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ISBN 978-3-031-53117-0 ISBN 978-3-031-53118-7 (eBook)
https://doi.org/10.1007/978-3-031-53118-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To my wife Monica*, who dedicated her time and energy to allow me to complete this work.*
To my mother Olga*, who never hesitates on my abilities and constantly asks about the progress of this work.*
To my children Isabella *and* Samuel*, which is why this work never has been left and continues abiding until its completion.*
To Professor Neil Guerrero González*, as evidence that this text can lead to the formation of great engineers.*

Preface

This book is based on practices carried out in the facilities of the Electricity and Electronics Laboratory of the National University of Colombia. The book is aimed at intermediate to postgraduate engineering students. The above implies prior knowledge in integral calculus, differential calculus, circuit theory, and statistics. However, a section is left to the reader to assess their knowledge, and if reinforcement is required, previous sections are provided in the mentioned areas. Each chapter is prepared in such a way that each item in the problem section is left to student for a formulation of a laboratory report, only dedicating themselves to filling in the concepts, results, and conclusions. This saves time for the student to properly prepare a report, enhancing the progress for a clear report (Ballesteros Horta and Hernández Maldonado, 2007). At the same time, as an example, it teaches the student to formulate a technical report (Imbermón Muñoz et al. 2011). Electrical element values, such as those for integrated circuits, capacitors, and resistances, are calculated as a result of device electronic design and presented in the appropriate tables to match design specifications, such as those for commercially available electronic components. Moreover, the simulation must be done with the real values obtained in the market. The implementation must be done on a PCB printed circuit, including measurement access points (Jacks if possible). Universal or prefabricated plates are not accepted. The breadboard will only be used for testing purposes. Though the simulation can be carried out in professional software like `Easy EDA` and the PCB in `Proteus ARES`, the design can be done with some other simulation and design program. Table 1 illustrates the test points arranged in the circuit and the measured variable.

The activities in this book suggest practical use in the laboratory, for proper performance. It is important to clarify that this book is specific for the Telecommunications area, which is why it also requires specialized equipment. Therefore, this book recommends the use of the following modes: (i) simulation using a computational tool suitable for this purpose and (ii) assembly, using a laboratory room with at least the following elements illustrated in Table 1 (Fig. 1).

Table 1 A model table for system testing of Fig. 1

Test point	Variable
TP1	
TP2	
TP3	
TP4	

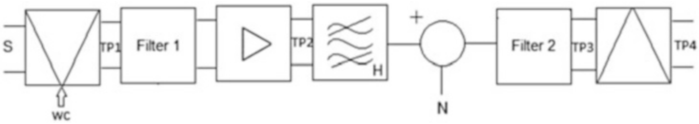

Fig. 1 Communication system with test points

Simulation Software This book illustrates an exploration of different software environments that were useful in their time, but that gave way to others that facilitate some processes. For this reason, some examples illustrate codes from previous and other recent software environments. The list of languages or applications is illustrated below:

- Easy Java Simulator (EJS) graphical interface can create laboratory test beds by algorithm routines. Concepts from the Deitel et al. (2012) book can be used as a starting point for learning about *Java* programming, concepts taken from the Deitel et al. (2012) book are taken as a basis.
- For electrical circuit analysis, the simulation is carried out in `Proteus ISIS` and the PCB in `Proteus ARES`. However, the design can be done with some other simulation and design program.
- For system modelling, we use MATLAB.

Signal Generator, used for arbitrary waveform generation and the carrier.
Measuring Instrument Two-channel oscilloscope and accessories (two BNC (coaxial) cables, two oscilloscope probes, plastic screwdriver, and a bifilar cable). It is possible to use some standard equipment that has a Baseband Transmission System and the required transmission components, such as coaxial, optical fiber or twisted pair wire. This book uses the PRO- 47 MAX EC-696 Analog Communications Trainer for most of its experiments.

Case Study Methodology

The *Case Study* is a detailed analysis of a specific subject, in this case a communication system. It links laboratory work with technical reports. This allows the student to generate a technical report (Cassani 2021; Garcia-Alvarez 2018). The following are some cases used as practical applications:

- Develop a communication system between instruments to control an irrigation system.
- Implement a lighting control system that at the same time allows data transfer through the light beam.

