Study Guide: Coding & Modulation, Multiplexing

Mobile Networking (MobNet) - Chapter 01, Module 02

Core Concepts

Learning Objectives

- Understand how digital bits are transmitted over wireless channels
- Learn fundamental coding and modulation techniques
- Understand multiplexing schemes and their tradeoffs
- Apply concepts to real wireless standards (WiFi, 5G)

Key Principle

Digital data must be converted to analog waveforms for transmission over wireless channels. A modem (modulator-demodulator) performs this translation at both transmitter and receiver.

Section 1: Coding & Modulation

1.1 Fundamentals

Coding (Error Detection/Correction)

- **Purpose**: Add extra bits (EDC = Error Detection, Correction bits) to detect and correct transmission errors
- **Process**: Original data bits → Coding → Original data + EDC bits
- **Parity bits**: Simple example of EDC
- **Applied at multiple layers**: Physical, link, network, transport, application

Modulation Process
The signal path follows: bits → symbols → waveform → continuous time signal → baseband signal

Components of Modulation

1. **Coding**: Add error detection/correction bits
2. **Digital Modulation**: Choose modulation scheme (ASK, FSK, PSK, QAM)
3. **Pulse Shaping**: Match transmission bandwidth to channel bandwidth
4. **RF Modulation**: Transmit as electromagnetic wave on carrier frequency

1.2 Sine Wave Fundamentals

Any sine wave can be described as: **$A \cdot \sin(2\pi ft + \varphi)$**

Where:

- **A** = Amplitude (height of wave)
- **f** = Frequency (how many cycles per second, Hz)
- **φ** = Phase (position shift, in degrees or radians)

1.3 Basic Modulation Techniques

Amplitude Shift Keying (ASK)

How it works: Vary the amplitude (height) of the carrier wave

- Input bit 1 → transmit signal at high amplitude (A = 1)
- Input bit 0 → transmit signal at low/no amplitude (A = 0.5 or 0)

Advantages:

- Very simple implementation
- Low bandwidth requirements
- One amplitude per bit

Disadvantages:

- Highly susceptible to noise and atmospheric interference
- Poor performance in real wireless channels
- Distortions severely affect signal reception

Applications: Optical fiber communication (minimal noise environment)

Constellation Diagram: Two points on plot (one for each amplitude level)

Frequency Shift Keying (FSK)

How it works: Vary the frequency of the carrier wave

- Binary FSK (BFSK): Two frequencies
  - Bit 0 → transmit at frequency f_1
  - Bit 1 → transmit at frequency f_2

Advantages:

- Less susceptible to channel noise than ASK
- More robust in noisy environments

Disadvantages:

- Requires larger bandwidth than ASK
- Bandwidth depends on distance between carrier frequencies
- Guard bands needed to prevent interference

Applications: High-frequency radio transmission, FMCW radar

Tradeoff: More bandwidth used, but better noise immunity

Phase Shift Keying (PSK)

How it works: Vary the phase (timing position) of the carrier wave

Binary PSK (BPSK) - Simplest form:

- Bit 0 → sine wave at phase 0°
- Bit 1 → inverted sine wave at phase 180° (π radians)
- Can represent two states with single carrier frequency

Advantages:

- Less susceptible to errors than ASK
- Same bandwidth as ASK
- More bandwidth efficient than FSK

Disadvantages:

- More complex signal detection/recovery than ASK or FSK
- Requires more sophisticated receiver

Applications: Satellite systems, early WiFi systems (802.11b), satellite

Key insight: Uses frequency same as ASK but encodes information differently

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1.4 Quadrature Phase Shift Keying (QPSK)

Evolution: Extend PSK to four phases

How it works:

- Use four distinct phase values instead of two
- Each symbol represents 2 bits ($2^2 = 4$ possible states)
- Four phase positions: 0°, 90°, 180°, 270°

Data Rate Benefit:

- QPSK at same frequency as BPSK achieves **2× the data rate**
- Same bandwidth as BPSK, but encodes 2 bits per symbol

Complexity: More complex to implement than BPSK but better spectral efficiency

Applications: WiFi standards (802.11b/g), satellite, early cellular

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1.5 Quadrature Amplitude Modulation (QAM)

