Analog and Digital Communication

Visualize and analyze the communication

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Dedicated to

My beloved wife:
Sarmila
and
My daughters ***Sinjini*** *and* ***Rishika***

About the Author

Rajarshi Mahapatra received a Ph.D. in Electronics and Electrical Communication Engineering from the Indian Institute of Technology Kharagpur, India, and B.Tech. and M. Tech. degree in Optics and Optoelectronics from University of Calcutta. In his postdoctoral research in CEA-LETI, Grenoble, France, he was engaged the FP7 Call4 BeFEMTO and Greentouch project. He is an Associate Professor with the Department of Electronics and Communication Engineering, Dr. SPM IIIT Naya Raipur. He also served as the Dean (Academics) of IIITNR. Earlier, he worked for Collins Aerospace, Hyderabad, on software-defined radio and electronic warfare.

Dr. Rajarshi Mahapatra has worked extensively in the domain of physical layer design and analysis of a wireless communication system. His team designed and developed software-defined radio and direction-finding systems for EW applications in Collins Aerospace. industry. He has about 18 years of teaching, research, and industry experience. He has guided Ph.D. scholars in the area of wireless communication. He has published several research papers in various refereed Journals and IEEE Journals. He regularly reviews premier IEEE Transactions and other peer-reviewed Journals and IEEE conferences. He has been organizing many workshops on 5G in recent years. He has also developed several high-valued research labs, including the 5G test bed. He has completed and undertaken high-value sponsored projects in the field of communication systems.

He has been awarded a National scholarship, an MHRD scholarship for research, and an EU-FP7 fellowship for a European project. He is a senior member of IEEE and a member of the Communication Society. He has published over 70 peer-reviewed papers in several international journals and conferences. His research interests include 5G and beyond communication, Machine Learning for communication, molecular communication, intelligent reflecting surfaces, and optical access networks.

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Preface

Analog and Digital Communication is the foundational course for students pursuing a Bachelor of Technology degree, particularly those pursuing a degree in electronics and communication engineering. In addition, it serves as a foundational course for students interested in the **Information and Communication Technology (ICT)** domain. Many books can be found on this topic, and many of them are regarded as classic literature in this field.

On the other hand, I have observed that students need to feel more comfortable with these great works during my many years of teaching these subjects. Even though these books are of high quality, the representation or discussion of a specific topic is somewhat lengthy (which may be necessary to understand the subject matter better). For self-evident reasons, the books concentrate mainly on mathematical analysis. Yet, they do not provide supporting diagrams, which can significantly assist students who are just beginning their studies.

This book aims to offer students first-hand information about the topic and increase their interest in acquiring a more in-depth understanding of the subject from classic books in this field. Throughout my years of teaching this subject, I have observed that students find it challenging to visualize communication systems conceptually. Consequently, students lack enthusiasm for this field. Therefore, the reasons in this book are substantiated by including relevant figures or diagrams. This will enhance students' ability to understand the content more effectively through visualization. Some books are designed to be easily understood without any explanation, while others contain many mathematics and extensive explanations. The purpose of this book is to attempt to bridge that gap.

A distinctive feature of this book is the extensive use of diagrams to aid in conceptualizing the topics covered. This chapters of this book contain numerous solved problems based on GATE, IES, and other competitive examinations. Each chapter also contains a sample of Python code.

This is an essential book of communication that discusses the fundamentals of analog and digital communication. It contains twelve chapters altogether to visualize the present-day communication system. The material in these chapters is organized as follows:

Chapter 1: Introduction to Communication – The first chapter presents a detailed overview of the history of communication systems. It describes the condition for distortion-less transmission over communication channels and the need for modulation.

Chapter 2: Mathematical Basics – This chapter explains everything the reader needs to understand communication. It presents the signals, system, and basic mathematical operations on them, which are required to realize communication systems. Fourier series and Fourier transform, which are the basic building blocks to analyze the communication process are also discussed here. This chapter also covers the basic principle of probability theory and its applications to random variables and processes.

