maximum 2^n symbols. Each transmitter transmits the packets one by one through a set of routers up to the receiver. Each router determines the paths available at a given instant or at receiving a packet. Each router transmits a packet at an instant after it assigns the packet to one of the paths available. Assume *k* paths are available for the destination at an instance. The router will send *k* packets along *k* paths at that instant. The network of transmitter, routers, and receivers is called *packet switched network*.

Circuit Switching

Circuit switching is a method of data transmission in which a circuit (communication channel or path) once established, continues to be used till the transmission is complete. The following example explains the circuit switching method.

Example 1.18

Let us assume, for example, that there are four base stations, A, B, C, and D. How does a radio carrier (mobile device), T_1, communicate with a receiver, R_1, using circuit switching technique?

Solution: Circuiting provides a path from the beginning to the termination of the transmission. A circuit is established and a path B to D (T_1 at B and D for R_1) is provided in a circuit-switched transmission. Each data frame transmitted along the path will take the same interval of time and the channel B to D is not available to any other circuit till the present circuit (interconnection) is terminated, irrespective of whether T_1 is idle during certain time intervals.

Packet Switching

Packet switching is a means of establishing connection and transmitting data in which the message consists of packets containing the data frames. A packet is a formatted series of data, which follows a distinct path directed by a router. Router selects a path from among a number of alternate paths available at that instant. Each packet can be routed by a router through different channels, carriers, or routes. Due to this, the packets reach their destination with variable delays. Delays in reaching the receiver depend on the hopped paths through the routers. The message is recovered by assembling the packets as per the original sequence. Packet switching improves the efficiency of the available transmission capacity. The following example explains the packet-switching method:

Example 1.19

Let us assume, for example, that there are four transceiver routers, A, B, C, and D. How does a radio carrier (mobile device), T_1, communicate with a receiver, R_1, using packet-switching technique?

Solution: Let us go back to Example 1.18 cited for circuit switching. If the transmission is packet switched, then sequences and groups of symbols (data) from T_1 are framed into packets. Let us say that the path T_1 at B to D for R_1 is available at an instance. Assume that at the same time, the path T_1 at B–A–C–D for R_1 is also available. Assume that 10 packets are being transmitted. In such a scenario, T_1 simultaneously transmits one packet through B–A–C–D and another through B–D. The router at B selects the path options at the receipt of each packet. A set of packets, say 5, 6, 9, 10, follows the first path, and another set, 1, 2, 3, 4, 7, and 8, follows the second path. Both sets of packets take different amounts of time. They reach with different delays. In addition, the packets may not reach their destination in a sequential manner. However, a unique number called the *sequence number* is also transmitted along with each packet. Using these sequence numbers, the receiver sequentially arranges the messages and constructs full sequences of messages transmitted through both set of packets.

1.9 GLOBAL SYSTEM FOR MOBILE COMMUNICATION (GSM)

First-generation (1G) wireless devices communicated only voice signals. The symbol 1G refers to the voice-only communication. Nowadays, voice transmissions also carry data. Second-generation (2G) devices communicate voice as well as data signals. 2G devices came onto the market in 1988 and have data rates of up to 14.4 kbps. The 2.5G and 2.5G+ are enhancements of the second generation and support data rates of up to 100 kbps. The third-generation (3G) mobile devices communicate at an even higher data rates and support voice, data, and multimedia streams. 3G supports data rates of 2 Mbps or higher for short distances and 384 kbps for long distance transmissions. High data rates in 3G devices enable transfer of video clips and faster multimedia communication. 4G facilitates even higher data rates than 3G and supports streaming data for video. 4G enables multimedia newspaper, high-resolution mobile TV, Internet protocol (IP) telephony, and data rates of up to 100 Mbps.

Figure 1.9 shows GSM-based standards. It also shows a mobile communication network used for long-distance communication.

The GSM was developed by the Groupe Speciale Mobile (GSM), which was founded in Europe in 1982. The GSM is a standard for mobile telecommunication through a cellular network at data rates of up to 14.4 kbps. Nowadays, it consists of a set of standards and protocols for mobile telecommunication.

Figure 1.9 shows GSM-based standards. Chapter 4 gives the details of GSM-based standards exhaustively.