Concept: Combine ASK and PSK - vary BOTH amplitude and phase

- 2-dimensional signaling (I and Q components)
- Can encode n bits per symbol using 2^n discrete levels

Complex Number Representation:
Symbols represented as: $A^{e^j}{}_{\varphi} = A[\cos(\varphi) + j\cdot\sin(\varphi)]$

- I (In-phase) = $A \cdot \cos(\varphi)$ [real part]
- Q (Quadrature) = $A \cdot \sin(\varphi)$ [imaginary part]

Common QAM Schemes:

- **4-QAM** (same as QPSK): 4 symbols, 2 bits per symbol
- **16-QAM**: 16 symbols, 4 bits per symbol
- **64-QAM**: 64 symbols, 6 bits per symbol
- **256-QAM**: 256 symbols, 8 bits per symbol
- **1024-QAM**: 1024 symbols, 10 bits per symbol

How 4-QAM Works:

1. Original data: $b(t) = \{0, 1\}$
2. Encode: $1 \rightarrow +1$, $0 \rightarrow -1$
3. Split into two parallel streams: $d_1(t)$ and $d_2(t)$
4. Modulate on cos and sin carriers:
    - $s(t) = d_1(t) \cdot \cos(2\pi fcT) + d_2(t) \cdot \sin(2\pi fcT)$
5. Transmit combined signal

Receiver Process (4-QAM):

1. Multiply received signal by $\cos(2\pi fcT)$ → extract $d_1(t)$
2. Multiply received signal by $\sin(2\pi fcT)$ → extract $d_2(t)$
3. Apply low-pass filter to each to remove high frequencies
4. Convert back to original bits

Advantages:

- High spectral efficiency (more bits per symbol)
- Efficient use of bandwidth
- Widely used in modern standards

Disadvantages:

- Bit error rate (BER) increases with more bits per symbol
- Requires higher signal-to-noise ratio (SNR)
- More complex receiver design

Applications: WiFi (802.11a/g/n/ac), 4G/5G cellular, satellite

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1.6 Constellation Diagrams

Purpose: Visualize all possible symbols in a modulation scheme

- **X-axis (I)**: In-phase component [$\cos(\varphi)$]
- **Y-axis (Q)**: Quadrature component [$\sin(\varphi)$]
- **Each dot**: One symbol (one or more bits)

Interpretation:

- ASK: Points arranged vertically (varying amplitude only)
- BPSK: Two points on opposite sides (0° and 180°)
- QPSK: Four points at 90° intervals (0°, 90°, 180°, 270°)

- 16-QAM: 16 points in 4×4 grid (varying amplitude and phase)

Spacing between symbols: Affects noise immunity

- Closer spacing = less noise-resistant, more errors
- Farther spacing = more noise-resistant, but lower spectral efficiency

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1.7 Adaptive Modulation

Concept: Change modulation scheme dynamically based on channel conditions

SNR-BER Tradeoff:

- Low SNR (noisy channel) → use robust scheme like BPSK
- High SNR (clean channel) → use efficient scheme like 64-QAM

Real-world example (WiFi to 5G):

- Start with BPSK (most robust)
- Upgrade to QPSK (2× bits/symbol)
- Continue to 16-QAM, 64-QAM, 256-QAM as SNR improves
- Downgrade if interference increases

Benefits:

- Maximize data rate in good conditions
- Maintain reliability in poor conditions
- Automatic optimization

1.8 Pulse Shaping

Purpose: Control intersymbol interference (ISI)

- Match transmission bandwidth to channel bandwidth
- Prevent signal spreading that causes overlap between symbols
- Filter pulses to optimize signal for channel

1.9 RF Modulation

Purpose: Shift baseband signal to carrier frequency for transmission

- Baseband signal: Low-frequency digital signal
- Carrier frequency (fc): High-frequency electromagnetic wave
- RF signal: Baseband modulated onto carrier at fc

Why necessary:

- Antenna size: Lower frequencies need impractically large antennas
- Frequency regulations: Different bands regulated differently
- Channel characteristics: Different frequencies have different propagation

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Section 2: Multiplexing/Channel Partitioning

