DIGITAL COMMUNICATION SYSTEMS DESIGN

Digital Communication Systems is an essential resource for students in electronics, communication, computer science, and information technology. It adopts a problem-based, outcome-focused approach to equip students with both fundamental and advanced problem-solving skills. The book integrates theory, application, and innovation, fostering a creative and practical learning experience. It covers a wide array of topics, from the basics of signal classification and modulation techniques to advanced subjects such as error control coding, channel equalization, and optimum communication system design. Students will explore key concepts like baseband and passband modulation, synchronization, and noise analysis. The book emphasizes real-world problem-solving through practical exercises, open-ended challenges, and innovative design strategies. In line with the shift toward outcome-based learning, it helps students achieve clear, defined objectives under expert guidance. Whether learning foundational principles or tackling complex system designs, this book prepares students to master digital communication systems with precision and forward-thinking innovation.

OTHMAN OMRAN KHALIFA holds a Bachelor's degree in Electrical and Electronics Engineering from Garyounis University, Libya, obtained in 1986. He earned his Master's degree in 1996 and PhD in 2000 from Newcastle University, UK. With over eight years of industrial experience, he is now a Professor in the Department of Electrical and Computer Engineering at the International Islamic University Malaysia (IIUM). From 2005 to 2014, Prof. Khalifa served as the Head of the Department, significantly contributing to its academic and research development. He is a Chartered Engineer (CEng, UK), a Senior IEEE Member, and a member of the Institution of Engineering and Technology (IET, UK). Prof. Khalifa has supervised over 80 graduate students and published more than 500 articles in journals, conferences, and books. He has authored 14 books and earned numerous awards, including the Highest Citation Award in 2013, the TOKOH Academic "Best Academician" Award in 2019, and the Murabbi "Best Teacher" Award in 2020. His work has been recognized internationally, including the Publication Award in 2021 and the National Best Book in Science and Technology Award in 2022.

ISBN 978-967-491-434-9
9 789674 914349

IIUM Press
(603) 6421 5014 / 5018
(603) 6421 6298
iiumbookshop@iium.edu.my
iiumbookshop.com
www.facebook.com/iiumpress
www.instagram.com/iium_press
https://twitter.com/PressIium

IIUM Press

DIGITAL COMMUNICATION SYSTEMS DESIGN

Othman Omran Khalifa

IIUM Press

DIGITAL COMMUNICATION SYSTEMS DESIGN

Othman Omran Khalifa

IIUM Press

DIGITAL COMMUNICATION SYSTEMS DESIGN

DIGITAL COMMUNICATION SYSTEMS DESIGN

Othman Omran Khalifa

IIUM
Press

Gombak • 2025

First Print, 2025

IIUM Press is a member of the Majlis Penerbitan Ilmiah Malaysia - MAPIM
(Malaysian Scholarly Publishing Council)
Persatuan Penerbit Buku Malaysia - MABOPA
(Malaysian Book Publishers Association)
Membership No. - 201905

Cataloguing-in-Publication Data

Perpustakaan Negara Malaysia

A catalogue record for this book is available from the National Library of Malaysia

eISBN 978-967-491-433-2

Published in Malaysia by
IIUM Press
International Islamic University Malaysia
P.O. Box 10, 50728 Kuala Lumpur

Printed in Malaysia by
Firdaus Press Sdn. Bhd.
No. 28, Jalan PBS 14/4
Taman Perindustrian Bukit Serdang
43300 Seri Kembangan, Selangor

CONTENTS

PREFACE

This century is the digital era, where digital information plays a key role in our daily lives. The digital communication industry is enormous and rapidly growing, roughly comparable in size to the computer industry. However, the tremendous growth of computing power in terms of speed, memory capacity, and the intervention of artificial intelligence, machine /deep learning algorithms, as well as the Internet of Things (IoT) introduced a variety of digital processing applications. Therefore, digital communication has become an important subject for students of electronics and communication, computer science, and information technology at undergraduate and postgraduate levels. Therefore, this book is prepared using problem-based and outcome-based education strategies. The problems incorporate most of the basic principles and proceed to implement more complex algorithms and techniques. Students are required to formulate a way to achieve a well-defined goal under the guidance of their instructor. This book follows a holistic approach and presents the theory and application of the design philosophy of the subject- digital communication systems. Developers should be able to solve problems with innovation, creativity, and active initiators of novel ideas. However, learning and teaching have changed from conventional education to outcome-based education.

