EEEN 464 – DIGITAL COMMUNICATION

STUDY GUIDE ON DIGITAL MODULATION

---

1. INTRODUCTION TO DIGITAL MODULATION

1. **DEFINITION**

   - Digital modulation refers to the conversion of digital bits into analogue waveforms usually by altering the amplitude, frequency or phase of a carrier for transmission over physical channels (e.g., cables, wireless).
   - Digital modulation is necessary since it makes efficient use of bandwidth, provides noise resilience, and enables compatibility with digital systems.

2. **KEY CONCEPTS**

   - **Symbol** are the individual elements of the modulated signal that carry the encoded digital data. Each symbol can represent one or more bits, depending on the modulation scheme. Each symbol is a waveform representing one or more bits (e.g., 00, 01, 10, 11 in QPSK).

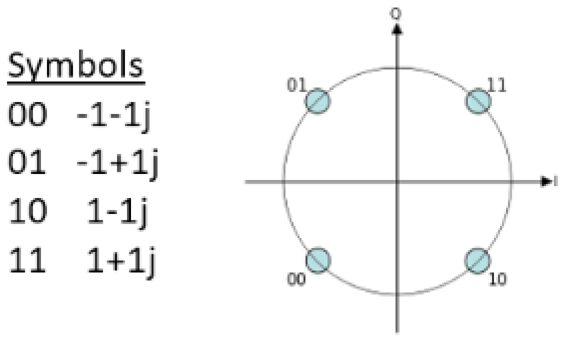

Figure 1. Symbols in QPSK

   - **Bit Rate vs. Symbol Rate**:
     - Bit rate, R_b = Number of bits transmitted per second (bps).
     - Symbol rate, R_s = Number of symbols transmitted per second (baud).
     - **Relationship**: $R_b = R_s \times \log_2(M)$, where M = number of symbol states.
   - **Bandwidth Efficiency**: Measured in **bps/Hz** (bits per second per Hertz). Higher efficiency = more data in less bandwidth.

2. CORE MODULATION TECHNIQUES

1. AMPLITUDE SHIFT KEYING (ASK):

- **Principle**: Bits modulate the **amplitude** of a carrier wave.

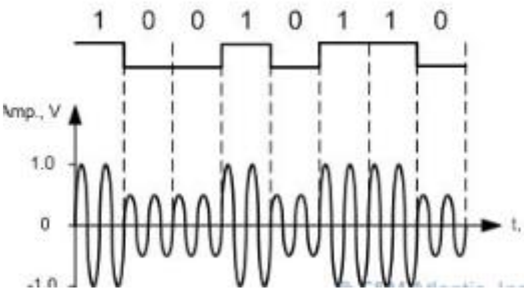

Figure 2. Principle of Amplitude Shift Keing (ASK)

- **Types** of ASK

  a) **OOK (On-Off Keying)**: "1" = carrier on, "0" = carrier off.

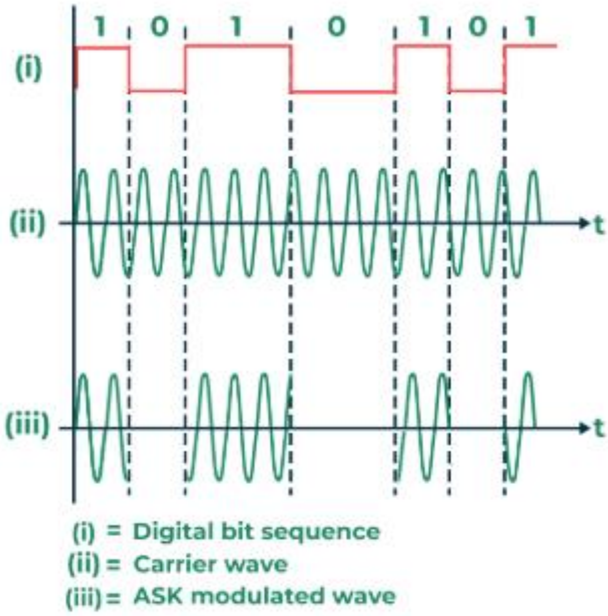

Figure 3. On-Off-Keying (OOK) as a special type of Amplitude Shift Keing (ASK)

- **Pros**: Simple implementation.
- **Cons**: Vulnerable to noise and fading.
- **Equation**: $s(t)=A_m\cos(2\pi f_c t))$, where A_m = amplitude for symbol m.

2. FREQUENCY SHIFT KEYING (FSK)

- **Principle**: Bits modulate the **frequency** of a carrier.

