Unit = 3

1. Structure of a Wireless Communication Link

A **wireless communication link** is the path through which information travels from a **transmitter** to a **receiver** over the air. It's more complex than a wired link due to **fading, noise, interference, and mobility**.

Basic Components:

1. **Transmitter**
   - Converts the information signal (voice, data, video) into a suitable form for transmission.
   - Components include:
     - **Source encoder:** Compresses and formats data.
     - **Channel encoder:** Adds redundancy for error correction.
     - **Modulator:** Maps bits to signal waveforms (e.g., QPSK, MSK).
   - Example: In a mobile phone, the microphone signal is digitized, encoded, and modulated.
2. **Channel**
   - The medium through which the signal propagates. In wireless, this is **air**.
   - Characteristics:
     - **Path loss:** Signal power decreases with distance.
     - **Shadowing:** Signal blocked or attenuated by obstacles.
     - **Fading:** Rapid fluctuations in amplitude/phase due to multipath propagation.
       - **Flat fading:** All frequencies affected equally.
       - **Frequency-selective fading:** Different frequencies affected differently.
     - **Noise and interference:** Thermal noise, other transmissions.
3. **Receiver**
   - Converts the received waveform back into the original information.
   - Components include:

- **Demodulator:** Extracts the transmitted symbols from the waveform.
- **Channel decoder:** Corrects errors introduced by noise/fading.
- **Source decoder:** Reconstructs the original data (voice, text, video).

Flow of a Wireless Link:

Information → Source Encoder → Channel Encoder → Modulator → Transmitter

→ Wireless Channel (fading, noise, interference)

→ Receiver → Demodulator → Channel Decoder → Source Decoder → Information

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Challenges in Wireless Communication:

1. **Fading** – Causes signal fluctuations; needs techniques like diversity, equalization, or adaptive modulation.
2. **Interference** – Signals from other users degrade performance.
3. **Noise** – Adds random errors; affects BER (Bit Error Rate).
4. **Doppler Effect** – Relative motion between transmitter and receiver changes frequency.

Summary:

The wireless communication link is a chain: **Transmitter → Channel → Receiver**, with **fading, noise, and interference** being the main challenges. Proper modulation, coding, and diversity techniques help maintain reliable communication.

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2. Principles of Offset-QPSK (OQPSK)

Offset Quadrature Phase Shift Keying (OQPSK) is a type of **phase modulation** used in digital communication to improve performance in fading channels.

Basic Concept:

- **QPSK (Quadrature Phase Shift Keying):** Transmits 2 bits per symbol by shifting the phase of a carrier among 4 values (0°, 90°, 180°, 270°).
- **Problem with QPSK:** Phase can jump by 180° instantaneously, causing large amplitude fluctuations. This is a problem for **non-linear amplifiers**.

OQPSK solves this problem by **offsetting the timing of the in-phase (I) and quadrature (Q) signals by half a symbol period (T/2)**.

How It Works:

1. The data stream is split into **I (In-phase)** and **Q (Quadrature)** components.
2. Q component is **delayed by T/2**, where T is the symbol duration.
3. Result: **No two bits change simultaneously**, so the **phase change is never 180°**, only ±90° at most.

Advantages of OQPSK:

- **Reduced amplitude fluctuations** → less distortion in non-linear amplifiers.
- **Better performance in fading channels** compared to standard QPSK.
- **Widely used in mobile and satellite communication**.

Constellation Diagram:

- Standard QPSK: Points at 0°, 90°, 180°, 270°; abrupt jumps possible.
- OQPSK: Points are the same, but the **transitions are smoother** because only one component changes at a time.

I-axis: In-phase

Q-axis: Quadrature

Symbols change along one axis at a time → smoother transitions

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Summary:

- OQPSK is a **modified QPSK** to reduce sudden phase shifts.
- Achieves **better power efficiency** and **less distortion**.
- Common in **satellite links, GSM, and other wireless systems**.

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3. π/4-DQPSK (pi/4-Differential QPSK)

π/4-DQPSK is a **phase modulation technique** used in wireless communication that combines **differential encoding** with **QPSK**, but with a **π/4 phase shift** to improve performance in fading channels.