This book is organised into ten chapters: Chapter One introduces the fundamental aspects of digital communications and design. The classification of signals and systems, as well as the spectral density, are also presented. Chapter Two describes the baseband modulation, formatting analogue information, sampling, quantisation, PCM, differential pulse modulation, and delta modulation. Chapter Three introduces the baseband transmission, transmission channels, matched filter, and intersymbol interference. Chapter Four introduces passband modulation, bandwidth efficiency, and coherent and noncoherent modulations. Chapter Five describes channel equalisation, channel models, adaptive implementations, and wireless channel equalisation in digital communication systems. Chapter Six explains synchronisation, including approach and assumptions, receiver design requirements, and parameter estimation for synchronisation. Chapter Seven describes error control coding-block coding, channel coding theorem, hamming codes, cyclic codes, and Reed–Solomon codes. Chapter Eight describes convolution codes, turbo codes, and low-density parity-check codes. Chapter Nine explains the noise in communication receivers. Finally, Chapter Ten demonstrates the design of optimum digital communication systems: bandwidth efficiency plan, transmitter design, and receiver design.

OTHMAN OMRAN KHALIFA

ACKNOWLEDGEMENTS

First and foremost, I would like to thank Allah Subhanahu Wata'ala for His greatness and for giving me the strength and courage to complete this book. While putting this book together, I realised how true this gift of writing is for me. You give me the power to believe in my passion and pursue my dreams. I could never have done this without the faith I have in You, the Almighty.

Secondly, I have made every effort to acknowledge all sources whenever I use a source of information or adapt any figures, and necessary permissions have been secured in most cases. Upon notification of any oversight, a proper acknowledgement will be made in future editions.

I would like to express my great appreciation to the IIUM Press staff for their valuable and constructive suggestions while revising this book. Their willingness to give their time so generously has been very much appreciated. Also, I would like to express my deep gratitude to my family for their patience and support.

Sincerely,

OTHMAN OMRAN KHALIFA

CHAPTER 1
INTRODUCTION

Learning Outcomes

By successfully completing this chapter, students will be able to:

1. Understand the building blocks of digital communication systems.
2. Describe the components of a digital transmission system, information source, transmitter, channel, and receiver.
3. Prepare mathematical background for communication signal analysis.
4. Understand and analyse the signal flow in a digital communication system.

1.1. A Review of the Communications Revolution

Digital communication refers to the use of electronic means to exchange information. The rise of digital technologies has greatly expanded the ways in which people can communicate, enabling constant and immediate communication with others through various channels such as email, messaging apps, and social media. This has significantly changed how people communicate and access information, allowing anyone to connect and access information from anywhere at any time. The proliferation of digital communication options has transformed the way we communicate and access information in an affordable way.

The digital communication revolution is transforming social dynamics and giving people greater power and a voice in global affairs. The media, telecommunications, and information technology industries are undergoing significant changes due to various interrelated developments, including the exponential growth of the internet and World Wide Web, digitisation, and the decreasing cost of computing power. These changes have led to the digital revolution and have sparked debates about the potential impacts of digital media and technology on various aspects of society, including literacy, attention span, social tolerance, and aggression. Digital communication, which involves the use of digital methods to communicate electronically, has become the dominant form of communication and has surpassed traditional forms of communication and media. Today, people have numerous ways to communicate using various multimedia tools like podcasts, newscasts, and YouTube. The digital communication revolution has also facilitated the instant connection of people in distant parts of the world and has shrunk the world through the flow of information. The interconnected nature of social networking has also had a major impact on communication. Digital communication systems are prevalent in the modern world and are essential to 21st-century society.

