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END OF STUDY PROJECT

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Master in*

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STUDY AND SIMULATION OF FSK NARROWBAND DIGITAL MODULATION

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DEDICATION

I dedicate this humble work...

To my parents, especially my dear mother who has been my source of inspiration, strength, and endless support throughout my life. Without your sacrifices, love, and prayers, I would never have achieved this milestone.

To my beloved brothers for always believing in me, motivating me, and standing by my side.

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Anis

ABSTRACT

This Master's end-of-study project provides a comprehensive theoretical, analytical, and practical study of Frequency Shift Keying (FSK) — a digital modulation technique that encodes binary data through discrete shifts in carrier frequency rather than amplitude or phase. The work spans modulation theory, in-depth FSK analysis, and hands-on simulation using MATLAB and Simulink.

Modulation Background

Chapter 1 surveys the landscape of modulation techniques, covering analog methods (AM, FM, PM) and the three principal digital schemes: Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). FSK stands out for its constant-envelope waveform, making it inherently robust against amplitude noise, fading, and non-linear amplifier distortion — critical advantages over ASK-based systems that encode information in the more noise-susceptible amplitude domain.

FSK: Technical Analysis

Chapter 2 traces FSK from its origins in Reginald Fessenden's two-tone Morse experiments (1910) through its modern variants. The chapter covers the complete FSK system architecture (binary source, carrier oscillators, modulator, transmission channel, demodulator, decision circuit), its mathematical formulation, and five key variants: Binary FSK (BFSK), Multiple FSK (MFSK), Continuous Phase FSK (CPFSK), Gaussian FSK (GFSK), and Minimum Shift Keying (MSK). Both coherent and non-coherent demodulation strategies are examined, with BER analysis showing coherent detection achieves $P_b = \frac{1}{2} \operatorname{erfc}(\sqrt{E_b/2N_0})$ versus non-coherent $P_b = \frac{1}{2} \exp(-E_b/2N_0)$. FSK's real-world applications include walkie-talkies, RFID systems, wireless sensor networks (IoT), satellite telemetry (TT&C), and telephone modems.

Simulation: MATLAB & Simulink

Chapter 3 implements FSK modulation and demodulation using two complementary approaches. The MATLAB script employs correlation-based coherent detection: the received signal is correlated against high- and low-frequency references for each bit interval, and the stronger correlation determines the decoded bit. The Simulink model builds a graphical block diagram using a Charge Pump Phase-Locked Loop (PLL) for non-coherent frequency tracking, mirroring real hardware receiver architectures. Both approaches were validated through scope

visualisations showing binary NRZ source, carrier frequencies, modulated signal, and recovered data.

Key Findings & Conclusions

The project confirms that FSK's constant-envelope property provides decisive advantages in noise-prone environments. Coherent detection yields superior BER performance, while non-coherent PLL-based detection is preferred in practical hardware for its simplicity and phase-jitter resilience. MATLAB scripting excels for academic signal analysis and BER studies, whereas Simulink is better suited to system-level prototyping and embedded code generation. Future directions include FPGA/SDR implementation, BER analysis under fading channels (Rayleigh/Rician models), and integration of FSK with emerging LPWAN and NOMA network frameworks.

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List of abbreviations

List of abbreviations:

Abbreviation	Full Form
AM	Amplitude Modulation
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BFSK	Binary Frequency Shift Keying
BPSK	Binary Phase Shift Keying
CPFSK	Continuous Phase Frequency Shift Keying
DMR	Digital Mobile Radio
FM	Frequency Modulation
FSK	Frequency Shift Keying
GFSK	Gaussian Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile communications
IoT	Internet of Things
ISM	Industrial, Scientific, Medical
LPWAN	Low-Power Wide-Area Network
MATLAB	Matrix Laboratory
MSK	Minimum Shift Keying
MFSK	Multiple Frequency-Shift Keying
NFC	Near Field Communication
NRZ	Non-Return-to-Zero
OOK	On-Off Keying
PLL	Phase-Locked Loop
PM	Phase Modulation
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying

List of abbreviations

RFID	Radio Frequency Identification
RTTY	RadioTeleTYpe
SDR	Software-Defined Radio
SNR	Signal-to-Noise Ratio
TT&C	Telemetry, Tracking, and Command
VLF	Very Low Frequency

INTRODUCTION

Introduction

1. Background and Context

The rapid advancement of digital communication technologies has transformed every aspect of modern life. From wireless sensor networks and satellite telemetry to mobile telephony and the Internet of Things (IoT), the efficient and reliable transmission of digital information has become a cornerstone of contemporary engineering. At the heart of these communication systems lies the fundamental concept of modulation — the process by which a message signal is superimposed onto a carrier wave for efficient transmission over a given medium.

Modulation techniques can be broadly categorised into analog and digital forms. Analog modulation methods — including Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM) — have historically served as the foundation of broadcasting and early telecommunications. However, with the advent of digital systems, digital modulation techniques have largely superseded their analog counterparts in applications requiring greater noise immunity, higher spectral efficiency, and compatibility with binary data processing. The three principal digital modulation schemes are Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK), each offering distinct trade-offs in terms of bandwidth, power efficiency, and receiver complexity.

Among these techniques, Frequency Shift Keying (FSK) occupies a particularly important position in the history and practice of digital communications. By encoding binary information through discrete shifts in the frequency of a carrier signal rather than through changes in its amplitude or phase, FSK achieves a constant-envelope waveform that is inherently robust against amplitude-based noise and fading. This property makes FSK well-suited to environments characterised by significant interference and signal distortion, including radio frequency channels, power line carriers, and low-power wireless links.

2. The Problematic: Challenges of Early Digital Communication

Before FSK became widely adopted, early digital communication systems relied almost exclusively on Amplitude Shift Keying (ASK), in which binary information was encoded by varying the amplitude of the carrier wave — a high amplitude represented binary 1, and a low or zero amplitude represented binary 0. While conceptually straightforward, this approach

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exposed a fundamental vulnerability: amplitude is the parameter most susceptible to corruption by channel noise, interference, and signal fading

The core challenge of any digital communication system is to transmit binary data reliably from a source to a destination despite the imperfections of the physical medium. Communication channels introduce several degradation mechanisms that significantly impair signal quality and, consequently, the fidelity of the recovered data:

- **Additive White Gaussian Noise (AWGN):** Thermal noise present in all electronic systems randomly alters the amplitude of the received signal. For ASK, even moderate noise levels can cause the receiver to misinterpret a transmitted symbol, resulting in bit errors.
- **Amplitude Fading:** In wireless channels, multipath propagation causes the signal to arrive at the receiver via multiple reflected paths, producing constructive and destructive interference that randomly varies the received signal amplitude. ASK signals, which rely entirely on amplitude for information encoding, are particularly vulnerable to such fading.
- **Non-linear Amplifier Distortion:** High-power transmitters often operate in a non-linear region to maximise power efficiency. Non-linear amplification distorts the amplitude envelope of the signal, rendering ASK demodulation unreliable.
- **Interference from Adjacent Channels:** In multi-user environments, signals from neighbouring frequency channels can overlap and corrupt the amplitude of the desired signal, further compromising ASK performance.

These challenges collectively meant that early amplitude-based digital systems could only achieve reliable communication at very low data rates and over short distances, or under carefully controlled conditions. The need for a more robust modulation technique — one that could maintain reliable data transmission even in the presence of severe amplitude distortions — became increasingly apparent as demand for long-distance, high-reliability digital communication grew throughout the early and mid-twentieth century

Frequency Shift Keying (FSK) directly addressed these limitations by relocating the information from the amplitude domain to the frequency domain. Since the carrier frequency is largely invariant under amplitude noise, fading, and non-linear amplification, an FSK signal can be detected reliably even when its amplitude is severely degraded. The receiver simply needs to determine which frequency was transmitted — a task that is far more robust than

Introduction

measuring an exact amplitude level. This fundamental insight — that frequency is a more resilient information carrier than amplitude in most practical channels — is the core motivation for FSK and remains the basis of its continued relevance today

3. Historical Overview of Frequency Shift Keying

The origins of FSK can be traced to the early twentieth century. Around 1910, the pioneering engineer Reginald Fessenden proposed a two-tone method of Morse code transmission, using distinct audio tones to represent the dots and dashes of telegraphic signals. This represented one of the earliest formal conceptualisations of frequency-based keying. Throughout the 1920s and into the mid-twentieth century, FSK was progressively refined and adopted for telegraphy, becoming the modulation of choice for early teleprinters and audio frequency shift keying (AFSK) modems, including the widely used Bell 103 and Bell 202 standards

During the 1960s and 1970s, the "Kansas City standard" applied FSK principles to digital data storage on audio cassettes, and FSK became a staple of amateur radio teletype communication. In the modern era, advanced variants such as Gaussian Frequency Shift Keying (GFSK) and Minimum Shift Keying (MSK) have further extended the applicability of the technique, finding use in Bluetooth wireless protocols, the Global System for Mobile Communications (GSM), and low-power IoT sensor networks. Despite the emergence of more spectrally efficient modulation schemes, FSK remains indispensable in applications where robustness, simplicity, and energy efficiency take precedence over raw data throughput

4. Motivation and Relevance of the project

The motivation behind this project stems from the continued relevance of FSK in a diverse array of real-world communication systems. While much contemporary research focuses on high-order modulation schemes such as Quadrature Amplitude Modulation (QAM) or Orthogonal Frequency Division Multiplexing (OFDM), FSK-based technologies continue to underpin critical applications including Radio Frequency Identification (RFID) systems, satellite telemetry and tracking, wireless sensor networks, industrial SCADA systems, and emergency communication devices such as walkie-talkies

Furthermore, a thorough understanding of FSK serves as an essential stepping stone for the study of more advanced digital modulation techniques. The mathematical framework underlying FSK — including its spectral properties, bit error rate (BER) analysis, and coherent

Introduction

versus non-coherent demodulation strategies — forms a conceptual bridge between classical analogue modulation theory and modern digital signal processing. Mastery of FSK therefore equips telecommunications engineers with both a practical tool and a theoretical foundation

From a practical standpoint, the simulation and implementation of FSK systems using industry-standard tools such as MATLAB and Simulink provide valuable experience in bridging theoretical design and physical realisation. MATLAB's rich suite of communications toolboxes allows precise mathematical analysis and bit error rate characterisation, while Simulink's graphical block-diagram environment enables system-level prototyping that closely mirrors real hardware architectures. The complementary use of both platforms constitutes an effective methodology for modern telecommunications engineering education and research

5. Objectives of the Project

This end-of-study project, undertaken within the framework of the Master's degree programme in Systems of Telecommunications aims to conduct a comprehensive study, simulation, and implementation of narrowband FSK digital modulation. The project addresses the following principal objectives:

- ▶ To establish a solid theoretical foundation by reviewing the principles of both analogue and digital modulation, situating FSK within the broader landscape of modulation techniques.
- ▶ To provide a technical analysis of FSK modulation, encompassing its mathematical representation, spectral characteristics, system block diagram, variants (BFSK, MFSK, CPFSK, GFSK, MSK), demodulation methods, and bit error rate performance.
- ▶ To design and implement FSK modulation and demodulation in MATLAB through a script-based, mathematically rigorous approach, enabling detailed signal analysis including power spectral density computation and correlator-based bit recovery.
- ▶ To construct an equivalent FSK system using Simulink's graphical block-diagram environment, employing a Phase-Locked Loop (PLL) based demodulation scheme that mirrors real-world hardware receiver architectures.
- ▶ To critically compare the two simulation approaches in terms of design methodology, signal visualisation, demodulation technique, and suitability for academic analysis versus hardware prototyping.

6. Structure of the project

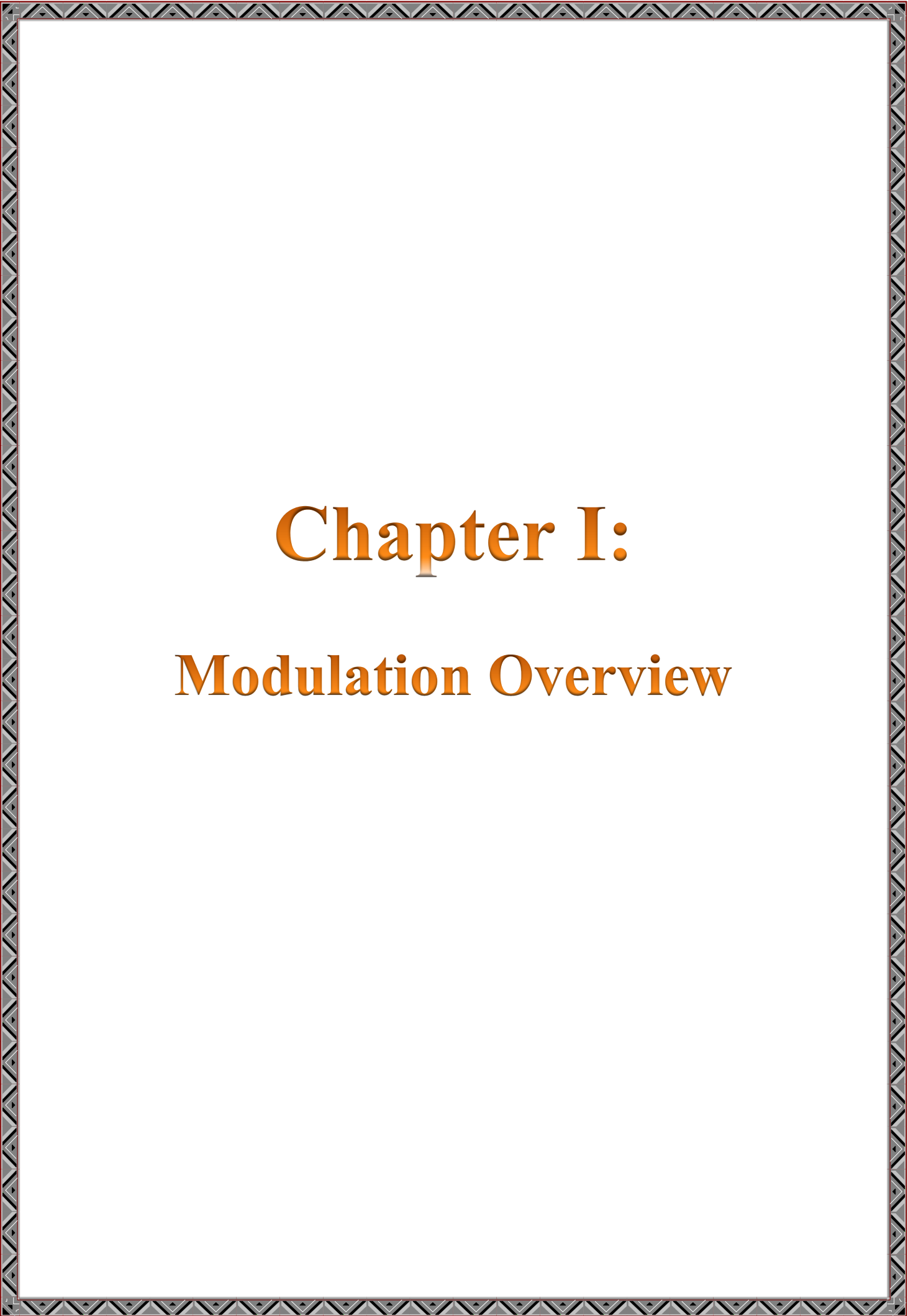
Introduction

In order to achieve the objectives outlined above, this project is organised into three main chapters, each building upon the foundations laid by the preceding one.

Chapter 1 — Modulation Overview provides a comprehensive introduction to the concept of modulation and its fundamental role in telecommunications. It systematically reviews the principal analogue modulation techniques — AM, FM, and PM — before transitioning to digital modulation. The three core digital methods (ASK, FSK, and PSK) are introduced and compared with respect to their modulated parameters, noise immunity, bandwidth efficiency, and typical application domains.

Chapter 2 — FSK Modulation constitutes the theoretical core of the project. It traces the historical development of FSK, provides a rigorous treatment of its operational principles, block diagram components, and mathematical formulation. The chapter further examines FSK variants, explores coherent and non-coherent demodulation strategies, presents a BER analysis, and surveys the diverse real-world applications of FSK across industries.

Chapter 3 — Simulation using MATLAB and Simulink translates the theoretical knowledge into practical implementation. It presents complete FSK simulation code in MATLAB and a Simulink block-diagram model using a Charge Pump PLL for frequency tracking. Visualisation results from both simulations are presented, analysed, and compared to guide tool selection for different engineering



Chapter I:

Modulation Overview

Chapter I: Modulation Overview

Introduction

Modulation is the process of modifying a characteristic of a high frequency carrier signal according to the information signal to be transmitted, it enables efficient transmission of data over long distances, improves spectrum utilisation and allows multiple signals to share the same communication medium.

1.1 What is Modulation?

Modulation is the process of superimposing high-frequency carrier signals with low-frequency message signals or binary signals resulting in a modulated wave. The carrier signal is expressed mathematically as:

$$s(t) = A_c \cos(2\pi f_c t + \phi) \dots \dots \dots (eq 1.1)$$

Where A_c is the carrier amplitude, f_c is the carrier frequency, and ϕ is the carrier phase. In modulation, one of the three parameters of the carrier wave (amplitude, frequency, or phase) is changed according to the amplitude of the message signal at a given time instant. It is an important technique used to increase the range of communication, increase the signal-to-noise ratio, and decrease the size of the antenna [I-1].

In simpler terms, modulation is like packing your message (data) into a special box (the carrier signal) that is suitable for traveling long distances through the air or a wire [I-2].

1.2 Why Do We Need Modulation?

In the current world, it is not necessary to have a wired connection to every communication device. Within minutes, signals, messages, and information can be sent across the globe. The modulation process plays a major role in achieving this.

Modulation enables efficient and reliable communication over long distances, even in the presence of noise and interference, making it an important component of modern telecommunications [I-3].

