CONTENTS

LEARNING OBJECTIVES

After studying this lecture, students should be able to:

1. Understand the basic concept of **digital modulation** in communication systems.
2. Explain the principle of **Frequency Shift Keying (FSK)** and how it represents binary data.
3. Describe different **FSK demodulation techniques**, including coherent and non-coherent detection.

4. Understand the operation of **matched filters and correlators** used in signal detection.

5. Explain the concept of **optimum frequency separation and orthogonality in BFSK**.

6. Analyze the **bandwidth requirements of FSK signals**.

7. Understand the principle of **Phase Shift Keying (PSK)** modulation.

8. Describe **Binary Phase Shift Keying (BPSK)** and its signal representation.

9. Explain different **BPSK detection methods**, such as correlator detection, square-law detection, and Costas loop.

10. Evaluate the **bandwidth efficiency and performance advantages of PSK** in digital communication systems.

1 INTRODUCTION

Digital modulation is a fundamental technique used in modern communication systems to transmit digital data efficiently and reliably over communication channels. In digital modulation, certain characteristics of a carrier signal—such as **frequency, phase, or amplitude**—are varied according to the digital information being transmitted.

Two important digital modulation techniques are **Frequency Shift Keying (FSK)** and **Phase Shift Keying (PSK)**. In **FSK**, the frequency of the carrier signal changes to represent binary data (0 and 1), while the amplitude and phase remain constant. This method provides good immunity to noise and is widely used in digital communication systems.

In **PSK**, the phase of the carrier signal is varied according to the digital input signal, while the frequency and amplitude remain constant. PSK techniques, such as **Binary Phase**

Shift Keying (BPSK) and **Quadrature Phase Shift Keying (QPSK)**, allow efficient transmission of digital data and provide better performance in noisy communication environments.

Understanding the principles of these modulation techniques, along with their **demodulation methods, bandwidth requirements, and error performance**, is essential for designing reliable communication systems used in many applications including **medical communication systems, wireless networks, and digital data transmission**.

2 FREQUENCY - SHIFT KEYING (FSK)

In a frequency - shift keying, the instantaneous frequency of the carrier signal is switched between two (or more) values in response to the PCM code. The frequency of the carrier signal is varied to represent binary 1 or 0 the frequency of the signal during each bit duration is constant, and its value depends on the bit (0 or 1): both peak amplitude and phase remain constant. Figure (1) shows an ideal FSK signal corresponding to the binary PCM code.

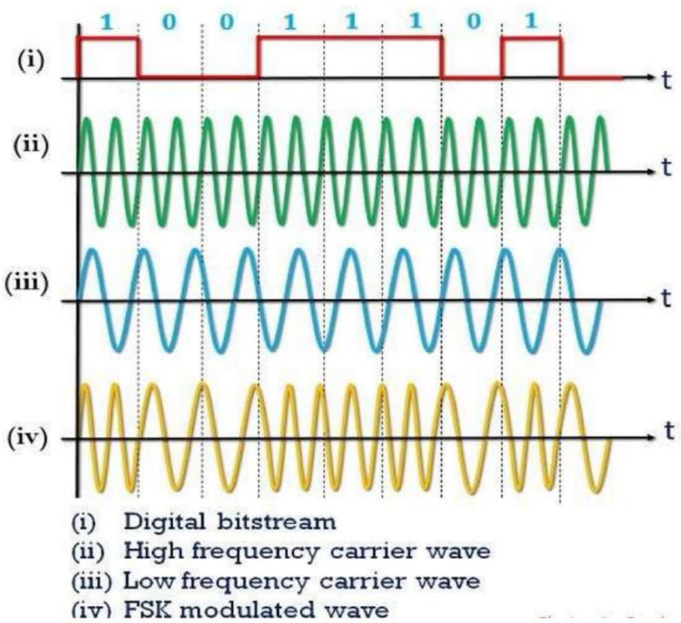

Figure 1: Ideal FSK.