Chapter 3: Communication Channel – This chapter describes the different physical mediums used for communication, such as copper, wireless, and optical fiber. The properties of different communication channels, including wireless and optical channels are also discussed.

Chapter 4: Analog Modulation Techniques – This chapter offers an in-depth discussion of different analog modulation techniques. It allows the reader to learn fundamental concepts of analog modulation techniques. Various forms of **Amplitude Modulation (AM)** techniques, such as **double sideband-suppressed carrier (DSB-SC)**, conventional AM, **single sideband (SSB)**, **vestigial sideband (VSB)**, along with **frequency modulation (FM)**, and **phase modulation (PM)** techniques, are generated through the modulation of the amplitude, frequency, and phase of a carrier signal following the message signal. In addition to the modulation strategies, demodulation techniques are also discussed here. Apart from the standard way of transmitting messages using a continuous carrier signal, an alternate approach known as pulse modulation is employed to transmit the message signal.

Chapter 5: Sampling, Quantization, and Line Coding – This chapter provides a closer look at the analog-to-digital conversion, explicitly focusing on the mechanism involving the sampling and quantization processes. The quantized digital bits of the message are now represented by various line coding schemes, which are discussed here. Furthermore, the chapter also explores other strategies, such as PN sequence generation, scrambling mechanism, and pulse-shaping technique.

Chapter 6: Digital Modulation Techniques – This chapter discusses the various techniques employed in digital systems for quantization and encoding, including **pulse-code modulation (PCM)**, **differential PCM (DPCM)**, **adaptive DPCM (ADPCM)**, **delta modulation (DM)**, and **adaptive DM (ADM)**. The chapter studies various digital modulation techniques, including **amplitude shift keying (ASK)**, **phase shift keying (PSK)**, **frequency shift keying (FSK)**, and **quadrature amplitude modulation (QAM)**. This chapter also provides an overview of the various multiplexing techniques: **time-division multiplexing (TDM)** and **frequency-division multiplexing (FDM)**.

Chapter 7: Signal Detection in Presence of Noise – This chapter examines the influence of noise on detecting the message signal from the received noisy signal, employing various analog and digital modulation schemes. This chapter calculates the error probability of a particular digital modulation scheme by designing an optimal filter and utilizing the associated constellation diagram. This chapter also presents an eye diagram to mitigate **intersymbol interference (ISI)**.

Chapter 8: Information Theory – This chapter discusses the information rate of the channel and the possibility of error-free transmission over the channel. The source coding techniques are also discussed here. Shannon's capacity theorem of a channel is the main topic in this chapter.

Chapter 9: Performance of Communication System – This chapter explores the performance of an end-to-end digital communication system. Error-free transmission or transmission with considerable error is one of the main performance criteria of the communication system that must be met. Apart from the **bit error rate (BER)**, the performance of end-to-end communication is measured with other factors, including capacity, coverage, outages, and so on. These criteria depend on several transmission and channel parameters such as the SNR, path loss, fading distributions, traffic conditions, service requirements, etc. In this chapter, we will have a detailed discussion of the many criteria and parameters, their interdependency, and how they affect one another.

Chapter 10: Channel Coding – This chapter deals with error-control coding, utilized inside digital communication systems to detect and correct bit errors. Several channel coding techniques, such as Linear block, Cyclic, Convolution, Viterbi decoder, BCH, and Turbo codes, are discussed here.

Chapter 11: Wireless Communication – This chapter presents various technologies used in wireless communication to improve the performance of wireless communication systems. Wireless communication has been developed from **first-generation (1G)** analog systems to **fifth-generation (5G)** digital systems to satisfy user requirements. Over the years, wireless communication has changed its requirements, characteristics, and services.

Chapter 12: Optical Communication – This chapter deals with optical communication. It provides an overview of the components of optical communications. The basic standards used in optical communication are also discussed.

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Chapter 1
Introduction to Communication

Communication is the transfer of information through a message signal. The goal is to reproduce the received message sent from the transmitter as accurately as possible. The message will be conveyed, or the information will be transmitted in the form of an electrical signal, thus known as an **electrical communication system**, which enables instantaneous interaction with a user located at a considerable distance. For example, we can communicate via voice with a person, download a file from a web page with the click of a mouse, watch a movie from YouTube, or send a message to a friend; all may be located anywhere on the globe. This illustrates the importance of communication systems in this information age.