2.1 Multiplexing Overview

Definition: How multiple users share the same medium with minimal or no interference

Analogy: Highway with multiple lanes

- Many users (drivers) share the same road
- Lanes separate traffic to prevent collisions
- Lanes represent different "channels"

Four Dimensions in Wireless:

1. **Space** (s): Geographic separation
2. **Time** (t): Temporal separation
3. **Frequency** (f): Spectral separation
4. **Code** (c): Code-based separation

2.2 Space Division Multiplex (SDM)

Concept: Use spatial separation to allow simultaneous transmissions

Methods:

- **Beamforming**: Direct signals in specific spatial directions
- **Sectorization**: Divide coverage area into sectors

How it works:

- Channel k_1 transmitted in space s_1
- Channel k_2 transmitted in space s_2
- Channel k_3 transmitted in space s_3
- Spatial separation prevents interference ranges from overlapping

Guard Space: Physical separation needed between channels

Advantages:

- Simultaneous use of spectrum
- Good spectral efficiency

Disadvantages:

- Requires precise spatial control
- Guard space needed

2.3 Frequency Division Multiplex (FDM)

Concept: Divide frequency spectrum into non-overlapping bands

How it works:

- Divide wide bandwidth into multiple narrow frequency bands

- Each channel gets fixed frequency band for entire duration
- All channels can transmit simultaneously
- Guard bands separate channels to prevent adjacent-channel interference

Advantages:

- No dynamic coordination needed
- Straightforward implementation
- Simultaneous transmission on all channels

Disadvantages:

- Inflexible: Fixed frequency assignment
- Wastes resources if traffic uneven
- Cannot reallocate spectrum to overloaded channels
- Guard bands reduce usable spectrum

Mathematical perspective:

- Wideband channel: 1 carrier per bandwidth
- Narrowband subchannels: Multiple carriers per bandwidth → better spectral efficiency
- WiFi example: 48 subcarriers in 20 MHz = 2400 carriers/GHz (vs. 11 for single channel)

Applications: Older cellular systems, broadcast radio

2.4 Time Division Multiplex (TDM)

Concept: Each channel gets entire bandwidth for fixed time slot

How it works:

- All channels use same frequency spectrum
- Each channel transmits in designated time slot
- Channels take turns in sequential order (frames/slots)
- Only one transmitter active at any moment

Frame Structure:

- Frame period: Total time for one cycle
- Slot: Time allocated to one channel
- Frame sync: Unique bit pattern marking start
- Guard band (time): Gap between slots for clock synchronization

Synchronization: Central node broadcasts timing reference

- All nodes must have synchronized clocks
- Guard gaps protect against clock skew (clocks tick at slightly different rates)

Advantages:

- Only one signal in medium at once → simple receiver
- High utilization - bandwidth shared fairly

- Flexible: Can assign more slots to high-traffic users
- Robust against certain types of interference

Disadvantages:

- Requires precise clock synchronization
- Guard gaps waste time
- Unused slots go idle if station has no data
- Co-channel interference if slots overlap (requires sync accuracy)

Applications: Cellular (GSM), some IoT protocols

2.5 Code Division Multiplex (CDM)

Concept: Each transmitter has unique code; all use same spectrum simultaneously

How it works:

- All channels use same frequency spectrum
- All channels transmit at same time
- Each channel encoded with unique orthogonal code
- Receiver can separate channels using unique codes

Guard Space: Implemented via code distance

- Codes must have necessary "distance" in code space
- Orthogonal codes: Codes perfectly separated mathematically
- Receiver can decode only intended channel

Advantages:

- Bandwidth efficient (all channels use full spectrum)
- No synchronization/coordination needed
- Provides some interference protection (using secret codes)
- Soft handoff possible in cellular

Disadvantages:

- High receiver complexity
- Requires equal signal strength from all transmitters
- Near-far problem: Strong signals can drown out weak signals
- More complex signal regeneration

Implementation: Spread spectrum technology

- Direct-sequence spread spectrum (DSSS)
- Frequency-hop spread spectrum (FHSS)

Applications: CDMA cellular (IS-95, CDMA2000), military communications

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2.6 Combined Time & Frequency Multiplex (TDM/FDM)