The rapid development of digital technologies has significantly changed the way people stay connected with their home cultures and diasporic networks. Each stage of technological development, particularly in the field of communication technology, has a broad impact on cultural relationships that span multiple disciplines, including social, economic, and political. It is often difficult to determine the sequence of these impacts or if they occur simultaneously. The quote by Andy Warhol, "the eternal [cultural] question: Does art imitate life, or does life imitate art?" highlights the complexity of the relationship between technology and culture and raises the question of whether technology precedes cultural changes or if cultural needs and desires drive the development of technology. The same can be said about the impact of technological development on politics and culture. It is difficult to determine if the transformation of communication technologies and techniques is driven by changes in the political landscape or if the technology itself prompts changes. The concept of migration has also evolved to encompass not only physical displacement but also the movement of ideas and imaginations. Digital communications and access to telecommunications and cable networks have had a profound impact on nearly every aspect of contemporary life. Society relies heavily on digital devices such as cell phones, computers, laptops, digital cameras, televisions, DVD players, gaming systems, and digital music players, which can all be used to communicate with each other seamlessly. From advanced wireless multimedia systems to simple home networking, communications and networking technologies are at the centre of a continuing revolution that has not only changed daily life but also raised important economic, public policy, and societal issues.

We also learned that to send any information through a communications system, it must be in the form of a signal (which is the name given to the function that conveys our information), and if our communication channel is free space, it means we are dealing with signals carried in the Electromagnetic Spectrum (EM). Finally, we learned that signals can be represented as a function of either time or frequency. Wireless channels have different vulnerabilities from those we saw in the host section of the course because of the transmission frequency. It is possible that a wireless network can be attacked like we saw in the networks section of the course, but to see how such a cyber-attack can be carried out on a wireless network or a wireless communication in general, you must first understand how information is carried through the wireless channel.

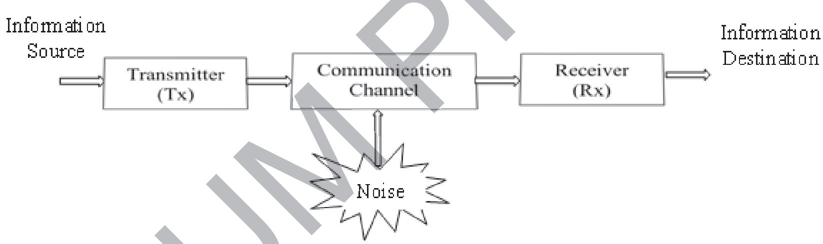

Figure 1.1 A general Communication System

To grasp the concepts behind contemporary communication systems, networks, and devices and to envision upcoming advancements, it can be helpful to look back at historical developments in the field of communications. Many individuals have made significant contributions to the numerous technological revolutions in communication, but due to limitations, we can only highlight a few of the most prominent contributors. In the 19th century, scientists such as Oersted, Faraday, Maxwell, and Hertz made crucial discoveries that laid the foundation for wireless communication, particularly that electric signals can be transmitted by altering electromagnetic fields to change the current in a distant device. The 20th century saw the work of researchers such as Nyquist and

Reeves, who contributed to signal sampling and pulse code modulation, and other figures such as North, Rice, Wiener, and Kolmogorov, who made contributions to optimal signal and noise processing. Shannon's exceptional contributions to the mathematical theory of communications ultimately led to the foundation for digital transmission and the current digital information era. Table 1.1 highlights some of the major events in the history of communications.

Table 1.1 Some of the major events in the history of communications

Year	Event
1820	Oersted demonstrated that electric currents generate magnetic fields.
1831	Faraday revealed that magnetic fields can create electric fields.
1844	Morse improved the method of sending telegraph messages over a wire.
1864	Maxwell formulated the principles of electromagnetism.
1866	The first transatlantic telegraph cable became operational.
1876	Bell invented the telephone.
1887	Hertz verified Maxwell's electromagnetic theory.
1896	Marconi demonstrated wireless telegraphy.
1907	The first transatlantic radio telegraphy service was implemented.
1915	First continental telephone service (in the US) deployed.
1918	Armstrong devised a superheterodyne radio receiver.
1920	First commercial AM radio broadcasting began.
1920s	Contributions on signal and noise by Nyquist, Hartley, and others.
1933	Armstrong demonstrated FM radio.
1936	The first commercial TV broadcasting by BBC in England resumed.
1937	Reeves proposed PCM.
1941	NTSC black and white TV standard was developed.
1945	Clarke proposed a geostationary satellite.
1948	Shannon published the mathematical theory of communications.