Basic Concept:

1. **QPSK:** Transmits 2 bits per symbol using 4 possible phases (0°, 90°, 180°, 270°).
2. **Problem with QPSK:** Phase transitions can be abrupt (up to 180°), leading to signal amplitude fluctuations.
3. **Solution (π/4-DQPSK):**
   - Introduces a **π/4 (45°) offset between successive constellations**.
   - Each symbol is **differentially encoded** with respect to the previous symbol.
   - Maximum phase change is **±135°** instead of 180°, which **reduces envelope variations**.

Differential Encoding:

- Instead of encoding the absolute phase, the **change in phase** from the previous symbol represents the data.

- This allows the receiver to **detect data without exact carrier phase reference**, making it **robust to phase shifts in fading channels**.

Constellation Diagram:

- Uses **two QPSK constellations**, rotated by **π/4 (45°)** relative to each other.
- Symbols alternate between these constellations, making **phase transitions smoother**.

Constellation 1: 0°, 90°, 180°, 270°

Constellation 2: 45°, 135°, 225°, 315°

- Only **one axis changes at a time**, reducing sudden amplitude changes.

Advantages of π/4-DQPSK:

1. **Reduced amplitude fluctuations** → better for non-linear power amplifiers.
2. **Differential detection** → avoids the need for exact phase synchronization.
3. **Better performance in fading channels** than standard QPSK.
4. Commonly used in **GSM mobile communication**.

Summary:

- **π/4-DQPSK = Differential QPSK + π/4 rotation**.
- Smooth transitions, lower amplitude variations, robust in fading channels.
- Ideal for **mobile and wireless communication systems**.

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4. Minimum Shift Keying (MSK)

MSK is a type of **continuous phase frequency shift keying (CPFSK)** that is **highly spectrally efficient** and commonly used in digital wireless communications.

Basic Concept:

1. **Frequency Shift Keying (FSK):**
   - Represents digital data by **changing the frequency** of the carrier signal.
   - Binary FSK uses two frequencies for 0 and 1.
2. **MSK Characteristics:**
   - Special case of **binary FSK** where the **frequency separation (Δf) = 1 / (2T)**, where **T = symbol duration**.
   - This is the **minimum frequency spacing** to maintain **orthogonality** between symbols → hence the name **Minimum Shift Keying**.
   - Ensures **continuous phase transitions**, reducing sudden changes in the signal.

Mathematical Representation:

The MSK signal can be written as:

s(t)=2EbTcos[2πfct+ϕ(t)]s(t) = \sqrt{\frac{2E_b}{T}} \cos \left[2\pi f_c t + \phi(t) \right]s(t)=T2Ebcos[2πfct+ϕ(t)]

Where:

- fcf_cfc = carrier frequency
- EbE_bEb = energy per bit
- ϕ(t)\phi(t)ϕ(t) = continuous phase term
- Phase continuity ensures **smooth transitions** between symbols.

Key Features of MSK:

1. **Constant envelope:**
   - Amplitude does not change, suitable for **non-linear power amplifiers**.

2. **Continuous phase:**
    - Phase changes **gradually**, reducing spectral side lobes.
3. **Spectral efficiency:**
    - Bandwidth = 1.5/T (narrower than standard FSK).
4. **Error performance:**
    - Similar to QPSK in **AWGN channels**.

Waveform of MSK:

- MSK can be seen as **OQPSK with sinusoidal pulse shaping**.
- In the I-Q plane:
    - I and Q components are **offset by T/2**, like OQPSK.
    - Each bit corresponds to a **half-cycle of a sine wave**.

Advantages of MSK:

- **High spectral efficiency** → fits more data in a given bandwidth.
- **Good power efficiency** → constant envelope allows use of non-linear amplifiers.
- **Smooth waveform** → less interference with adjacent channels.

Applications:

- GSM mobile communication (precursor to GMSK)
- Satellite and military communications
- Low-power wireless devices

✅ **Summary:**
MSK is a **continuous phase, minimum frequency shift keying** scheme. It's **power-efficient, spectrally efficient, and smooth**, making it ideal for fading channels and non-linear amplifiers.

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5. Gaussian Minimum Shift Keying (GMSK)

GMSK is an **enhanced version of MSK** where the data signal is **shaped by a Gaussian filter** before frequency modulation. It is widely used in **GSM mobile communication**.