The Case Study Report

A general case study presents the following reports:

1. Technical report with the solution of telecommunications problems from a systemic point of view.
2. Quote of the equipment, based on the specifications given in the technical report. This document includes prices and must be raised from an established company, including a quote for labor and cost of engineer(s), in addition to equipment and space rentals.
3. Any proposal on the implementation of the network to be considered, in a real region. Additionally, this must be proposed under a company name proposed by the group or already established, if it exists.

In this book, the technical report will be specified, which contains the following sections: (i) Introduction, (ii) Problem Statement/Theoretical Framework, and (iii) Experimental Framework. Each case study is then linked to laboratory work. The steps to follow are illustrated below.

The `Introduction` must be written in a continuous manner, that is, without interruption or bullet points. This section consists of the following elements: (i) search for information through keywords; (ii) list of at least three works published in the last 5 years; these works must be published in databases such as IEEEXplore, SCOPUS, or ScienceDirect; (iii) the problem statement, which is made up of one of the following two aspects:

1. What the three published works have not been able to resolve.
2. An improvement or change of application of what was done by these three works. This allows you to prepare the proposal (objective of the work), which is the final part of the introduction.

The problem statement is distributed in the document as follows: (1) The problem explained in a general and summarized way, in the introduction section; (2) the problem and the proposal, expanded in the Background (Theoretical Framework) and the proposal (Proposed method). For Part 1. When the problem is written in the introduction, it must be written in a continuous manner, that is, without interruption or bullet points. This section must relate to the three works published in the last 5 years. As before, these works must be published in databases such as IEEEXplore, SCOPUS, or ScienceDirect. Thus, it is possible to prepare the proposal (objective of the work), which is the final part of the introduction.

For Part 2. The problem statement is made up of one of the following two aspects:

- What the three referenced works have not been able to resolve.
- An improvement or change of application of what was done by these three works.

As the problem has to do with communication systems, the following aspects will be considered in this work:

- The characteristics of the source: Bandwidth in Baseband; Operating frequency (modulation) in its most common applications: Analog/Digital, Random/Deterministic.
- The characteristics of the channel: Channel Bandwidth (if the modulation is analog) and Channel Capacity (if the modulation is digital). Modulation scheme to use. Problems due to the channel.
- Noise model: Gaussian/Weibull/Uniform, type of interference. How do these affect the modulation scheme?
- Expected issues: Signal dropout, SNR loss, low fidelity, transmission errors.

Up to this point, there are three sections: Introduction, Background, and Proposal. Next, the Experimental Framework is added. In Communications Systems, this section identifies three groups: (1) Signal Variation due to Noise. Evidenced by Signal Distortion, Aliasing, and statistical disparities. (2) Disparity in data. Evidenced by Inter-Symbol Interference, Bit Error Rate, and Lost Packet measurement. (3) The "Bottlenecks" in the Canal. Evidenced by the growth in bandwidth consumption and the limitations given by the BER versus Eb/N_0 ratio. With the above, a brief paragraph of each of these problems is described, and it is expanded in the case that corresponds to the case study, justifying their relationship.

Two sections remain: (iv) the *Results* section illustrates the values found through the Experimental Framework; (v) at the end, in the *Conclusions* section, among other questions, the following question should be answered: Does the proposed modulation scheme meet the conditions for the adequate transmission of a signal?

For the assessment, the following guidelines are recommended (Eide et al. 2023):

1. Presentation. Most text editing software comes with templates. Although it does not have to be in IEEE or APA format, it must meet the following conditions: (i) Summary. (ii) Introduction section, with the definition of the system to be implemented; (iii) Theoretical Framework, where they clearly define the technology to which they applied the communication system; (iv) Experimental Framework, where the variables to be measured, the software used, and the analysis methodology of the communication system are defined; (v) Results, where each figure and table of results obtained are explained; (vi) Conclusions, with what was obtained from the results; (vii) References.