FSK avoids most of the problems from noise. Because the receiving device is looking for specific frequency changes over a given number of periods, it can ignore voltage spikes. The limiting factors of FSK are the physical capabilities of the carrier. This suggests that we can consider the FSK waveform as composed of two ASK waveform of differing carrier frequencies as shown in Figure 2. Thus, to convey either of the binary symbols, we have:

$$\phi_1(t) = \begin{cases} A\sin\, m\omega_0 t & 0 < 1 \leq T, \\ 0 & \text{elsewhere,} \end{cases}$$
$$\phi_2(t) = \begin{cases} A\sin\, n\omega_0 t & 0 < t \leq T, \\ 0 & \text{elsewhere.} \end{cases} \quad (1)$$

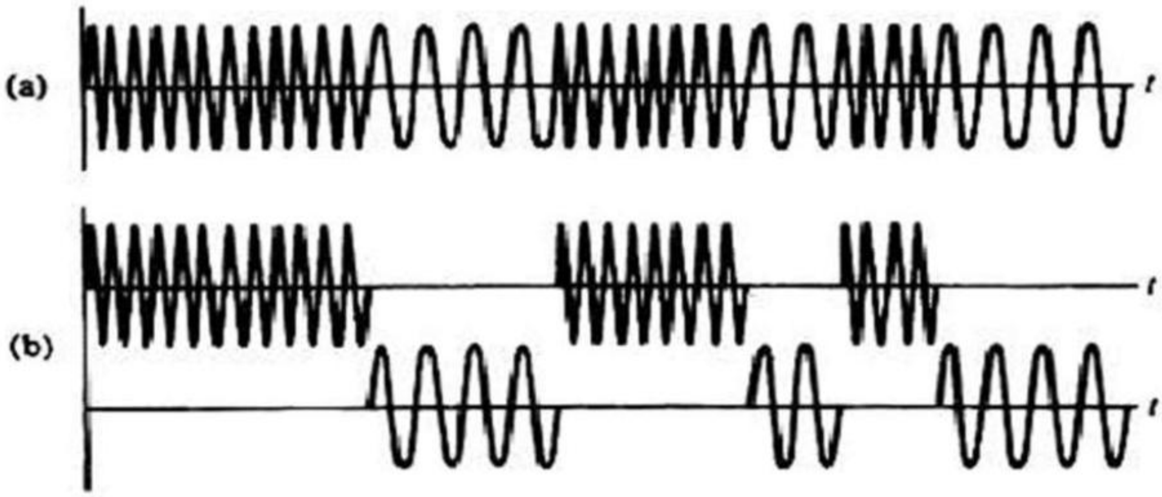

Figure 2: (a) An idealized FSK waveform and (b) its decomposition into two ASK waveforms.

2.1 FSK DEMODULATION

There are various techniques for demodulating an FSK signal. The two primary methods are **synchronous detection** and **asynchronous detection**. The **synchronous detector** is a **coherent** approach that requires a reference signal, whereas the **asynchronous detector** is a **non-coherent** method that operates without the need for synchronization.

2.1.1 MATCHED FILTER AND CORRELATOR

The two received signal waveform are now different so we use two matched filters, one for each waveform. Two possible matched-filter receivers for FSK are shown in Figure 3.

