Lecture 04 - Wireless Communication and Networking

Wireless communication:

Differences from wired: confined by where you can go and how much physical do you have

- Broadcast medium: everyone can hear your transmission
- Path loss: signal strength decreases rapidly with distance
- Interference: multiple transmitters share spectrum,
- Fading: signal varies due to multipath obstacles
- regulation: spectrum is licensed or restricted
- Power constraints: battery powered devices

Benefits:
- Mobility: no physical connection needed
- Deployment: no cable installation
- Flexibility: easy to add/ remove devices

Basic transmitter architecture:

[data] → [encoder] → [modulator] → [upconverter] → [PA] → [antenna]

Data: The original information you want to send, like bits from a file, voice, or video.
Encoder: Converts the raw data into a form that is more robust to errors, often by adding redundancy for error detection and correction.
Modulator: Maps the encoded bits onto a waveform by changing properties of a carrier signal such as amplitude, phase, or frequency.
Upconverter: Shifts the modulated signal from baseband to a higher radio frequency suitable for wireless transmission.
PA (Power Amplifier): Boosts the signal's power so it can travel a long distance without being overwhelmed by noise.
Antenna: Converts the electrical RF signal into electromagnetic waves that radiate through space.

Encoder → error correction (FEC), interleaving, scrambling
Modulator → maps bits to symbols (I and Q signals)
Upconverter → translates baseband to RF carrier

$s(t)=I(t)\cos(2\pi f_c t)-Q(t)\sin(2\pi f_c t)$ → That equation is the passband representation of an I/Q-modulated signal.

Power amplifier(PA) → amplifies to transmit power

Tradeoff: power vs linearity vs efficiency

Typical efficiency: 20-40%

Antenna: converts electrical signal to EM waves

Basic Receiver Architecture:

[antenna] → [LNA] → [downconverter] → [demodulator] → [decoder] → [data]

Low noise amplifier (LNA) → most critical component

Minimized noise figure

High gain

down converter → translates RF to baseband/IF

Demodulator → extracts I and Q signals, symbol recovery

Decoder → error correction decoding

Antenna fundamentals:

Isotropic (same value in all directions) antenna(theoretical):

- Radiates equally in all directions (sphere)
- Reference for antenna gain
- Doesn't exist IRL !!

Antenna gain(G): concentration of power in preferred direction

- omni directional: ~2dBi
- directional : 6 to 20 dBi
- dish(satellite) : 30 to 50 dBi

Effective aperture: $$A_e = \frac{G\lambda^2}{4\pi}$$

Reciprocity: same gain for transmit and receive

Free space path loss (FSPL)

Friis Transmission Equation: $$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$ → used to calculate the power received by an antenna from another antenna at a distance under ideal free-space conditions

Pat loss in dB: $$L_{\mathrm{FSPL}}(\mathrm{dB}) = 32.45 + 20\log_{10}(f_{\mathrm{MHz}}) + 20\log_{10}(d_{\mathrm{km}})$$

Key insights:

Real world propagation:

Empirical Path Loss model:

$$L(d) = L_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma$$

n = path loss exponent
X = shadow fading

Environment	n	**Loss/decade**
Free space	2	20 dB
Urban cellular	2.7-3.5	27-35 dB
Indoor (LOS)	1.6-1.8	16-18 dB
Indoor (NLOS)	3-5	30-50 dB
Obstructed urban	4-6	40-60 dB

→ obstacles increase path loss

Fading:

Fading in antennas refers to the fluctuation in signal strength received, caused by multipath propagation, obstacles, and atmospheric changes.

Shadow fading/ slow fading:

- Random variations due to obstacles
- Log normal distribution: X ~ N(0,o)
- Typical
- Changes slowly

Multipath fading/ fast fading:

- Multiple signal path arrive at receiver
- Constructive and destructive interference
- Rayleigh fading (no LOS) or Rician fading (LOS + multipath)
- Changes rapidly
- Can cause 20-30 dB signal variation !!

Wireless link budget:

A wireless link budget is a detailed, decibel-based (dB) accounting of all power gains and losses from a transmitter to a receiver, ensuring sufficient signal strength for reliable communication.

Link budget equation:

$$P_r(\text{dBm}) = P_t(\text{dBm}) + G_t(\text{dBi}) + G_r(\text{dBi}) - L_{\text{path}}(\text{dB}) - L_{\text{misc}}(\text{dB})$$

$$\text{Margin} = P_r - S_{\text{min}}$$

Margin calculator:
S_{min} → receiver sensitivity

Adequate Margins:

- 10-15 dB: Acceptable for static links
- 20-30 dB: Needed for mobile/fading environments
- 40+ dB: Excellent, very reliable

Modulation:

Modulation is the process of varying properties (amplitude, frequency, or phase) of a high-frequency carrier signal with a lower-frequency information signal (voice, data, video) to enable efficient, long-distance transmission

→ shift baseband signal to higher carrier frequency
→ different users/channels use different carriers
→ practical antenna sizes
→ frequency division multiple access (FDMA)

Quadrate amplitude modulation → modulate both amplitude and phase

Transmitted Signal:

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

where:

- $I(t)$ = in-phase component
- $Q(t)$ = quadrature component
- These are **independent** data streams!