2. Fluency about the definition. The introduction section should not be longer than half a page. You will be graded if you do not explain the system coherently.
3. Clarity in the Theoretical Framework. This is a complete explanation of the technology to which they applied the communication system. It must be explained by yourselves, so it's essential that the redaction be original. If a figure or diagram is used, it must also be explained, and the source from which it was extracted should be named.
4. Clarity in the experimental methodology. This section is a compilation of all the practices carried out during the semester, through the proposed system. This is why it is the most important section. It is necessary to declare all the variables associated with the system to be analyzed, including noise, attenuation, sensitivity, bandwidth, and so on. Additionally, the transmitter, channel, and receiver stages of the system where the variable is measured or analyzed, their generation method (which need not involve source codes), and the expected results of the analysis must be stated.
5. Results. A suitable presentation of the findings is included in this section. Since given data are frequently shown in tables and figures, the text should use connection terms like "Results of Table (...)" or "As it is shown in Fig. (...)" when referencing given data. Any occurrence of "As illustrated in the following. . ." will be graded. Deliver, in respective tables, the calculation and measurement procedures for the values of resistances, capacitances, amplifiers, and other elements, in such a way that they coincide with the design parameters. The simulation must be done with the real values obtained in the market. Measurement access points must be described and listed.
6. Conclusions. The more consistent the conclusions are with each result, the better.
7. References. Web links are not accepted. All references cited must be in the document.

Manizales, Colombia
December, 2023

Julio César García-Álvarez

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Acknowledgments

This work is the result of the experience obtained from the research and extension projects carried out in the research group *Applied Electromagnetic Propagation (PROPELA)* (Minciencias COL0127629) of the Universidad Nacional de Colombia Sede Manizales, between 2004 and 2023. This book is a product of the Laboratory of Applied Electromagnetic Propagation, officially created by the Faculty of Engineering and Architecture of Universidad Nacional de Colombia in December of 2023.

I wish to thank Professor Néstor Peña Traslaviña, who bring me the basic knowledge about signal theory and the guidelines about the topics for the first part of this book. In the postgraduate degree (master's-doctorate), I was a collaborator in the work of Professor Nestor Peña Traslaviña in electromagnetic compatibility (University of Los Andes), as well as Professor Hartmut Führ in algebra and wavelet techniques (RWTH Aachen University). These observations as an assistant gave me the initial push to the preparation of this book (2013). Thus, I greatly appreciate those named above for their contribution in time, space, and energy.

Contents

Acronyms

Although each acronym is defined a priori throughout each text, the main ones are listed below.

AMI	Alternate Mark Inversion
ASK	Amplitude-Shift Keying
FSK	Frequency-Shift Keying
PCM	Pulse Code Modulation
PSK	Phase-Shift Keying
PWM	Pulse Width Modulation
RZ	Return to Zero
TDM	Time-Division Multiplexing
WDM	Wavelength Division Multiplexing

List of Symbols

The symbols used in this book are listed together with the proper units of measurement, according to the International System of Units (SI).

Bit rate	R	bit per second (bps)
Electric capacitance	C	farad (F)
Electric current	I	ampere (A)
Electric potential, Electromagnetic force, Amplitude	V	volt (V)
Electric power	P	watt (W)
Power ratio	P	decibel (dB)
Pulse width	τ	second (s)
Time	t	second (s)

International Standards

IEC 61280-4-1:2009. Fibre-optic communication subsystem test procedures – Part 4–1: Installed cable plant – Multimode attenuation measurement.
IEC 80000-13:2008. Quantities and units Part 13: Information science and technology.
G.711:1990. Pulse code modulation (PCM) of voice frequencies

Part I
Single-Channel Communications

The study of single-channel communication systems is the subject of this part. One aspect of the study is an assessment of the efficiency constraints of the system. Research turns its attention to understanding how channel capacity affects information transmission. Finding the ideal conditions to maximize data transfer and reduce errors is the aim. This involves testing the data transmission rates generated by different modulation strategies. The considerations in electronic design will be demonstrated by the use of the experiment findings reported in this part. This section's experiment findings will be used to highlight how crucial it is to choose the best modulation method possible in order to achieve the best possible data transfer and error.

Chapter 1
Introduction to Communication Systems

1.1 A Brief History of Communications

In mankind's history there have always been big motivations for making technical advances possible:

- Economics: Ease the trade process between nations.
- Military.