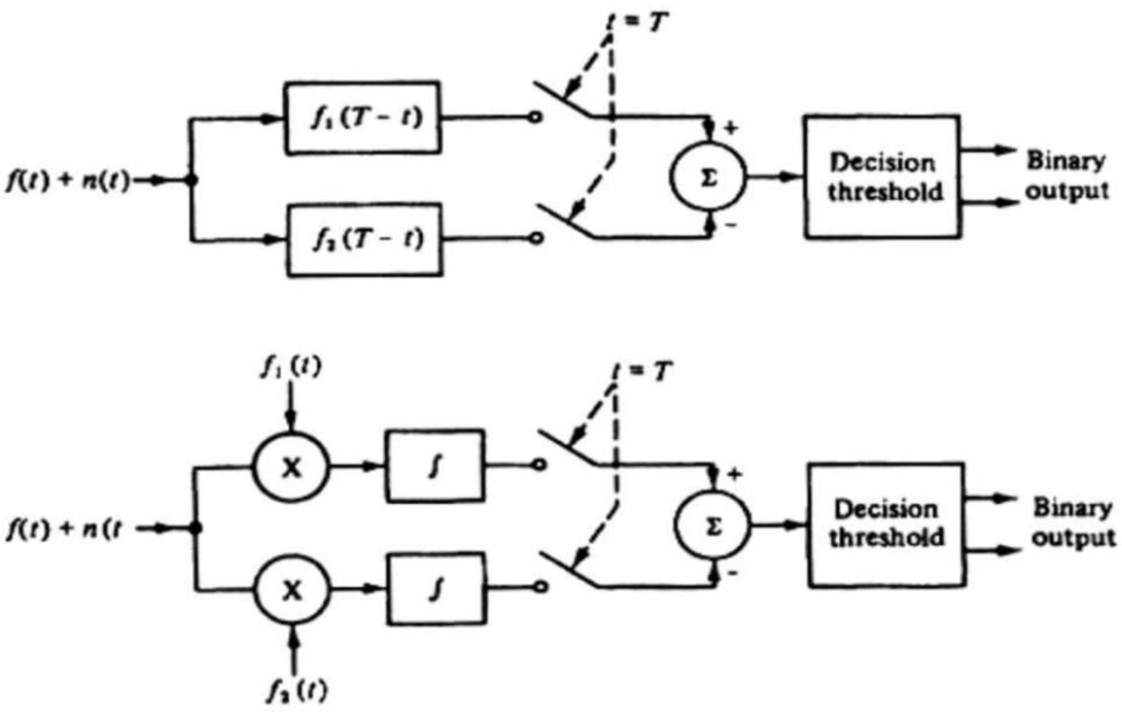

Figure 3: Detection of FSK.

The average energy per binary digit is:

$$E = \int_0^T A^2 \sin^2 \; m\omega_0 t dt = A^2 T/2. \qquad (2)$$

If one signaling frequency is present in the absence of noise, we assume that the one matched-filter output is zero and the other output is at $+E$. Conversely, if the second signaling frequency is present, the first matched-filter output is zero and as a result of the subtraction the net output is at $-E$. This is illustrated in Figure 4.

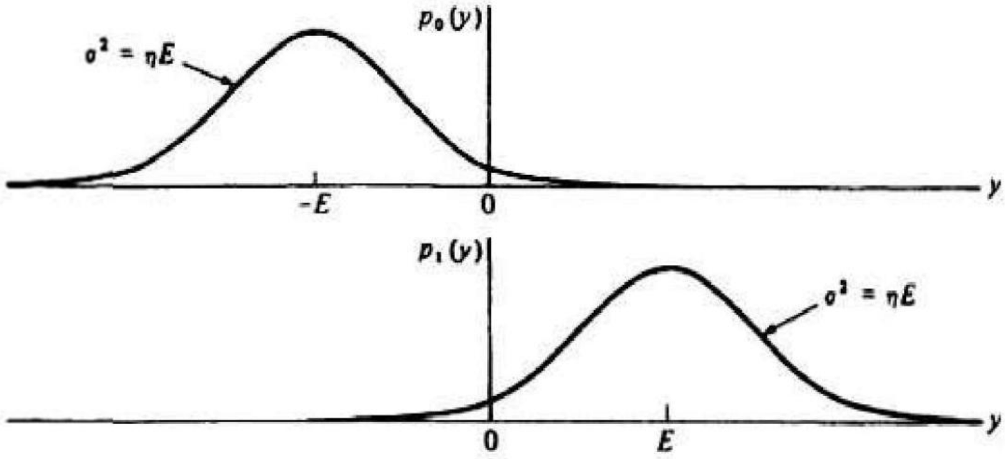

Figure 4: Probability density functions for binary FSK waveforms.

2.1.2 COHERENT FSK DEMODULATOR (USING VCO)

This method is "coherent" because it uses local oscillators (VCOs) that are synchronized with the incoming carrier frequencies.

- Operation: The incoming signal $f(t) + n(t)$ is split into two paths. Each path contains a multiplier and a Voltage-Controlled Oscillator (VCO) set to one of the two signaling frequencies (f_1 or f_2).
- The Process: When the input frequency matches the VCO frequency of a specific branch, the multiplier produces a low-frequency (baseband) component.
- Filtering: The Low-Pass Filter (LPF) removes high-frequency noise and the double frequency terms from the multiplication, leaving only the DC or near-DC data signal.
- Decision: The outputs of the two branches are subtracted (Σ). If the top branch is stronger, the result is positive; if the bottom is stronger, it is negative. The Decision Threshold block then converts this into a clean binary 1 or 0.