Basic Concept:

1. **MSK recap:**
   - MSK is a continuous-phase FSK with minimum frequency spacing.
   - Smooth phase transitions → constant envelope → efficient for non-linear amplifiers.
2. **Enhancement in GMSK:**
   - MSK is passed through a **Gaussian low-pass filter** before modulation.
   - Gaussian filter **reduces the signal bandwidth**, making it **more spectrally efficient**.
3. **Key idea:**
   - Smooth transitions in phase and **bandwidth limitation** → lower interference with adjacent channels.

Mathematical Representation:

$$s(t) = \sqrt{\frac{2E_b}{T}} \cos \left[2 \pi f_c t + 2\pi h \int_0^t m(\tau) d\tau \right]$$

Where:

- $m(t)$ = filtered digital data (after Gaussian shaping)
- $h = 0.5$ for MSK/GMSK
- Gaussian filter **reduces high-frequency components**, lowering side lobes.

Key Features of GMSK:

1. **Constant envelope:**
   - Can use **non-linear power amplifiers** → energy efficient.
2. **Bandwidth-efficient:**

    - Gaussian filter compresses spectrum → **narrow bandwidth**.
3. **Continuous phase:**
    - Smooth phase transitions → lower interference.
4. **Parameter BT (Bandwidth × Time):**
    - Determines **filter width**:
        - Small BT → narrower bandwidth, smoother signal, slightly slower rise time.
        - Typical GSM value: **BT = 0.3**.

Advantages:

- **High spectral efficiency** → supports more channels in limited spectrum.
- **Power-efficient** → suitable for mobile phones with battery constraints.
- **Robust in fading channels** → good BER performance.

Applications:

- **GSM cellular systems** (most common)
- **Satellite communication**
- **Military and low-power wireless systems**

✅ **Summary:**
GMSK = **MSK + Gaussian filtering**.

- Reduces bandwidth
- Maintains constant amplitude
- Smooth phase transitions
- Widely used in GSM due to spectral and power efficiency.

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6. Error Performance in Fading Channels

In wireless communication, the **channel is not ideal**. Signals undergo **fading**, which affects their amplitude and phase, leading to errors. Understanding **error performance** is critical for designing reliable systems.

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1. Fading in Wireless Channels

Fading is the **variation of signal strength** over time or space due to **multipath propagation**.

Types of fading:

1. **Flat Fading**
    - Bandwidth of transmitted signal < channel coherence bandwidth.
    - **All frequencies affected equally.**
    - Causes **signal amplitude variations** → affects SNR and BER.
2. **Frequency-Selective Fading**
    - Bandwidth of transmitted signal > channel coherence bandwidth.
    - **Different frequency components experience different fading.**
    - Causes **inter-symbol interference (ISI)**.
3. **Slow vs. Fast Fading**
    - **Slow fading:** Channel changes slowly compared to symbol duration.
    - **Fast fading:** Channel changes quickly → rapid fluctuations within symbol duration.

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2. Error Performance Metrics

1. **Bit Error Rate (BER)**
    - Probability that a received bit is incorrect.
    - Depends on modulation type, SNR, and channel characteristics.
2. **Symbol Error Rate (SER)**
    - Probability of a symbol being incorrectly detected.

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3. BER in Fading Channels

- Fading increases BER compared to **AWGN (Additive White Gaussian Noise) channels**.
- Example: For BPSK in Rayleigh fading:

- Example: For BPSK in Rayleigh fading:

$$P_b = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma}{1+\gamma}}\right)$$

Where:

- γ = average SNR per bit
- Rayleigh fading → no line-of-sight component
- BER for QPSK/MSK/OQPSK in fading channels is generally **worse than AWGN** because of random amplitude variations.

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4. Techniques to Improve Error Performance

1. **Diversity Techniques**
   - Use multiple antennas, frequencies, or time slots to **combat fading**.
   - Types:
     - **Time diversity:** Repeat signal at different times
     - **Frequency diversity:** Transmit on different frequencies
     - **Spatial diversity:** Multiple antennas (MIMO)
2. **Equalization**
   - Compensates for **ISI caused by multipath**.
3. **Adaptive Modulation & Coding**
   - Modulation order and coding rate adapt according to **channel conditions**.
4. **Forward Error Correction (FEC)**
   - Adds redundancy to correct errors at the receiver.

Summary:

- **Fading** significantly affects wireless signal reliability.