1.3 Types of Modulation

There are two main types of modulation: analog modulation and digital modulation.

1.4 Analog Modulation

In analog modulation, the information signal is continuous, meaning it varies smoothly over time. The carrier signal (a sine wave, typically) is then modified in terms of its amplitude, frequency, or phase to reflect these smooth changes in the information signal [I-2].

An analog message signal is expressed mathematically by:

$$M(t) = A_m \cos(\omega_m t + \theta) \dots \dots \dots (eq 1.2)$$

Where $M(t)$ is the modulating signal, A_m is the amplitude of the modulating signal, and $(\omega_m t + \theta)$ is the phase of the signal.

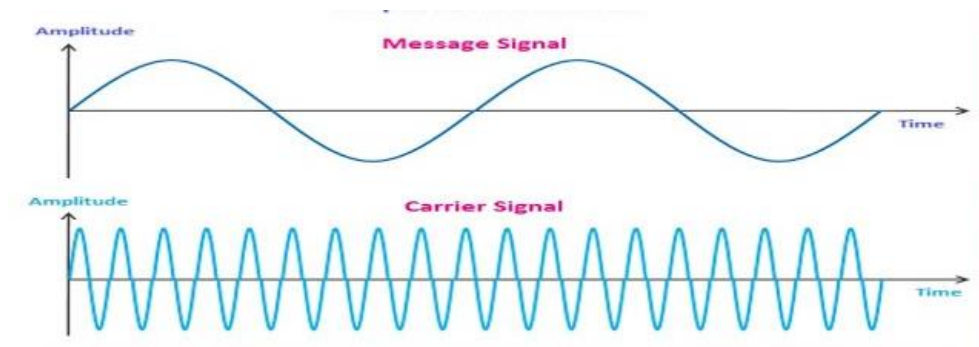


Figure 1.1: Data signal and carrier signal used for analog modulation

1.4.1 Amplitude Modulation (AM)

Definition

Amplitude modulation, or AM, is a modulation technology mainly used for radio carrier wave-based message transmission. Amplitude modulation modifies the carrier wave's amplitude (signal intensity) in accordance with the message signal, such as an audio signal, i.e., a modulating signal [I-3].

AM is the oldest method of broadcasting radio programs. Commercial AM stations operate at frequencies spaced 10 kHz apart between 540 and 1,700 kHz. Radio waves in this frequency range are effectively reflected back to Earth's surface by the ionosphere and can be detected by receivers hundreds of kilometres away. In addition to its use in commercial radio broadcasting, AM is employed in long-distance shortwave radio broadcasts and in transmitting the video portion of television programs [I-4].

Chapter I: Modulation Overview

Mathematical Definition

The basic equation for amplitude modulation is:

$$S(t) = A_c[1 + m(t)] \cos(\omega_c t) \dots \dots \dots (eq 1.3)$$

Where $S(t)$ is the modulated signal, A_c is the carrier amplitude, $M(t)$ is the modulating signal (message signal), ω_c is the angular carrier frequency, and m is the modulation index which quantifies the relative amplitude of the modulating signal and is also referred to as modulation depth when expressed as a percentage.

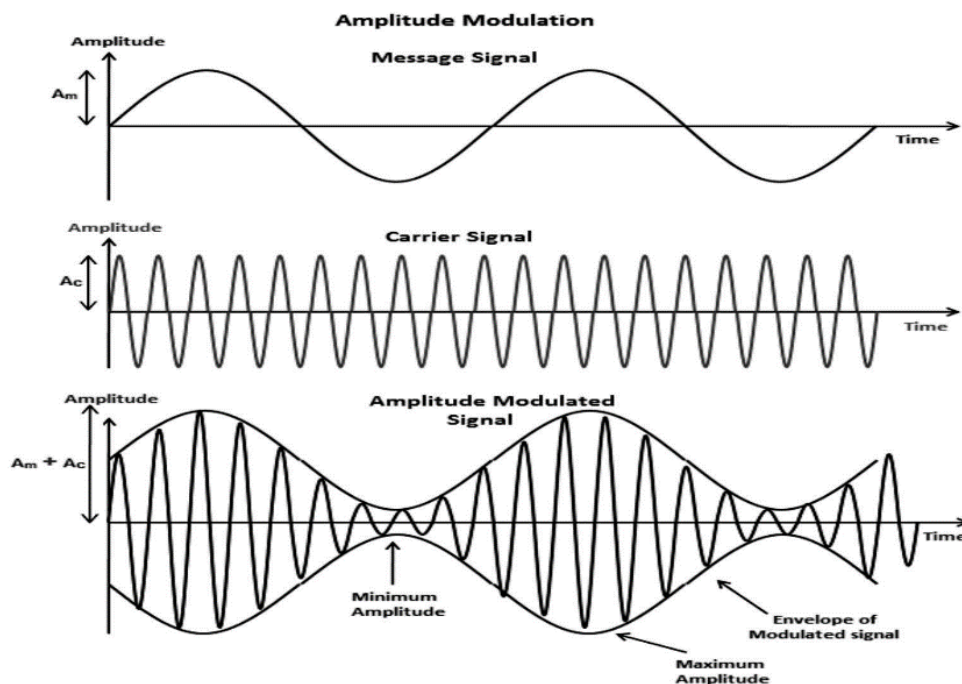


Figure 1.2: Amplitude Modulation waveform

Applications of AM

- Amplitude modulation is used in :
- AM radio broadcasting
- Aircraft and maritime communication
- Amplitude Shift Keying (ASK) in digital communication
- QAM-based modem technologies
- Low-frequency RF applications [I-5]

Chapter I: Modulation Overview

Advantages and Limitations of AM

Advantages:

- Simple modulation and demodulation circuits
- Cost-effective implementation
- Suitable for low-frequency signal transmission [I-5]

Limitations:

- Poor noise immunity
- Inefficient in power and bandwidth
- Limited data capacity [I-5]

1.4.2 Frequency Modulation (FM)

Frequency Modulation (FM) is a method of signal transmission in which the carrier wave's frequency is varied in proportion to the amplitude of the modulating signal (unlike in amplitude modulation where the amplitude of the carrier is varied). The amplitude of the carrier remains constant. FM offers improved noise resistance and better signal quality compared to Amplitude Modulation (AM) [I-6].

Mathematical Representation

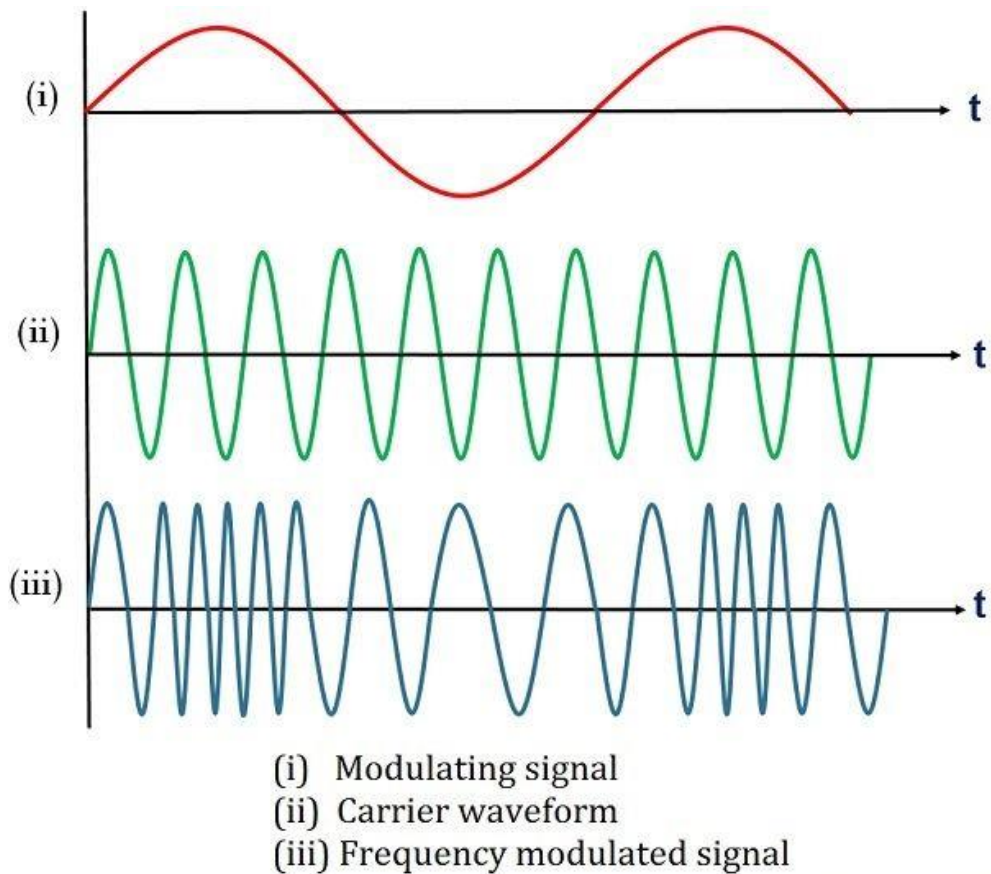
The FM signal can be described as:

$$S(t) = A_c \cos(\omega_c t + \beta \sin(\omega_m t)) \dots \dots \dots (eq 1.4)$$

Where S(t) is the modulated signal, A_c is the carrier amplitude, ω_c is the angular carrier frequency, ω_m is the angular frequency of the modulating signal, β is the modulation index, and T is time [6].

The frequency deviation indicates how far the instantaneous frequency moves from the carrier frequency: $\Delta f = \beta \times F_m$, where Δf is the frequency deviation and F_m is the modulating signal frequency [I-6].

Chapter I: Modulation Overview



Electronics Coach

Figure 1.3: Frequency Modulation waveform

Types of FM

Narrowband FM (NBFM): $\beta < 1$, features:

- Small frequency deviation
- Minimal sideband generation
- Used in voice communication (e.g., handheld radios) [I-6].

Wideband FM (WBFM): $\beta > 1$,

- Large frequency deviation
- Many sideband components
- Used in high-fidelity audio (e.g., FM radio broadcasting)
- Practical Considerations

Chapter I: Modulation Overview

- Good noise immunity
- Constant signal amplitude
- Wider bandwidth than AM
- More complex circuitry and modulation schemes [I-6].

FM Applications

FM is used in a wide range of systems: FM radio broadcasting, two-way radios (e.g., aviation, police), telemetry and control systems, wireless microphones, satellite communications, medical imaging systems, and audio synthesis (FM synthesis) [I-6].

Advantages and Limitations of FM

Advantages:

- High noise rejection
- Superior audio quality
- Amplitude stability (resistant to fading) [I-6]

Limitations:

- Higher bandwidth requirements
- Increased system complexity
- More expensive to implement [I-6]

Comparison between AM and FM

Feature	AM	FM
Sound Quality	Poor compared to FM	Good compared to AM
Cost	Cheaper technology	More expensive
Distance	Can be sent over large distances	Can be blocked by obstacles

Chapter I: Modulation Overview

Feature	AM	FM
Power Efficiency	Less power efficient	More power efficient
Broadcast Range	Shorter range	Longer range
Parameter Modulated	Amplitude	Frequency

Listing 1.1: comparing between AM and FM

1.4.3 Phase Modulation (PM)

Phase modulation (PM) is a modulation pattern for conditioning communication signals for transmission. It encodes a message signal as variations in the instantaneous phase of a carrier wave. Phase modulation is one of the two principal forms of angle modulation, together with frequency modulation.

The phase of a carrier signal is modulated to follow the changing signal level (amplitude) of the message signal. The peak amplitude and the frequency of the carrier signal are maintained constant, but as the amplitude of the message signal changes, the phase of the carrier changes correspondingly.

Phase modulation is widely used for transmitting radio waves and is an integral part of many digital transmission coding schemes that underlie a wide range of technologies like Wi-Fi, GSM and satellite television. PM is used for signal and waveform generation in digital synthesizers, such as the Yamaha DX7, to implement FM synthesis [I-7].

Mathematical Representation

$$S(t) = A_c \cdot \cos(\omega_c t + k_p \cdot m(t)) \dots \dots \dots (eq 1.5)$$

Where $S(t)$ is the modulated signal, A_c is the carrier amplitude, ω_c is the angular carrier frequency, k_p is the phase sensitivity (rad/V), and $M(t)$ is the modulating signal.

Chapter I: Modulation Overview

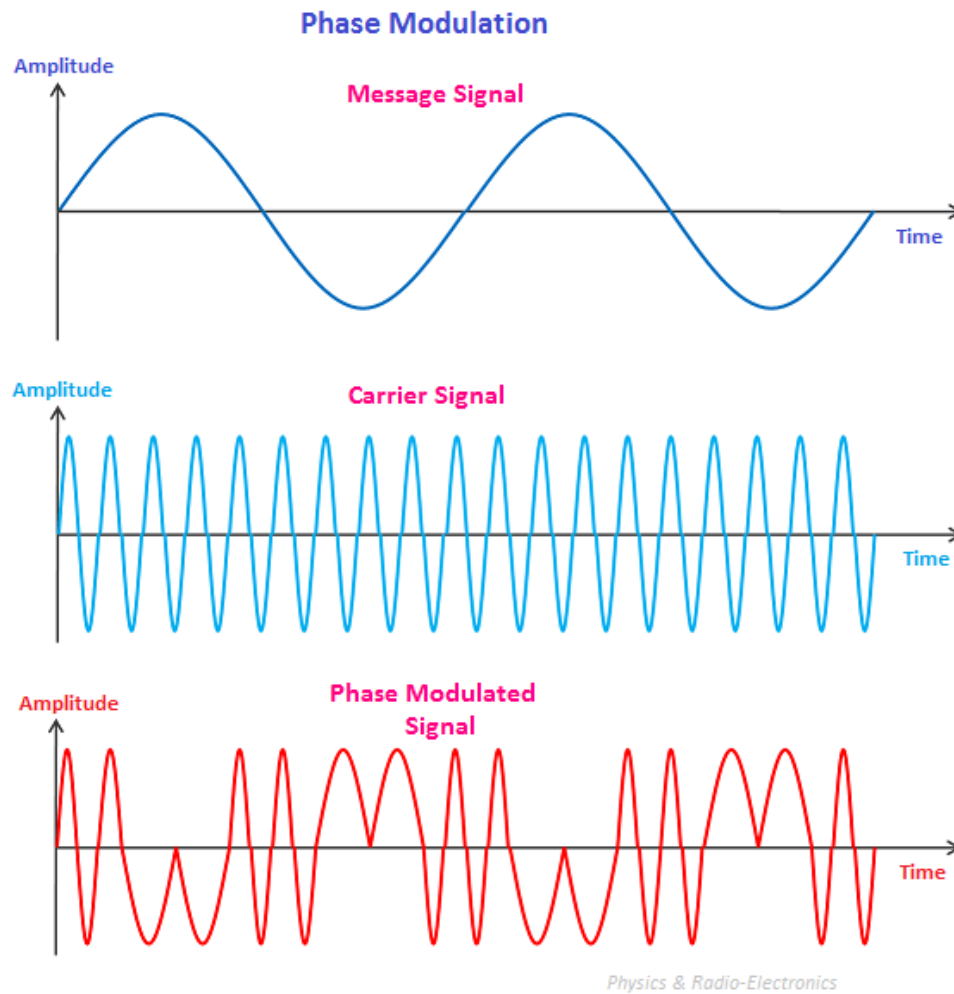


Figure 1.4: Phase Modulation waveform

Applications

PM is mainly used in :

- Digital modulation schemes (e.g., BPSK, QPSK)
- RFID and NFC
- Satellite links and optical systems
- Radar signal processing
- High-speed modems
- FM synthesis (via mathematical equivalence)

Chapter I: Modulation Overview

Advantages and Limitations

Advantages

- Immunity to amplitude noise
- High spectral efficiency (in digital systems)
- Phase continuity can reduce spectral spreading

Limitations

- Complex demodulation (requires phase reference)
- Sensitive to phase noise
- Not widely used for analog audio

1.5 Digital Modulation

In Digital Modulation, only the carrier signal is analogue and the message signal is in digital form.

Digital signals?

Digital signals are binary values that can take either logic 0 as in zero volts or logic 1 as in any other voltage. There are no in-between voltage levels in the digital signal.

There are mainly three types in Analog Modulation which are Amplitude Modulation, Frequency Modulation and Phase Modulation. Here the amplitude, frequency and phase of carrier wave changes with respect to amplitude of message signal. Whereas in Digital Modulation a process called as Shift Keying is used.

Shift Keying means that the amplitude, frequency or phase of the carrier wave is shifted between two or more discrete values rather than varying continuously like Analog Modulation. Binary data requires two discrete levels of amplitude, frequency or phase for modulation called as Binary Shift Keying. A group of bits can be clubbed together to form M-ary Shift Keying [1-8].

There are mainly three types of Digital Modulation techniques. They are :

Chapter I: Modulation Overview

- Amplitude Shift Keying
- Frequency Shift Keying
- Phase Shift Keying [I-8]

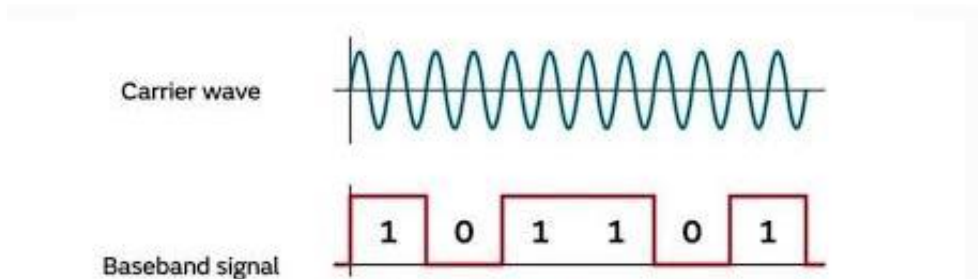


Figure 1.5: Digital signal and carrier wave

1.5.1 Amplitude Shift Keying (ASK)

Amplitude Shift Keying (ASK) is a digital modulation technique used to

Transmit digital information by modulating the amplitude of a carrier signal. In ASK, a high-amplitude carrier signal represents a binary '1', while a low-Amplitude carrier signal represents a binary '0'.