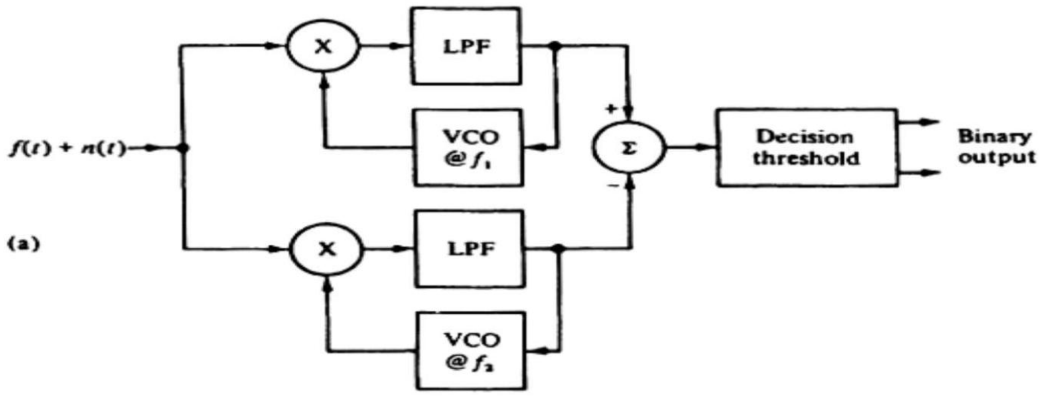

Figure 5: Probability density functions for binary FSK waveforms.

2.1.3 NON-COHERENT FSK DEMODULATOR (ENVELOPE DETECTION)

This method is "non-coherent" because it does not require the receiver to track the exact phase of the incoming signal, making it simpler and cheaper to implement.

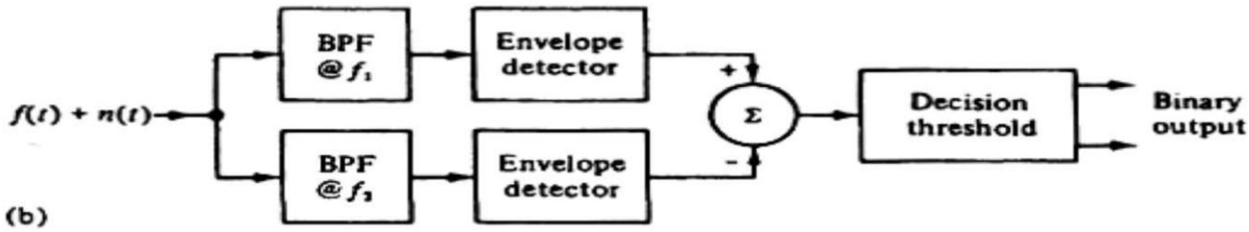

Figure 6: Envelope Detection of FSK.

- Operation: The signal is split into two branches, each starting with a Band-Pass Filter (BPF) tuned specifically to f_1 or f_2.
- Isolation: If the incoming signal is at frequency f_1, it passes through the top BPF while the bottom BPF blocks it (and vice versa).
- Envelope Detector: These blocks rectify and smooth the signal, essentially measuring the "strength" or amplitude of the signal in that specific frequency band.

- Decision: The summer (Σ) subtracts the two strengths. The Decision Threshold (typically a comparator) looks at which branch has the higher energy to output the corresponding binary bit.

2.2 OPTIMUM FREQUENCY SEPARATION IN COHERENT BFSK

In Binary Frequency Shift Keying (BFSK), we typically define frequency separation ($2\Delta f$) based on orthogonality. However, there is a distinction between the separation required for signals to be "independent" and the separation required for minimum probability of error ($\boldsymbol{P_e}$).

2.2.1 THE ORTHOGONALITY CONDITION

For two FSK signals to be orthogonal over a bit interval T, the frequency separation must satisfy:

$$2\Delta fT = \frac{n}{2} \quad \text{(where } n \text{ is an integer)} \tag{3}$$

This ensures that the signals do not interfere with each other during the detection process.

2.2.2 THE "OPTIMAL" ERROR PERFORMANCE

While orthogonality is the standard, the minimum probability of error is actually achieved when the signals are negatively correlated. According to the text, this occurs when the frequency separation is approximately three-fourths of a cycle:

$$2\Delta fT \approx 0.75 \text{ (or } 3/4, 7/4, 11/4, \dots \text{)} \tag{4}$$

2.2.3 DETECTION GAIN AND ERROR FORMULA

By using this specific 3/4 cycle separation, we achieve a "detection gain." The crosscorrelation coefficient (ρ) becomes negative, which modifies the standard error formula by a factor of 1.21:

$$P_e = Q\left(\sqrt{1.21\frac{E}{\eta}}\right) \quad (5)$$

2.3 BANDWIDTH OF FSK

FSK shifts between two carrier frequency, it is easier to analyze as two coexisting frequencies. We can say that the FSK spectrum is a combination of two ASK spectrum centered on f_{c0} and f_{c1}. The bandwidth required for FSK transmission is equal to the baud rate of the frequencies): signal plus the frequency shift (difference between the two carrier See Figure 7.

$$BW = f_{c1} - f_{c0} + N_{baud} \quad (6)$$

Although there are only two carrier frequencies, the process of modulation produces a composite signal that is a combination of many simple signals, each with a different frequency.

