EEEN 464 – DIGITAL COMMUNICATION

QUADRATURE AMPLITUDE MODULATION (QAM) - STUDY GUIDE/REVISION

---

1. FUNDAMENTAL CONCEPTS

1. Definition

QAM is a modulation scheme that conveys data by **simultaneously modulating the amplitude** of two carrier waves:

- In-phase carrier (I): $\cos(2\pi f_c t)$
- Quadrature carrier (Q): $\sin(2\pi f_c t)$

2. Key Principle

- Combines **amplitude-shift keying (ASK)** and **phase-shift keying (PSK)**
- Transmits 2 independent signals on the **same frequency** using orthogonal carriers

3. Mathematical Representation

$$s(t)=I(t)\cos 2\pi f_c t) + Q(t)\sin(2\pi f_c t)$$

where:

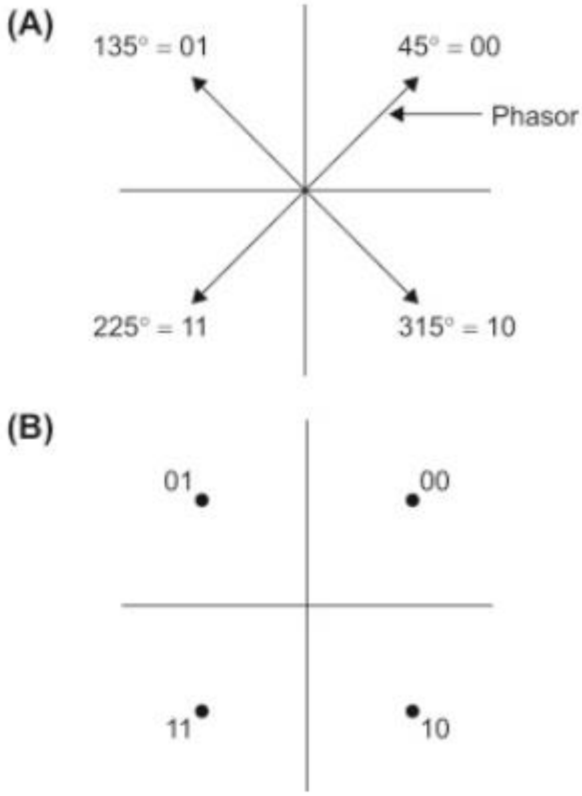
$I(t)$ = In-phase component (amplitude)

$Q(t)$ = Quadrature component (amplitude)

2. CONSTELLATION DIAGRAMS

Visual Representation:

- **I-Q Plane**: Points represent symbol states
- **Distance from origin**: Signal amplitude
- **Angle**: Signal phase



- Figure 1. Constellation diagram of 2-QAM

Common Configurations:

QAM Type	Symbols	Bits/Symbol	Example Use
4-QAM	4	2	Identical to QPSK
16-QAM	16	4	Cable modems
64-QAM	64	6	Wi-Fi (802.11ac)
256-QAM	256	8	DOCSIS 3.1

Decision Boundaries:

- Symbols partitioned into regions
- Minimum Euclidean distance determines error resilience

3. MODULATION PROCESS

Transmitter Block Diagram:

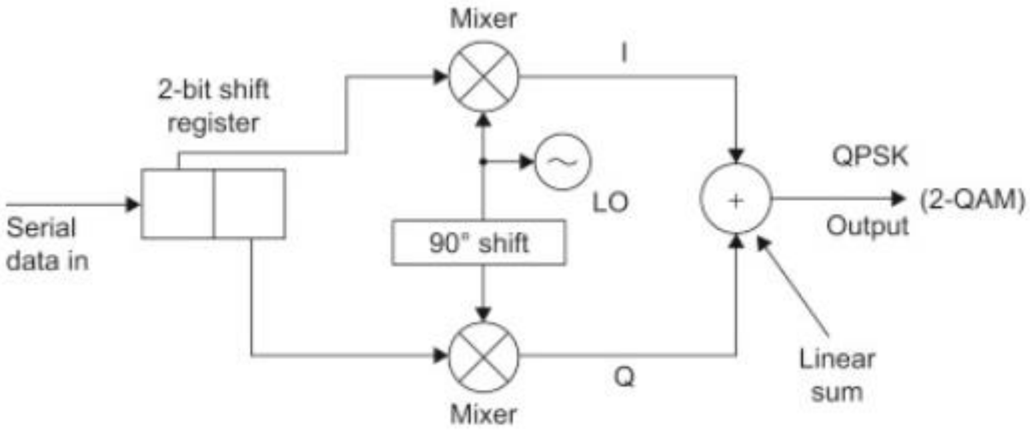


Figure 2. Block diagram of 2-QAM

Steps:

1. **Bit Grouping**:
    - For M-QAM, group $k=\log_2(M)$
    - Example: 16-QAM → 4 bits/symbol (2 bits → I, 2 bits → Q)

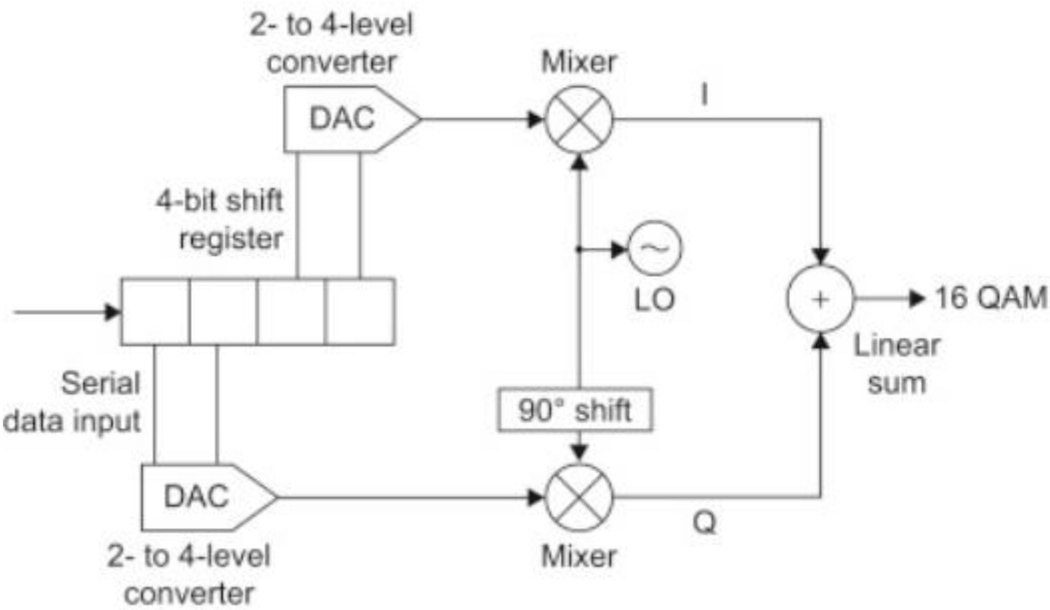


Figure 3. Block diagram of 16-QAM

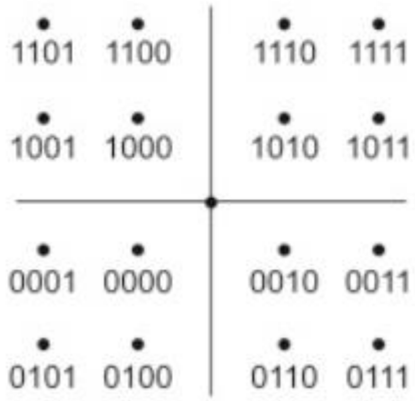


Figure 4. Constellation diagram of 16-QAM

2. **Symbol Mapping**:
   - Convert bits to analogue amplitudes (e.g., ±1V, ±3V for 16-QAM)
   - Gray coding minimizes bit errors
3. **Carrier Modulation**:
   - Multiply I-channel by $\cos(2\pi f_c t)$
   - Multiply Q-channel by $-\sin(2\pi f_c t)$
4. **Signal Summation**:
   - $s(t) = I \cdot \cos(2\pi f_c t) - Q \cdot \sin(2\pi f_c t)$

4. DEMODULATION PROCESS

Receiver Block Diagram:

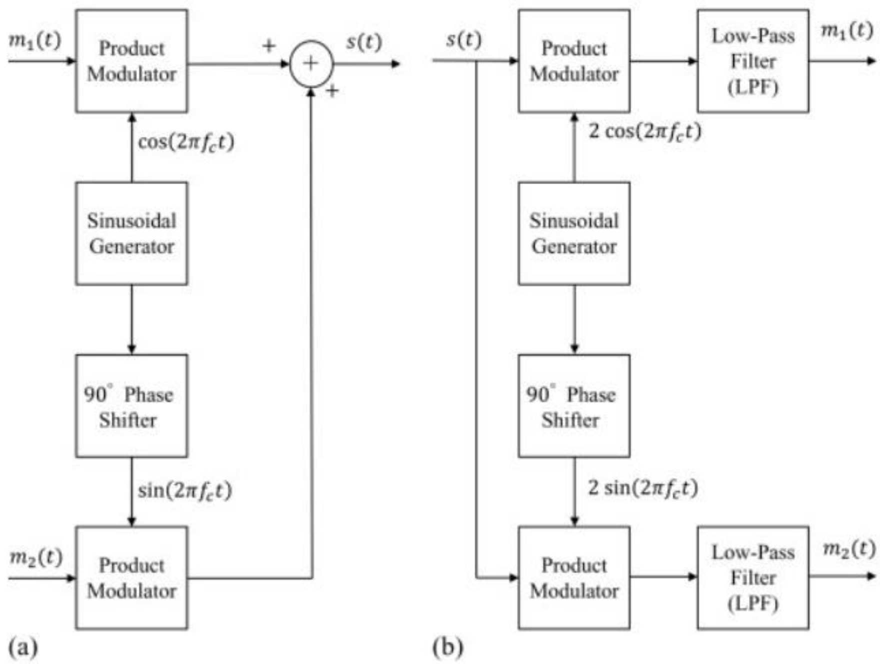


Figure 5(a) QAM transmitter and **(b)** QAM receiver

Coherent Detection Steps:

1. **Carrier Recovery**: Regenerate phase-synchronized carriers
2. **Down conversion**:
    - $I(t)=s(t)\cdot 2\cos(2\pi f_c t)$
    - $Q(t)=s(t)\cdot(-2\sin(2\pi f_c t))$
3. **Low-Pass Filtering**: Remove high frequency components at $2f_c$.
4. **Sampling & Decision**:
    - Sample I/Q at symbol rate
    - Map to nearest constellation point

5. PERFORMANCE ANALYSIS

Key Metrics:

1. Bandwidth Efficiency:
    - Symbol rate $R_s = \frac{R_b}{\log_2 M}$
    - Bandwidth $B \approx R_s$ (Nyquist criterion)
2. Error Probability:
    - Approximation for high SNR:

$$P_e \approx 4\left(1-\frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3E_b \log_2 M}{(M-1)N_0}}\right)$$

3. Key SNR vs BER Trade-off:

- Higher-order QAM → More bits/symbol → Higher BER at same SNR
- Example: 256-QAM requires ~12 dB higher SNR than 16-QAM for same BER

6. PRACTICAL CONSIDERATIONS

Impairments & Mitigation:

Impairment	**Effect**	**Mitigation**
Phase Noise	Constellation rotation	Phase-locked loops (PLL)
Amplitude Imbalance	Non-square constellations	Digital pre-distortion
Carrier Frequency Offset	Rotating constellation	Frequency recovery circuits
Nonlinear Distortion	Warped constellations	Linear amplifiers (e.g., Class A)

Equalization:

- Adaptive filters (e.g., LMS algorithm) compensate for channel distortion

7. VARIATIONS & ADVANCED QAM

Differential QAM (DQAM):

- Encodes data in phase/amplitude changes between symbols
- Avoids carrier recovery (robust to phase offsets)

Trellis-Coded QAM:

- Combines QAM with convolutional coding
- Gains 3–6 dB coding gain without bandwidth expansion

OFDM with QAM:

- Used in Wi-Fi, 5G, DVB-T
- Divides channel into orthogonal subcarriers
- Each subcarrier modulated with QAM

8. APPLICATIONS

- **Cable TV**: 64-QAM/256-QAM in DOCSIS
- **Wi-Fi**: 256-QAM in 802.11ac/ax
- **Fiber Optics**: Polarization-multiplexed QAM (e.g., 16-QAM @ 400Gbps)
- **Digital Radio**: DAB+ uses 64-QAM

9. ADVANTAGES & LIMITATIONS

Advantages:

1. High spectral efficiency
2. Flexible trade-off between data rate and robustness
3. Compatible with coherent detection

Limitations:

1. Requires linear amplifiers (inefficient)
2. Sensitive to phase noise and nonlinearities
3. Complex receiver design