Communication Systems rely on those advances as a way to ease these motivations. Throughout history, there are different communication mechanisms:

- Face to face
- Signals
- Written word (letters)
- Image/event description

In ancient times, the transmission of information often involved oral storytelling (Religion, Tradition) and passing messages through messengers. Other mechanisms include:

- Writing knowledge (Papyrus, Library of Alexandria)
- Printed editions (Guttenberg)
- The network: commercial routes, food, wear, services, slaves
- Storing services: accounting, logs

Communications are no exception, and its great progress has been made thanks to them. Remote communications were born to facilitate trade between different nations and empires.

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https://doi.org/10.1007/978-3-031-53118-7_1

Inadequate infrastructure and natural disasters frequently contributed to problems in the ancient communication networks, which resulted in the following problems:

- Delay in transmission time (days, months)
- Inaccurate carriers (routes, addresses, receivers)
- Information message distortion (oral)

Paper was discovered in China in 105 AD. In the fifteenth century Johann Gutenberg created the printing press: He favored rationalism, scientific research, and literature. In the seventeenth century, the first newspapers appeared with the objective of making current events available to the public. The word "postal service" comes from the Latin positus (which means post), since in the beginning they were postal posts located throughout the Roman Empire, and horse messengers carried correspondence from position to position. The speed and efficiency of this type of communication are better with the appearance of means of transportation such as: Railways, Automobiles, and Planes.

1.2 Electronic Communications

With the discovery of electricity in the eighteenth century, the world enters to a revolution in communications. From the studies of many scientists, compiled by James Clerk Maxwell in 1873 in his Treatise on Electricity and Magnetism, we began to contemplate the possibility of transmitting information by wireless media. The telegraph appeared in the nineteenth century and used the Code Morse International. In 1874, Thomas Alba Edison developed a method of quadruple coding that allows transmitting twice as much information. The great advance that the telegraph represented was improved widely with the development of the telephone, since it allows the transmission of the human voice in the form of electricity. Antonio Meucci was its inventor in 1871; however, he did not able to patent it due to economic difficulties. There has been constant innovation and progress in the field of telecommunications since Alexander Graham Bell received a patent for this invention in 1876, particularly with regard to the devices that change physical variables into electronic signals, such as:

- Telegraph $\Rightarrow$ Digital signals
- Telephone $\Rightarrow$ Voice, Data
- Radio $\Rightarrow$ Voice, Data
- Television $\Rightarrow$ Video, Data
- Internet (computer) $\Rightarrow$ Data

This revolution was possible with the use of physical transmission lines (cable pair, coaxial, fiber optic) or air (propagation) as a propagation medium. It is possible to emit or receive multiple signals that propagate through a medium, detecting all signals propagated through that medium, in addition to identifying them by parameters; the most used is frequency. It can also be identified by the content of the information (voice, data, images, among others).

The first radio broadcast in the USA happened in 1906. Television appeared at the beginning of the twentieth century and had its peak during the Second World War I:

1. Analog Television: It was broadcast over radio waves in the VHF and UHF bands.
2. Cable Television: Allows signals to be delivered to the home of each subscriber without the need for receivers and/or antennas. Additionally, it allows the return of signals (loop of feedback) without any additional infrastructure.
3. Satellite Television: It began with the development of the career space during the Cold War. Allows access to Television from remote and isolated areas.
4. IP Television (IPTV): Uses broadband connections over the IP protocol. Can be used in televisions, computers, and mobile phones.

1.3 Basic Elements of a Communication System

To understand the function performed by communications systems, it is important to know what type of variables are involved in the processing of information. The important thing for a communication system is to maintain, regardless of the process carried out, the greatest fidelity of a certain type of information that is to be sent from one place to another. For this, certain techniques are used that help visualize and process the information. In this chapter the theories necessary to determine these techniques are explained. Fourier's conjecture has a lot of truth: "Only" some concepts need to be conveniently developed: What is meant by a function, how to construct the integral of a function and establish the nature or convergence of the series of functions in general and trigonometric in particular (Stremler 1989; Tomasi 2003). It is the set of devices that constitute the link of information between the source and destination. Its primary objective is to transmit information from one point to another so that the message obtained from the receiver differs as much as possible from the message that was originally sent (Couch II 1997; Lathi 1998; Stark Henry B. Tuteur 1979; Carlson and Crilly 2009). The recovered message must be fully reconstructed and usable at your destination point. In general, communication systems are composed of a message, a transmitter, a means of transmission, and a receiver. Figure 1.1 illustrates a setup for the basic elements required for an adequate communication system:

Data and message. Message is the physical manifestation of the information that is wanted to communicate: (1) Series of symbols (2) Voice (3) Music (4) Images (5) Measurements of some physical variable

Transducer. Device capable of transforming or converting a certain type of input energy into a different type of energy to the exit: (1) Microphone: Acoustic

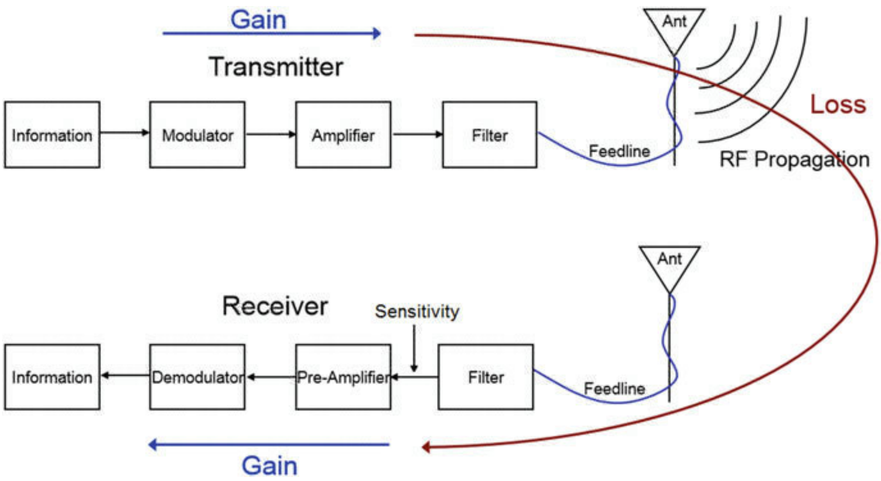

Fig. 1.1 Example: wireless link

energy to electrical energy (2) Thermocouple: Transformation of thermal energy into electrical energy (3) Speaker: Electrical Energy into Acoustic Energy

Signal. For a communications system to transmit appropriately, the message is required to adopt some of the following ways: (1) Electrical, (2) Electromagnetics, (3) Optics. Consequently, a transducer is required that converts the message into signal.

1.4 Aspects in the Design of Digital Communication Systems

The interference constitutes one of the most undesirable factors that modify the content of information of a transmitted signal (Haykin 2001; Roddy and Coolen 1995; Miller 1999):

Signal Distortion. Manifested by flaws in the transmission medium, such as cables or fiber optics.

Crosstalk. These are disturbances that the signal suffers due to the effect of signals outside the system. As an example, radio stations interfering with a walkie-talkie or Wi-Fi interfering with wireless devices making use of the same allocated transmission frequency.

Random Noise. The initial signal may be partially or totally corrupted by erratic and random processes. For instance, an increase in temperature has the potential to modify the flow of electric current by influencing the motion of charged particles within a conductor; this phenomenon is known as thermal noise.

1.5 Measurements in a Communication System

These measurements are made on the different elements of a communication system as follows:

- The *source of information*, **X**, can be measured through the *Entropy* $H(\mathbf{X})$, due to the statistical characteristics of the source (mean, variance, and spectral density).
- In the transmitter, which is composed of the modulator, the filter, and the amplifier, it can be measured by the *modulation index*, the *transmission bandwidth*, and the *transmission power*. The bandwidth contains the *frequency response* of the signal. This means that for certain frequencies within the bandwidth, the signal may or may not be transmitted properly. This frequency response is analogous to the frequency response of a filter. This means that there are frequencies where the message can be attenuated, called *cutoff frequencies*. Typically cutoff frequencies are found when the channel gain is 3 dB below the maximum channel gain.
- The channel can be monitored through *channel bandwidth* and *attenuation. Bandwidth* is the difference between the upper and lower frequencies where the channel allows transmission of a message. For the message, its bandwidth is the difference between the upper and lower frequencies that make up the signal that represents the message. Normally the message bandwidth is reduced to the higher frequency, called the fundamental frequency of the message. Thus, for effective transmission, the channel bandwidth must exceed the value of the fundamental frequency of the message. Otherwise, the message will be distorted.
- Measurements on the Receiver can be made using *Sensitivity* and *Channel Capacity*.
- The received message $\mathbf{X}'$, which is interpreted as an estimate of the source, is evaluated through the *Error Rate*.