Table 1.1 *cont.*

Year	Event
1948	Brattain, Bardeen, and Shockley invented the transistor.
1940s	Contributions on optimal filtering by Kolmogorov, Wiener, and others.
1953	NTSC colour TV standard developed.
1953	The first transatlantic telephone cable was deployed.
1957	The first satellite (Sputnik I) was launched.
1960	The laser was developed.
1962	First dial-up (300-bps) modem developed.
1962	The first communication satellite (Telstar I) was launched.
1966	The first facsimile (fax) machine was developed.
1969	ARPANET (precursor to Internet) developed.
1970	Low-loss optic fibre was developed.
1971	The microprocessor was invented.
1976	Personal computers were developed.
1979	The first (analogue) cellular mobile telephone system (in Japan) deployed.
1989	GPS developed.
1992	The first digital cellular mobile telephone system (in Europe) was deployed.
1993	The HDTV standard was developed.
1997	The Wireless LAN was developed.
1990s	Ubiquitous use of the Internet accelerated.
1998	Mobile satellite hand-held phones.
2003	VoIP Internet Telephony.
2004	Facebook goes online, and the era of social networking begins.
2005	YouTube.com launches.
2006	Twitter launches.

Table 1.1 *cont.*

Year	Event
2011	Zoom Video Communication was founded.
2019	Fifth-generation (5G) networks were launched.
2022	Low–Earth orbit satellite internet is closer to reality. In early January 2022, Space X launched more than 1,900 Starlink satellites overall.
2023	AI technologies.
2024	Research into 6G technology began.

1.2. Fundamental Aspects of Digital Communications

Communication is vital and omnipresent in today's world, as the ability to communicate with anyone at any time and place has become a reality. The trend is towards multimedia- the combination of various forms of media such as voice, data, image, music, text, graphics, and video that are transmitted simultaneously. As digital technology advances and public demand for new applications grows, it is expected that digital communications will continue to expand and bring about new developments. The current trend is towards low-cost, high-speed, high-performance, secure, personalised, context-aware, location-sensitive and time-critical multimedia applications. Figure 1.2 shows the basic functional blocks of a typical communication system.

All information transmission systems, regardless of purpose or design, have three key components: the sender, the medium, and the receiver. The information source generates an output, which can be probabilistic as it does not need to be completely determined. A device such as a microphone then transforms the source output into an electrical signal that varies over time, called the message signal. The sender then modifies the message signal to be suitable for transmission through the medium, which could be a cable or other physical path. This process is called modulation, and it adjusts the characteristics of the message signal to match the characteristics of the channel. The sender also performs other functions like filtering and amplifying the signal. The medium is the physical link between the sender and the receiver, where the two are physically separated. No medium is perfect, so the message signal will be affected by various forms of degradation.

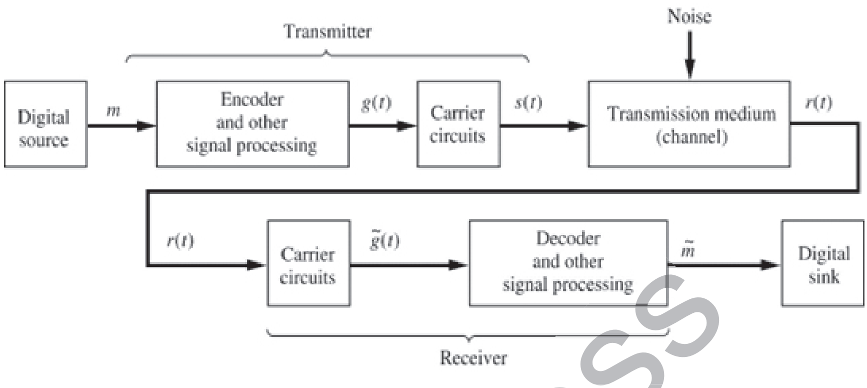

Figure 1.2 A general Digital Communication system

The quality of transmission can be affected by various factors such as attenuation, noise, distortion, and interference. One of the key goals in designing a communication system is to counteract these impairments. The main function of the receiver is to extract the original message signal from the received signal. The primary task is to demodulate the signal, as well as perform other functions such as amplification and filtering. The receiver is generally more complex than the transmitter because it must also minimise the impact of channel impairments. Finally, a device such as a loudspeaker then converts the receiver's output into a signal that can be understood by the intended recipient.