Table 1.2 lists the features of GSM 900 for an overview.

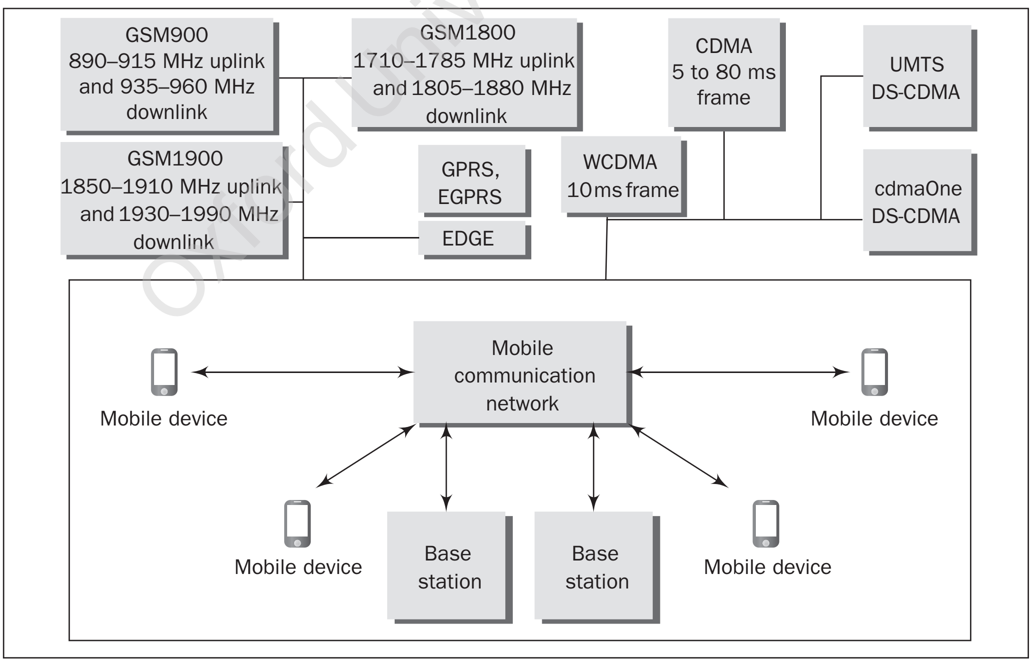

Fig. 1.9 GSM- and CDMA-based standards and a mobile communication network for long-distance communication

Table 1.2 Features of the GSM 900 standard

Feature	Description
GSM900	GSM standard was founded in 1988 by GSM.
Modulation	GSM uses GMSK for transmitting 1s and 0s.
Multiplexing	GSM uses FDMA for channels and TDMA for user access in each deployed channel. Analog signals of up to 8 radio carriers are transmitted when using one common digital channel of bandwidth 200 kHz.
Frequency channels	GSM 900 operates at 890 to 915 MHz for uplink and 935 to 960 MHz for downlink. Uplink and downlink frequency bands of 25 MHz each provide FDMA access for each channel. Each link thus provides 124 channels, each of 200 kHz. Each channel provides 8 TDMA access slots, thus providing channel access to each user (radio carrier) every 4.615 ms. Eight users have time slices of 577 µs each.
Data transfer rates	The data rates of a GSM mobile-communication network are at maximum 14.4 kbps.

1.10 2.5G VOICE AND DATA COMMUNICATION STANDARDS: ENHANCED DATA RATES FOR GSM EVOLUTION, GPRS, EGRS, AND EDGE

GSM has been enhanced to tri-band services and packet-oriented data communication. Table 1.3 gives the standards.