1.6 Communication System Specifications

Assuming that you have been assigned a communication system, the first step is to determine the technical characteristics of the system. The design for a Communication System can be deployed by using the following features:

Modulation index. It defines the modulation scheme, given by:

- Amplitude
- Frequency
- Phase
- A combination of some of the above

Communication scheme:

- Continuous Wave Analog: Analog Baseband, Analog Carrier
- Pulsed Wave Analog: Analog Baseband, Pulsed Carrier

– Digital: Pulsed Baseband, Analog Carrier
– Line: Pulsed Baseband, Pulsed Carrier

Improvement Strategy. From easy to very complex:

– Increasing the carrier power
– Changing the modulation scheme
– Varying the modulation index
– Optimizing receiver sensitivity

1.7 Assessment

Exercise 1.1 Solve $3^{(x+1)} = 81$ for x.

Exercise 1.2 If in the equation $2000^2 - 1996^2 = 111ak^2$, where a and k are integers, what is the maximum value of $k - a$?

Exercise 1.3 In a school, the ratio between the number of boys and the number of girls is 2 : 3, and the ratio between the number of girls and the number of teachers is 8 : 1. What is the ratio between the total number of students and the number of teachers?

Exercise 1.4 An aircraft has a glide ratio of 12 : 1, meaning that the plane drops 1 meter in each 12 meter it travels horizontally. A building 45 m high lies directly in the glide path to the runway. If the airplane is 12 m above the building, how far from the building does the aircraft touch down on the runway?

Exercise 1.5 A perfect square is the square of an integer. How many positive integers x are there such that both x and $x + 99$ are perfect squares?

Exercise 1.6 In a soccer tournament each of the eight teams plays each of the other teams exactly once. Two points are credited for each game won, one point for each game tied, and zero points for each game lost. How many points must a team accumulate to ensure being in one of the first four places (that is, having more points than at least four of the other teams) in the tournament?

Exercise 1.7 Two trains cover the route between two cities traveling on parallel rails. The ratio between the speeds of the two trains is equal to the ratio between the time they face each other when one passes the other traveling in the same direction and the time they last facing each other when they cross each other traveling in opposite directions. What is the ratio between the speeds of the two trains?

Exercise 1.8 If x, y, z are real numbers such that $(x-3)^2+(y-4)^2+(z-5)^2 = 0$, what is the result of $x + y + z$?

Exercise 1.9 If a is greater than c by 50%, and b is greater than c by 25%, by what percentage is a greater than b?

Exercise 1.10 The Gerrinsp publishing house designates the price of its latest book titled "The Engineer in His Labyrinth" as follows:

$$C(n) = \begin{cases} 12n & 1 \leq n \leq 24 \\ 11n & 25 \leq n \leq 48 \\ 10n & n \geq 49 \end{cases}$$

where n is the number of books ordered, and $C(n)$ is the cost of n books. Noting that the cost of 25 books is less than 24 books, for how many values of n is it cheaper to buy more than n books than to buy exactly n books?

Exercise 1.11 The number of geese belonging to a certain group is increased such that the difference between the population in year $n+2$ and the population in year n is directly proportional to the population in year $n+1$. If the population in the years 1994, 1995, and 1997 was 39, 60, and 123, respectively, determine the population in 1996.

Exercise 1.12 Augusta, Beatriz, Carlos, David, and Esteban go shopping. Each one has a whole number of money bills to spend, and between them they have \$56. The absolute difference between the amounts that Augusta and Beatriz have is \$19. The absolute difference between the amounts that Beatriz and Carlos have is \$7, between Carlos and David it is \$5, between David and Esteban it is \$4, and between Esteban and Augusta it is \$11. How many money does Esteban have?

Exercise 1.13 Consider the functions f that satisfy the following equality:

$$f(x+4) + f(x-4) = f(x)$$

for every real number x. Each of these functions is periodic ($f(x+p) = f(x)$ for some whole number p), and there is a smallest common positive period p for all of them. Calculate the value of period p.