Concept: Divide both time and frequency dimensions

How it works:

- Channel gets specific frequency band for specific time slot
- 2D grid of time slots × frequency bands
- Each cell represents one unique channel

Advantages:

- Higher multiplexing degree (more channels possible)
- More robust: Channel affected only during time slot
- Frequent frequency changes → harder to eavesdrop
- Good against frequency-selective fading

Disadvantages:

- Requires precise coordination across time AND frequency
- Guard bands in both dimensions → less usable spectrum
- More complex receiver

Real-world Example: GSM (2G cellular)

- 8 time slots per frame
- Multiple frequency bands
- Each user gets (time slot, frequency) pair

2.7 Comparison Table

Dimension	FDM	TDM	CDM	Combined
Separation	Frequency	Time	Code	Time + Freq
Synchronization	Not needed	Required	Not needed	Required
Guard space	Guard bands	Guard gaps	Code distance	Both
Simultaneous transmission	Yes	No	Yes	Partial
Flexibility	Low	High	Medium	Medium
Complexity	Low	Low	High	High
Typical use	Broadcast	Cellular	CDMA	2G/3G cellular

Section 3: OFDM (Orthogonal Frequency Division Multiplexing)

3.1 OFDM Concept

Problem with single-carrier:

- Spectral efficiency low: Only 1 carrier per bandwidth
- WiFi with single carrier: 11 carriers per GHz

Solution: OFDM

- Use multiple orthogonal subcarriers
- Each subcarrier modulated with its own data (BPSK, QPSK, 16-QAM, etc.)
- WiFi with OFDM: 48 carriers per 20 MHz = 2400 carriers per GHz

Key insight: Subcarriers are orthogonal = no interference between them despite overlapping spectrally

3.2 OFDM Advantages

- **Mitigate ISI (Intersymbol Interference)**: Longer symbols reduce ISI from multipath
- **Frequency-selective fading**: Only some subcarriers affected, not entire signal
- **Adaptive modulation per subcarrier**: Use BPSK on weak subcarriers, 64-QAM on strong ones
- **High spectral efficiency**: 48 parallel subcarriers in 20 MHz

3.3 OFDM Disadvantages

- **High peak-to-average power ratio**: Expensive amplifiers needed
- **Complex signal processing**: FFT/IFFT at receiver/transmitter

3.4 Applications

- **WiFi**: 802.11a/g/n/ac (not 802.11b)
- **Cellular**: 4G LTE, 5G NR
- **Digital TV**: DVB-H (Digital Video Broadcast)
- **WiMAX**: 802.16

Section 4: Channels in Wireless Standards

4.1 WiFi Channels (2.4 GHz Band)

Frequency Range: 2.412 - 2.462 GHz

Channel Configuration:

- 11 channels (North America)
- Each channel: 22 MHz wide
- Channels overlap partially

Non-overlapping Channels: 1, 6, 11

- Use these to minimize interference between nearby APs
- Spacing of 5 channels = no overlap

WiFi Transmission:

- Traditional approach: Modulate single carrier at channel center frequency
- Modern approach (OFDM): Use 48 subcarriers within 20 MHz bandwidth
- Much higher spectral efficiency

4.2 WiFi Channels (5 GHz Band)

Advantages over 2.4 GHz:

- Less crowded (more channels available)
- Wider channel bandwidth options
- Shorter range due to higher frequency

Channel Bandwidth Options:

- **20 MHz**: Baseline channels
- **40 MHz**: Combines two 20 MHz channels
- **80 MHz**: Combines four 20 MHz channels
- **160 MHz**: Combines eight 20 MHz channels

Key rule: Channels of same bandwidth don't interfere

- 20 MHz channels don't interfere with other 20 MHz channels

- But 20 MHz and 40 MHz channels can interfere

Modern WiFi: 802.11ac uses 80-160 MHz for high data rates

4.3 5G NR (New Radio) Frequency Bands

Wide range of bands: n1 through n109

- Sub-6 GHz: Longer range, lower bandwidth
- mmWave (> 24 GHz): Short range, very high bandwidth
- Country-specific availability

Key difference from WiFi:

- Licensed spectrum (not freely available)
- More efficient use due to licensing
- Multiple frequency bands per device

Non-terrestrial networks (NTN): Satellite integration in 5G

Section 5: Summary & Key Takeaways

Core Principles

1. **Bits to Waveforms**: Digital data converted to analog signals via modulation
2. **Modulation tradeoff**: Bandwidth vs. Bit error rate vs. Spectral efficiency
3. **Simple techniques** (ASK, FSK, BPSK): Robust but slow
4. **Complex techniques** (QAM, OFDM): Fast but need better SNR
5. **Multiplexing**: Multiple users share spectrum using space, time, frequency, or code

Modulation Summary

Technique	Encoding	Bandwidth	Noise Immunity	Spectral Efficiency
ASK	Amplitude	Low	Poor	Low
FSK	Frequency	High	Good	Low
BPSK	Phase	Low	Good	Low (1 bit/symbol)
QPSK	Phase (4 states)	Low	Good	Medium (2 bits/symbol)
16-QAM	Amplitude + Phase	Low	Fair	High (4 bits/symbol)
64-QAM	Amplitude + Phase	Low	Fair	Very high (6 bits/symbol)
OFDM	Multiple subcarriers	Medium	Excellent	Very high (48+ carriers)

Multiplexing Summary

Type	Best for	Spectral Efficiency	Complexity
SDM	Spatial separation	Good	High
FDM	Broadcast, static systems	Good	Low
TDM	Flexible allocation	Good	Low
CDM	Simultaneous users	Good	Very high
OFDM	Multipath channels	Excellent	High

Study Tips

Key Concepts to Memorize

- Sine wave parameters: A, f, φ
- Modulation techniques: ASK, FSK, BPSK, QPSK, QAM
- Bits per symbol: BPSK (1), QPSK (2), 16-QAM (4), 64-QAM (6)
- Multiplexing dimensions: Space, Time, Frequency, Code
- WiFi channels: 2.4 GHz (11 channels), 5 GHz (multiple widths)

Constellation Diagrams

- Practice reading/drawing them
- Understand what each point represents
- Recognize modulation type from diagram

Tradeoffs to Understand

1. **Efficiency vs. Robustness**: QAM faster but needs higher SNR
2. **Bandwidth vs. Complexity**: OFDM uses more spectrum but handles fading better
3. **Synchronization vs. Flexibility**: TDM needs sync, FDM doesn't

Practice Problems

- Convert between modulation schemes and data rates
- Analyze constellation diagrams
- Identify best multiplexing scheme for given scenario
- Calculate WiFi channel widths and overlaps

Appendix: Important Formulas

Sine Function:

- $A \cdot \sin(2\pi ft + \varphi)$

QAM Complex Representation:

- $A^{ej}{}_{\varphi} = A[\cos(\varphi) + j\cdot\sin(\varphi)]$
- Baseband: $A \cdot \cos(2\pi ft + \varphi) = A\cdot\cos(\varphi)\cdot\cos(2\pi ft) - A\cdot\sin(\varphi)\cdot\sin(2\pi ft)$
- $I = A\cdot\cos(\varphi)$, $Q = A\cdot\sin(\varphi)$

OFDM Subcarrier Frequency:

- $A \cdot \cos(2\pi fct + 2\pi fsct + \varphi)$
- where fc = carrier frequency, fsc = subcarrier frequency

Data Rate:

- Data rate = (bits per symbol) × (symbol rate) × (number of carriers for OFDM)

Key Abbreviations

Abbreviation	Meaning
ASK	Amplitude Shift Keying
FSK	Frequency Shift Keying
PSK	Phase Shift Keying
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
OFDM	Orthogonal Frequency Division Multiplexing
SDM	Space Division Multiplex
FDM	Frequency Division Multiplex
TDM	Time Division Multiplex
CDM	Code Division Multiplex
WLAN	Wireless Local Area Network
SNR	Signal-to-Noise Ratio
BER	Bit Error Rate
ISI	Intersymbol Interference
EDC	Error Detection and Correction
BFSK	Binary Frequency Shift Keying
RF	Radio Frequency
5G NR	5G New Radio