Table 1.3 Standards based on the 2.5 EDGE and GPRS and 3G evolution of edge UWT-136

Extension/ Enhancemententent	Description
EGSM and GSM900/1800/1900 tri-band	Extended global system for mobile communication (EGSM) provides an additional spectrum of 10 MHz on both uplink and downlink channels. Therefore, the operating frequencies for EGSM are 880 to 915 MHz (uplink) and 925 to 960 MHz (downlink). The link frequencies are just below and above the original GSM 900 band. The additional 10 MHz on each side provides an additional 50 channels of 200 kHz each. EGSM (enhanced GSM) communication frequency spectrum lies in three bands, 900/1800/1900 MHz. It is therefore known as tri-band. A tri-band radio carrier in the mobile phone facilitates global roaming. GSM 1800 uses 1710-1785 MHz for uplink and 1805-1880 MHz for downlink. GSM 1900 uses 1850-1910 MHz for uplink and 1930-1990 MHz for downlink.
GPRS [GSM Phase2+ (2.5G)]	GPRS is a packet-oriented service for data communication of mobile devices and utilizes the unused channels in the TDMA mode in a GSM network.
Enhanced data rates for GSM evolution (EDGE)	EDGE is an enhancement of the GSM Phase 2 (known as *GSM Phase 2.5G+*). It uses 8-PSK communication to achieve higher rates of up to 48 kbps per 200 kHz channel as compared to up to 14.4 kbps data transmission speed in GSM. Using coding techniques the rate can be enhanced to 384 kbps for the same 200 kHz channel.

Table 1.3 (*Contd*)

Extension/ Enhancementent	Description
Enhanced GPRS (EGPRS)	EGPRS is an extension of GPRS using 8-PSK modulation. It enhances the data communication rate. EGPRS is based on EDGE and is used for high-speed circuit-switched data (HSCSD)—an enhanced circuit-switched data (ECSD) network. HSCSD is a GSM Phase2+ (2.5G) communication standard. For example, the Nokia 9300 Series Smartphone has high-speed data connectivity with EGPRS (EDGE), mobile Internet connectivity and tri-band (EGSM 900/1800/1900) operation for use in all five continents.
EDGE UWT-136 IMT-2000 (SC) 3G	3G evolution of EDGE UWT-136 is IMT-2000 Single-Carrier (IMT—SC). It uses FDD and TDMA. [IMT means International Mobile Telecommunication standard.]

1.10.1 CDMA-based 2.5 G+ Standard

Figure 1.9, lower part, shows CDMA-based standards. It also shows a mobile communication network used for long-distance communication. The modulation methods and standards in CDMA 2.5G+ and CDMA 3G are described in Tables 1.4 and 1.5.

Besides GSM, CDMA is the most popular mobile communication standard (Fig. 1.9). The initial evolution of CDMA was as 2.5G. It started in 1991 as cdmaOne (IS-95). Table 1.4 summarizes the standards based on CDMA.

Table 1.4 CDMA 2.5G+ standards

Extension / Enhancement	Description
cdmaOne/IS-95	cdmaOne founded in 1991, developed by QUALCOM, USA, belongs to 2G+, also known as IS-95 (interim standards 95). IS-95 operates at 824-849 MHz and 869-894 MHz. A CDMA channel can transmit analog signals from multiple sources and users.

1.11 NEW-GENERATION MOBILE COMMUNICATION STANDARDS: 3G NETWORKS

Nowadays, CDMA supports high data rates and is considered 3G. CDMA devices transmit voice as well as data and multimedia streams. CDMA 2000, IMT 2000, wide CDMA (WCDMA), and universal mobile telecommunication system (UMTS), like the GSM, also support cellular networks (Section 2.1).

1.11.1 CDMA 3G

Table 1.5 summarizes the 3G standards based on CDMA.