Exercise 1.14 A shot takes a golf ball to a circular green of radius 12 m. Assuming that all positions on the green are equally probable, what is the probability that the ball stops less than 1 meter from the hole? Assume that the hole is at least 1 meter from the edge of the green.

Exercise 1.15 Two cubic dice are fair in the sense that, when rolled, each of the six faces has the same probability of coming up as the top face. However, on one of the dice the number 4 has been replaced by the 3 and on the other the number 3 has been replaced by the 4. When these two dice are thrown, what is the probability that the sum obtained is odd?

Exercise 1.16 In the sixth, seventh, eighth, and ninth games of the basketball season, a certain player scored 23, 14, 11, and 20 points, respectively. Her points per game average are higher after nine games than it was after the first five games.

If her average after ten games is greater than 18 points, what is the fewest number of points she could have scored in the tenth game?

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Chapter 2
Signal Analysis in Digital Communications

2.1 The Baseband Signal

The signal that represents the message, when the signal is not modulated, is called *baseband*. Baseband means that the characteristics of the message are not altered at the time of transmission, that is, the signal is at the same frequency as its analog representation (Garcia-Alvarez et al. 2014). Examples include the following: An audio message is transmitted in baseband at a frequency range between 20 and 20 kHz; a video message is transmitted in baseband at the audio frequency of 5.25 MHz, the luminance frequency of 1.25 MHz, and the chromatic frequency of 4.83 MHz. Thus, it is intended to show the difficulties involved in sending a message without any processing, giving rise to the need for modulation of the message in its transmission.

2.1.1 Harmonic Signals

According to the Fourier transformation (Haykin 2001), any signal that describes the above characteristics, such as those used in communications, is described by sine-type functions (Garcia-Alvarez and Gomez 2014). Indeed, they are modulated into sine wave forms. A sinusoidal signal is described mathematically by the expression:

$$f_i(t) = A_i \sin(\omega_c t + \psi_i) \tag{2.1}$$

The quantities A_i, ω_c, and ψ are called the amplitude, frequency, and phase of the function, respectively, and you can describe this signal in two ways: One way is to describe its evolution in time (time domain model), and the equation is a mathematical representation of this evolution. The second way is to describe its

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https://doi.org/10.1007/978-3-031-53118-7_2

frequency content (frequency domain model). The function $f_i(t)$, in this case, has a single frequency ω_i.

Example 2.1 The Time Domain sinusoidal function is a commonly used basis for signal representation. The amplitude, frequency, and phase arguments, A_i, ω_i, and ϕ_i, respectively, indicate the function's evolution over time. As a result, this function is defined as

$$f_i(t) = A_i \sin(\omega_i t + \phi i)$$

2.2 Modulation Principle

Both multiplexing and modulation are methods for moving the spectral components of a baseband signal to a different frequency range (the latter is covered in part two of this book). The purpose of moving a signal into a different frequency bandwidth is to prevent interference, sometimes known as crosstalk, from occurring between signals. These benefits will be explored in later chapters. These methods can also be applied to effectively transfer information between locations. Modulation makes the information signal more compatible with the medium. Multiplexing allows more than one signal to be transmitted concurrently over a single medium. In the electrical sense, they are variations of voltage (V) and current (I) with respect to time. In the electromagnetic sense, they are variations of the electric field (**E**) and magnetic field (**H**) with respect to time. In the optical sense, they are variations in the mode of light propagation (polarization and wavelength).

The resulting signal from modulation is $s(t)$, representing the *passband* signal (*modulated*):

$$g(t) = \underbrace{A}_{Amplitude} \sin\left(\underbrace{\omega}_{Frequency} t + \underbrace{\theta}_{Phase}\right)$$

- $A \Rightarrow$ Amplitude variation
- $\omega \Rightarrow$ Frequency variation
- $\theta \Rightarrow$ Phase wave variation

In that way, the **information** given by the baseband signal is **carried** by the variation of parameters in the carrier wave.