This modulation method involves the superimposition of a digital message Signal onto a high-frequency carrier signal, typically a sinusoidal waveform. The Binary message signal, composed of '1's and '0's, directly controls the amplitude Of the carrier wave. As a result, the modulated signal, formed by combining the Carrier and message signal, is then transmitted over the communication channel.

ASK is widely used in various communication systems due to its simplicity And efficiency, particularly in applications such as optical fiber transmission and Infrared remote controls. [I-9].

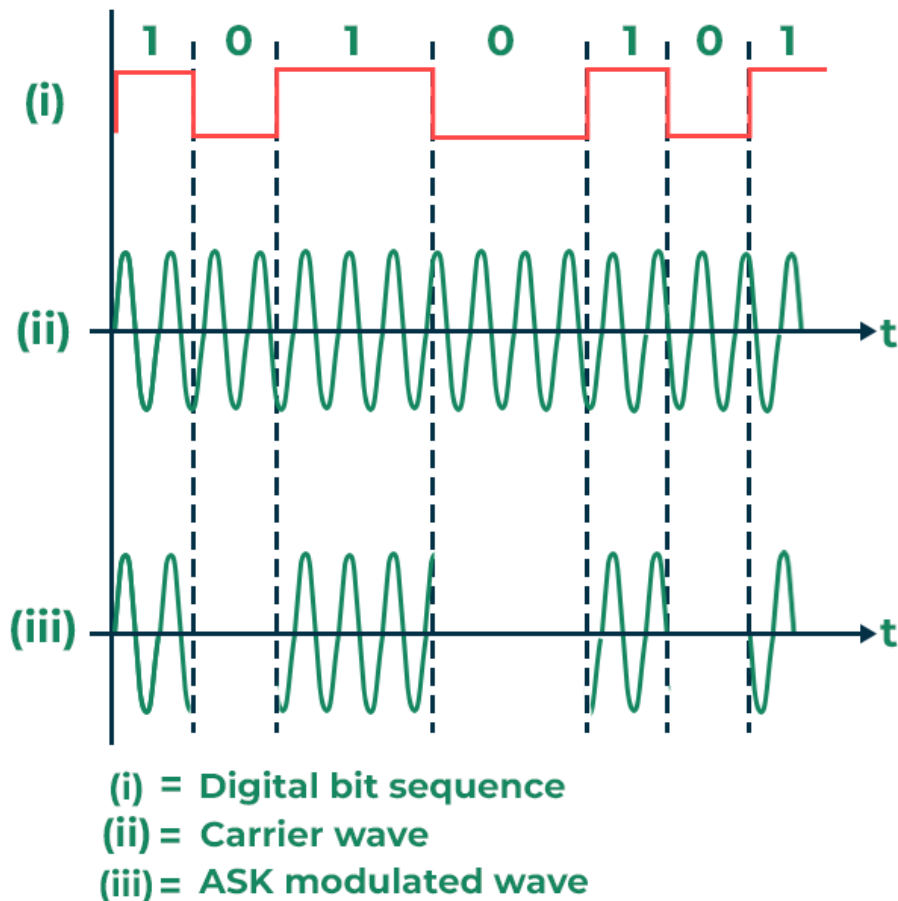


Figure 1.6: ASK Modulation waveform

Advantages and Limitations

- **Advantages** It is one of the simplest modulation techniques which makes it easy to implement in both analog and digital systems.
- It is a cost-effective modulation technique, which is one reason for its widespread use in various applications.
- It is compatible with various transmission media, including radio waves, optical fibers, and wired communication systems.
- It is efficient in terms of bandwidth utilization as it only requires two levels of amplitude i.e. 0 and 1. [I-9].

Disadvantages:

- Susceptibility to Noise

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- Bandwidth Inefficiency
- Power Inefficiency .
- Limited Data Rate
- Signal-to-Noise Ratio Sensitivity
- Lack of Phase or Frequency Information [I-9]

Applications

- ASK is commonly used in wireless communication systems, such as keyless entry systems, remote controls, and radio frequency identification (RFID) tags.
- In optical fiber communication, ASK is used to transmit digital data over long distances.
- ASK is often used in digital broadcasting, including television and radio transmissions, for transmitting audio and video signals.
- ASK can be used for low to medium data rate communication, such as in binary data transmission over short distances.
- ASK is used in medical telemetry systems for monitoring and transmitting patient data[I-9]

1.5.2 Frequency Shift Keying (FSK)

Frequency Shift Keying (FSK) is a digital modulation technique in which the frequency of the carrier signal changes in response to variations in the digital input signal. In FSK modulation, the output waveform exhibits a higher frequency when the input signal represents a binary '1' and a lower frequency when the input corresponds to a binary '0.' These distinct frequencies are referred to as the Mark frequency (for binary 1) and the Space frequency (for binary 0) [I-9].

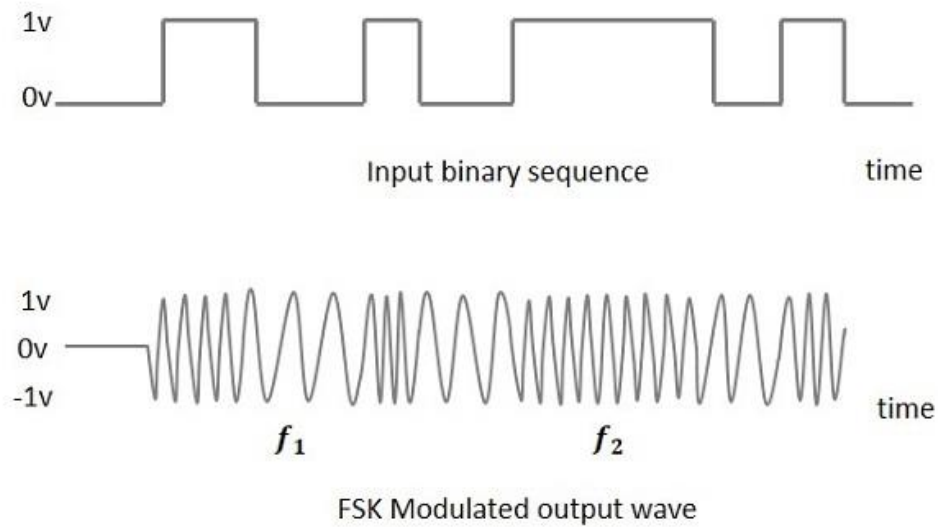


Figure 1.7: FSK Modulation waveform

Advantages and Applications

Advantages:

- High noise immunity,
- simplicity,
- reliability [I-10].

Applications:

- Telemetry and SCADA systems (e.g., smart meters)
- Bluetooth® and other short-range wireless protocols
- Low-speed modems (e.g., for credit card terminals)
- Radio Frequency Identification (RFID) tags

Optical Communication systems[I-10]

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1.5.3 Phase Shift Keying (PSK)

Phase Shift Keying (PSK) is a digital modulation scheme in which the phase of a carrier wave is varied in discrete steps to encode digital data. Each phase state represents a distinct symbol or bit pattern. PSK enables bandwidth-efficient digital transmission, particularly in wireless and satellite communication [I-11].

Mathematical Representation

$$S(t) = A_c \cdot \cos(\omega_c \cdot t + \phi_n) \dots \dots \dots (eq 1.6)$$

Where $S(t)$ is the modulated signal, A_c is the carrier amplitude, ω_c is the carrier angular frequency, and ϕ_n is the phase corresponding to symbol n .

In BPSK (Binary PSK), only two phases are used:

Bit 0 $\rightarrow$ phase 0 , Bit 1 $\rightarrow$ phase π

This results in:

$$S(t) = A_c \cdot \cos(\omega_c \cdot t) \text{ for bit 0} \dots \dots \dots (eq 1.7)$$

$$S(t) = -A_c \cdot \cos(\omega_c \cdot t) \text{ for bit 1} \dots \dots \dots (eq 1.8)$$

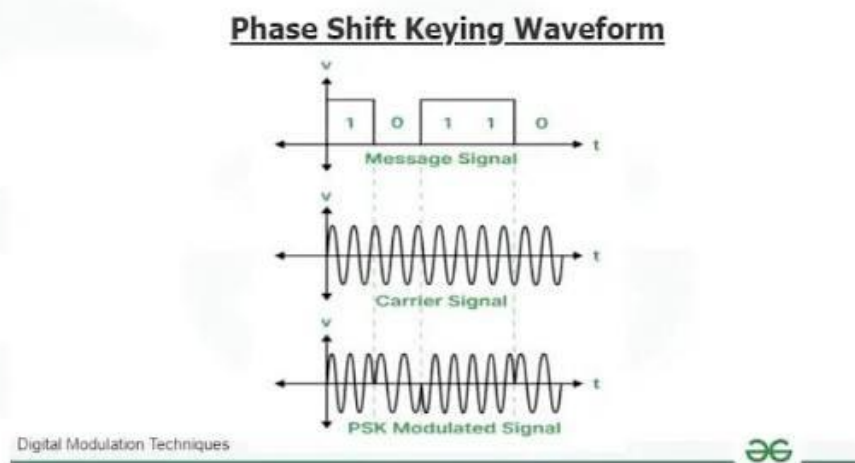


Figure 1.8: PSK Modulation waveform

PSK Variants

BPSK (Binary PSK): 2 phases ($0, \pi$), 1 bit per symbol, constant envelope, high robustness, low spectral efficiency.

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QPSK (Quadrature PSK): 4 phases ($0, \pi/2, \pi, 3\pi/2$), 2 bits per symbol, common in satellite and cellular systems.

8-PSK and Higher-Order PSK: More than 4 phases, higher data rates, reduced noise resilience.

DPSK (Differential PSK): Phase difference encodes data (no absolute reference), simplifies receiver design. [I-11]

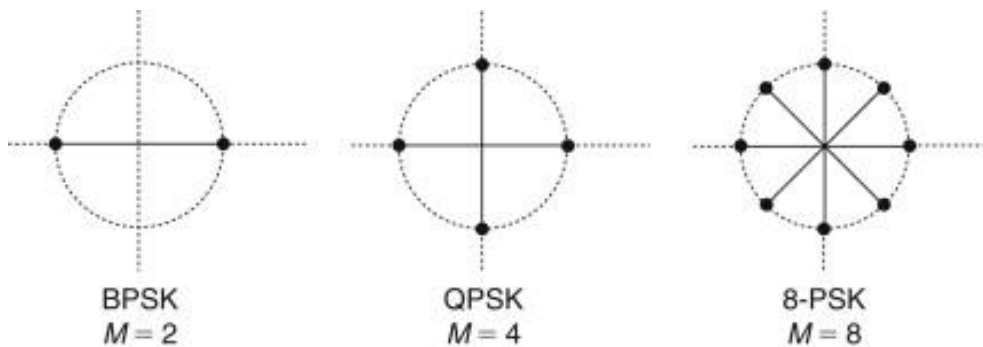


Figure 1.9: PSK Modulation variants

Applications

PSK is used across a range of communication technologies :

- Satellite systems (e.g., BPSK/QPSK in DVB-S)
- Cellular networks (e.g., QPSK in LTE uplink)
- RFID systems
- Wireless sensors and telemetry
- Optical networks (differential PSK formats) [I-11]

Advantages and Limitations

Advantages

- Efficient use of power and bandwidth
- Constant-envelope (BPSK, QPSK) supports nonlinear amplification
- Scalable for moderate data rates

Limitations

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- Higher-order PSK (e.g., 8-PSK) susceptible to noise
- Requires phase synchronization [I-11]

Comparison between ASK, FSK, and PSK

Feature	ASK	FSK	PSK
Parameter Varied	Amplitude	Frequency	Phase
Noise Immunity	Poor	Better than ASK	Best among the three
Bandwidth Efficiency	Low	Medium	High
Power Efficiency	Low	Medium	High
Receiver Complexity	Simple	Moderate	Complex
Typical Applications	Optical fiber, RFID	Radio links, pagers	Wi-Fi, satellite, modern digital

Listing 1.2: comparing between digital modulation techniques

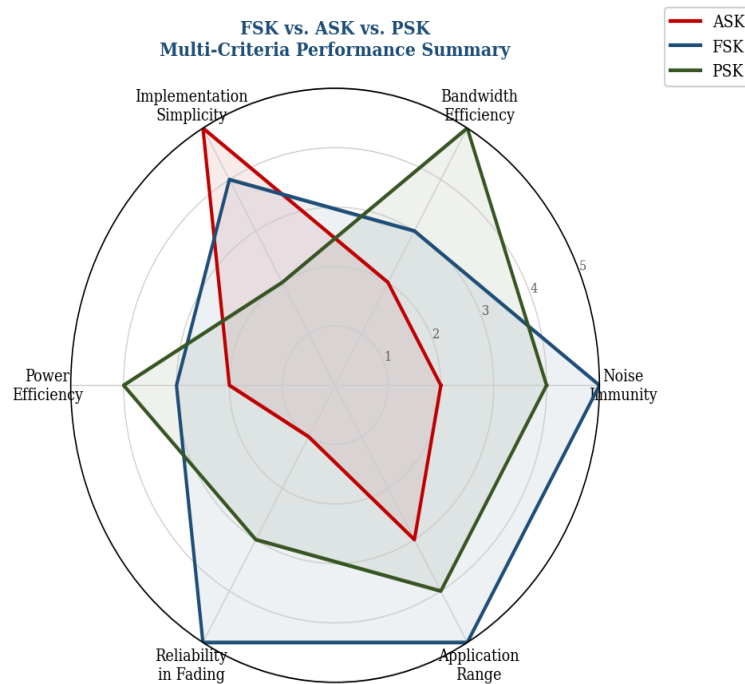


Figure 1.10 Radar chart comparing digital modulation techniques

Chapter I: Modulation Overview

Conclusion

This chapter introduced the basic principles of modulation and its role in communication systems. It reviewed the main analog modulation techniques (AM, FM, and PM) and digital modulation techniques (ASK, FSK, and PSK), emphasizing their characteristics and applications.

Based on the theoretical background presented in this chapter, the next chapters will focus on the detailed study of Frequency Shift Keying (FSK) modulation, including its mathematical model, performance analysis, and practical implementation.

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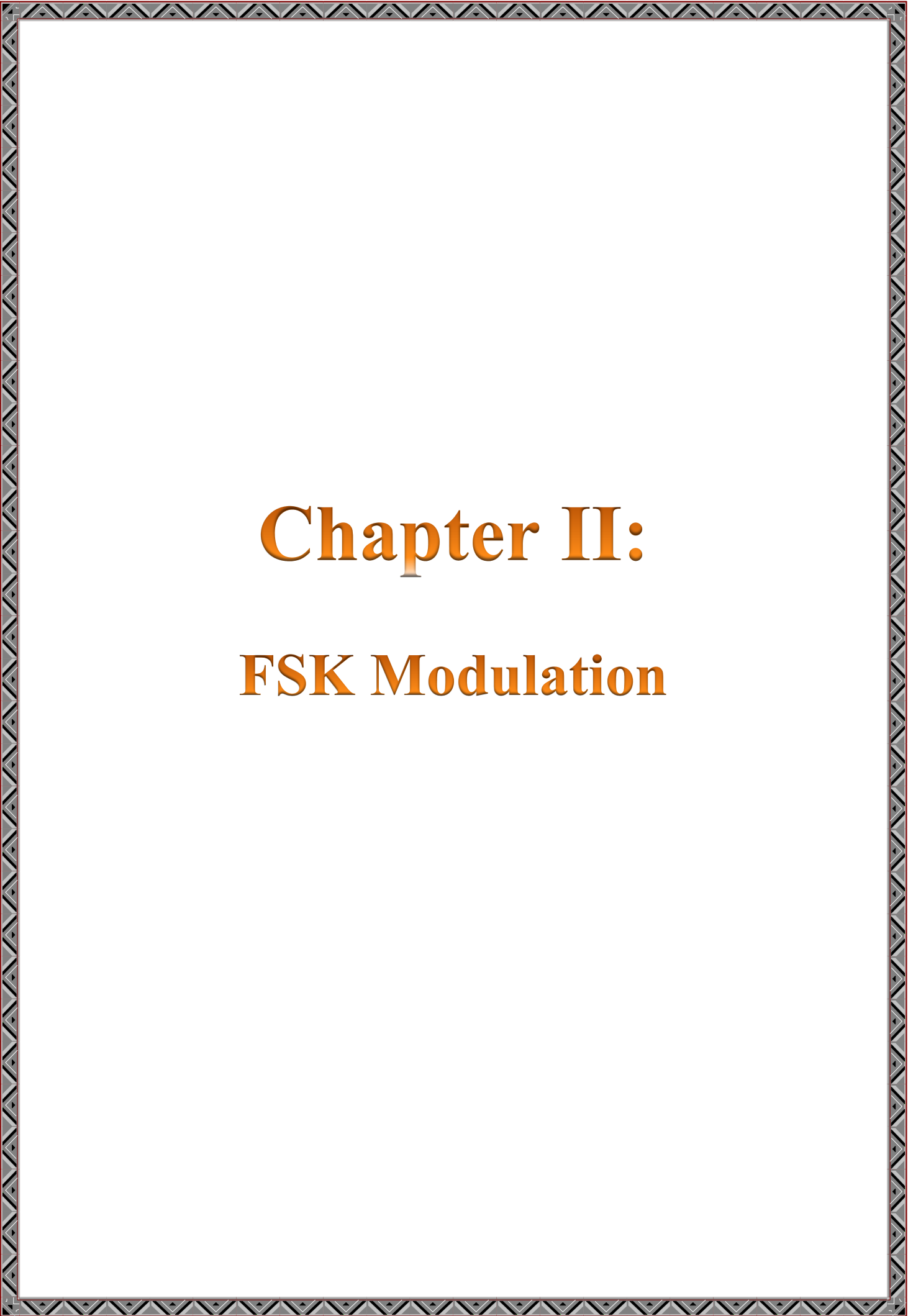
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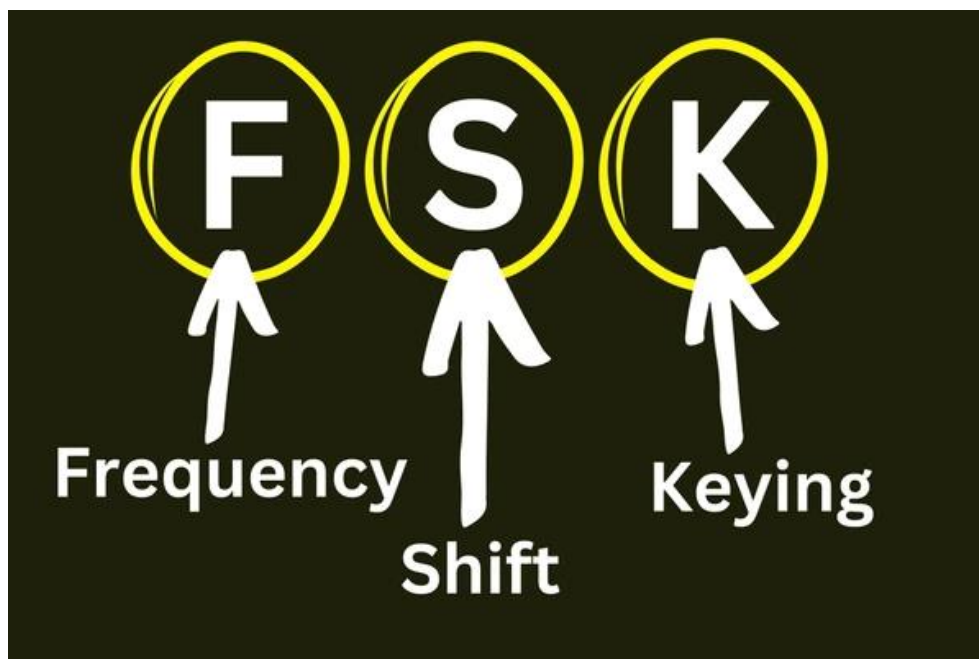
Chapter II:

FSK Modulation

Chapter II:FSK modulation

2.1 Introduction to FSK

Frequency-shift keying (FSK) is a digital modulation technique that involves using two different frequencies to transmit binary data. The digital data is stored in the frequency of the modulated signal, and the carrier frequency is changed depending on which binary symbol is being represented. FSK is known for its robustness, ability to communicate over long distances, and good noise immunity. FSK modulators and demodulators are commonly used to provide these noise immunity properties [II-1].



2.2 History of FSK Modulation

Frequency Shift Keying (FSK) originated in the early 20th century, with Reginald Fessenden proposing a two-tone method around 1910 to improve Morse code transmission. It evolved from “compensation-wave” methods used in arc transmitters to overcome keying limitations. By the mid-20th century, it became standard for teleprinters, modems (Bell 103/202), and is still used today in radio, paging, and utility metering due to its high noise immunity [II-1].

Key Historical Milestones

1910s (Origins): Reginald Fessenden introduced a system using two different tones to represent dots and dashes, aiming to reduce transmission time. Early arc transmitters used a

“compensation-wave” method, where the frequency shifted slightly rather than turning the transmitter on and off [II-1].

1920s (Transition): By 1921, spark transmitters using this method were discouraged due to high bandwidth consumption and interference [II-1].

Mid-20th Century (Teleprinters & Modems): FSK became essential for telegraphy and early data communication. It was widely adopted for audio frequency-shift keying (AFSK) in modems like the Bell 103 and 202, which operated up to 1200 bits per second [II-1].

1960s-1970s (Computing & Radio): The “Kansas City standard” was developed for storing digital data on audio cassettes. It also became a standard for amateur radio (radio teletype) [II.1].

Modern Era: FSK (and its variants like GFSK) remains in use for low-power, high-reliability applications such as Caller ID, paging systems, and wireless sensor networks [II-1].

FSK emerged as an early digital modulation method to improve robustness against noise and amplitude distortion in communication systems. Unlike amplitude-based schemes, FSK relies on frequency variations, which are less susceptible to signal fading and nonlinear amplification effects. Initially used in low-speed data transmission over wired and radio links, FSK became a foundational modulation approach for telegraphy, telemetry, and early modems. Over time, variants such as binary FSK (BFSK) and multiple-frequency FSK (MFSK) were developed to balance spectral efficiency and noise immunity

Although more spectrally efficient modulation schemes are widely used in modern high-speed systems, FSK remains relevant in applications prioritizing reliability, simplicity, and low power consumption. [II-1].

2.3 Block Diagram of Frequency Shift Keying

The basic frequency shift keying circuit diagram consists of the following blocks [II-2]:

- Binary Data Source: Generates digital data (0s and 1s).
- Carrier Oscillators: Produce two carrier frequencies corresponding to binary states.
- FSK Modulator: Selects the appropriate frequency based on input data.
- Transmission Channel: Medium through which the FSK signal travels.

- FSK Demodulator: Detects frequency changes in the received signal.
- Decision Circuit: Recovers the original digital data.

Binary Data Source

The binary data source generates the digital information to be transmitted in the FSK system. It produces a sequence of binary symbols, typically in the form of 0s and 1s, which may originate from a computer, sensor, or digital communication device. This data stream represents the message or information signal. Each binary value controls the frequency selection in the modulator. Accurate and stable data generation is essential for correct modulation and reliable communication. [II-2]

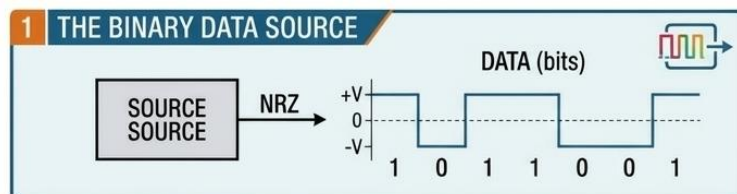


Figure 2.1: Binary data source block in an FSK system

Carrier Oscillators

Carrier oscillators generate two sinusoidal carrier signals of different frequencies. In binary frequency shift keying, one carrier frequency represents binary '1', while the other represents binary '0'. These oscillators operate at fixed and stable frequencies to ensure accurate modulation. The frequency separation between the two carriers must be sufficient to avoid interference at the receiver. Carrier oscillators play a critical role in defining the spectral characteristics of the FSK signal [II-2].

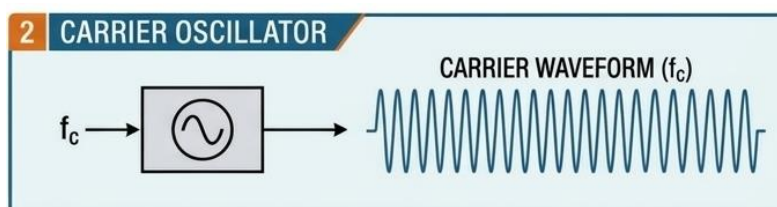


Figure2.3: Carrier oscillators generating two frequencies for FSK modulation

FSK Modulator

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The FSK modulator converts the binary input data into a frequency-modulated signal. It works by selecting one of the carrier frequencies based on the incoming digital bit. When the input is binary '1', the modulator outputs the higher carrier frequency, and when the input is binary '0', it outputs the lower carrier frequency. The amplitude of the carrier remains constant throughout the process. This method improves noise immunity and makes FSK suitable for wireless and low-power communication systems [II-2].

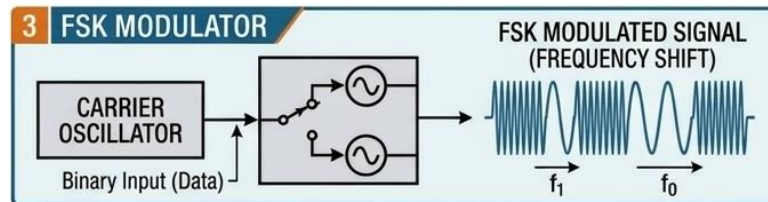


Figure 2.4: FSK modulator selecting carrier frequency based on binary input

Transmission Channel

The transmission channel is the physical medium through which the FSK signal travels from the transmitter to the receiver. It may be a wired channel, optical fiber, or wireless medium such as air. During transmission, the signal may experience attenuation, noise, interference, and distortion. These channel effects can alter the signal frequency and reduce system performance. Channel characteristics greatly influence the reliability and quality of FSK communication [II-2].



Figure 2.5: Transmission channel carrying the FSK signal

FSK Demodulator

The FSK demodulator is responsible for recovering the original digital data from the received FSK signal. It detects which frequency was transmitted during each symbol interval. This is typically achieved using band-pass filters, frequency discriminators, or correlators. The demodulator converts frequency variations into voltage levels suitable for digital decision-making.

Chapter II: FSK Modulation

Accurate frequency detection is essential to minimize bit errors and ensure reliable data recovery [II-2].

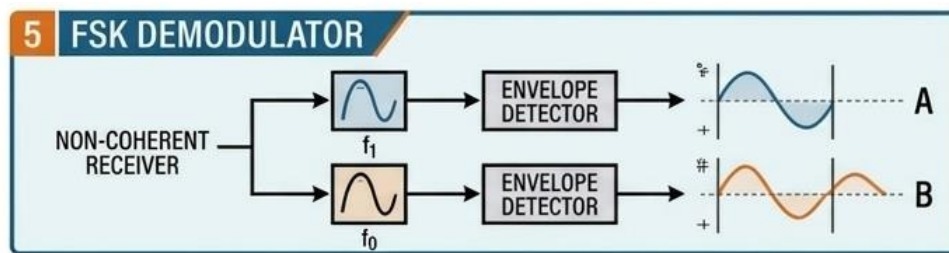


Figure 2.6: FSK demodulator block recovering digital data

Decision Circuit

The decision circuit processes the output of the FSK demodulator and determines the transmitted binary data. It compares the detected signal against predefined threshold levels. If the detected frequency corresponds to the higher frequency, the output is interpreted as binary '1'; otherwise, it is interpreted as binary '0'. The decision circuit helps reduce the effect of noise and distortion [II-2].

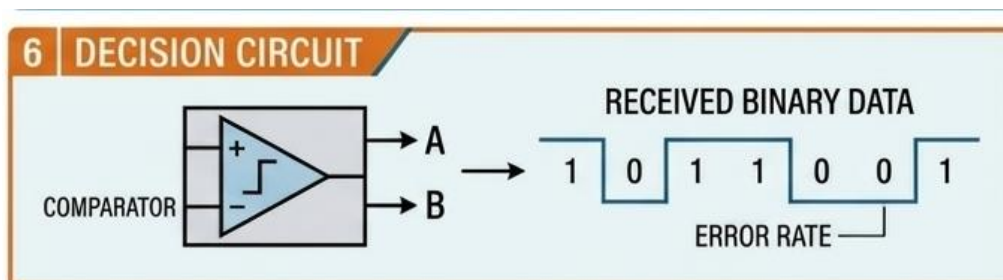


Figure 2.7: Decision circuit determining the final binary output

Complete FSK Block Diagram

Below is the full FSK modulation and demodulation block diagram with all components

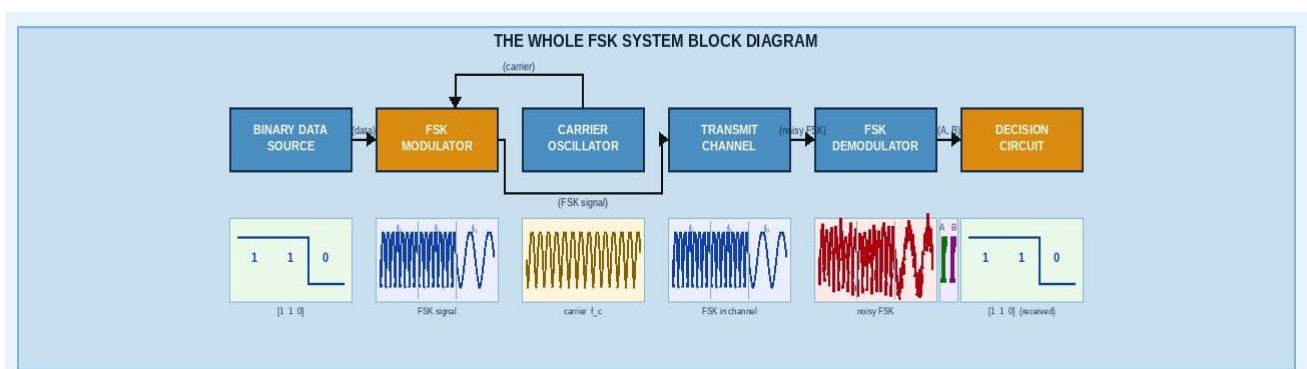


Figure 2.8: Complete FSK block diagram showing all system components

2.4 How Does Frequency Shift Keying Work

Frequency Shift Keying (FSK) operates by modulating a carrier wave's frequency to represent digital data. In its simplest form, FSK uses two distinct frequencies: one for the binary digit 0 and another for the binary digit 1. The transmitter continuously shifts between these frequencies as the data stream is processed. An FSK modulator is used to shift the carrier frequency according to the input data, and may include pulse shaping or filtering techniques to improve spectral efficiency and reduce interference. This frequency modulation allows the signal to convey information over various communication channels. The receiver decodes the signal by detecting the changes in frequency, thereby reconstructing the original binary data [II-3].

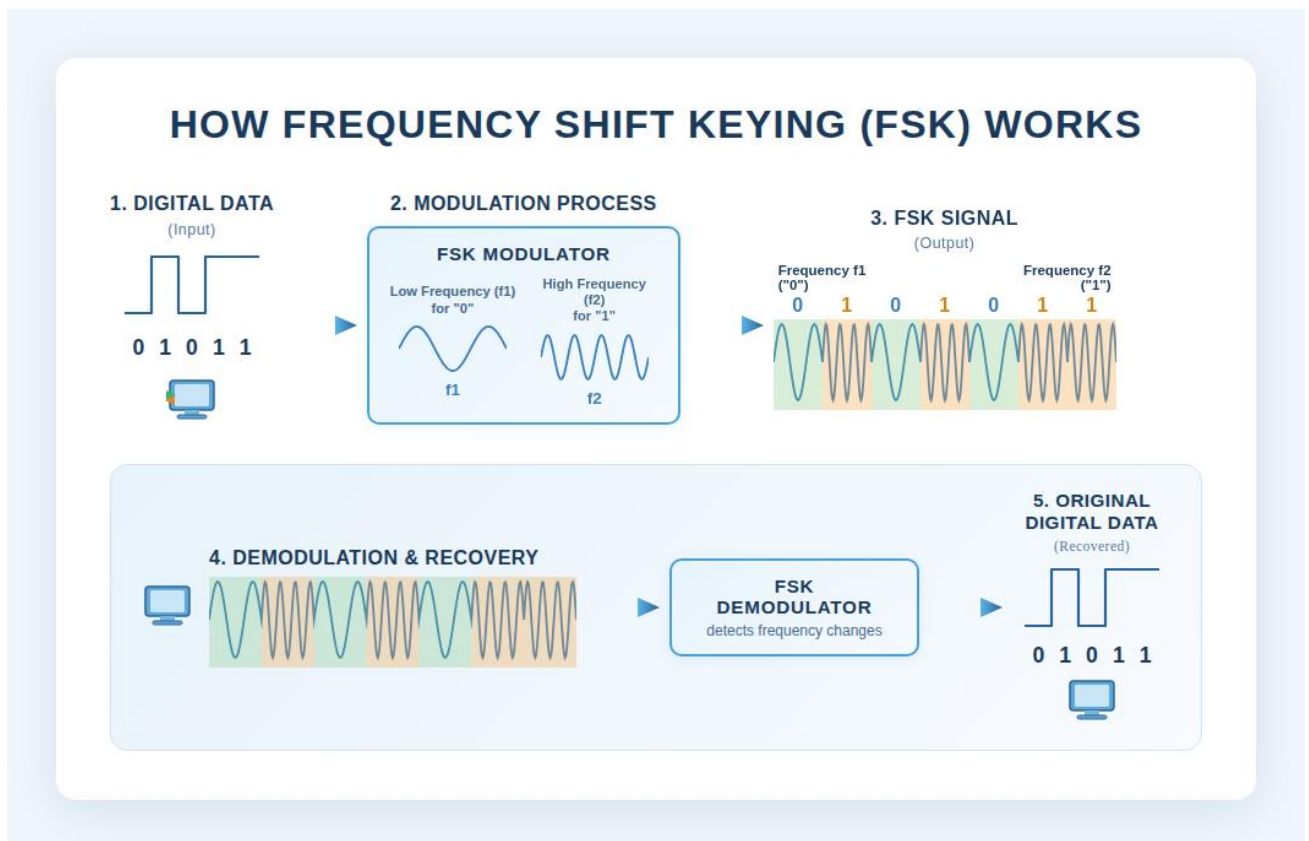


Figure 2.9: FSK waveform illustrating frequency transitions for binary data

FSK's effectiveness is rooted in its ability to manage interference and noise, which can distort amplitude-based signals. The frequency is switched at each symbol period, which is important for maintaining proper timing and signal integrity. There's also the more advanced form, known as Minimum Shift Keying (MSK), which minimises bandwidth usage. By understanding the mechanics of FSK, one can appreciate its application in technologies requiring reliable data

transmission, such as mobile communication and telemetry systems. Its straightforward mechanism makes FSK an enduring choice in digital communication. [II-3].