Figure 1.2 shows the basic functional elements of a digital communication system. The transmitter and receiver are each divided into three parts. The transmitter has a source encoder, a channel encoder, and a modulator, while the receiver has a demodulator, a channel decoder, and a source decoder. The received signal goes through the inverse of the operations that were performed at the transmitter and attempts to minimise the impact of channel impairments. The three functions of source coding, channel coding, and modulation, are designed to work together to meet system goals while also taking into account the overall constraints of the system.

The information being transmitted can be either digital, such as computer data, or analogue, such as voice. If the information is in analogue form, it must be converted to digital form at the transmitter and then converted back to analogue form at the receiver. The source encoder removes redundant information to make efficient use of the channel. Source coding, also known as data compression, helps to conserve bandwidth as it is a limited resource. The primary parameters associated with source coding are the efficiency of the coder and the complexity of the encoder and decoder. The channel encoder at the transmitter adds redundancy to the data in a controlled way. This redundancy is used by the channel decoder at the receiver to correct errors caused by the channel. The primary parameters associated with channel coding are the efficiency of the coder, error control capability, and the complexity of the encoder and decoder.

The modulator at the transmitter and the demodulator at the receiver act as the interface between the signal and the communication channel. The modulator converts a sequence of bits into a waveform, and the demodulator converts the received waveform back into a sequence of bits. The primary parameters of modulation are the number of bits in a sequence, the types of waveforms used, the duration of the waveforms, the power level and bandwidth used, as well as the complexity of demodulation. There are also other functional blocks in Figure 1.2 that are required in a practical digital communication system, such as synchronisation, equalisation, amplification, and filtering.

1.2.1. Why Digital?

The invention of the telegraph in the mid-nineteenth century was a precursor to digital communications. However, it is only in recent times that we can confidently say that digital is the dominant technology for the twenty-first century and beyond, as the first generation of cellular phones in the late seventies was the last major analogue communication invention. Over the past three decades, communication networks, systems, and devices have all transitioned to digital.

Examples of this trend include wireless networks, the internet, MP3 players, smartphones, HDTV, GPS, and satellite TV and radio. Digital communication technology will continue to drive the development of intelligent infrastructures and advanced end-user devices, providing a wide range of applications in areas such as entertainment, education, information, and business. Digital communications will continue to impact nearly all aspects of our daily lives.

A basic definition of digital communications is the transmission of a message using binary digits (bits) or symbols from a finite alphabet during a finite time interval (bit or symbol duration). A bit or symbol occurring in each interval is mapped onto a continuous-time waveform that is then sent across the channel. Over any finite interval, the continuous-time waveform at the channel output belongs to a finite set of possible waveforms. This is different from analogue communications, where the output can assume any possible waveform. Digital communications bring many benefits but also have some drawbacks.

1.2.2. Advantages of Digital

Advantages of digital communications include design efficiency, versatility of hardware, new and improved services, and quality control. Digital is more efficient than analogue in terms of exchanging power for bandwidth, which are valuable communications resources. Digital circuits are less sensitive to physical effects and offer greater dynamic range, which allows for more design flexibility. Additionally, digital communications enable a wide range of internet services and make it easy to integrate different services into the same transmission scheme. Finally, the distortion level of a digital signal can be initially set and then kept fixed at every step of the communication path. This allows for greater control over the quality of the signal.

Design efficiency: Digital is inherently more efficient than analogue in exchanging power for bandwidth, the two premium resources in communications. Since an essentially unlimited range of signal conditioning and processing options are available to the designer, effective trade-offs among power, bandwidth, performance, and complexity can be more readily accommodated. For any required performance, there is a three-way trade-off between power, bandwidth, and complexity (i.e., an increase in one means the other two will be reduced).