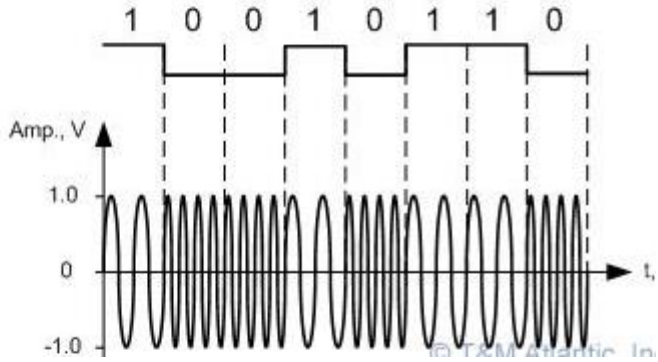

Figure 4. Principle of Frequency Shift Keying (FSK)

- **Types**:
  a) **Binary FSK (BFSK)**: "1" = f_1, "0" = f_0.
  b) **Minimum Shift Keying (MSK)**: FSK with smooth phase transitions (used in GSM).
- **Pros**: Resilient to amplitude noise.
- **Cons**: Requires more bandwidth than PSK.
- **Equation**: $s(t)=\cos(2\pi(f_c+f_d\cdot d_k)t)$, where d_k = bit value, f_d = frequency deviation.

3. **PHASE SHIFT KEYING (PSK):**

- **Principle**: Bits modulate the **phase** of a carrier.

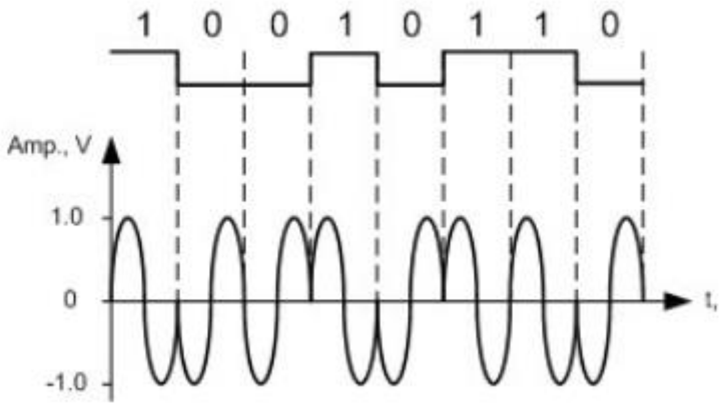

Figure 5. Principle of Phase Shift Keying

- **Types**:
  a) **BPSK (Binary PSK)**: "0" = 0°, "1" = 180° (2 symbols).
  b) **QPSK (Quadrature PSK)**: 2 bits/symbol; phases at 45°,135°,225°,315°

c) **DPSK (Differential PSK):** Encodes data in phase *changes* (avoids carrier synchronization).

- **Pros**: Better noise immunity than ASK/FSK.
- **Equation**: $s(t)=\cos(2\pi f_c t+\phi_m)$, where ϕ_m = phase for symbol m*m*.

4. **QUADRATURE AMPLITUDE MODULATION (QAM):**

- **Principle**: Combines **ASK and PSK** to modulate both **amplitude and phase**.
- **Types of QAM**

a) **16-QAM** uses 16 distinct combinations of amplitude and phase to represent 4 bits of data per symbol. This means that each symbol transmitted can encode one of 16 possible values, corresponding to 4 binary digits (0000 to 1111) as shown in figure 6.