Table 1.5 CDMA-based 3G standards

Extension / Enhancement	Description
3GPP (WCDMA)IMT-DS (Direct Spread)	The 3G partnership project (3GPP), also known as WCDMA, supports asynchronous operations and has a 10 ms frame length with 15 slices. It has a smaller end-to-end delay in the 10 ms frame as compared to 20, 40, or 80 ms frames. Each frame length is modulated by QPSK both for uplink and downlink. It uses DS (direct sequence) CDMA. It supports a 3.84 Mbps chipping rate. Both short and long scrambling codes are supported, but for uplink only. UMTS supports it.
3GPP2(IMT-2000, CDMA 2000)	3GPP2 started in 2001. It is compatible with CDMA2000 and CDMA2000 1x. The 3GPP2 chipping rates are in multiples of f_s = 1.2288 Mbps. 3G IMT 2000 carrier frequency f_{c0} = 2 GHz. The CDMA2000 1x f_s = 1.2288 Mbps and is also backward compatible to 2.5G cdmaOne IS-95. 3GPP2 is used for voice communication, for circuit as well as packet-switched communication, IP packet transmission, and multimedia and real-time multimedia applications. It supports higher data rates; synchronous operations; and 5, 10, 20, 40, or 80 ms frame length. Each frame length is modulated by QPSK and BPSK—for uplink and down link, respectively. IMT multi-carrier (IMT—MC) FDD CDMA2000 1x EVDO (evolution for data optimized) and CDMA2000 1x EVDV (evolution for high-speed integrated data and voice) are enhancements, accepted as standards in 2004. CDMA2000 3x uses three 1.2288 Mbps channels. Earlier planned as pre-4G UMB. CDMA TDD (IMT—TC) HSPA or pre 4G LTE based TD-CDMA and TD-SCDMA channels. LTE stands for Long Term Evolution.
UMTS	UMTS supports both 3GPP and 3GPP2. UMTS transmitter communicates at data rates of 100 kbps to 2 Mbps. It combines CDMA for bandwidth efficiency and GSM for compatibility. It supports several technologies for transmission and gives a framework for security and management functions. It uses DS (direct sequence) CDMA and supports a 3.84 Mbps chipping rate.
IMT—FT FDMA/TDMA	Digital Enhanced cordless telecommunication) duplex and FDMA/TDMA channel and used in wireless in local loop.
pre-4G Mobile WiMax IP—OFDMA	Worldwide interoperability for microwave access (WiMAX; IEEE 802.16e OFDMA defines a specification for new generation innovative technology that delivers high-speed broadband, fixed, and mobile services wirelessly to large areas with much less infrastructure using the IEEE 802.16 standard.

1.11.2 Upgraded WCDMA Methods for Downlink and Uplink

WCDMA supports a 3.84 Mbps chipping rate. High-speed packet data access (HSPA) is provided by high-speed packet downlink data access (HSPDA) and high-speed uplink packet access (HSUPA). It supports downlink and uplink data rates of up to 14 Mbps and 5.8 Mbps, respectively. HSPA and HSPA+ are enhancements for mobile phones based on evolution of WCDMA.

HSPA, introduced in 2005, provides increased capacity as well as higher data rate transfers—7.2 Mbps, 14 Mbps, 21 Mbps, 28 Mbps, and 42 Mbps for high-performance packet data applications. It evolved from WCDMA and 3GPP standards. HSPA+ standard evolved from HSPA, introduced in 2008 and adopted 2010. It has theoretically possible data rates, uplink 34 Mbps and downlink 33.7 Mbps. Practically achieved rates are lower.

Main features of HSPDA are multi-code transmission and higher-order modulation—16-QAM—which yields higher bit rates and shared channel transmission. Features of HSUPA enhanced dedicated channel (EDCH) addition, which facilitated faster uploading of pictures, multi-code transmission, and short transmission time interval (TTI) and significantly reduced latency.

Table 1.6 gives a list of features of these WCDMA enhancements.

Table 1.6 WCDMA enhancements in 3G standards

WCDMA Enhancement	Features
HSDPA	3GPP WCDMA enhancement Supports downlink data rates of 7.2 Mbps, 14 Mbps, 21 Mbps, 28 Mbps, and 42 Mbps for high-performance packet data applications Short TTI and significantly reduced latency Fast link adaptation and scheduling Fast hybrid Automatic Repeat reQuest (ARQ) for good error correction performance
HSUPA	3GPP Release 6 Supports uplink data rates of 1.9 Mbps and 5.8 Mbps Fast link adaptation and scheduling Fast hybrid automatic repeat request (ARQ)
HSPA	HSDPA and HSUPA for mobile phones with new protocol for mobile phone and base station Supports 14 Mbps downlink and 5.8 Mbps uplink
HSPA+ (evolved HSPA or I-HSPA or Internet HSPA)	3GPP release 7 and 8—evolution of HSPA 42 Mbps downlink and 11 Mbps uplink (2 carrier of 5 MHz each) MIMO antennae Higher order modulation 64-QAM

1.11.3 Super 3G and Pre-4G: 3GPP Long-term Evolution and WiMax 802.16e Standards

Long-term evolution (LTE) and WiMax 802.16e standards provide the features of pre-4G. Table 1.7 lists the features of pre-4G evolution and standards. The LTE pre-4G specifications provide downlink peak rates of 300 Mbit/s. It enables 75 Mbps uplink maximum rates. Radio access transfer latency is below 5 ms. It supports scalable carrier bandwidths, 1.4 MHz to 20 MHz. [WCDMA permitted only 5 MHz wide cells.] It supports five classes of quality of service (QoS). It supports mobile device mobility up to 350 km/hr; OFDM for the downlink; single-carrier FDMA for uplink; and macro, pico, and femto cell-based communication.