- **BER in fading channels** is worse than in AWGN channels.
- **Techniques like diversity, equalization, and adaptive coding** help improve error performance.
- Understanding fading and error performance is essential for choosing **modulation schemes** like OQPSK, MSK, or GMSK.

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7. OFDM (Orthogonal Frequency Division Multiplexing) Principle

OFDM is a **multicarrier modulation technique** used to efficiently transmit data over **frequency-selective fading channels**. It is widely used in **4G, 5G, Wi-Fi, and LTE systems**.

Basic Concept:

1. **Problem with Single-Carrier Systems:**
   - In frequency-selective fading, different frequencies of the signal experience different attenuation.
   - This causes **inter-symbol interference (ISI)** and limits data rates.
2. **OFDM Solution:**
   - Splits the high-rate data stream into **multiple low-rate streams**.
   - Each low-rate stream modulates a **separate subcarrier**.
   - Subcarriers are **orthogonal** to each other → no interference between them.

Key Features of OFDM:

1. **Orthogonality:**
   - Subcarriers are spaced such that **peak of one aligns with nulls of others**.
   - Allows **overlapping in frequency** → high spectral efficiency.
2. **Parallel Transmission:**

- Data is transmitted in **parallel** across multiple subcarriers.
- Reduces the **symbol rate** per subcarrier → mitigates ISI.

3. **Robustness Against Fading:**
    - Frequency-selective fading affects only some subcarriers.
    - Easy to recover data using **equalization**.

Mathematical Representation:

- An OFDM signal with N subcarriers:

$$s(t) = \sum_{k=0}^{N-1} X_k \cos(2\pi f_k t)$$

Where:

- X_k = symbol on k-th subcarrier
- f_k = frequency of k-th subcarrier
- Subcarriers satisfy **orthogonality**: $f_k = f_0 + k/T$

Advantages of OFDM:

1. **ISI reduction** due to low symbol rate per subcarrier.
2. **Efficient bandwidth usage** due to overlapping subcarriers.
3. **Simple equalization** using frequency-domain techniques.
4. **Adaptable to channel conditions** → supports adaptive modulation per subcarrier.

Applications:

- 4G LTE, 5G NR
- Wi-Fi (IEEE 802.11a/g/n/ac)
- Digital TV (DVB-T)
- Power-line communications

✅ **Summary:**
OFDM divides a high-rate data stream into **many low-rate substreams**, transmits them over **orthogonal subcarriers**, and is **highly robust against frequency-selective fading**.

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8. Cyclic Prefix (CP) in OFDM

Cyclic Prefix (CP) is a key technique in OFDM systems to **combat inter-symbol interference (ISI)** caused by **multipath propagation**.

Problem: Inter-Symbol Interference (ISI)

- In wireless channels, signals reflect from buildings, walls, and other objects → **multipath propagation**.
- Multipath causes **delayed copies** of the transmitted symbol to arrive at the receiver.
- If these delayed copies overlap with the next symbol, **ISI** occurs → errors in detection.

Solution: Cyclic Prefix

1. **Definition:**
    - A **cyclic prefix** is a **copy of the last part of an OFDM symbol**, prepended to the symbol before transmission.
2. **How it works:**
    - If the OFDM symbol is x[n]x[n]x[n] of length N, the last L samples are copied and added at the beginning.
    - This ensures that **linear convolution with the channel becomes circular convolution**.
    - Circular convolution allows **simple frequency-domain equalization** using FFT.

3. **Length of CP:**
    - Must be **longer than the maximum delay spread** of the channel.
    - Too short → ISI not fully eliminated
    - Too long → **reduces spectral efficiency**

Mathematical Illustration:

- Transmitted OFDM symbol with CP:

$$x_{CP}[n] = [x[N-L], x[N-L+1], ..., x[N-1], x[0], x[1], ..., x[N-1]]$$

- At the receiver, after removing CP:

$$y[n] = h[n] * x[n] + noise$$

- Circular convolution ensures **simple division in frequency domain** for equalization.

Advantages of Cyclic Prefix:

1. **ISI elimination** if CP ≥ channel delay spread.
2. **Simplifies equalization** → FFT can recover transmitted symbols.
3. **Maintains orthogonality** of subcarriers.

Disadvantages:

- Reduces **data rate** slightly (overhead from CP).
- Longer CP → more spectral inefficiency.