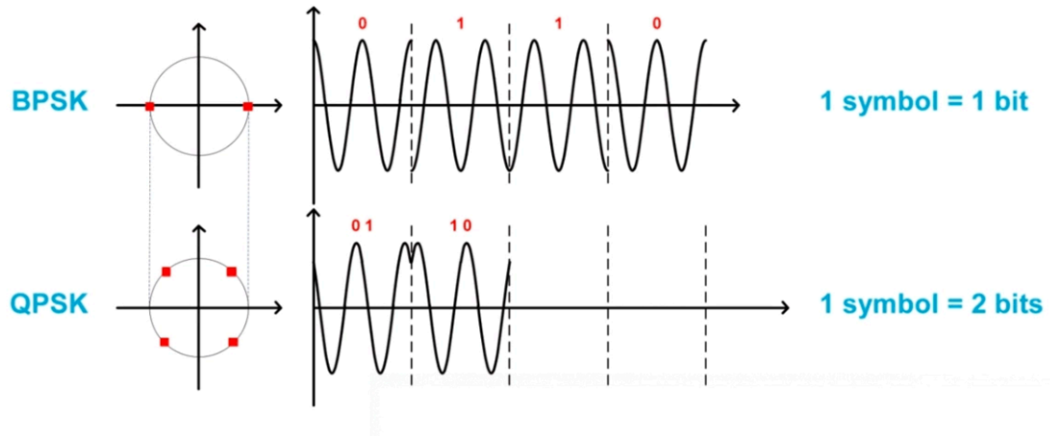
Complex Envelope:

$$z(t) = I(t) + jQ(t)$$

Visualized in constellation diagram (I-Q plane)

Constellation diagrams:

A constellation diagram is a 2D plot in the complex plane (I/Q plane) representing possible signal points (symbols) in digital modulation, where the x-axis is in-phase (I) and y-axis is quadrature (Q) amplitude



BPSK → binary phase shift keying:

- 2 symbols: +/- 1
- 1 bit/ symbol
- Minimum distance: d = 2

QPSK → quadrature PSK

- 4 symbols at +/- 1 +/- j
- 2 bits/symbol
- distance: d = root 2

16-QAM: 16 symbols in 4x4 grid, 4 bits/ symbol
64-QAM, 256 QAM, 1024 QAM: used in Wifif
Quadrate amplitude modulation

QAM performance requirements:

Required SNR for BER $= 10^{-6}$**:**

Modulation	E_b/N_0 (dB)	Bits/symbol
BPSK	10.5	1
QPSK	10.5	2
16-QAM	14.5	4
64-QAM	18.5	6
256-QAM	23.5	8

Key Insight: Each doubling of M requires $\sim$3-4 dB more SNR

Adaptive Modulation:

Modern systems adapt modulation to channel quality

WiFi (802.11ac/ax) Rate Table:

MCS	Modulation	Code Rate	Rate (80 MHz)
0	BPSK	1/2	29 Mb/s
1	QPSK	1/2	58 Mb/s
3	16-QAM	1/2	117 Mb/s
5	16-QAM	3/4	175.5 Mb/s
7	64-QAM	5/6	263 Mb/s
9	256-QAM	3/4	351 Mb/s
11	1024-QAM	3/4	468 Mb/s

Far from AP: Low MCS (robust, slow) — **Near AP:** High MCS (fast, fragile)

Radio Frequency Spectrum:

Band	Frequency	Wavelength	Use
VLF	3-30 kHz	100-10 km	Submarine comm
LF	30-300 kHz	10-1 km	Navigation
MF	300-3000 kHz	1 km-100 m	AM radio
HF	3-30 MHz	100-10 m	Shortwave
VHF	30-300 MHz	10-1 m	FM radio, TV
UHF	300-3000 MHz	1 m-10 cm	TV, cellular, WiFi
SHF	3-30 GHz	10-1 cm	Satellite, 5G
EHF	30-300 GHz	1 cm-1 mm	mmWave 5G

Cellular Spectrum(US):

Licensed Bands (exclusive use, FCC auctions):

4G LTE Frequencies:

- **Band 2 (PCS):** 1850-1910 MHz (UL), 1930-1990 MHz (DL)
- **Band 4 (AWS):** 1710-1755 MHz (UL), 2110-2155 MHz (DL)
- **Band 12 (700 MHz):** 699-716 MHz (UL), 729-746 MHz (DL)

5G Frequencies:

- **Low band (Sub-6 GHz):** 600-900 MHz (wide coverage)
- **Mid band (C-band):** 3.7-3.98 GHz (capacity + coverage)
- **High band (mmWave):** 24-47 GHz (ultra-capacity, short range)