Table 1.7 Features of super 3G and pre-4G LTE and WiMax standards

Pre-4 G evolution and standards	Features
LTE	3GPP high-speed OFDM packet access (HSOPA) 100 Mbps downlink and 50 Mbps uplink for voice, Support for IPTV with full mobility-speed video conferencing

(Contd)

Table 1.7 (*Contd*)

Pre-4 G evolution and standards	Features
IEEE 802.16e WiMax	Support for up to 2048 sub-carriers and a single-channel support OFDMA 128, 256, 512, 1024, and 2048 fast Fourier transform (FFT) Adaptable number of channels (closer to cell, more channels and farther from cell, less channels) Sub-channelisation for subscriber links (this reduces interference from multiple paths) 64-QAM, 16-QAM, QPSK, and BPSK adaptive modulation (64-QAM for strong signals and BPSK for weak signals) MIMO antennae (giving higher bandwidth) Dynamic Fast hybrid Automatic Repeat reQuest (ARQ) MAC sublayers for IP, Ethernet, Handover mechanisms and classification of data DES or AES encryptionIdle and sleep modes for Power saving Allocation of channel by Base station to the subscriber station

1.12 4G FEATURES: LTE ADVANCED AND WIMAX 802.16M

LTE Advanced and WiMax 802.16m standards will provide the features of 4G [1000 Mbps (1 Gbps) data rates]. The f key features in all suggested 4G technologies are as follows: (a) mobile IP for mobility, (b) IP-based femto cells, (c) no circuit-switching support, (d) MIMO for high spectral efficiency, (e) single-carrier frequency domain equalisation or frequency domain equalization, (f) linearly pre-coded OFDMA uplink, (g) channel-dependent scheduling, (h) adaptive modulation, and (i) use of error-correcting codes.

Table 1.8 lists the features of 4G and its standards.

Table 1.8 Features of 4G LTE Advanced and WiMax 802.16m standards

Evolution and standards	Features
LTE Advanced	IMT advanced multi-carrier OFDMA in downlink and hybrid of OFDMA and single-carrier (SC-FDMA) in uplink Scalable bandwidth support between 20 MHz and 100 MHz Supports 100 MHz downlink bandwidth Adaptable spectrum usage 1000 Mbps fixed systems and 100 Mbps mobile data rates for multimedia news-papers and high-resolution TV. Supports 100 Mbps for mobile Faster switching between different power levels Improved performance during Cell edge handover Use of relay nodes Support for Single user Support for coordinated and diversified MIMOs Dual transmission [CDMA, HSPA Support Node GGSN to the packet data network] Automatic and autonomous network operations

Table 1.8 (*Contd*)

Evolution and standards	Features
	Interference management and suppression Advanced networks topology, Optimized heterogeneous networks Both high and low data rates 40 Mbps and 154 Mbps per nodes Use of picocells (very short region cells) and femtocells (tiny region cells) [http://qualcomm.com/technology]
IEEE 802.16m WiMax	Wireless metropolitan area network (WMAN) WiMax 802.16e enhanced to multi-carrier support (two different channels not necessarily in adjacent bands) Multi-hop relay Enhanced multi-cast broadcast Single- and multi-user MIMO Supports up to 120 Mbps downlink and 60 Mbps uplink using a 4 × 2 MIMO/TDD 5:3 (self-configuration for the FDD and TDD) to users Adaptable to 20 ms superframes to give 20 MHz, 30 MHz and 40 MHz bandwidths two, three and four times data transfer rates two carriers Interference compression Reduced latency of a link 1000 Mbps fixed and 100 Mbps mobile— That enables video conferencing, videos, high resolution TV and multimedia newspapers (http://www.ieee802.org/16/tgm/docs/80216m-08_003r1.pdf)

1.13 GENERATIONS OF WIRELESS COMMUNICATION: 1G, 2G, 3G, 4G AND 5G

The following is an example of iPhone X, announced in September 2017. The phone supports 2G, 3G, and 4G bands as follows:

Example 1.20
What are the radio carrier standards that iPhone X supports?