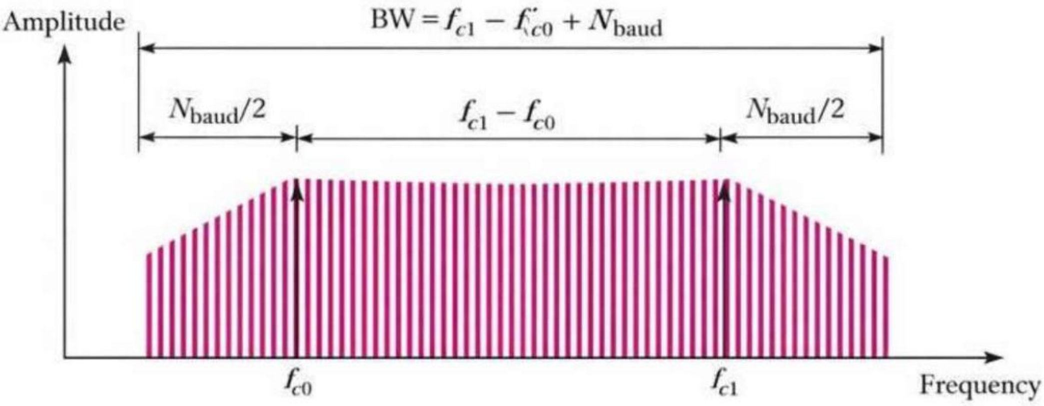

Figure 7: Relationship between baud rate and bandwidth in FSK.

3 PHASE - SHIFT KEYING (PSK)

In phase shift keying, the phase of the carrier is varied to represent binary 1 or 0. Both peak amplitude and frequency remain constant as the phase changes. For example, if we start with a phase of 0° to represent binary 0, then we can change the phase to 180° to send binary 1. The phase of the signal during each bit duration is constant, and its value depends on the bit (0 or 1). Figure 8 gives a conceptual view of PSK.

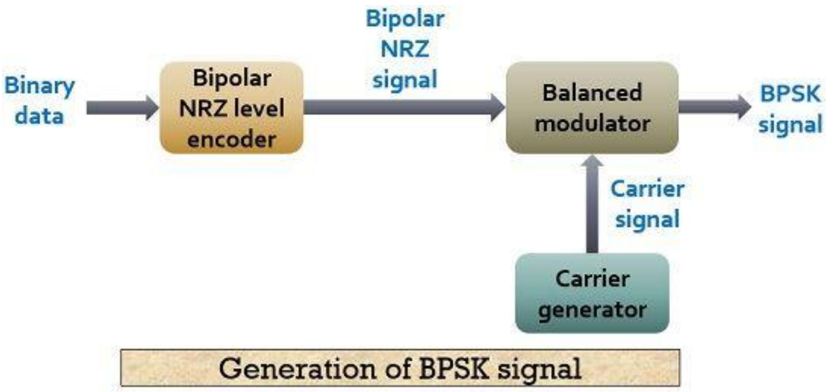

Figure 8: BPSK Modulator.

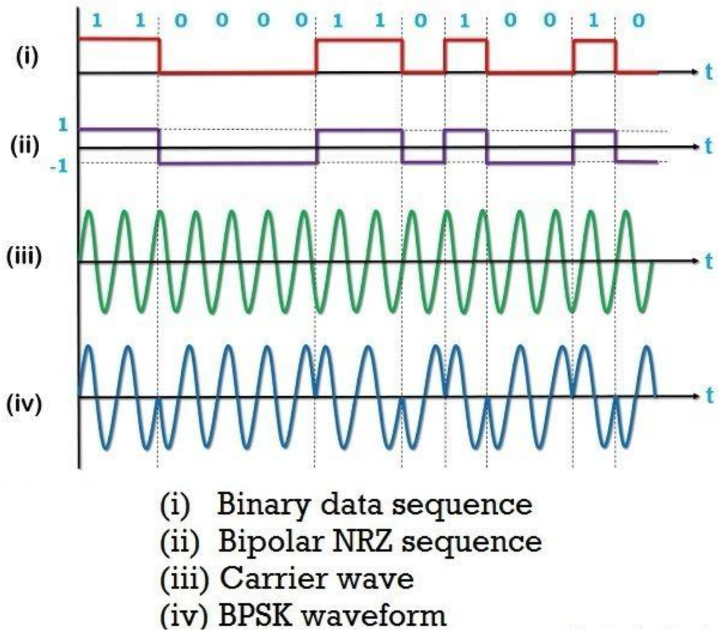

Figure 9: BPSK Waveform.