Key Concepts and Terminology

To fully grasp Frequency Shift Keying (FSK), it's essential to understand some key concepts and terminology. At its core, FSK involves a carrier wave—a continuous waveform that can be modulated to carry information. In FSK, modulation occurs through changes in frequency. Bit rate refers to the number of bits transmitted per second, while baud rate refers to the number of signal changes or symbols per second. In FSK, these two rates can differ because one symbol can represent multiple bits.

Another crucial term is frequency deviation, which is the difference between the carrier frequency and the modulated frequencies representing digital data. The modulated signal is the output of the FSK process, where the frequency of the carrier signal varies according to the digital data, resulting in a constant amplitude waveform that reflects the information being transmitted. Understanding bandwidth, the range of frequencies within which the FSK signal operates, is also important. It determines the capacity of the channel to carry data. Familiarity with these terms helps demystify FSK and its operation, paving the way for a deeper understanding of its applications in digital communication systems [II-3].

2.5 Mathematical Representation of FSK

The general analytic expression for FSK modulation is:

$$S_i(t) = A \cos(2\pi f_i t + \theta), \quad 0 \leq t \leq T; \quad i = 1, \dots, M \dots \dots \dots (eq \ 2.1)$$

Where the frequency term f_i can take M possible values and T is the duration of a symbol.

The simplest form of FSK modulation is binary FSK (BFSK) where two frequencies separated by Δf are used [II-4].

$$S_1(t) = A \cos(2\pi f_1 t) \quad S_0(t) = A \cos(2\pi f_2 t) \dots \dots \dots (eq \ 2.2)$$

In FSK schemes, it is common to specify the frequency spacing in terms of the modulation index h , defined as

$$h = \frac{\Delta f}{R_b} \dots \dots \dots (eq \ 2.3)$$

where

Δf is the frequency separation between the two carrier frequencies

R_b is the bit rate [II-4].

Energy and Power of FSK Signals

Constant Envelope: FSK typically uses a constant amplitude (A) regardless of the frequency being sent (0 or 1). This keeps the average power constant, which is beneficial for power-limited systems [15].

The average signal power is

$$P = \frac{E_b}{T_b} \dots\dots\dots(\text{eq 2.4})$$

where E_b is the bit energy and T_b is the bit duration. The energy per bit is

$$E_b = \frac{1}{2} A^2 T_b \dots\dots\dots(\text{eq 2.5})$$

where A is the amplitude of the signal [II-4].

Impact of Modulating Frequency: While FSK switches between frequencies, the amplitude usually remains constant, meaning the energy per bit is the same for both 0 and 1 frequencies in a coherent FSK system. [II-4]

Power Efficiency: FSK is known for its ability to operate efficiently in low-power systems. Increasing the modulation index or alphabet size (M -ary FSK) can improve power efficiency but often at the cost of requiring more bandwidth. [II-4]

Signal Type: FSK signals are generally treated as power signals because they consist of continuous sinusoidal waveforms rather than pulses, which means their energy over infinite time is infinite, but their power over one period (or bit) is finite [II-4]

2.6 Types of FSK Modulation

Binary Frequency Shift Keying (BFSK)

BFSK is the most straightforward form of FSK. In BFSK, two distinct frequencies are used to represent binary data—one frequency for a binary 0 and another for a binary 1. This simplicity

makes BFSK a fundamental building block in digital communication systems, especially where reliable transmission of digital signals is required [II-3].

Multiple Frequency-Shift Keying (MFSK)

Multiple Frequency-Shift Keying (MFSK) is a digital modulation technique that uses distinct frequencies to represent data, allowing more than one bit per symbol, unlike Binary FSK (BFSK). It is a form of M-ary orthogonal modulation, popular in low-SNR, fading scenarios like amateur radio (e.g., FT8, Olivia) utilizing multiple tones to achieve high power efficiency [II-5].

utilizing multiple tones to achieve high power efficiency MFSK is a generic family of multi-frequency shift keying digital transmission modes in which one tone from a set of M tones is transmitted at any given time. Amateur radio modes using forms of MFSK include WSPR, FT-4, FT-8, MFSK-8 and MFSK-16. MFSK-8 uses a set of 8 tones with equal distance of 15.625 Hz, MFSK-16 uses 16 tones with equal distance of 7.8125 Hz [II-5].

Continuous Phase Frequency Shift Keying (CPFSK)

Continuous Phase Frequency Shift Keying (CPFSK) is a modulation that, as its name implies, can be characterized as a traditional frequency shift keyed (FSK) signal constrained to maintain continuous phase at its symbol time boundaries. This constraint offers important advantages in error rate performance as well as signal spectrum containment. In this paper, the modulation is introduced and its relationship to the more general Continuous Phase Modulation (CPM) is outlined. The spectrum of CPFSK is presented and optimal coherent and noncoherent receiver structures are developed. Finally, the coherent and noncoherent error-rate performance of CPFSK is presented [II-6].

Gaussian Frequency Shift Keying (GFSK)

Gaussian Frequency Shift Keying (GFSK) is a modulation technique used in wireless communication systems to encode digital information by smoothly transitioning the carrier signal's frequency between different values. It employs a Gaussian filter to shape the baseband waveform signal before modulation, reducing the abrupt frequency changes typically associated with traditional FSK. GFSK is known for its robustness in the presence of interference and its ability to confine emissions to a narrow spectral band [II-7].

Minimum Shift Keying (MSK)

Another FSK variation that has received considerable interest is minimum-shift-keying (MSK). MSK is a special case of CP-FSK where $h = 1/2$ and coherent detection is used. MSK can be also interpreted as a special case of OQPSK with sinusoidal pulse weighting (Pasupathy 1979). This scheme possesses constant envelope which allows the use of power-efficient nonlinear amplifiers. This is very beneficial for high-power transmissions. Furthermore, since MSK is a variation of FSK, we can employ noncoherent detection (e.g., by means of a Discriminator). Gaussian MSK (GMSK), which has been used in the GSM mobile cellular system (Cox 1992), is a modified form of MSK where Gaussian low-pass filtering is used for pulse shaping, resulting in reduced out-of-band interference. [II-1].

2.7 FSK Applications

FSK modulation has numerous applications across various fields [II-8]:

- It offers reliable communication due to its resistance to noise and interference. It is simple to implement and is used in low power, low data rate communication systems like walkie-talkies and amateur radio [II-8].
- It is reliable in transmitting data in noisy environments and is efficient for transmitting low bandwidth data over long distances. In telemetry, it is used for transmitting sensor data from remote locations (controlling devices remotely) [II-8].
- It is used in modems for transmitting digital data over telephone lines due to its compatibility with existing telephone infrastructure [II-8].
- It offers effective and secure long distance communication and is used in satellite communication for telemetry, tracking, and command (TT&C) systems [II-8].
- It offers scalability and energy efficiency and is used in wireless sensor networks (WSNs) for battery operated and low power consuming devices [II-8].
- It provides accurate identification and tracking of objects or individuals and is used in Radio Frequency Identification (RFID) for retail, logistics, and access control [II-8].

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- It is used in digital radio systems for broadcasting audio as it delivers high quality audio with minimal interference and noise [II-8].

Future Outlook

As digital communication systems evolve, FSK continues to remain relevant due to its robustness and low complexity. Future development directions include: [II-8]

- Higher data throughput through advanced M-FSK schemes and improved signal processing
- Expanded adoption in low-power IoT where GFSK’s energy efficiency aligns with battery-constrained devices
- Integration with modern network frameworks, including NOMA and cooperative communication systems
- Enhanced coexistence and spectrum efficiency, enabling FSK to work alongside newer and more bandwidth-intensive modulation methods
- FSK is expected to remain a reliable and practical modulation technique for specialized communication scenarios where energy efficiency, stability, and low device complexity are essential. [II-8].

2.8 Comparison between FSK and Other Digital Modulations

In the field of wireless communication, the choice of modulation method is critical for signal transmission efficiency and anti-interference capability [II-9].

Characteristic	OOK	ASK	FSK	PSK
Core Principle	Carrier on/off	Varying amplitude	Varying frequency	Varying phase
Complexity	Simplest	Simple	Moderate	Highest
Data Rate	Low (<100 kbps)	Low to moderate	Moderate to high	High to very high
Anti-Interference	Weak	Weak	Strong	Strongest

Chapter II: FSK Modulation

Characteristic	OOK	ASK	FSK	PSK
Power Efficiency	High	Moderate	Moderate	Moderate to low
Applications	Remote controls	IoT sensors	Bluetooth, ZigBee	WiFi, 4G/5G

Listing 2.1: comparing between OOK, ASK, FSK and PSK

Comparison between ASK, FSK and PSK

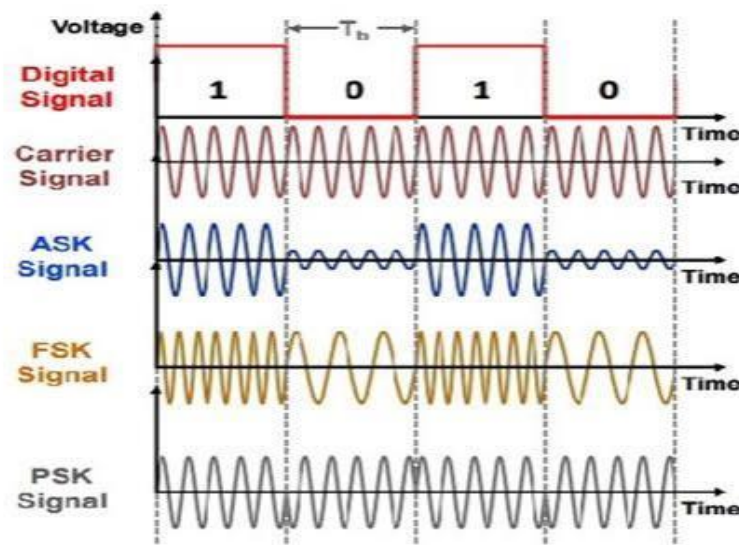


Figure 2.10: Comparison of ASK, FSK, and PSK modulation techniques

2.9 FSK Demodulation Detection

There are two types of demodulation detection:

Coherent FSK Detection

In this synchronous FSK detection, the modulated wave gets affected by noise while reaching the receiver. This noise can be eliminated using the bandpass filter (BPF). At the multiplier stage, the noisy FSK modulated signal is multiplied with the carrier signal from the local oscillator device. Then the resultant signal passes through the BPF. This bandpass filter is assigned to cut off frequency equal to the binary input signal frequency. The decision device gives 0 and 1 for space and mark frequencies of the FSK modulated waveforms [II-10].

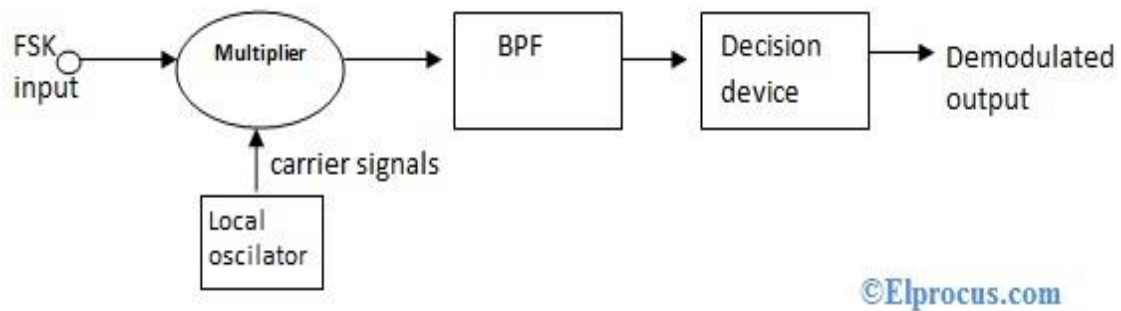


Figure 2.11: Coherent FSK detection block diagram

Non-coherent FSK Detection

The modulated FSK signal is forwarded from the bandpass filter 1 and 2 with cut off frequencies equals to space and mark frequencies. So, the unwanted signal components can be eliminated from the BPF. And the modified FSK signals are applied as input to the two envelope detectors. This envelope detector is a circuit having a diode (D). Based upon the input to the envelope detector it delivers the output signal. This envelope detector used in the amplitude demodulation process. Based upon its input it generates the signal and then it is forwarded to the threshold device. This threshold device gives the logic 1 and 0 for the different frequencies. This would be equal to the original binary input sequence. So, the FSK generation and detection can be done in this way. This process can be known for the frequency-shift keying modulation and demodulation experiment also. In this FSK experiment, FSK can be generated by the 555 timer IC and detection can be possible by 565IC which is known as a phase-locked loop (PLL). [II-10].

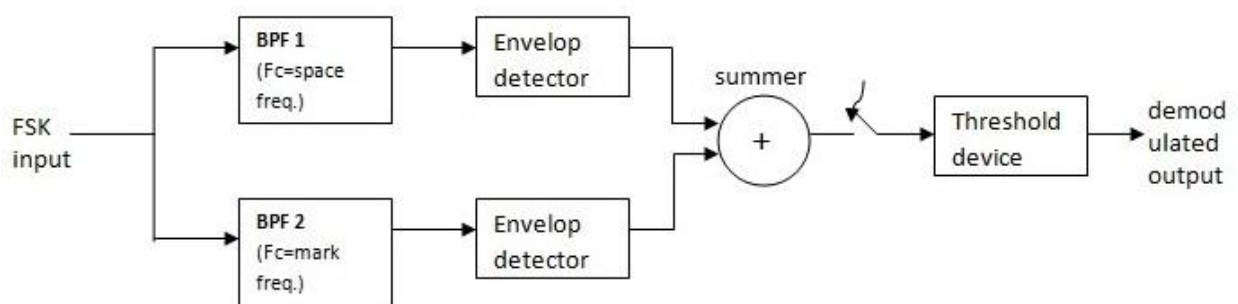


Figure 2.12: Non-coherent FSK detection using envelope detectors and a threshold device

2.10 Advantages and Disadvantages of FSK

Advantages

- It offers a lower probability of error (P_e) due to a higher SNR (Signal to Noise Ratio) [II-11].
- It has higher immunity to noise due to a constant envelope compared to ASK modulation, making it robust against variations in attenuation through the channel [II-11].
- The demodulation process for FSK signals is relatively simple, often requiring frequency discriminators or filters [II-11].
- FSK transmitter and FSK receiver implementations are simple for low data rate applications [II-11].

Disadvantages

- It uses larger bandwidth compared to other modulation techniques such as ASK and PSK. Hence, it is not bandwidth efficient [II-11].
- The BER performance in the AWGN channel is worse compared to PSK modulation [II-11].
- FSK may not be the ideal choice for mobile communication systems due to its potential vulnerability to frequency-selective fading [II-11].
- FSK modulation may exhibit reduced power efficiency compared to some other modulation schemes [II-11].
- FSK systems may require accurate frequency synchronization between the transmitter and receiver [II-11].

2.11 Bit Error Analysis of FSK Demodulation

The Bit Error Rate (BER) for FSK depends on whether the receiver is coherent (phase-synchronized) or non-coherent (simpler, no phase tracking) [II-12].

Coherent BFSK

In a coherent system, the receiver knows the exact phase of the carrier. This is more accurate but complex. The probability of error is defined by:

$$P_b = Q\left(\sqrt{\frac{E_b}{N_0}}\right) \dots \dots \dots (eq\ 2.6)$$

Where E_b is the energy per bit and N_0 is the noise power spectral density [II-12].

Non-coherent BFSK

Most standard FSK systems use non-coherent detection because it's cheaper and more robust against phase jitter. However, it requires a higher Signal-to-Noise Ratio (SNR) to achieve the same error rate:

$$P_b = \frac{1}{2} e^{-\frac{E_b}{2N_0}} \dots \dots \dots (eq 2.7)$$

Methods for Decreasing FSK Bit Error Rate

- M array Frequency Shift Keying (m-FSK): Increasing

(e.g., from 2-FSK to 4FSK or 8FSK) improves power efficiency, allowing for a lower BER at the same

However, this typically comes at the cost of reduced spectral efficiency and higher receiver complexity.

- Forward Error Correction (FEC): Implementing coding techniques such as Convolutional codes, Reed-Solomon codes, or Turbo codes adds redundancy, allowing the receiver to detect and correct transmission errors. Reed-Solomon codes are particularly effective for improving BER in noisy, multipath fading channels.
- Optimized Detection Techniques
- Coherent Detection: Ideal when perfect phase synchronization exists, generally offering better BER performance than non-coherent methods.
- Matched Filters: Used to maximize the received signal-to-noise ratio (SNR) in coherent FSK systems.
- Nonlinear Frequency Discriminator: Used in FSK receivers to reduce error floors, specifically by cutting off noise-induced bursts in the instantaneous frequency.
- Signal Conditioning and Filtering:
- Bandpass Filtering: Restricts the noise bandwidth to improve the SNR before demodulation.

- Equalization: Mitigates intersymbol interference (ISI) and frequency-selective fading.
- Higher SNR: Increasing the ratio of energy per bit to noise power density is the most direct way to reduce BER [II-12].

2.12 Real-World Applications of FSK

Walkie-Talkies (Two-Way Radios)

Walkie-talkies use FSK (or similar frequency-based modulation) to transmit voice/data signals by switching frequencies. FSK works well in noisy environments, is reliable over long distances, and is simple and robust [II-8].

- Works well in noisy environments
- Reliable over long distances
- Simple and robust



Figure 2.13: Walkie-talkie as a real-world FSK application

RFID Systems (Contactless Cards)

RFID systems use FSK to transmit data between the tag (card) and the reader. Applications include access control (doors), contactless payments, and inventory tracking [II-2].



Figure 2.14: RFID contactless card system using FSK

Wireless Sensor Networks (IoT)

Sensors send small amounts of data using FSK signals. FSK offers low power consumption, is good for battery-operated devices, and is reliable in harsh environments [II-8].