Solution:
Apple iPhone X supports GSM, CDMA, HSPA, EVDO, and LTE networks.
2G bands: GSM 850/900/1800/1900 - A1549 (GSM), GPRS, EDGE, A1549 (CDMA), A1586. CDMA
800/1700/1900/2100 - A1549 (CDMA), and A1586.
TD-SCDMA 1900 (F), 2000 (A)

3G bands:
UMTS/ HSDPA+/HSPDA 850/900/1700/1900/2100 - A1549 (GSM),
A1549 (CDMA) CDMA EV-DO Rev. A (800, 1900, 2100 MHz), A1586, CDMA2000 1xEV-DO - A1549 (CDMA), A1586, and TD-SCDMA 1900/2000 - A1586.

4G bands: LTE
FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 12, 13, 17, 18, 19, 20, 25, 26, 28, 29, 30, 66)
TD-LTE (Bands 34, 38, 39, 40, 41) 700/800/850/900/1700/1800/1900/2100/2600 (1, 2, 3, 4, 5, 7, 8, 13, 17, 18, 19, 20, 25,
26, 28, 29) - A1549 (GSM), Speeds are HSPA 42.2/5.76 Mbps, LTE Cat4 150/50 Mbps, and EV-DO Rev.A 3.1 Mbps.

Table 1.9 Features of 2G, 3G, and 4G technologies

Generation	Features
2G	Enables digital encoding of voice and enables mobile phone and SMS. It is based on circuit switching.
2.5 G	Enables packet switching, Internet, and e-mail.
	3G Enables wide band wireless communication Internet, video conferencing, video calls, and mobile TV. It enables 14.4 kbps mobile phone, data communication at 384 kbps, 1.2288 Mbps (using CDMA 2000 1x) and 3× 1.2288 Mbps when using three carriers of 1.2288 Mbps each (using CDMA 2000 3x).
3.5G	3.5G Example is HSPA+ data communication at 28 Mbps uplink and 56 Mbps down link.
Pre-4G	Pre-4G Enables mobile WiMax using IEEE 802.16e standard and very high data rates using LTE.
4G	Enables multimedia newspaper, mobile TV of high resolution, IP telephony, and 100 Mbps data rates. Uses mobile WiMax IEEE 802.16m standard and LTE advanced.
5G	Will enable followings: (i) fast uploading and downloading speed; bi-directional large bandwidth shaping (ii) high resolution providing large broadcasting of data in Gigabit which supporting almost 65,000 connections (iii) High data rates and connectivity 1 Gbs second simultaneously to many workers (iv) Signalling efficiency enhanced and Spectral efficiency significantly enhanced compared to 4G (v) FCC approved the spectrum for 5G: 28 Gigahertz, 37 GHz and 39 GHz bands (vi) Significantly reduced latency compared to LTE (vii) Lower battery consumption, for better implementation of the Internet of things (Refer Section 5.20 for other details.)

KEYWORDS

16-QAM It is a modulation technique in which there is QPSK modulation with 16 distinct quadruplets. Each quadruplet has its phase angle in one of the four quadrants and has one of the three possible peak amplitudes, A_1, A_2, and A_3.

64-quadrature amplitude modulation It is a modulation technique in which there is 8-PSK modulation with 64 distinct octets. Each octet has its phase angle in one of the eight phase angles and has one of the eight possible peak amplitudes, A1, A2, A3, and A4. It is called *higher-order modulation*.

8-PSK It is a modulation technique in which the phase angle of a carrier frequency shifts to one of the eight different angles in one of the eight octets between 0° and 360° as per the eight combinations, 000, 001 … 111 in a set of three consecutive bits.

CDMA It is an access method in which multiple carriers, channels, or sources are allotted different codes (sequences of symbols) to access the same channel (set of frequencies at the same time in same space).