The above method is often called 2-PSK, or binary PSK, because two different phases (0° and 180°) are used. Figure 9 makes this point clearer by showing the relationship of phase to bit value. A second diagram, called a constellation or phase-state diagram, shows the same relationship by illustrating only the phases.

Bit	Phase
0	0
1	180

Bits

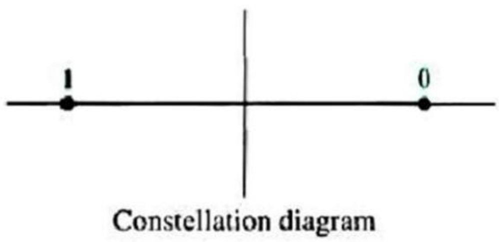

Figure 10: BPSK Constellation diagram

The BPSK(PRK) can be written as:

$$\phi_1(t) = A\sin\ \omega_c t, \phi_2(t) = -A\sin\ \omega_c t \qquad (7)$$

PSK is not susceptible to the noise degradation that affects ASK or to the band-width limitations of FSK. This means that smaller variations in the signal can be detected reliably by the receiver. Therefore, instead of utilizing only two variations of a signal, each representing 1 bit, we can use four variations and let each phase shift represent 2 bits (see Figure 11).

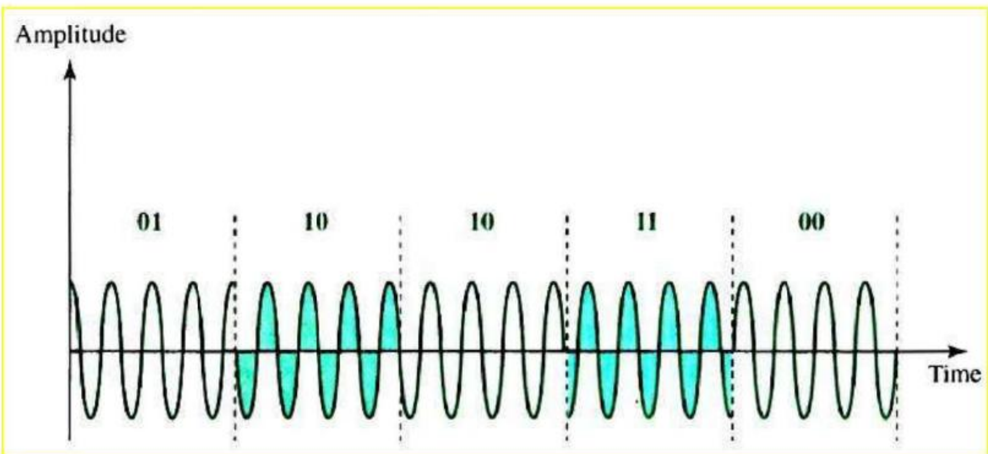

Figure 11: BPSK Output wave.

A phase of 0° now represents 00; 90° represents 01; 180° represents 10 ; and 270° represents 11 . This technique is called 4-PSK or Q-PSK. The pair of bits represented by each phase is called a dibit. We can transmit data twice as efficiently using 4-PSK as we can using 2PSK.

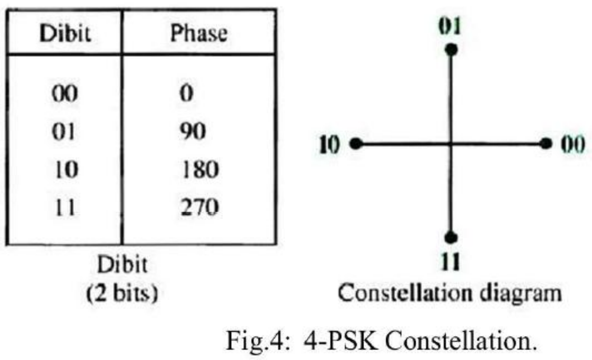

Figure 12: 4-PSK Constellation.