Why FSK:

- Low power consumption
- Good for battery-operated devices
- Reliable in harsh environments

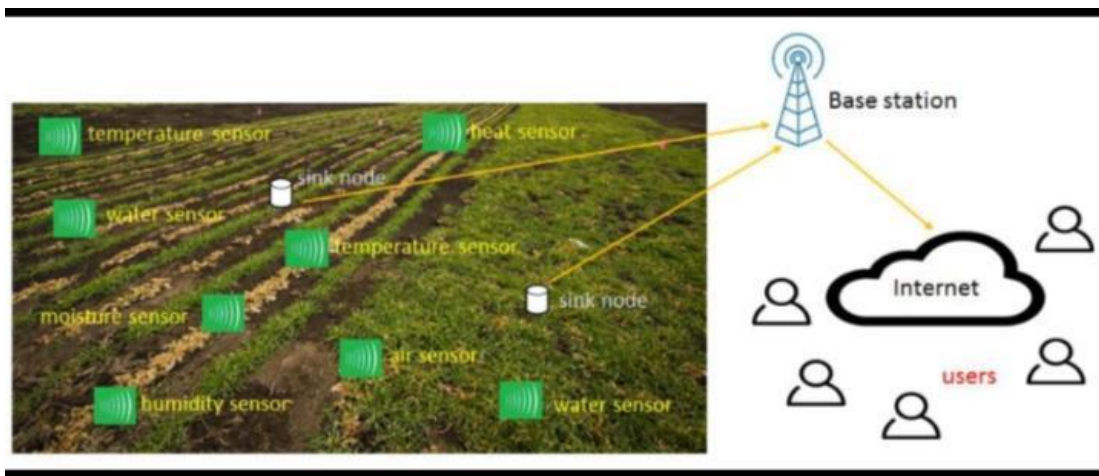


Figure2.15: Wireless sensor network node using FSK for low-power data transmission

Modems (Telephone Data Transmission)

Early modems used AFSK (Audio FSK) to send digital data over telephone lines. Examples include the Bell 103 modem and Caller ID systems [II-2].

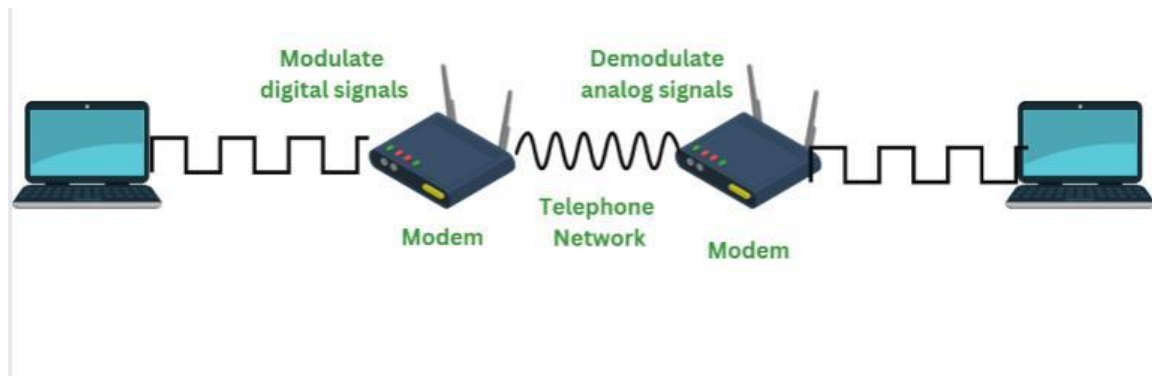


Figure 2.16: Early telephone modem using AFSK for data transmission

Satellite Communication (Telemetry)

FSK is used in Telemetry, Tracking, and Command (TT&C) systems. It is highly reliable, resistant to signal degradation, and suitable for long-distance communication [II-2].

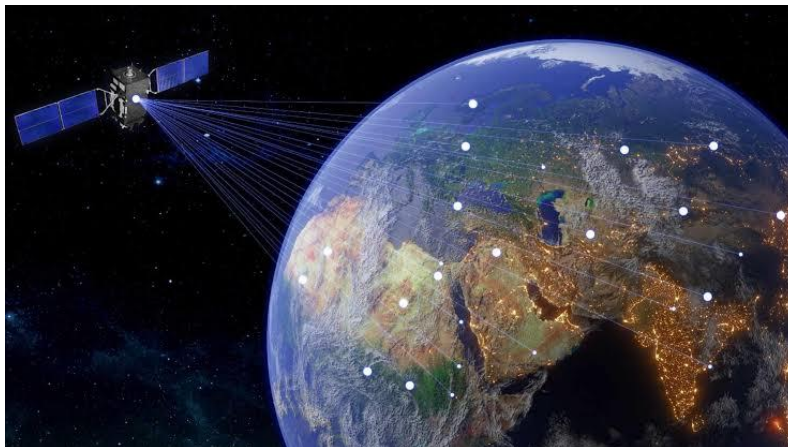


Figure 2.17: Satellite communication system using FSK for telemetry

Conclusion

Frequency Shift Keying (FSK) is a fundamental digital modulation technique that encodes information through variations in the frequency of a carrier signal. Throughout this chapter, we explored its historical development, operational principles, mathematical representation, and practical implementation through different system blocks.

FSK stands out for its robustness against noise and interference, making it highly suitable for reliable communication in challenging environments. Although it is less bandwidth-efficient compared to other modulation techniques such as PSK, its simplicity, constant envelope property, and ease of implementation ensure its continued relevance.

Chapter II: FSK Modulation

Various forms of FSK, including BFSK, MFSK, CPFSK, GFSK, and MSK, demonstrate the adaptability of this technique to different communication needs, from low-power IoT systems to wireless and satellite communications. Additionally, its applications in real-world systems such as RFID, telemetry, and early modems highlight its practical importance.

In conclusion, despite the evolution of more advanced modulation schemes, FSK remains a dependable and efficient choice for many communication systems where reliability, simplicity, and energy efficiency are critical.

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Chapter III:

Simulation of FSK Modulation and Demodulation using MATLAB and Simulink

3.2 introduction: What is MATLAB?

MATLAB is a programming and numeric computing platform for engineering and scientific applications like data analysis, signal and image processing, control systems, wireless communications, and robotics. MATLAB includes a programming language, interactive apps, highly specialized libraries, and tools for automatically generating embedded code. MATLAB is also the foundation for Simulink, a block diagram environment for simulating complex multi-domain systems [III-1].

3.3 MATLAB Code for FSK Simulation

The following MATLAB code implements FSK modulation and demodulation with visualization:

```
clear all;
close all;
clc;
N=10
% Number
% of bits
b =randi([0 1], 1, N);

n = length(b);
t = 0:.01:n;
x = 1:1:(n+1)*100;

for i = 1:n
    if (b(i) == 0)
        b_p(i) = -1;
    else
        b_p(i) = 1;
    end

    for j = i:.1:i+1
```

Chapter III: Simulation of FSK Modulation and Demodulation using MATLAB and Simulink

```
        bw(x(i*100:(i+1)*100)) = b_p(i);
    end
end

bw = bw(100:end);

% frequencies stay very close to each other (Narrowband).
wo = 10*(2*pi*t);    % Higher carrier frequency
W = 0.2*(2*pi*t);    % Small frequency deviation

sinHt = sin(wo + W);    % High frequency
sinLt = sin(wo - W);    % Low frequency
st = sin(wo + (bw).*W); % FSK signal

%% ===== Plotting =====
figure

subplot(4,1,1)
plot(t,bw,'LineWidth',1.5)
grid on
axis([0 n -2 +2])
title('Binary Polar Signal')
xlabel('Time')
ylabel('Amplitude')
legend('Binary Data')

subplot(4,1,2)
plot(t,sinHt,'LineWidth',1.5)
grid on
axis([0 n -2 +2])
title('High Frequency Carrier ( $f_H$ )')
xlabel('Time')
ylabel('Amplitude')
legend('sin( $\omega_o + \omega$ )')

subplot(4,1,3)
plot(t,sinLt,'LineWidth',1.5)
```

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```
grid on
axis([0 n -2 +2])
title('Low Frequency Carrier (f_L)')
xlabel('Time')
ylabel('Amplitude')
legend('sin(\omega_o - \omega)')

subplot(4,1,4)
plot(t,st,'LineWidth',1.5)
grid on
axis([0 n -2 +2])
title('FSK Modulated Signal')
xlabel('Time')
ylabel('Amplitude')
legend('FSK Signal')

%% ===== Spectrum =====
Fs = 1;
figure
periodogram(st)
title('Power Spectral Density of FSK Signal')
xlabel('Frequency')
ylabel('Power/Frequency')
grid on
```

Listing 3.1: MATLAB initialization and FSK signal generation [III-2]

Code Explanation

Initialization: The script starts by clearing the workspace and command window.

Random binary sequence : generating a random binary sequence of N(10) Bits

Bit Representation: The code maps binary 0 to -1 and binary 1 to +1. This is represented by b_p.

Chapter III: Simulation of FSK Modulation and Demodulation using MATLAB and Simulink

```
Enter the Bit stream
[0 1 0 1 1 1 0]
Demodulated Bits:
    0     1     0     1     1     1     0
```

Figure 3.1: Binary polar signal representation

Waveform Generation: Sine waves are generated for the higher frequency ($\sin Ht$) and lower frequency ($\sin Lt$) carriers, keeping them close in value so we get a narrowband fsk ,The st variable holds the final FSK modulated signal.

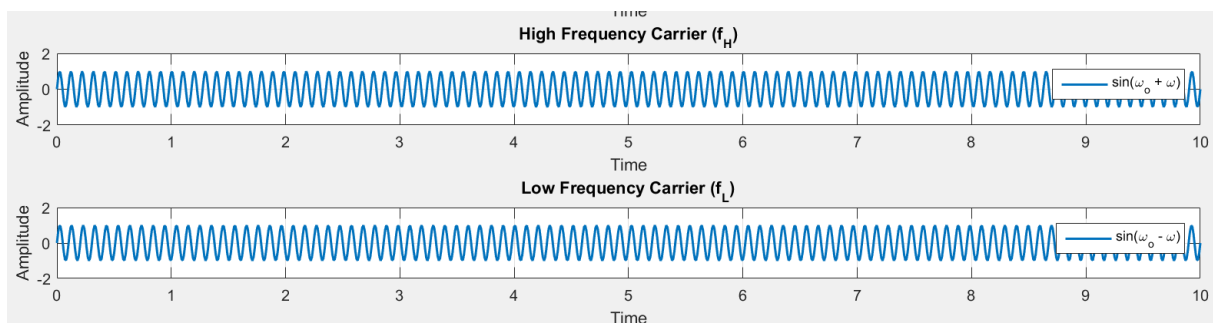


Figure 3.2: High and low modulating frequencies

Plotting

: The code plots the following in subplots:

Binary data representation.

High-frequency carrier.

Low-frequency carrier.

FSK modulated signal.

Chapter III: Simulation of FSK Modulation and Demodulation using MATLAB and Simulink

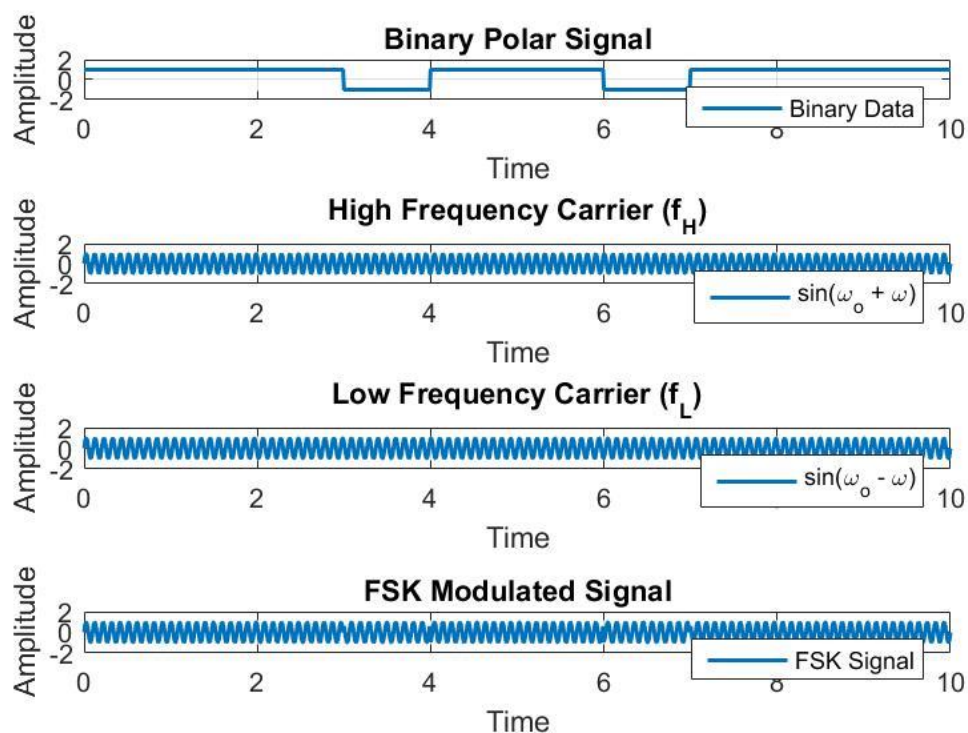


Figure 3.3: process of fsk modulation using matlab script plotting

Periodogram: A periodogram is generated to display the frequency spectrum of the FSK signal.

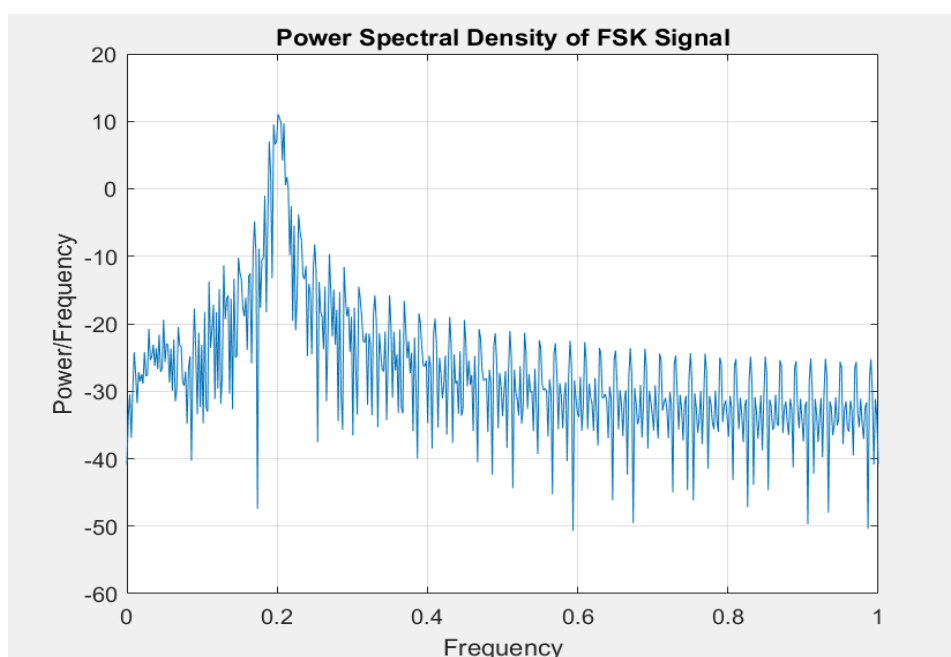


Figure 3.4: Power spectral density of FSK signal

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FSK Demodulation Code

The received signal is divided into time intervals, each corresponding to one bit. For every interval, the signal is compared with two reference signals: a high frequency (representing bit 1) and a low frequency (representing bit 0). The receiver determines which frequency is more dominant and assigns the corresponding bit value [III-3].

```
%% ===== FSK Demodulation =====

% Reference signals (same as carriers)
refH = sin(wo + W);    % High frequency reference
refL = sin(wo - W);    % Low frequency reference

% Initialize
demod_bits = zeros(1,n);

for i = 1:n
    % Extract one bit duration (100 samples per bit)
    idx_start = (i-1)*100 + 1;
    idx_end   = i*100;

    segment = st(idx_start:idx_end);

    % Correlate with both references
    corrH = sum(segment .* refH(idx_start:idx_end));
    corrL = sum(segment .* refL(idx_start:idx_end));

    % Decision
    if corrH > corrL
        demod_bits(i) = 1;
    else
        demod_bits(i) = 0;
    end
end

disp('Demodulated Bits:')
disp(demod_bits)

%% ===== Demodulated Signal Plot =====
```

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```
t = 0:0.01:n-0.01;    % Ensure correct length

demod_wave = repelem(2*demod_bits - 1, 100);

figure
plot(t, demod_wave, 'LineWidth',1.5)
grid on
ylim([-1.5 1.5])
title('Demodulated Signal')
xlabel('Time')
ylabel('Amplitude')
legend('Recovered Data')
```

Listing 3.2: matlab code for FSK demodulation [III-2]

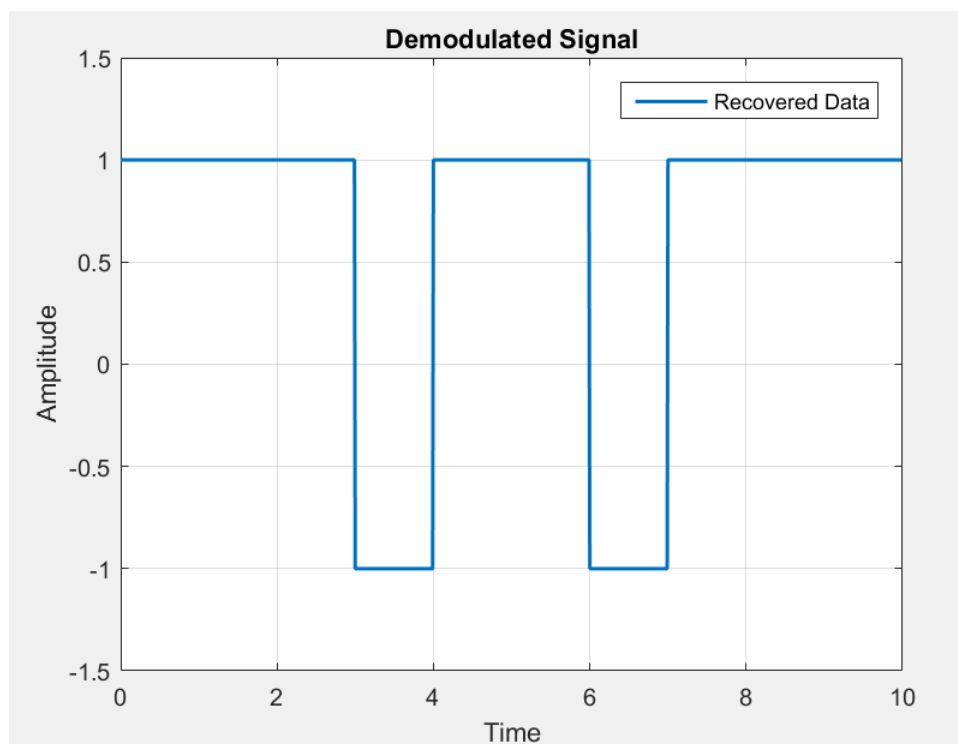


Figure 3.5: Restored signal after demodulation

3.4 Simulink Simulation

What is Simulink?