Cellular network It is a network in which space is divided into cells such that each cell has a base station for providing service to mobile devices and when a mobile device roams into another cell, a hand-off takes place from the previous station and handover takes place to the new base station.

Circuit switching It is a method of establishing connection and data transmission in which a circuit (communication channel or path), once established, continues till the end of the communication.

Digital modulation It is a technique in which amplitude, frequency, or phase angle parameters of carrier frequency or sub-carrier frequencies are varied with time according to the variation in modulating signal bit 1 or 0, modulating signal pair, or set of bits with time.

EDGE It is an enhancement of the GSM Phase 2, which uses 8-PSK modulation to achieve higher transmission rates of up to 48 kbps per 200 kHz channel compared to the up to 14.4 kbps data transmission speed in GSM.

FDMA It is a technique in which a wireless transmitter channel transmits a modulated signal and accesses using a frequency slice in a band and another modulated signal accesses via another frequency slice in the band. The available frequency in a band is divided into slices for use by multiple sources. Therefore, signals from two sources or of two data services can use the same time interval and channel and propagate in the medium without affecting each other.

GPRS It is a packet-oriented service for mobile devices' data communication, which utilises the unused channels in TDMA mode in a GSM network and also sends and receives packets of data through the Internet.

GSM It is a standard for mobile telecommunication through a cellular network at the data rates of 14.4 kbps. It was developed by Groupe Spéciale Mobile (GSM) founded in Europe in 1982.

MIMO MIMO antenna system is one in which more than one physically spaced antenna are used for transmission, are appropriately spaced, and their frequencies and phase angles are appropriately selected in a advanced pre-4G and 4G communication technology.

Mobile computing It is a computation during an application done on a mobile device in which a set of distributed computing systems or service provider servers participate, connect, and synchronize through mobile communication protocols.

Modulation It is the process of varying one signal, called the *carrier*, according to the information provided by another signal (modulating signal). The carrier is usually an analog signal selected to match the characteristics of a particular transmission system. The amplitude, s_{c0}, frequency, c, or phase angle, jct0, of a carrier wave are varied in proportion to the variation in the amplitude of the modulating wave or bits (the data or information signal).

OFDM It is a multi-carrier, multi-tone access method for transmitting multiple carriers for a set of symbols such that each carrier transmits a distinct set of sub-carriers and each set of sub-carriers has a code that is orthogonal to another.

Packet A packet is a part of data that can take a distinct path from other packets from the same source, and each packet can have variable delays.

Packet switching It is a method of establishing connection and packet transmission in which the message consists of packets containing the data frames. Each packet can be routed through different channels, carriers, or routes. Thus, different packets reach their destination with variable delays. Delay in reaching the receiver depends on the path followed through the routers. The message is recovered by assembling the packets as per the original sequence.

QPSK It is a modulation technique in which phase angle of the carrier shifts in one of four quadrants between 0° and 360°, and the shift depends on whether the modulating signal pair of bits is (1, 0), (0, 1), (0, 0), or (1, 1).

SDMA A technique in which a wireless transmitter transmits the modulated signal and accesses a space slot and another transmitter accesses another space slot such that signals from both can propagate in two separately spaced media without affecting each other.

Symbol It is a bit 0 or 1 that is to be transmitted after encoding and processing the bits of a data service, voice, picture, or video.

TDMA It is a technique in which a wireless transmitter channel transmits a modulated signal and accesses in a time slice and another modulated signal accesses in another time slice such that the signals from two sources or from two data services can propagate in the medium without affecting each other and use the same frequency band and the same channel. The available time slice is divided for use by multiple sources.

WiMax It is a specification for new-generation innovative technologies for delivering high-speed, broadband, fixed, and mobile services wirelessly to large areas with much less infrastructure using 802.16 standards.