3.1 BPSK DETECTION

3.1.1 DETECTION USING CORRELATOR

In the receiver we required only one reference function in the correlation detector, as shown in Figure 13 below:

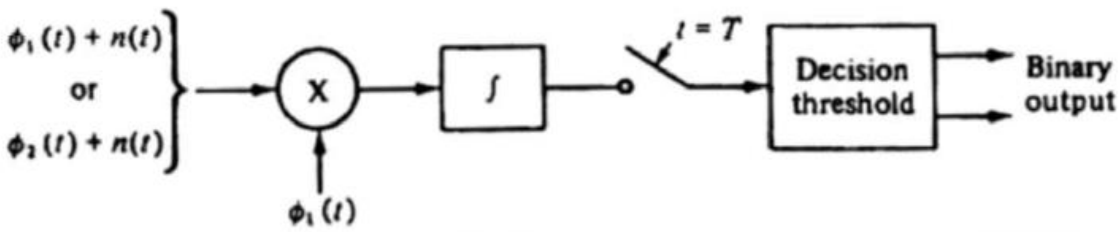

Figure 13: BPSK Correlator detection.

The probability of error (Pe) in terms of the average signal energy per bit $\mathbf{E}_{avg} = \mathbf{ST}$ so that can be written the probability of error as:-

$$P_e = Q\left(\sqrt{\frac{2E}{\eta}}\right). \tag{8}$$

The average signal power is $S = (1/2)(A^2/2), N = \eta B$ and if we assume Nyquist sampling, B $= 1/(2$ T) and η the (one-side) noise power spectral density.

3.1.2 SQUARE-LAW

This circuit is a Squaring Loop, used to recover the carrier frequency from a Phase Reversal Keying (PRK) signal. In PRK, the phase shifts by 180°, which makes the "average" carrier disappear, so you can't just use a standard filter to find it.

- Square-Law Device: This squares the input signal. Mathematically, squaring a signal with a 180° phase shift removes the phase modulation and produces a pure sine wave at twice the carrier frequency ($2f_c$).
- BPF @ $2f_c$: This Band-Pass Filter isolates that $2f_c$ component and removes noise.
- Frequency Divider / 2: This divides the frequency back down to $f_{c'}$, giving you a clean, synchronized local carrier.
- Multiplier & LPF: The original PRK signal is multiplied by this recovered carrier. This "unwraps" the phase shifts into high and low voltage levels. The Low-Pass Filter (LPF) smooths the result, sending a baseband signal to the decision threshold.

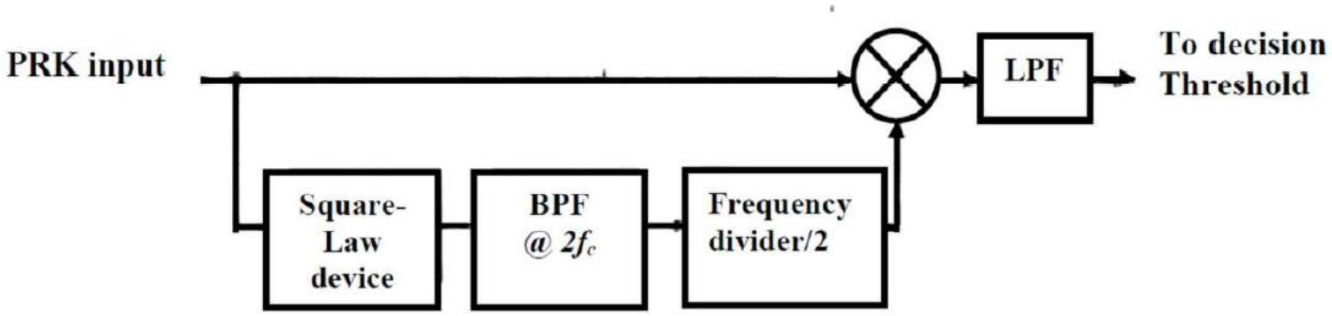

Figure 14: BPSK Square-Law Detection.

3.1.3 COSTAS LOOP

This diagram illustrates a Costas Loop, which is a more sophisticated method for demodulating Phase Reversal Keying (PRK/BPSK) signals. Its genius lies in its ability to perform carrier recovery and data demodulation simultaneously without needing to square the signal first. Here is the brief breakdown:

3.1.3.1 Dual-Path Architecture

The loop splits the PRK input into two parallel branches:

- In-Phase (I) Channel (Top): Multiplies the input by the local VCO signal. When the loop is "locked," this branch extracts the actual digital data.
- Quadrature (Q) Channel (Middle): Multiplies the input by a version of the VCO signal shifted by **90°**. This branch is used to detect phase errors.

3.1.3.2 The Error Correction Logic

- **The Third Multiplier (Right):** The outputs of the I and Q Low-Pass Filters (LPF) are multiplied together. This creates a DC error voltage that represents the phase difference between the incoming carrier and the local VCO.