Using phase velocity equation $V_p = x/t = \lambda\omega/(2\pi)$, carrier signal can be converted into electromagnetic representation, traveling a distance x :

$$g(x) = \underbrace{A}_{Amplitude} \sin\left(\underbrace{\frac{2\pi x}{\lambda}}_{Distance} + \underbrace{\theta}_{Phase}\right)$$

- $A \Rightarrow$ Amplitude variation
- $\lambda \Rightarrow$ Wavelength variation
- $\theta \Rightarrow$ Polarization wave variation

Let $s(t) = \cos \omega_s t$ the baseband (or original analog) signal and $f_c(t) = \cos \omega_c t$ the carrier wave, with $\omega_s \ll \omega_c$. A multiplier device generates the output signal $g(t)$:

$$\begin{aligned} g(t) = s(t) f_c(t) &= (\cos \omega_s t)(\cos \omega_c t) \\ &= \frac{1}{2}\left[\cos(\omega_s + \omega_c) t + \cos(\omega_s - \omega_c) t\right] \end{aligned} \tag{2.2}$$

The bandwidth is obtained from Eq. (2.5), using $f_c(t)$ as a periodic signal with only the fundamental frequency $\omega_0 = \omega_c$. The Fourier transform of generated signal of Eq. (2.2) $G(\omega) = F\{g(t)\}$ has bandwidth of $B = \frac{4\pi}{\tau}$

$$\tau = \frac{2\pi}{\omega_c}$$

Therefore, modulation is a technique used to transport information on a high frequency carrier signal, which is typically an electromagnetic wave, in order to make it suitable for transmission over a communication channel, allowing more transmission, information simultaneously, protecting it from possible interference or noise. The modulation process involves two signals: (i) the *modulator* signal and (ii) the *carrier* signal. The modulation procedure consists of using the carrier wave as a transport for the message, represented by the modulating signal (audio, video, data, etc.). These two signals result in the *modulated* signal. The idea of using a carrier signal is to increase the transmission power, in such a way that distortion phenomena, such as distance, propagation medium, and noise, do not significantly affect the fidelity of the message (Arenas. and Garcia-Alvarez 2005). The methodology for generating a carrier and modulating signal for a band-limited communication channel uses two types of signals: analog and digital.

2.3 Signal Representation

The Fourier transform is a linear mapping between time space and frequency space and vice versa.

$$f(t) \Leftrightarrow F(\omega)$$

The spectral density function of $f(t)$ $F(\omega)$ is obtained from the Fourier transform of the signal $f(t)$. The Fourier transform is a linear mapping between time space and frequency space and is defined as

$$f(t) \Leftrightarrow F(\omega)$$

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t} dt$$

The amplitude of the spectral components is proportional to $F(\omega)$, so $F(\omega)$ constitutes the frequency spectrum of $f(t)$. It is also called *spectral density function*. Unlike the Fourier series, the Fourier transform is applied to functions that are not necessarily periodic and generates a continuous spectrum in ω.

2.3.1 Hermitian

Hermite functions are also useful in mathematics, as they form an orthonormal basis (complete orthonormal set) for the Hilbert space $\mathcal{L}^2(\mathbb{R})$. For instance, Hermite functions are applied for elementary quantum mechanics to solve the quantum nonrelativistic harmonic oscillator problem (Celeghini et al. 2021). These functions are obtained by multiplying Hermite polynomials and a Gaussian function and have the property of being highly concentrated around the origin (Stremler 1989). The Fourier transform is an operator that preserves the unitary structure of $\mathcal{L}^2(\mathbb{R})$. Therefore, the Hermite functions are the eigenfunctions of this operator and enable a decomposition of $\mathcal{L}^2(\mathbb{R})$ into four eigenspaces that correspond to the cyclic group C_4. This decomposition can have practical implications. The Fourier transform and its inverse act as automorphisms in the Hilbert space $\mathcal{L}^2(\mathbb{R})$, which means that they keep the Hilbert space norm unchanged, according to the Plancherel theorem (Celeghini et al. 2021). This theorem can be generalized to other spaces that are relevant for physics, such as the space of smooth functions that vanish at infinity faster than any polynomial inverse and the space of tempered distributions. In both spaces, the Fourier transform and its inverse are also automorphisms that are compatible with the usual topologies defined on them (Aakash et al. 2019).

2.4 Signal Classification

The names of some signals, classified by some properties, are shown as follows:

Signal	Features
Baseband	Ergodic, nonperiodical
Carrier	Deterministic, periodical
Noise	Random, nonperiodical
Attenuation	Ergodic, nonperiodical
Interference	Ergodic, nonperiodical