EXERCISES

Objective Type Questions

Choose the correct or most appropriate statement among the choices given:

1. UHF 900 MHz frequencies are used in mobile communication due to:
   (a) line-of-sight propagation making the waves accessible directly anywhere.
   (b) small antenna length requirement, line of sight, and the reflected signals ensure that the mobile device signal reaches the base station and transmitter signals reach at the receiver.
   (c) non-availability of frequencies less than 900 MHz, as these have been allotted to radio, FM radio, and TV VHF/UHF.
   (d) regulations and standards.
2. Modulation of a modulating signal with a very large carrier frequency in wireless transmission is necessary due to:
   (a) antenna requirements, signal-propagating medium properties, and need to multiplex the multiple channels and users at the transmitter.
   (b) smaller antenna size at high frequencies.
   (c) little bending of the beams at high frequencies.
   (d) mobility requirements.
3. A GSM service uses:
   (a) FDMA for multiple users.
   (b) FDMA for multiple channels and TDMA for the multiple users of a channel.
   (c) different uplink and downlink modulation methods.
   (d) TDMA for multiple channels.
4. 8-PSK and QPSK are the modulation techniques in which:
   (a) the phase angle of the carrier frequency can be in one of the eight or four different angles as per one of the eight or four combinations of three or two bits, respectively.
   (b) the carrier frequency can use one of the eight or four channels as per one of the eight or four combination of three or two bits, respectively.
   (c) the carrier frequency time slices can use one of the eight or four angles as per one of the eight or four bits, respectively.
   (d) the phase angle of the carrier frequency can be in one of the eight or four different angles as per one of the eight or four bits, respectively.

5. Which one of the following is correct?
   (a) Circuit switching results in uniform delays between the end points for each message.
   (b) Packet switching results in uniform delays between the end points for all packets of the messages.
   (c) Packet switching results in variable delays between the end points for the packets of the messages.
   (d) Circuit switching results in variable delays between the end points for all messages.
6. 4G mobile communication uses:
   (a) Advanced LTE or IEEE 802.16m WiMax
   (b) MIMO antenna and OFDM
   (c) UHFs
   (d) Multi-carrier OFDA signals and encoded multiple antennas

Review Questions

1. IS-95 uses the 824 to 849 MHz and 869 to 894 MHz frequencies. What is the range of wavelengths used? What are the ways by which the signals are received at the base station from the transmitting devices?
2. A signal $s(t) = s_0 \sin(2\pi \times 2000 \times t)$ is to be transmitted. Find the time period, frequency, and phase angle at $t = 0$, 0.25 ms, 0.5 ms, 0.75 ms, 1 ms, 1.25 ms, and 3 ms for the signal.
3. A signal $s(t) = \text{a1} \sin(2\pi \times f \times t) + 0.5\ \text{a1} \sin(2\pi \times 3 \times f \times t) + 0.25\ \text{a1} \sin(2\pi \times 5 \times f \times t)$. Show the frequency spectrum of the signal. If signal is amplitude modulated with a signal $s(t) = +0.5\ \text{a1} \sin(2\pi \times 2000 \times t)$, what will be the new frequency spectrum?
4. Assume that a 24-symbol code (111000011110000111100001) is used with chipping frequencies of 900.000, 900.020, 900.040, …, MHz.
   (a) What will be the bandwidth used in CDMA transmission of the signal?
   (b) Assume that the symbols are transmitted after 8-PSK modulation. What will be the new carrier signal bandwidth? What will be the phase angles and amplitudes of the resulting signal?
   (c) Assume that the symbols are transmitted after QAM modulation. What will be the new carrier signal bandwidth? What will be the phase angles and amplitudes of the resulting signal?
   (d) Assume that the four sub-carriers are used for transmission. What will be the frequencies in the frequency spectrum of the transmitted signal?
5. What are the advantages and disadvantages of using a wireless transmission as compared to a fibre or wire transmission?
6. Describe the signal propagation at UHF frequencies. List the UHF frequencies for the TV, DAB, DECT, and GSM applications.
7. Describe amplitude and frequency modulation.
8. Explain the features of ASK, FSK, BPSK, QPSK, and 8-PSK. Describe QAM.
9. Describe various multiplexing techniques. Explain why a given bandwidth is used most efficiently in CDMA.
10. Explain the differences between 1G, 2G, 2.5G, 2.5G+, and 3G mobile communications.
11. Describe the modulation frequencies and modulation methods in GSM 900.
12. Describe 3GPP2 communication.
13. What are the advantages of packet switching compared to circuit switching networks?
14. Compare features of 3G, 3.5G, and 4G.
15. Describe the features of Advanced LTE and WiMax 802.16 m.