- **VCO Feedback:** This error voltage is fed back into the **VCO**. It automatically speeds up or slows down the oscillator until it is perfectly synchronized with the incoming carrier's phase.

3.1.3.3 Data Output

- **The Bottom Multiplier/LPF:** Once the VCO is locked, the multiplier at the bottom (which is synchronized with the carrier) effectively "flips" the phase-shifted signal back into a standard baseband signal.
- **LPF:** The final filter removes any remaining high-frequency noise, sending a clean signal to the **Decision Threshold** to be read as binary 1s and 0s.

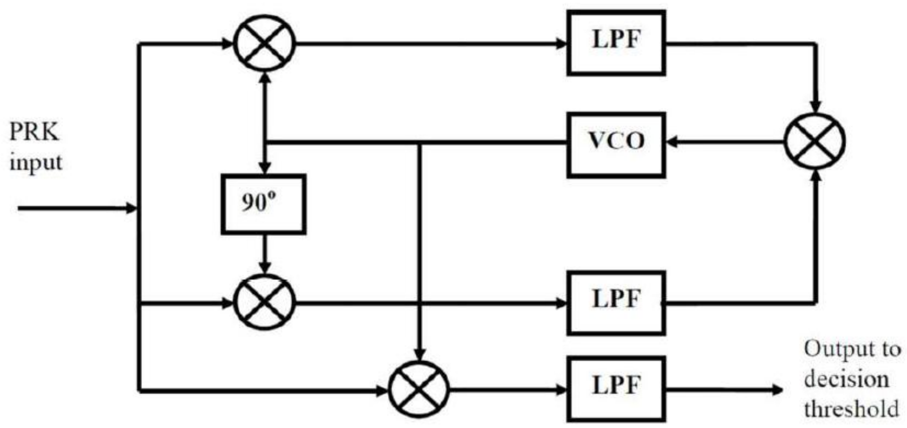

Figure 15: BPSK COSTAS LOOP.

3.2 BPSK BANDWIDTH

The minimum bandwidth required for PSK transmission is the same as that required for ASK transmission-and for the same reasons (see Figure 16). As we have seen, the maximum bit rate in PSK transmission, however, is potentially much greater than that of ASK. Sc while the maximum baud rates of ASK and PSK are the same for a given bandwidth, PSK bit rates using the same bandwidth can be 2 or more times greater.

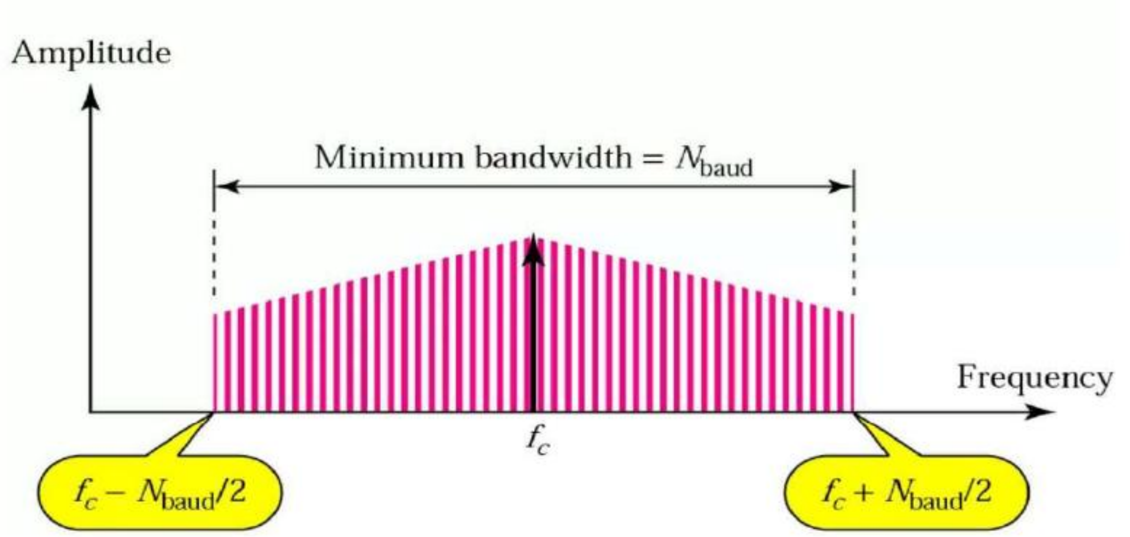

Figure 16: BPSK Bandwidth.

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