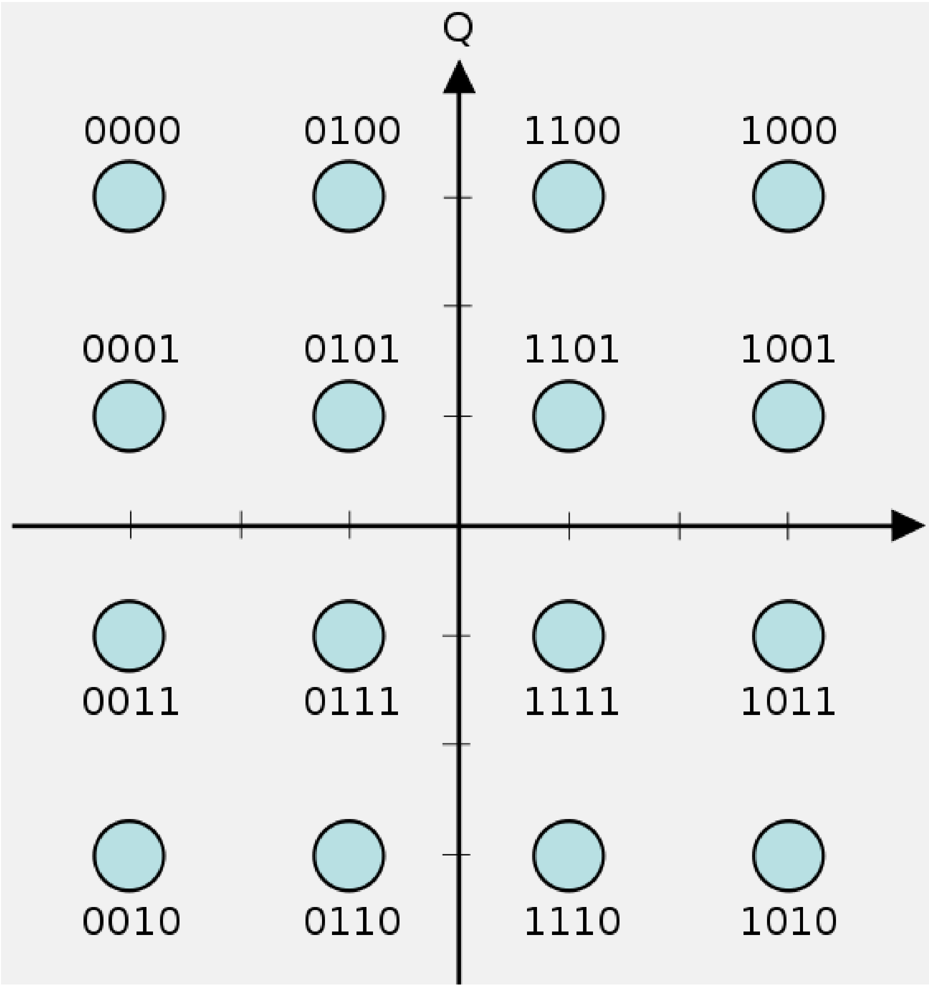

Figure 6. Constellation diagram of 16 QAM

b) **64-QAM** uses 64 distinct combinations of amplitude and phase to represent 6 bits of data per symbol. This means that each symbol transmitted can encode one of 64 possible values, corresponding to 4 binary digits (000000 to 111111) as shown in figure 7.

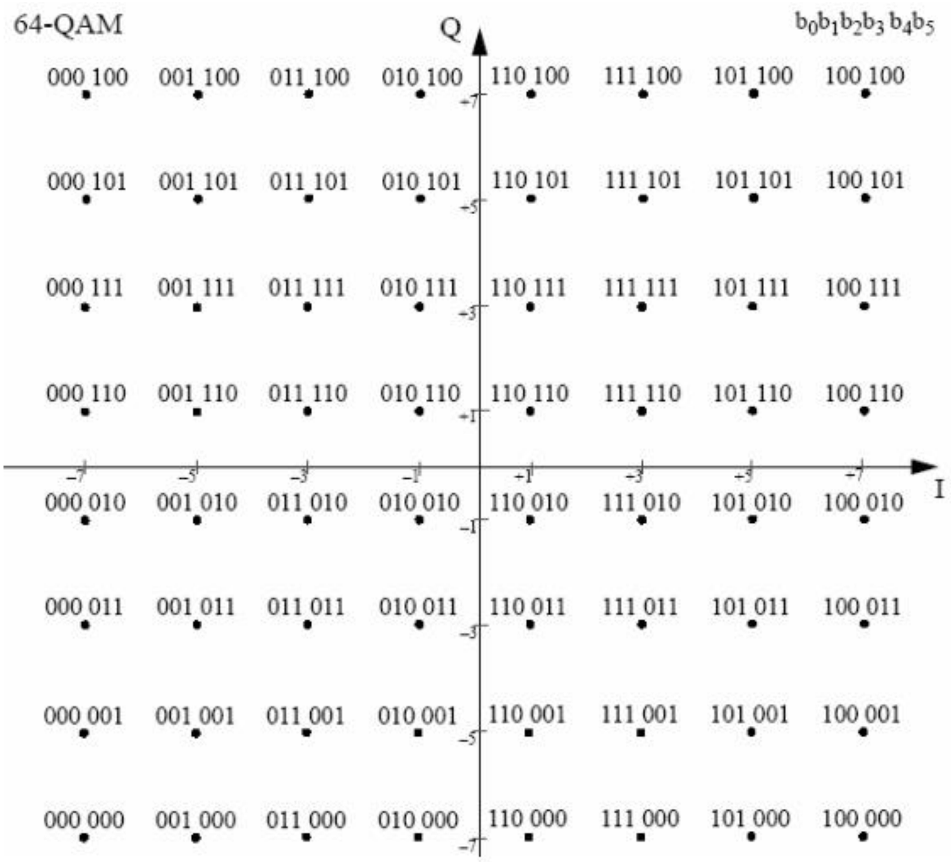

Figure 7. Constellation diagram of 64 QAM

- **Pros**: Highest spectral efficiency (e.g., 64-QAM > 64-PSK).
- **Cons**: Sensitive to noise and distortion.
- **Equation**: $s(t)=I(t)\cos(2\pi f_c t)-Q(t)\sin(2\pi f_c t)$, where I = in-phase, Q = quadrature.