Chapter III: Simulation of FSK Modulation and Demodulation using MATLAB and Simulink

Simulink is a functional diagram environment for multi-domain simulation and Model-Based Design. It supports system-level design and simulation, automated code generation, and continuous testing and verification of embedded systems [III-3].

Simulink offers a graphical editor, a customizable set of block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, allowing you to incorporate MATLAB algorithms into models and export simulation results back to MATLAB for further analysis [III-3].

The main features of SIMMULINK are:

- Graphical editor for creating and managing hierarchical functional diagrams.
- Predefined block libraries for modeling continuous-time or discrete-time systems.
- Simulation engine with fixed or variable step ODE solvers.
- Scopes and data display for viewing the simulation result.
- Data and project management tools for model data and files.
- Model analysis tools for refining model architecture and increasing simulation speed.
- MATLAB Function block for importing MATLAB algorithms into models.
- Legacy Code Tool for quickly importing existing C and C++ code into models [III-3]

How Does Simulink Work?

Simulink provides a library browser that allows you to select blocks from libraries of standard blocks and a graphical editor that allows you to draw lines connecting the blocks. You can model virtually any real-world dynamic system by selecting and interconnecting the appropriate Simulink blocks [III-4].

Block Diagrams

A Simulink block diagram is a pictorial model of a dynamic system. It consists of a set of symbols, called blocks, interconnected by lines. Each block represents an elementary dynamic system that produces an output either continuously (a continuous block) or at specific points in time (a discrete block). The lines represent connections of block inputs to block outputs. Every block in a block diagram is an instance of a specific type of block. The type of the block determines the relationship between a block's outputs and its inputs, states, and time. A block

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diagram can contain any number of instances of any type of block needed to model a system. [III-4].

Simulink Block Types

Blocks represent elementary dynamic systems that Simulink knows how to simulate. A block comprises one or more of the following: a set of inputs, a set of states, and a set of outputs.

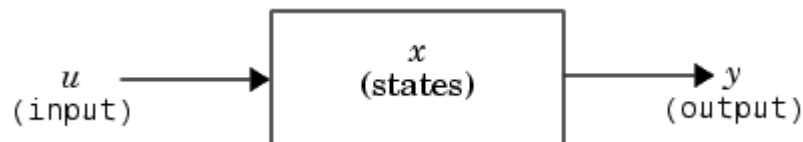


Figure 3.6 example of a Simulink block

A block's output is a function of time and the block's inputs and states (if any). The specific function that relates a block's output to its inputs, states, and time depends on the type of block of which the block is an instance [III-4].

3.5 Creating FSK Modulation Simulation in Simulink

The following steps describe how to build the FSK modulation and demodulation model in Simulink after creating a new Simulink model [III-5]:

Binary Source Code

1. In the library browser, search 'Bernoulli Binary Generator' block then drag it to the Simulink model. This component generates a random binary code for modulation.
2. Search for a 'gain' block then change the gain in it to 2, search a 'bias' block then change the bias to -1, those 2 block turn the binary code into NRZ (no return to zero) code which turns the 0 value into -1
3. Connect the three blocks in order to generate the binary source code.
4. Connect the bias block output to a Scope block input to view the NRZ code.

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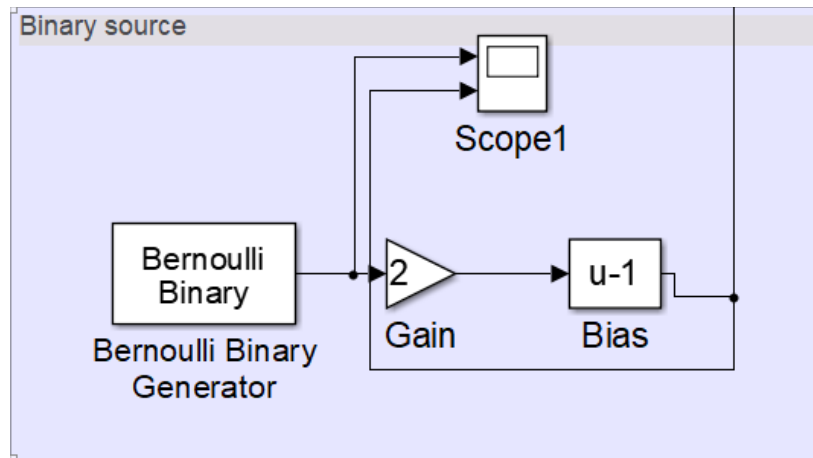


Figure 3.7: Simulink block diagram of NRZ code generator

FSK modulator

Search for 'sine wave' block and drag 2 of it to the model

change the frequency in first sine wave to ' $2\pi \cdot 11.4$ ' and sample time to 0.01

change the frequency in second sine wave to ' $2\pi \cdot 10.6$ ' and sample time to 0.01

those blocks represent the high frequency and the low frequency in our simulation

we keep those frequencies very close in value so we satisfy the condition of our modulation being narrowband

1. Search for 'switch' block and drag it to the model.

Connect the high frequency to the top port of the switch and the low frequency to the bottom port of switch and the source code to the middle port .

The source code represents a control signal for the switch, if the control is greater than 0 , the switch takes the high frequency , and if its less than 0 it takes the low frequency , and thats how the modulated signal is generated

Connect the output of the switch block to a scope for visualising

2. (optional) Create an area for those 4 block and name it 'FSK modulation'

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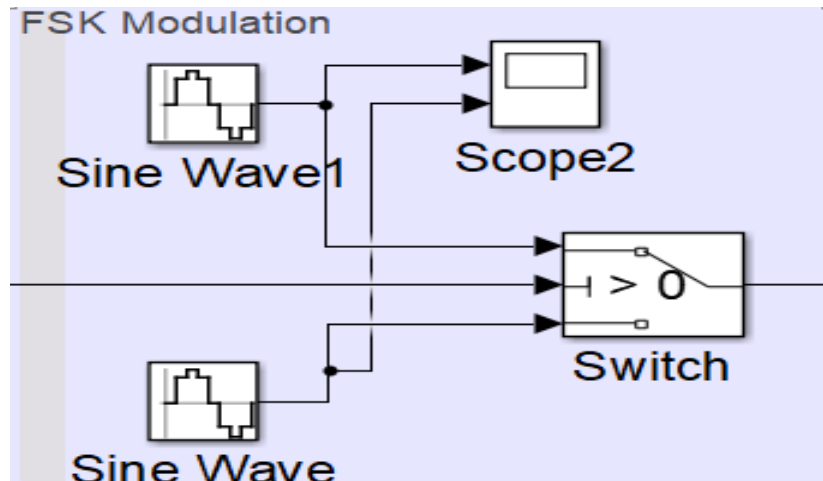
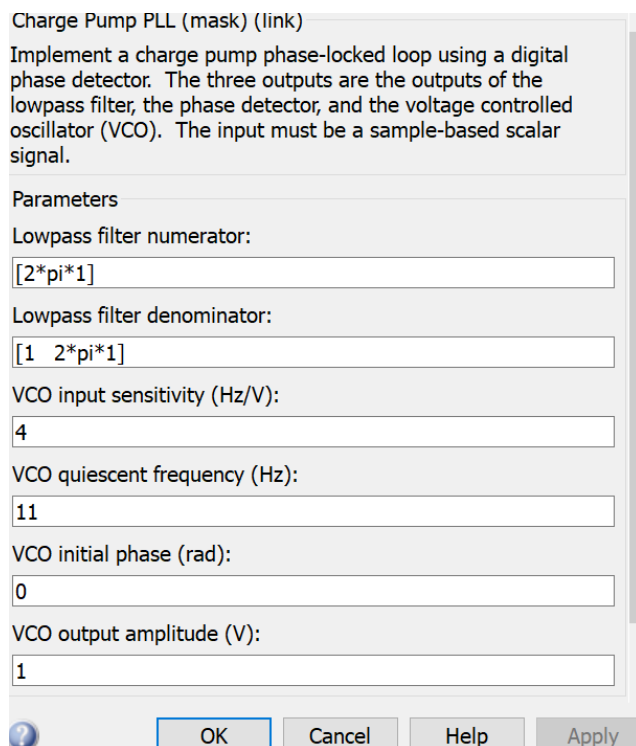


Figure 3.8: Simulink block diagram of FSK modulator

FSK Demodulator

1. Search for 'Charge Pump PLL' block and drag it to the model then connect then connect the switch output (modulated signal) to its input , change its parameters into the following



This component locks into the frequency of the signal coming to it and converts it into voltage

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High frequency = high voltage

Low frequency = low voltage

2. Search 'constant' block and change the constant in it to 0

This block acts as the threshold reference, it compares the PLL voltage to 0

3. Search for 'relational operator' block and drag it to the model, change the operation to '>' then connect the top output the PLL to the top input of the relational operator and constant output to the bottom input of the relational operator

This block checks the pll output and compares to the constant block output (0)

if the pll output is greater than 0 then the output is 1

and if the pll output is less than 0 then the output is 0

and thats how we get the restored data after demodulation

connect the output of the relational operator to a scope to visualise the demodulated signal

4. (optional) Create an area for those 3 blocks named 'FSK demodulation'

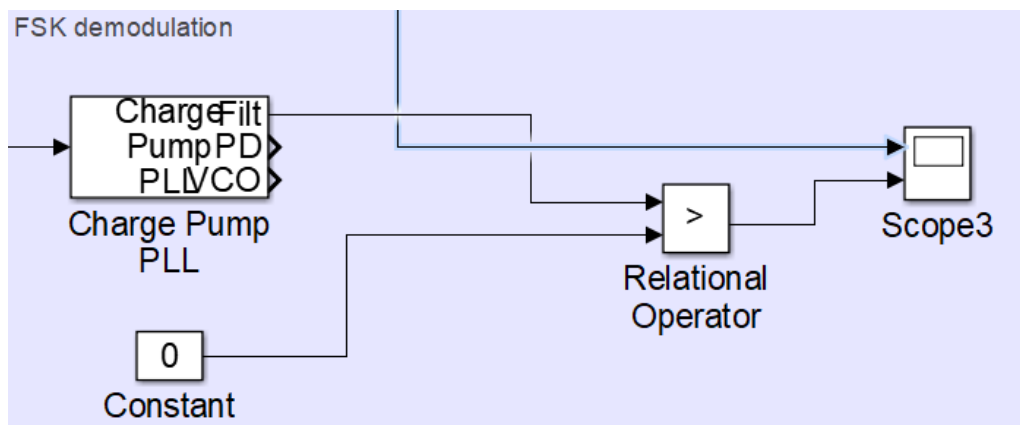


Figure 3.9: Simulink block diagram of FSK demodulator

Complete Block Diagram

Below is the complete FSK modulation and demodulation block diagram showing all components connected together:

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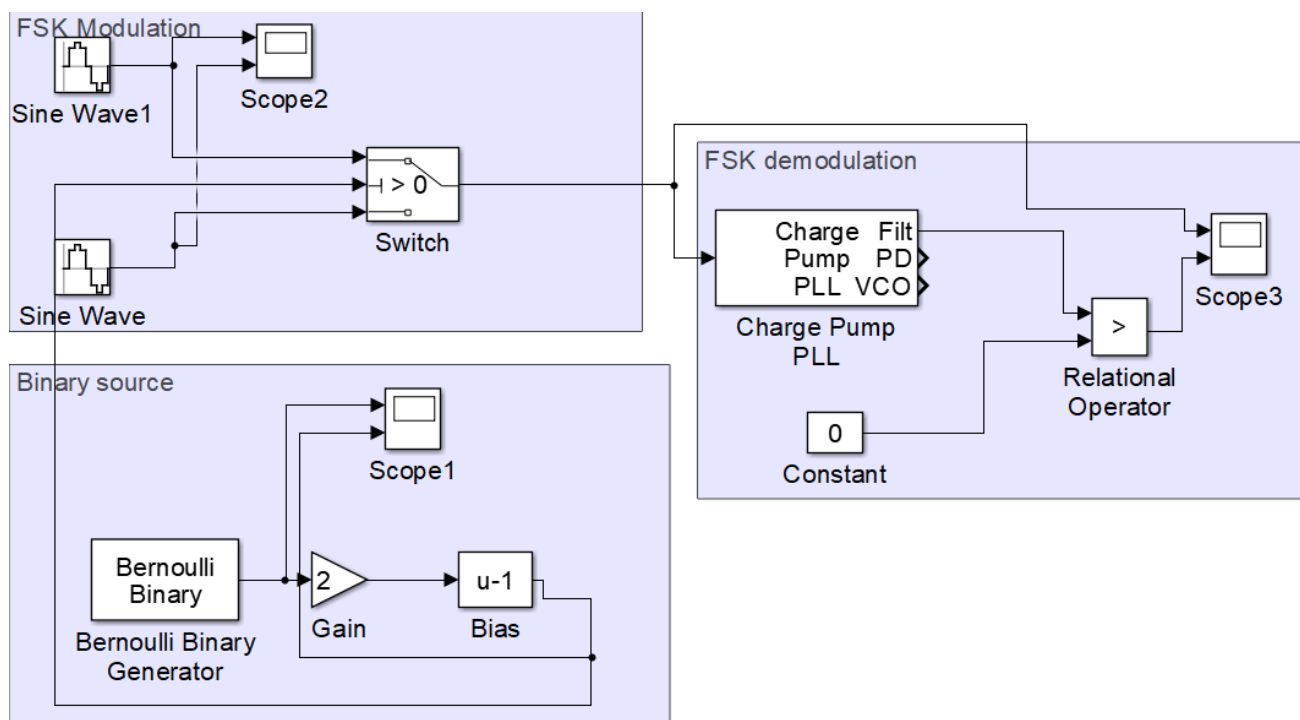


Figure 3.10: Complete Simulink block diagram of FSK modulation and demodulation

3.6 Visualization Results

To visualize the results, click the run button , then click each scope to see the displayed figures:

Scope 1: Binary NRZ Source Code

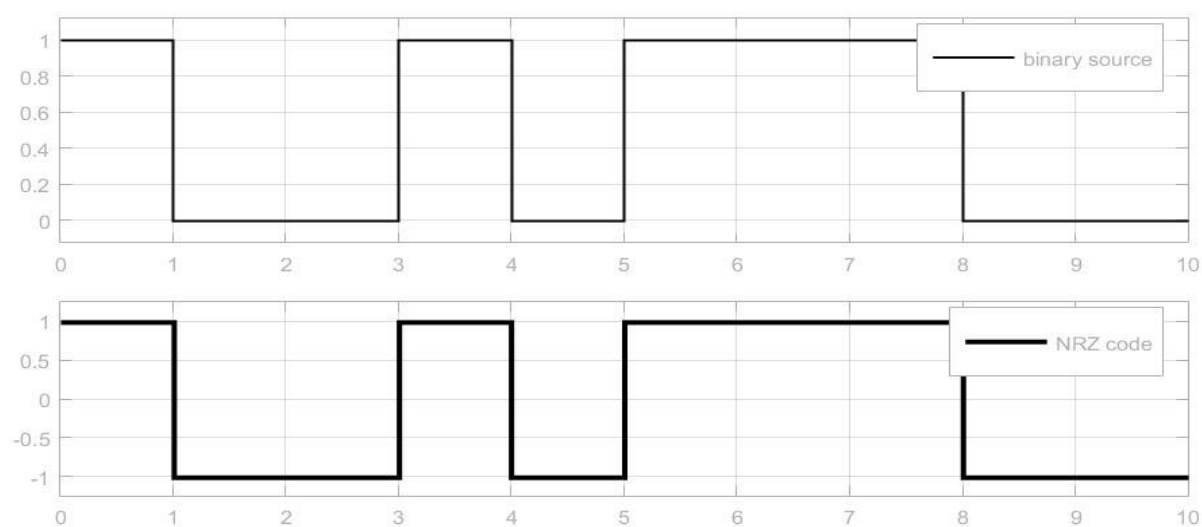


Figure 3.11: Binary and NRZ source codes (shown in scope block)

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The first scope is connected to the output of the Bias block and displays two superimposed signals: the original binary sequence and its NRZ (Non-Return-to-Zero) equivalent. The binary signal is a rectangular pulse train that alternates between the logic levels 0 and 1 at the rate defined by the Bernoulli Binary Generator. The NRZ conversion, applied by the Gain ($\times 2$) and Bias (-1) blocks in series, transforms this into a bipolar signal that switches between -1 (for binary 0) and $+1$ (for binary 1).