This chapter introduces communication and its evolution. It describes the condition for distortion-less transmission over communication channels and the need for modulation. Later, it discusses the basic framework of a communication system with an example of the latest smartphone.

Structure

In this chapter, we will cover the following topics:

- Electrical or electronic communication
- Evolution of communication describes the evolution of wired, wireless, and optical communication.

- Basic communication presents the distortion-less transmission, need for modulation, and types of modulation.
- Communication receiver describes the basic requirements and architecture of the radio receiver.
- Basic framework of communication system briefs the building blocks used for communication.

Objectives

The main objectives of this chapter are to develop a basic understanding of communication systems, commencing with an exploration of the evolutionary progression of various communication systems, including wired, wireless, and optical systems. The reader is expected to gain an understanding of the method by which signals are transmitted through various systems, as well as the concept of distortion-free transmission. This observation further emphasizes the need for modulation in communication systems. Readers also need to examine the fundamental characteristics of receivers and explore various receiver structures. In conclusion, it is essential to explore the fundamental components of a communication system.

1.1 Electrical or electronic communication

Communication was initiated to send voice signals from one place to a distant location. The voice signal is analog and can be described as a voltage signal. This voltage signal is nothing but an electrical signal. In the initial days, communication occurred through the analog domain. This analog communication transmitted the electrical signal over the communication channel. The signal was received at the destination through simple electrical components like tune circuits, filters, amplifiers, multipliers, and so on. The processing, analyzing, transmitting, and receiving of the entire communication system is considered the voice signal as an electrical signal, and the devices used in communication are also simple in nature. In this context, the communication can be named as **electrical communication**.

After the advancement of digital signal processing, the entire communication system has slowly been incorporated into the electronics domain. All complex processing, controls, monitoring, and others are done at the baseband level. The voice signal is first converted into the baseband domain, the digital domain. All kinds of signal processing algorithms are used to improve the quality of communication, and finally, it is converted back to the analog domain. Humans can produce and understand the voice signal in analog form. However, present-day communication systems not only transmit voice signals, they transmit digital data as well. This digital data is generated by the devices and used by the device only. Digital electrical signals contribute an important but small part of the process.

The tasks involved in digital communication are so complex that all tasks are divided into different layers: physical (the lowest), data link, network, transport, session, presentation, and application (the upper). The physical layer consumes higher power as it represents the digital bits. This layer takes part in data transmission from one node to another. Most of the tasks of other layers are done at the baseband level through the complex switch, router, desktop, laptops, mobile, and so on. Electronic communication, which employs computers, e-mail, telephones, video calling, FAX machines, and so on, uses electronic means to send information or a message rather than a basic circuit. This sort of communication can be produced by exchanging data like images, graphics, sounds, photos, maps, software, and so on. Eventually, electrical communication is known as more of an electronic communication than electrical communication.

1.2 Evolution of communication

Communication enables us to pass information. It is exchanging words, signs, or information among users or devices. It is done either verbally or non-verbally. It existed in ancient times as smoke signals, flags, flashing mirrors, fires, and so on, as shown in *Figure 1.1*:

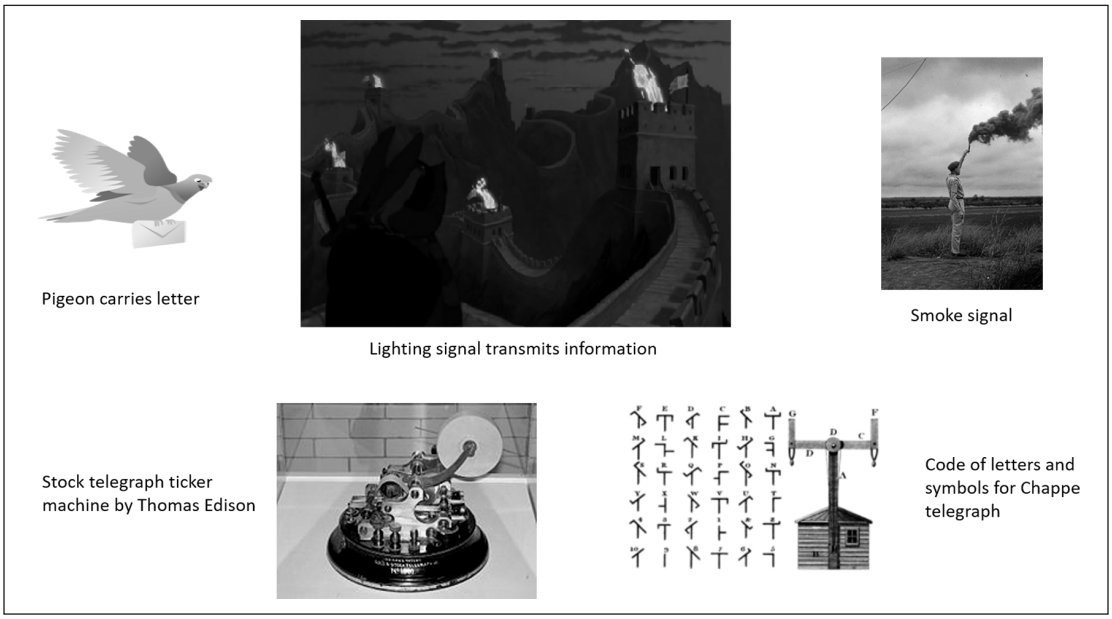

Figure 1.1: *Early communication mechanism*

Based on the communication channel, the telecommunication system is divided into three categories: wired, wireless, and optical. The division is mainly based on the transmission medium (as elaborated in *Chapter 3, Communication Channel*) and information-carrying signals. The transmission medium of wired and optical communication is bounded

by copper wires and optical fiber, respectively, and wireless communication uses the unbounded wireless medium.

1.2.1 Wired communication

Samuel Thomas, a German physician, anatomist, and inventor, conducted an early electrical telegraphy experiment in 1809. In contrast, *Francis Ronalds* used static electricity to create the first functional telegraph in 1816. By 1878, *Alexander Graham Bell* had developed the electric telephone in the United States. In 1880, *Bell* and his co-inventor *Charles Tainter* transmitted signals via modulated light beams projected by photophones.

In New Haven, Connecticut, the first commercial telephone exchange in North America was established in 1878. Point-to-point link is used for voice communication using analog signals. Telephones had to be interconnected by copper wires to establish a call between two people. Different types of copper wire are used in telephone and data communication. These are twisted pair cables, coaxial cables, and so on. However, the usage of copper wires is limited by their transmission capacity over a larger distance. Present day, its use is limited by the in-house data network and cable TV network.

A more practical solution was adopted rather than connecting every telephone. A manually controlled switchboard is used, which connects the phones. The switchboard works in a central telephone network mechanism. The **public switched telephone network** (**PSTN**) was first implemented using mechanical switchboards in the US in 1878. PSTN consists of phones, telephone exchanges, and interconnecting facilities, which provide phone service to the public.