Versatile hardware: The capabilities of digital integrated circuits continue to improve rapidly, with processing power doubling approximately every 18 months to 2 years. This allows for the implementation of improved designs or changes to requirements with ease. Digital circuits are also less affected by physical conditions such as vibration, component ageing, and temperature fluctuations, and they offer a wider range of signal values. The processing cost has become less expensive than bandwidth and power, enabling greater flexibility in communication system design. The widespread availability of internet services such as web browsing, email, texting, e-commerce, streaming, and interactive multimedia services have become feasible and increasingly necessary in today's society. Additionally, it is now easier to integrate different types of services into the same transmission scheme or to enhance services by transmitting additional information, such as playing music or receiving phone calls with additional details.

Control of quality: A desired distortion level can be initially set and then kept nearly fixed at that value at every step (link) of a digital communication path. This reconstruction of the digital signal is done by appropriately spaced regenerative repeaters, which do not allow accumulation of noise and interference. On the other hand, once the analogue signal is distorted, the distortion cannot be removed, and a repeater in an analogue system (i.e., an amplifier) regenerates the distortion together with the signal. In an analogue system, the noises add, whereas in a digital system, the bit error rates add. In other words, with many regenerative repeaters along the path, the impact in an analogue system is a reduction of many decibels (dBs) in the signal-to-noise ratio (SNR), while the effect in a digital system is a reduction of only a few dBs in the SNR.

Improved security: Digital encryption, unlike analogue encryption, can make the transmitted information virtually impossible to decipher. This applies especially to sensitive data, such as electronic banking and medical information transfer. Secure communications can be achieved using complex cryptographic systems.

Flexibility, compatibility, and switching: By combining various digital signals from various sources and digitised analogue signals, it becomes easier and more efficient to manage streams of different sizes and speeds. It is also much easier and cost-effective to store, reproduce, and access information in electronic databases and interface with computers. The use of digital techniques in communication allows the production of components that can easily connect and interface with components produced by other manufacturers. Additionally, digital transmission allows for dynamic switching and routing of various types of messages, resulting in more diverse network connectivity options such as unicast, multicast, narrowcast, and broadcast.

1.2.3. Disadvantages of Digital

Digital communication systems have a high level of signal processing needs, with the three primary functions of source coding, channel coding, and modulation all requiring a variety of sub-functions, especially in the receiver. This causes high computational load and complexity. However, this is no longer a significant disadvantage thanks to the significant advancements in digital signal processing technologies in recent decades.

Additional bandwidth: Digital communication systems generally require more bandwidth than analogue systems unless digital signal compression (source coding) and *M*-ary (vis-a`-vis binary) signalling techniques are heavily employed. Due to major advances in compression techniques and bandwidth-efficient modulation schemes, the bit rate requirement, and the corresponding bandwidth requirement can be considerably reduced by a couple of orders of magnitude. As such, additional bandwidth is no longer a critical issue.

Synchronisation: Digital communication systems always require a significant share of resources allocated to synchronisation, including carrier phase and frequency recovery, timing (bit or symbol) recovery, and frame and network synchronisation. This inherent drawback of digital transmission cannot be circumvented. However, synchronisation in a digital communication system can be accomplished to the extent required, but at the expense of a high degree of complexity.

Non-graceful performance degradation: Digital communication systems yield non-graceful performance degradation when the SNR drops below a certain threshold. A modest reduction in SNR can give rise to a considerable increase in bit error rate (BER), thus significantly degrading performance.