This bipolar NRZ format is critical for the correct operation of the Switch block downstream. The Switch block uses the middle input as a control signal and routes the top input (high-frequency carrier) when the control exceeds 0, or the bottom input (low-frequency carrier) when it falls below 0. Without the NRZ conversion, a binary 0 value would produce a control signal of exactly 0, causing ambiguous switch behavior. The NRZ encoding eliminates this ambiguity by ensuring the control signal is always clearly positive ($+1$) or negative (-1).

Observing this scope during simulation, the transitions between -1 and $+1$ appear as clean, sharp edges synchronized with the bit clock. The time axis represents the simulation time in seconds, and the amplitude axis spans from -1.5 to $+1.5$ to accommodate both NRZ levels with visual margin.

Scope 2: Frequencies

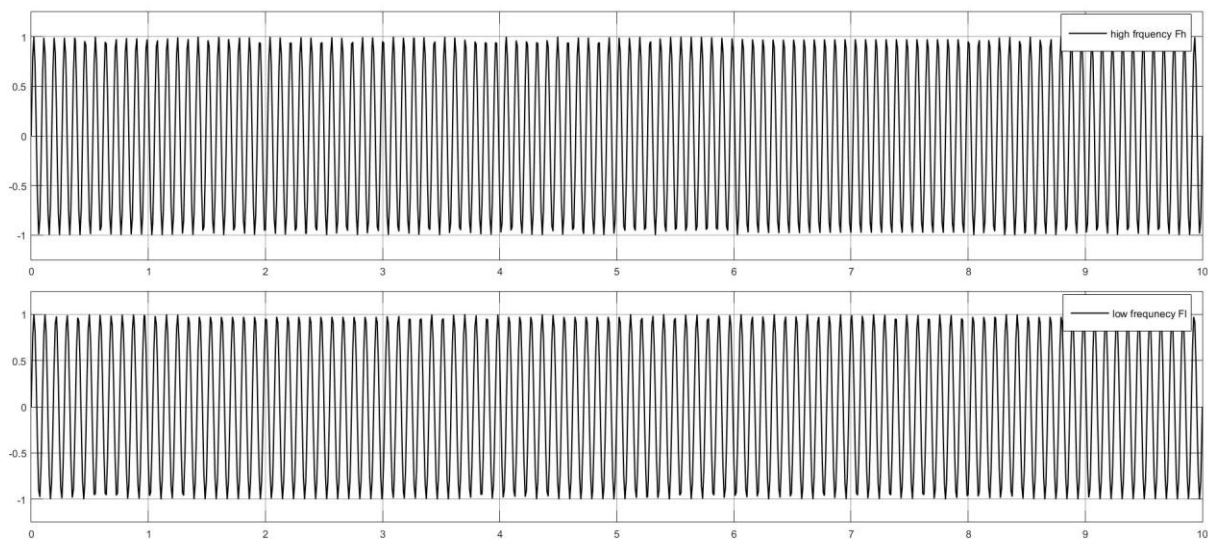


Figure 3.12: High and low frequencies (shown in scope block)

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The second scope is connected directly to the outputs of both Sine Wave blocks, displaying the two carrier sinusoids simultaneously. The high-frequency carrier, set to $f_1 = 11.4$ Hz (angular frequency $2\pi \times 11.4$ rad/s), completes three full oscillation cycles per unit time, while the low-frequency carrier, set to $f_0 = 10.6$ Hz (angular frequency $2\pi \times 10.6$ rad/s), completes only one cycle in the same interval. This frequency ratio is not visible in the scope display: but it satisfies the condition of FSK modulation being narrowband $h < 1$.

Both carriers share the same amplitude (1 V peak) and sample time (0.01 s), meaning they are sampled at 100 samples per second. At this sample rate, the Nyquist criterion is comfortably satisfied for both frequencies (Nyquist limit = 50 Hz), ensuring accurate digital representation of both sinusoids. The scope provides visual confirmation that the two oscillator blocks are generating the correct waveforms before they reach the Switch block.

This display is also useful for verifying frequency stability during simulation. Since both sine waves are generated by independent blocks, any configuration error — such as a mistyped frequency parameter — would be immediately visible as an unexpected oscillation rate in one of the traces. The scope thus serves as an intermediate checkpoint in the modulation chain.

Scope 3: Modulated and Demodulated Signals

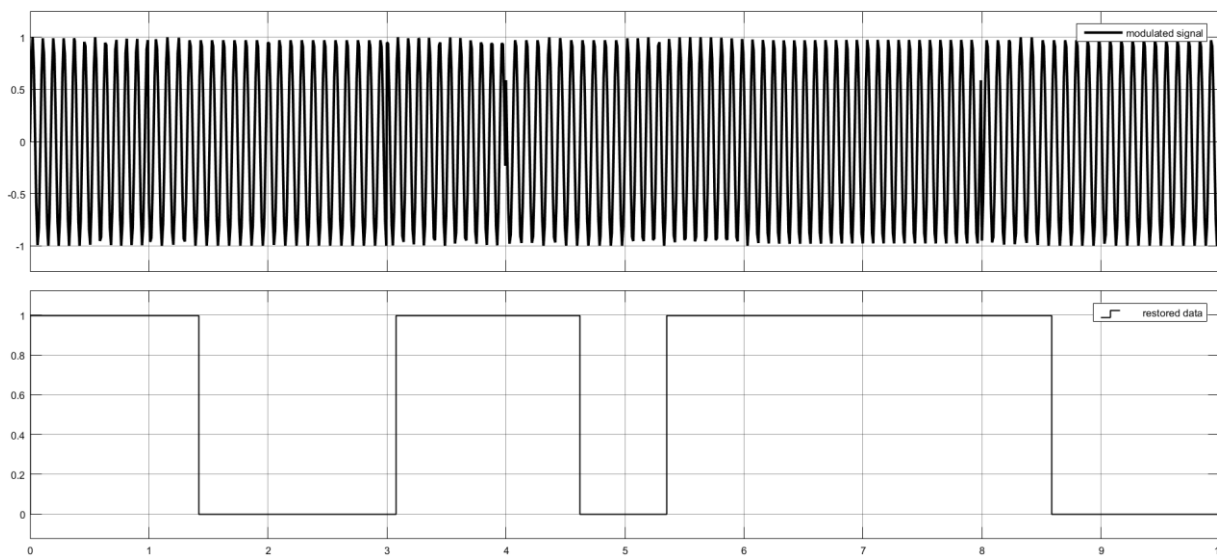


Figure 3.13: Modulated signal and restored data (shown in scope block)

The third scope is the most informative of the three, simultaneously displaying the FSK modulated signal at the output of the Switch block and the recovered digital data at the output of the Relational Operator block. These two traces together demonstrate the complete modulation-demodulation cycle in a single view.

The upper trace shows the FSK modulated signal. Its most distinctive visual feature is the frequency switching: during bit periods where the NRZ control signal is +1 (binary 1), the

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waveform oscillates at the high frequency (11.4 Hz), completing three cycles per bit period. During bit periods where the NRZ control signal is -1 (binary 0), the waveform oscillates at the low frequency (10.6 Hz), completing only one cycle per bit period. The amplitude remains perfectly constant throughout — a visual confirmation of the constant-envelope property of FSK. At each bit boundary, the frequency switches instantaneously, producing the characteristic "frequency-keyed" appearance that gives FSK its name.

The lower trace shows the binary output of the Relational Operator block, which compares the PLL output voltage against the zero threshold. It is a rectangular pulse train taking values of 0 or 1. Observing both traces in alignment, it is clear that the demodulated output correctly tracks the original data stream: a high-frequency region in the upper trace corresponds to a logic 1 in the lower trace, and a low-frequency region corresponds to a logic 0. The slight temporal delay between the modulated signal transitions and the demodulated output transitions is attributable to the settling time of the Charge Pump PLL — the time the PLL requires to lock onto the new frequency after each bit transition. This delay is a known characteristic of PLL-based non-coherent FSK receivers and does not affect the final bit decision as long as the PLL settles within the bit period.

Together, the three scopes provide a complete visual walkthrough of the FSK simulation: Scope 1 confirms correct data formatting, Scope 2 confirms correct carrier generation, and Scope 3 confirms correct modulation and successful demodulation — validating every stage of the Simulink model.

3.7 Comparison: MATLAB Script vs. Simulink Model

Both approaches simulate the same FSK modulation and demodulation process, but they differ significantly in methodology, flexibility, and use case.

Aspect	MATLAB Script	Simulink Model
Design Approach	Text-based programming	Graphical block diagram
Ease of Use	Requires MATLAB syntax knowledge	Intuitive drag-and-drop
Modulation	Mathematical $\sin(\omega_0 \pm \omega)$ formula	Switch block with sine waves
Demodulation	Correlation-based detection	PLL-based frequency tracking

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Aspect	MATLAB Script	Simulink Model
Signal Source	User-defined fixed bit stream	Random continuous bit stream
Visualization	Static figures after simulation	Real-time scope displays
Flexibility	Highly flexible, any parameter	Flexible via block parameters
Code Generation	MATLAB Coder for C code	Automatic HDL/C++ generation
Best For	Academic analysis, BER studies	Hardware prototyping, real-time

Listing 3.3: comparing between MATLAB and SIMULINK

Demodulation Techniques Analysis

MATLAB implements coherent FSK demodulation using a correlator receiver. For each bit interval, the received signal is multiplied by two locally-generated reference carriers, and the products are integrated over the bit period. The bit decision is made by comparing the two correlation values. This method is theoretically optimal in an AWGN channel [III-5].

The Simulink model uses a Charge Pump PLL (Phase-Locked Loop) block, which represents a non-coherent or frequency-tracking demodulation approach. The PLL continuously tracks the instantaneous frequency and produces a proportional output voltage. A comparator then makes the bit decision. This approach is closer to how a real hardware FSK receiver operates [III-3]

Conclusion : Which Approach to Choose?

Use the MATLAB Script when: you need to study signal theory in depth, compute BER versus SNR performance curves, test different detection algorithms, or process a specific known bit sequence for academic purposes.

Use the Simulink Model when: you want to prototype a system that closely resembles real hardware, simulate real-time continuous data streams, or eventually generate code for deployment on an embedded platform or FPGA.

Chapter 3 References

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- [III-3] MATLAB Pour Tous, “Présentation de Simulink,” matlabpourtous.com/presentation-de-simulink/
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General conclusion

General Conclusion

1. Summary of Work Accomplished

This project set out to study, simulate, and implement narrowband Frequency Shift Keying (FSK) digital modulation — a technique that encodes binary data through discrete changes in carrier frequency rather than amplitude or phase. The work was structured across three progressive chapters, each addressing a distinct layer of understanding: theoretical foundations, in-depth technical analysis of FSK, and practical simulation using industry-standard software tools.

Chapter 1 established the conceptual landscape by reviewing the full spectrum of modulation techniques — from classical analogue methods such as Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM) to the three principal digital modulation schemes: Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). This comparative overview positioned FSK clearly within the broader context of digital communications, highlighting the trade-offs between noise immunity, bandwidth efficiency, power consumption, and implementation complexity [I-1].

Chapter 2 provided a rigorous and comprehensive examination of FSK itself. Beginning with the historical roots of the technique — from Reginald Fessenden's two-tone Morse experiments in 1910 to modern GFSK implementations in Bluetooth and IoT — the chapter progressed through the mathematical formulation of the FSK signal, the functional roles of each block in the modulation and demodulation chain, and the performance characteristics of both coherent and non-coherent detection. The chapter further examined the principal FSK variants (BFSK, MFSK, CPFSK, GFSK, and MSK) and surveyed the real-world application domains in which FSK continues to play an indispensable role [II-1].

Chapter 3 translated theoretical knowledge into practical realisation by implementing FSK modulation and demodulation in two complementary environments: a MATLAB script employing correlation-based coherent detection, and a Simulink block-diagram model using a Charge Pump Phase-Locked Loop (PLL) for non-coherent frequency tracking. Both implementations were validated through scope visualisations and a comparative analysis, demonstrating that each tool offers distinct advantages depending on the engineering objective [III-5, III-6]

General conclusion

2. Key Technical Findings

The study yielded several significant technical conclusions regarding the properties and performance of FSK modulation:

- **Robustness as the defining advantage:** FSK's most important property is its constant-envelope waveform. By encoding information in frequency rather than amplitude, the modulated signal is inherently resistant to amplitude noise, fading, and non-linear amplifier distortion. This characteristic renders FSK superior to ASK in virtually all practical channel conditions.
- **Demodulation strategy governs BER performance:** The study confirmed that coherent BFSK detection, which exploits knowledge of the carrier phase, outperforms non-coherent detection in terms of bit error rate (BER) at any given signal-to-noise ratio (SNR). The coherent BER follows $P_b = (1/2) \operatorname{erfc}(\sqrt{E_b/2N_0})$, while the non-coherent BER is given by $P_b = (1/2) \exp(-E_b/2N_0)$, requiring a higher SNR to achieve equivalent reliability. Nevertheless, non-coherent detection remains the preferred approach in practical hardware systems due to its lower complexity and greater robustness against phase jitter.
- **FSK variants extend the design space:** The five main FSK variants — BFSK, MFSK, CPFSK, GFSK, and MSK — each represent a specific engineering trade-off. CPFSK and GFSK improve spectral containment by eliminating abrupt phase discontinuities; MSK achieves minimum bandwidth at a modulation index of 0.5; and MFSK increases power efficiency by transmitting multiple bits per symbol, albeit at the cost of bandwidth. This flexibility makes FSK adaptable across a wide range of application requirements.
- **MATLAB vs. Simulink — complementary, not competing:** The comparative simulation study established that MATLAB scripting and Simulink modelling serve distinct but complementary purposes. MATLAB is best suited for academic analysis, BER curve generation, and algorithm-level signal processing studies. Simulink, by contrast, excels at system-level prototyping, real-time signal visualisation, and the generation of deployable code for embedded targets — making it closer to a real hardware design flow.

3. Persistent Relevance of FSK in Modern Systems

A recurring theme throughout this project has been the continued practical relevance of FSK despite the dominance of higher-order modulation schemes in bandwidth-intensive applications. FSK's combination of implementation simplicity, constant-envelope robustness,

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and low power consumption ensures its enduring presence across a diverse set of critical technologies:

- **Satellite Telemetry and Tracking (TT&C):** FSK provides reliable one-way data links over extreme distances where signal fading and Doppler shift make amplitude-sensitive schemes impractical.
- **RFID and Contactless Identification:** The frequency-switching mechanism of FSK is ideally suited to the simple transponder circuits of passive RFID tags, enabling reliable, low-cost identification in retail, logistics, and access control.
- **Wireless Sensor Networks and IoT:** GFSK's narrow spectral footprint and energy efficiency align precisely with the battery-constrained, low-data-rate requirements of IoT edge devices.
- **Industrial SCADA Systems:** FSK's noise immunity makes it reliable for supervisory control and data acquisition over electrically noisy industrial environments.
- **Emergency and Amateur Radio Communication:** The robustness of FSK over degraded high-frequency (HF) radio channels makes it a standard for emergency communications and amateur radio teletype (RTTY).

These applications confirm that FSK is not a legacy technology awaiting obsolescence, but rather a mature, well-understood modulation scheme that continues to be selected — deliberately and appropriately — where its properties provide a decisive advantage over more complex alternatives.

4. Perspectives and Future Directions

While this project has provided a thorough treatment of narrowband FSK within the scope of a Master's end-of-study project, several directions remain open for further investigation and development.

From a theoretical standpoint, the extension of the BER analysis to include frequency-selective fading channels — such as Rayleigh or Rician models — would provide a more realistic characterisation of FSK performance in mobile and wireless environments. Similarly, an investigation of diversity reception techniques or forward error correction (FEC) coding schemes applied to FSK systems could quantify achievable gains in reliability without increasing transmit power.

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On the implementation side, the realisation of the FSK modem on programmable hardware — such as a Field-Programmable Gate Array (FPGA) or a software-defined radio (SDR) platform — would constitute a natural and valuable next step, bridging the gap between Simulink-level prototyping and physical deployment. Simulink's automatic HDL code generation capability, introduced in Chapter 3, provides a direct pathway for this transition.

Furthermore, the study of hybrid and advanced FSK variants merits attention. Minimum Shift Keying (MSK) and its Gaussian-filtered derivative (GMSK), which underpins GSM mobile communications, represent extensions of the core FSK concept that achieve significantly improved spectral efficiency. Investigating the conditions under which such variants offer advantages over conventional binary FSK would enrich the design methodology available to the telecommunications engineer.

Finally, the integration of FSK within emerging network paradigms — including Non-Orthogonal Multiple Access (NOMA), cooperative relay networks, and low-power wide-area networks (LPWAN) such as LoRa — represents a promising frontier where the simplicity and robustness of FSK can be leveraged within architectures designed for the next generation of connected devices.

5. Closing Statement

Frequency Shift Keying stands as one of the most enduring and instructive techniques in the field of digital communications. Its conception as a solution to the fundamental vulnerability of amplitude-based encoding — and its subsequent evolution into a family of sophisticated variants deployed in systems ranging from Bluetooth headsets to satellite command links — traces a compelling arc from early radio engineering to the present day.

This project has demonstrated that a deep understanding of FSK, encompassing its mathematical foundations, system architecture, demodulation theory, and simulation methodology, constitutes an essential component of a telecommunications engineer's knowledge base. The skills developed through this work — theoretical analysis, MATLAB signal processing, and Simulink system modelling — provide a transferable framework applicable to the study and design of a broad range of modern communication systems.

In conclusion, FSK is neither obsolete nor merely transitional. It is a rigorously understood, practically validated, and actively deployed modulation technique whose simplicity, robustness, and adaptability ensure its continued relevance in the evolving landscape of digital

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communications. The results obtained in this project confirm its value both as an object of academic study and as a tool of practical engineering.