Summary:

- **Cyclic Prefix = Guard interval** in OFDM to combat ISI.
- Converts **linear convolution → circular convolution** → easy frequency-domain equalization.
- Must be **longer than channel delay spread** to be effective.

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9. Windowing in OFDM

Windowing is a technique used in OFDM systems to **reduce spectral leakage** and **improve signal quality**.

Problem: Spectral Leakage

- OFDM uses **rectangular pulses** in time domain for each symbol.
- Rectangular pulses have a **sinc-shaped spectrum**, which causes **side lobes** → interference with adjacent channels.
- High side lobes reduce **spectral efficiency** and can violate regulatory limits.

Solution: Windowing

1. **Definition:**
    - Windowing multiplies the OFDM signal with a **smooth window function** (like Hanning, Hamming, or Raised Cosine) before transmission.
2. **How it Works:**
    - Smoothly ramps up and ramps down the symbol at the edges.
    - Reduces abrupt transitions in time domain → **reduces side lobes in frequency domain**.
3. **Mathematical Representation:**
    - Let $x[n]$ be an OFDM symbol of length N.
    - Windowed signal:

$$x_w[n] = x[n] \cdot w[n], \quad 0 \le n \le N-1$$

- Where $w[n]$ = window function (e.g., Hanning, Hamming).

Common Window Functions:

Window Type	Characteristics
Hanning	Smooth, reduces side lobes significantly

Window Type	Characteristics
Hamming	Slightly higher main lobe, lower side lobes
Raised Cosine	Controlled roll-off, widely used in OFDM

Advantages of Windowing:

1. **Reduces spectral leakage** → less interference to adjacent channels.
2. **Improves signal quality** → lower bit error rate.
3. **Maintains orthogonality** of subcarriers.

Disadvantages:

- Slight **increase in symbol duration** → reduces throughput slightly.
- **Additional complexity** in implementation.

Summary:

- Windowing is used to **smooth OFDM symbol edges**, reducing **side lobes** in the frequency domain.
- Improves **spectral efficiency** and **signal quality**, making it essential for practical OFDM systems.

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10. PAPR (Peak-to-Average Power Ratio) in OFDM

PAPR is a critical parameter in OFDM systems that measures the **ratio of the peak power to the average power** of the transmitted signal.

Problem: High PAPR in OFDM

- OFDM combines **many subcarriers** in the time domain.
- When multiple subcarriers **constructively add**, the instantaneous signal power can become very high.
- This leads to **high PAPR**, causing issues like:
    1. **Non-linear distortion** in power amplifiers.
    2. **Reduced power efficiency**.
    3. Increased **out-of-band radiation**.

Definition:

$$\text{PAPR} = \frac{P_{\text{peak}}}{P_{\text{avg}}} = \frac{\max |x(t)|^2}{\mathbb{E}[|x(t)|^2]}$$

Where:

- $x(t)$ = OFDM signal in time domain
- P_{peak} = maximum instantaneous power
- P_{avg} = average signal power
- PAPR is usually expressed in **dB**:

$$\text{PAPR(dB)} = 10 \log_{10} \frac{P_{\text{peak}}}{P_{\text{avg}}}$$

Why PAPR is a Problem

- High PAPR requires **linear amplifiers with large dynamic range**.
- Linear amplifiers are **less power-efficient**, which is critical for **battery-powered devices**.
- Non-linear amplifiers cause **signal distortion** → higher **BER**.

Techniques to Reduce PAPR

1. **Clipping and Filtering:**
   - Clip peaks of the signal → reduces PAPR, but may cause **in-band distortion**.
2. **Coding Techniques:**
   - Special codes reduce peak occurrences in the OFDM signal.
3. **Selective Mapping (SLM):**
   - Generate multiple versions of OFDM symbols → choose the one with **lowest PAPR**.
4. **Partial Transmit Sequence (PTS):**
   - Divide OFDM symbol into sub-blocks → phase rotate to reduce PAPR.
5. **Tone Reservation / Tone Injection:**
   - Reserve certain subcarriers or inject signals to **cancel peaks**.

Summary:

- **PAPR** measures the ratio of the **highest peak power to average power** in OFDM.
- High PAPR is a major issue for **power efficiency and amplifier linearity**.
- **Techniques like clipping, coding, and SLM** help reduce PAPR in practical OFDM systems.