1.3. Communications Modalities

The main sources of information can be broadly grouped into text, audio, and visual. The combination of these different types of information, known as multimedia, includes voice, data, image, music, text, graphics, and video. Each of these modalities has distinct characteristics and transmission requirements. Audio and visual signals are typically produced and perceived in an analogue form, so digital transmission of these signals requires analoge-to-digital and digital-to-analogue conversions. After converting the analogue sources to digital, they are compressed at a high ratio by exploiting redundancy and assigning the shortest binary codes to the most likely outcomes. There are two main types of compression methods:

1. Lossless is used for text and sensitive data, in which the original data can be exactly reconstructed. On the other hand, lossy is used for audio and visual signals, in which there is a permanent loss of information, but it allows for a higher compression ratio than lossless.
2. Lossy compression is used when the degradation in performance is either unnoticeable or acceptable to the end user. However, Lossy compression is capable of achieving a compression ratio higher than that attainable with lossless compression. Lossy compression is only employed when degradation in performance to the end user is either unnoticeable or noticeable but acceptable. In a discrete memoryless source (DMS), the output symbols are statistically independent, and the goal is to find a source code that gives the minimum average number of bits per symbol. Shannon's source coding theorem states that for a discrete memoryless source, the average codeword length cannot be less than its source entropy, which is the average information content per symbol, providing a bound for the best lossless data compression that can be achieved.

1.3.1. Digital Versus Analogue Performance Criteria

A principal difference between analogue and digital communication systems is how we evaluate their performance. Analogue systems draw their waveforms from a continuum, which forms an infinite set – that is, a receiver must deal with an infinite number of possible waveshapes. The figure of merit for the performance of analogue communication systems is a fidelity criterion, such as signal-to-noise ratio, per cent distortion, or expected mean-square error between the transmitted and received waveforms. By contrast, a digital communication system transmits signals that represent digits. These digits form a finite set or alphabet, and the set is known a priori to the receiver. A figure of merit for digital communication systems is the probability of incorrectly detecting a digit or the probability of error (PE).

1.4. Digital Communication Design Aspects

In a communication system, whether analogue or digital, two primary resources are used: transmitted power and channel bandwidth. Transmitted power is the average power of the signal being transmitted, while the channel bandwidth is the range of frequencies allocated for the transmission of the input signal. Depending on the specific communication channel, one of these resources may be more valuable than the other. For example, the channel bandwidth in telephone systems is limited, while the transmitted power in optical fibre links and satellite channels is limited. These two resources have a significant impact on different aspects of the communication system. There are many digital communication system design goals, but they are not all equally important. Some are essential, while others are desirable. Some goals are also more difficult to achieve than others because they are complex and may require additional resources to implement. Table 1.2 provides a list of digital communication design objectives. It is virtually impossible to achieve all digital communication design objectives simultaneously because they are all inherently interrelated, and some are clearly in conflict with other design imperatives, so difficult trade-offs must be made. For instance, high-speed transmission conflicts with low channel bandwidth, and low bit error rate conflicts with low transmit power.

Table 1.2 Digital communication design objectives and constraints

Design objectives	Design constraints
• Maximise transmission rate (bps) • Minimise bit error rate • Minimise signal bandwidth (Hz) • Minimise transmit power (W) • Maximise system throughput • Minimise overhead and signalling bits • Minimise noise and interference (W) • Minimise overall delay (s) • Minimise jitter (s) • Maximise system security • Maximise system flexibility • Maximise system capacity (bps) • Minimise computational load • Minimise system complexity • Maximise system utilisation • Maximise system reliability • Minimise system cost ($) • Minimise access/usage fee ($)	• The Shannon capacity theorem (and the Shannon limit) • The Nyquist theoretical minimum bandwidth requirement • Source entropy for lossless compression • Subjective perception for lossy compression • Government regulations (e.g., frequency allocations and coordination) • Technological limitations (e.g., state-of-the-art components) • Laws of nature (e.g., multipath fading, ionospheric propagation) • De jure and de facto standards (e.g., IEEE, ISO, Bluetooth) • User device specifications (e.g., aesthetics, size, weight, cost) • User interface requirements (e.g., user-friendly features) • Mass, power and real estate envelopes (e.g., satellite buses) • Networking requirements (e.g., mobile service coverage) • Radiation restrictions (e.g., acceptable health hazard in mobile devices) • Service and traffic differentiation (e.g., user and application priority) • Maintainability (e.g., ease of testing, monitoring and control) • Upgrade requirements (e.g., forward and backward compatibility) • Application requirements (e.g., traffic patterns and characteristics) • Market considerations (e.g., risks, economies of scale, affordability)

Designing digital communication systems and networks poses many challenges, as it requires balancing multiple competing objectives and constraints. This is a complex, multidimensional, non-linear problem that requires making trade-offs between different requirements. Some constraints, such as those dictated by communication theory or government regulations, are non-negotiable, while others, such as user preferences, are desirable but not essential. This process can be further complicated by the presence of numerous system variables and parameters that are difficult to quantify and take into account in the design process. Despite these challenges, it is important to strive to meet as many objectives as possible while taking all constraints into account. Table 2.2 also provides a list of digital communication design constraints.