3. PERFORMANCE METRICS

1. **Constellation Diagram** is a graphical representation used in digital modulation to visualize the symbols of a modulated signal in the complex plane (I-Q plane).

   Applications of constellation diagram include:

   a) Modulation scheme selection: Choosing the most appropriate modulation technique for a given application.
   b) Performance analysis: Evaluating the quality and reliability of a digital communication system.
   c) Troubleshooting: Identifying and diagnosing issues in a system based on how the constellation diagram appears.

2. **Key Metrics**:

   - **Euclidean Distance** is a measure of how different two modulated signals are. It's calculated as the straight-line distance between the signal points on a constellation diagram, which represents the possible signal values in a modulation scheme. A larger Euclidean distance generally indicates a greater difference between the signals, potentially leading to better noise immunity and lower error rates. Larger Euclidean distance = better noise immunity.

- **Gray Coding**: Adjacent symbols differ by 1 bit to minimize bit errors.

3. **Error Probability**:

   a) **BER (Bit Error Rate)** is a measure of the quality of a digital communication or storage system. It represents the ratio of bit errors (incorrect bits) to the total number of bits transmitted or stored. BER is a crucial metric in various fields like telecommunications, networking, and data storage. Bit Error Rate Testers (BERT) are used to measure the BER of a system.

   b) **SER (Symbol Error Rate)** quantifies the rate at which symbols are incorrectly received during data transmission. It represents the probability that a received symbol is different from the transmitted symbol.

   c) **Approximation for BPSK**: $BER \approx \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_o}}\right)$

4. **Bandwidth Requirements**:

   - **Nyquist Criterion**: Minimum bandwidth = $\frac{R_s}{2}$ Hz (for zero ISI with ideal filtering).
   - **Raised-Cosine Filter**: Used to limit bandwidth while minimizing ISI.

---

4. ADVANCED CONCEPTS

1. **Synchronization**

   - **Carrier Recovery**: Aligning receiver oscillator with incoming carrier (e.g., using PLL).
   - **Symbol Timing**: Synchronizing sampling instants to avoid ISI.

2. **Pulse Shaping**

   - **Goal**: Limit bandwidth without causing ISI.
   - **Filters**: Rectangular (causes ISI), Raised-Cosine (ISI-free).

3. **Diversity Techniques**

   - **Frequency Hopping**: Transmit data over multiple frequencies (used in Bluetooth).
   - **Spread Spectrum**: Spread signal over wide bandwidth (resists interference).

---

5. APPLICATIONS

Modulation	**Applications**

ASK	Optical communications (fibre), RFID.
FSK	Pagers, legacy modems.
PSK/QPSK	Wi-Fi (802.11b/g), satellite TV (DVB-S).
QAM	Cable internet (DOCSIS 3.1), 5G, Wi-Fi 6.
MSK/GMSK	GSM, Bluetooth.

---

6. KEY FORMULAS

1. **Bit Rate**: $R_b=R_s\times\log_2(M)$
2. **Bandwidth**: BW≈Rs2×(1+α)2*Rs*×(1+*α*), where α = roll-off factor.
3. **SNR to Eb/N0**: EbN0=SN×BWRb*N*0*Eb*=*NS*×*RbBW*.
4. **Shannon Capacity**: $C=BW\times\log_2(1+SNR)$ (max theoretical bit rate).

---

7. STUDY TIPS

1. **Master Constellation Diagrams**: Sketch 16-QAM vs. 16-PSK to understand efficiency trade-offs.
2. **Practice Calculations**:
   - *Example*: For 256-QAM at 40 Mbps, symbol rate = $40\times10^6/\log_2(256)=5$ Msymbol/s.
3. **Compare Techniques**:
   - **Noise Resilience**: PSK > ASK, but QAM requires higher SNR.
   - **Bandwidth Efficiency**: QAM > PSK > FSK > ASK.
4. **Simulate**: Use MATLAB/Python to generate modulated signals and plot constellations.
5. **Real-World Focus**: Relate concepts to Wi-Fi (QAM), GSM (GMSK), and cable modems (QAM).

---

8. EXAM FOCUS AREAS

- Calculate bit/symbol rates, bandwidth, and BER.
- Interpret constellation diagrams.
- Compare modulation schemes for given SNR/bandwidth constraints