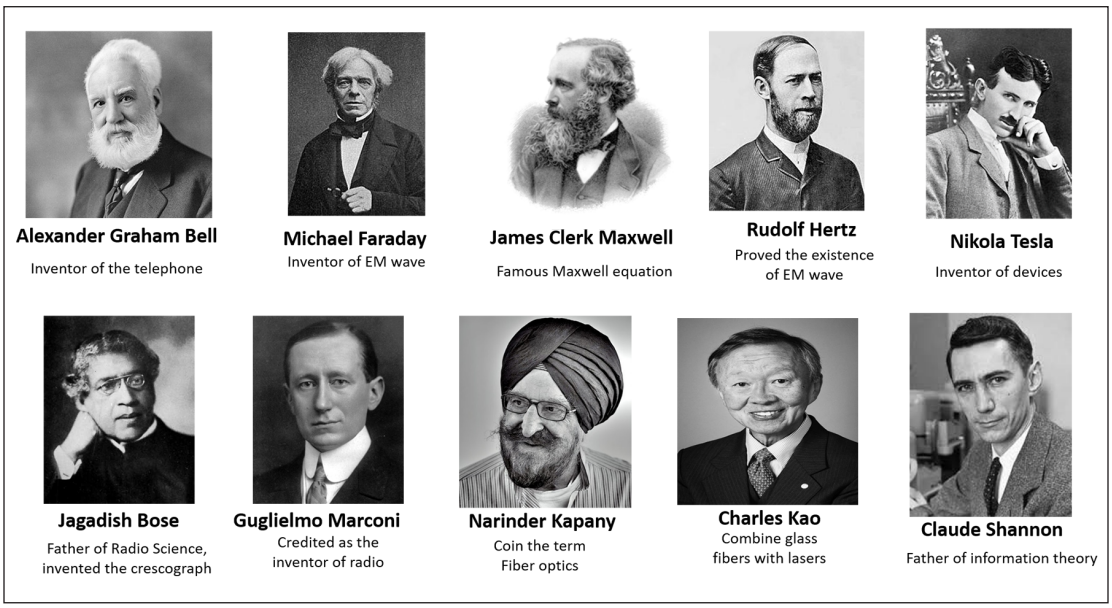

Figure 1.2: *A few famous pioneers in the field of communication*

Almon Strowger patented the Strowger switch, the first Automatic telephone exchange, in 1891. The first transcontinental telephone call occurred in 1915. In 1926, the first transatlantic telephone call was made from London to New York.

Although it started as analog communication, the telephone network slowly started digital with the introduction of digital equipment. Introducing digital telephony into the telephone network improves the quality, adds new features, and reduces the cost of conventional voice services. In addition to voice services, a digital network is a natural environment for data communication services.

With the advent of digital telephony, voice and signaling were transformed into a stream of bytes, sending numerous signals over a single channel. This has enhanced sound quality, decreased network costs, and boosted call capacity per cable. New possibilities in telephony have emerged due to digital technology and the introduction of the personal computer in the 1980s. Making phone calls and managing the calling process using a computer became possible. Computer networks began to *gain* capabilities akin to those of telecommunications networks; simply conveying voices of high quality was no longer enough.

Since the 1990s, improvements in digital telephony have increased its dependability and reduced its cost. **Voice over IP** (**VoIP**) technology has made it possible for voice and data to transmit over the same lines, which helps to cut expenses. ARPANET considered the forerunner of the Internet, was used to transmit speech samples between two computers. It is believed that the first two-way voice call via the ARPANET in December 1974 marked the beginning of VoIP. Dynamic technologies, like SIP trunking, which interact with VoIP to increase power and dependability, provide significant cost savings for businesses on their telecommunication expenses.

1.2.2 Wireless communication

Radio communication started after *Faraday* invented electromagnetic waves in the 1880s. Later, *Maxwell* derived four famous equations, named *Maxwell Equation*, in 1884. The oscillation unit of the e. m. wave is Hz after *Hertz* detected its oscillation and various properties around 1887. In the 1890s, *Nikola Tesla* tried to develop electrical power transmission without wires. This was an expansion of his wireless lighting work. *Prof. Jagadish Chandra Bose* first demonstrated **electromagnetic** (**EM**) waves as a communication medium. In 1894, *Bose* gave his first public demonstration to ring a bell and explode some gunpowder remotely using EM waves. In 1896, the *Daily Chronicle* of the U.K. reported that, *the inventor (J. C. Bose) has transmitted signals to a distance of nearly a mile, and herein lies the first and obvious and exceedingly valuable application of this new theoretical marvel.*

Guglielmo Marconi demonstrated the wireless telegraph in 1896 at the English telegraph office. However, *Marconi* successfully transmitted a radio signal using the Morse code letter ‘s’ across the Atlantic Ocean from Cornwall to Newfoundland at a distance of 3500 km in 1901. But it will take another 13 years to send the voice-over radio transmission.