1.5. Classification of Signals

Representation and processing of a signal highly depend on the type of signal being considered. Signals can be broadly classified in various ways.

1.5.1. Continuous-Value and Discrete-Value Signals

A continuous-value signal is one that may have any value within a continuum of allowed values; the continuum on the vertical axis can be finite or infinite. An analogue speech transmitted over a twisted-pair telephone line can be categorised as a continuous-value signal, as the signal level over time can continuously range from a quiet whisper to a deafening scream.

A discrete-value signal can only have values taken from a discrete set consisting of a finite number of values. A discrete-value signal may be derived from a continuous-value signal when the signal value is quantised (rounded). Figure 1.3 shows continuous-value and discrete-value signals.

1.5.2. Continuous-Time and Discrete-Time Signals

A signal is tagged continuous-time if it is defined for all time t, a real number. Continuous-time signals arise naturally when a physical signal, such as a light wave, is converted into an electrical signal by a transducer, such as a photoelectric cell. A continuous-time signal can have zero value at certain instants of time or for some intervals of time. A signal is considered discrete-time if it is defined only at discrete instants of time *n*. In other words, the independent variable on the horizontal axis has discrete values only (i.e., it takes its value in the set of integers). It should be noted that it does not mean a discrete-time signal has zero value at non discrete (non-integer) instants of time. It simply implies we do not have (or probably do not care to have) the values at non-integer instants of time. A discrete-time signal $g(n)$ is often derived from a continuous-time signal $g(t)$ by the sampling process. Figure 1.3 shows continuous-time and discrete-time signals.

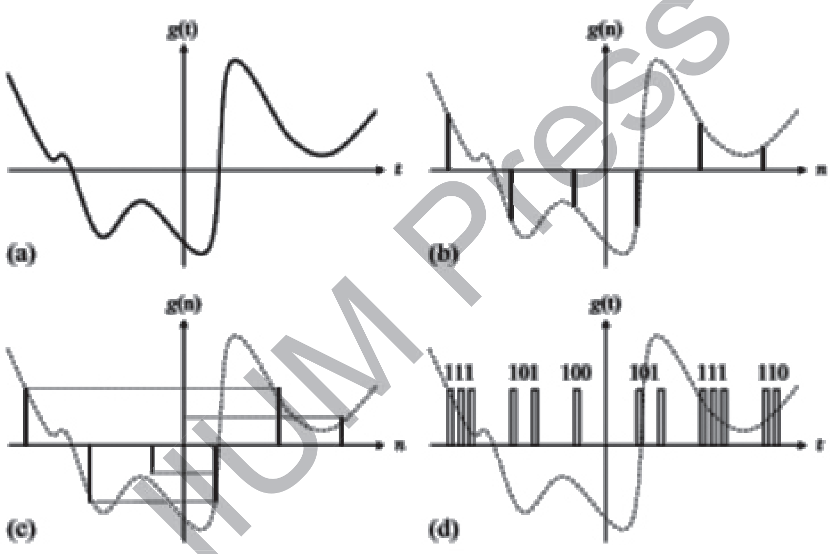

Figure 1.3 Continuous/discrete-value, continuous/discrete-time signals: (a) continuous-value, continuous-time signal; (b) continuous-value, discrete-time signal; (c) discrete-value, discrete-time signal; and (d) discrete-value, continuous-time signal

1.5.3. Analogue and Digital Signals

The terms analogue and digital describe the nature of the signal amplitude on the vertical axis, as analogue and digital signals are both continuous-time signals defined for all time *t*. For an analogue signal, the dependent