FDD: Separate uplink/downlink frequencies
TDD: Same frequency, alternate in time

WiFi Spectrum (unlicensed ISM Bands):

Anyone can use these bands (with power limits):

2.4 GHz Band (2.400-2.4835 GHz):

- Channels 1-11 (US), 20 MHz width
- Non-overlapping: Channels 1, 6, 11
- Crowded: Bluetooth, microwaves, cordless phones
- Good range (lower frequency)

5 GHz Band (5.150-5.825 GHz):

- Many channels, widths: 20, 40, 80, 160 MHz
- Less crowded, shorter range
- Higher speed (wider channels)

6 GHz Band (5.925-7.125 GHz): WiFi 6E

- 1200 MHz of spectrum! Very wide channels (320 MHz)

Other wireless systems:

Bluetooth (2.4 GHz ISM):

- 79 channels, 1 MHz each
- Frequency hopping (1600 hops/sec)
- Short range (10-100 m), low power

GPS:

- L1: 1575.42 MHz, L2: 1227.60 MHz
- Receive-only, weak signal (-160 dBW!)

Satellite:

- C-band: 4-8 GHz, Ku-band: 12-18 GHz, Ka-band: 26-40 GHz

LoRaWAN (IoT):

- 915 MHz (US), ultra-long range (10+ km), very low data rate

Spectrum Management:

Licensed	Unlicensed
Exclusive use	Shared
Expensive (auctions)	Free
Regulated power/quality	Best effort
Predictable performance	Interference possible
Example: Cellular	Example: WiFi, Bluetooth

Spectrum is incredibly valuable!

- Recent US C-band auction (2021): **$81 billion**
- Limited resource (like real estate)
- Tradeoff: coverage (low freq) vs. capacity (high freq)

Cellular Concept:

Cellular networking splits large geographic areas into smaller "cells," each served by a low-power base station, to maximize capacity and frequency reuse

Key idea: Divide coverage area into cells

- Each cell has a base station

- Reuse frequencies in non adjacent cells
- Increases total system capacity

Without reuse:

- One transmitter covers entire city
- All users share single channel set
- Very limited capacity

With reuse:

- Many transmitters (cell towers)
- Same frequencies used in distant cells
- Capacity multiplied by reuse factor

<u>Hexagonal Cell Patterns:</u>

Why hexagons?

- Approximate circular coverage
- Tile without gaps
- Geometric regularity

Cell cluster: group of N cells using difference frequencies

Common patterns: more reuse --> more capacity ; smaller N = more reuse

- N (cluster size=number of cells in cluster)= 3: aggressive reuse → more capacity → higher interference (In computer networking, reuse generally refers to the practice of using existing network resources, connections, or frequencies multiple times to improve efficiency, increase capacity, and reduce latency)
- N = 4: moderate reuse → balance capacity and quality
- N = 7: conservative reuse → lower interference and lower capacity

How reuse correlates with capacity

Capacity = how many users / how much data the network can support

Key idea:

$$\text{Capacity per area} \propto \frac{1}{N}$$

- **Smaller** N → frequencies reused more often → **higher capacity**
- **Larger** N → frequencies reused less often → **lower capacity**

Examples

- $N = 3$:
  - Same spectrum reused very frequently
  - **High capacity**, but lots of interference
- $N = 7$:
  - Frequencies reused far apart
  - **Lower capacity**, but much cleaner signals

So capacity goes **up** as reuse becomes **more aggressive**.

<u>Reuse Distance</u>:

$$D = R\sqrt{3N}$$

Distance to nearest co-channel cell: where R = cell radius, N = cluster size

Carrier to interference ratio (C/I): assuming 6 interfering cells in first tier:

$$\frac{C}{I} = \frac{(3N)^{n/2}}{6}$$

where n = path loss exponent

Reuse Factor = 1:

Legacy Systems (2G GSM, 3G):

- Used $N = 3$, 4, or 7
- Different frequencies in adjacent cells
- Simple, but wastes spectrum

Modern Systems (4G LTE, 5G NR):

- **Reuse factor = 1** (all cells use all frequencies!)
- Advanced techniques:
    - Orthogonal Frequency Division Multiple Access (OFDMA)
    - Interference coordination between base stations
    - Beamforming (directional antennas)
    - Power control
    - Advanced receivers (interference cancellation)

Result: Much higher spectral efficiency!

Sectoring:

Problem: Omnidirectional antennas waste power and create interference

Solution: Divide cell into sectors

- Typically 3 sectors per cell (120° each)
- Directional antennas (17-21 dBi gain)
- Each sector like a separate cell

Benefits:

- 3× capacity (3 sectors)
- Lower interference (directional)
- Better link budget (antenna gain)

Towers Typically Have:

- 3 sectors (120° each)
- Multiple antennas per sector (MIMO)
- Multiple frequency bands