Principles of Wireless Communications

Module-1

Module-1: Contents

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Introduction to Wireless Communications

- **Wireless communication** enables data transmission without physical connections.

- It is the backbone of modern technologies:
- Mobile phones
- Wi-Fi
- Bluetooth
- Satellite systems

- Offers **mobility**, **flexibility**, and **ubiquitous access** to information.

Introduction to Wireless Communications

- Focuses on key concepts such as:
- Signal propagation and channel modeling
- Modulation techniques
- Fading and interference
- Bandwidth and power efficiency

Introduction to Wireless Communications

- Essential for designing efficient systems in:

•5G networks
•Internet of Things (IoT)
•Wireless sensor networks
•Enables innovations in communication and connectivity.

The Wireless Communication Environment:

➢ **Introduction**

- Wireless communication relies on **radio wave propagation** through the environment.
- Unlike wired media, the wireless environment is **unpredictable** and **dynamic**.
- Key environmental factors affect signal strength and quality.

The Wireless Communication Environment:

➢ **Key Components of the Wireless Environment**

- **Radio Path:** The route taken by radio waves from transmitter to receiver.
- **Propagation Attenuation:** Signal loss as it travels through the environment.
- **Mobile Radio Channel:** Time-varying nature due to movement and obstacles.

The Wireless Communication Environment:

➢ **Propagation Mechanisms**

- **Reflection:** Occurs when signals bounce off surfaces (e.g., buildings).
- **Diffraction:** Bending around sharp edges or corners.
- **Scattering:** Caused by small objects like trees or lamp posts.

➢ **Fading Effects**

- **Fast Fading:** Rapid changes due to small movements (multipath interference).
- **Slow Fading (Shadowing):** Gradual signal strength variation due to large obstacles.

The Wireless Communication Environment:

- **Path Loss Models**

- **Free-Space Model:** Ideal case with line-of-sight.
- **Two-Ray Model:** Considers direct and ground-reflected paths.
- **Empirical Models:**
  - **Hata Model (Urban/Rural)**
  - **Okumura Model**
  - **Log-distance Path Loss Model**

The Wireless Communication Environment:

- **Indoor vs Outdoor Environments**

- **Indoor:** Complex due to walls, furniture; dominated by reflection/scattering.
- **Outdoor:** Impacted by terrain, buildings, foliage, and atmospheric conditions.

- **Doppler Shift & Mobility**

- **Doppler Shift:** Frequency change due to relative motion.
- Affects **signal coherence** and **communication reliability** in mobile scenarios.

The Wireless Communication Environment:

➢ Challenges in Wireless Environments

- **Signal Degradation** due to multipath and fading.
- **Interference** from other users/devices.
- **Coverage gaps** and **dead zones**.
- **Dynamic resource allocation** needed to adapt to changing conditions.

➢ Summary

- Wireless environment is complex and dynamic.
- Understanding **propagation** and **channel behavior** is essential for system design.
- Accurate **modeling** ensures reliable communication and efficient spectrum use.

Modelling of wireless systems:

➢ **Introduction to Wireless System Modelling**

- **Purpose:** To mathematically represent the behavior of a wireless communication system.
- Helps in:
  - Performance analysis
  - Simulation and optimization
  - System design and development

Modelling of wireless systems:

➢ **Key Components of Wireless System Model**

- **Transmitter (Tx):** Source of the signal
- **Channel:** Wireless medium (free space, urban, indoor)
- **Receiver (Rx):** Receives and decodes the transmitted signal
- **Noise and Interference:** Real-world impairments affecting the signal

Modelling of wireless systems:

➢ **Types of Wireless Channel Models**

- **Deterministic Models:**
  - Based on physical parameters and environment geometry
  - Example: Ray Tracing
- **Stochastic Models:**
  - Use random variables to model fading and mobility
  - Example: Rayleigh, Rician fading models
- **Empirical Models:**
  - Based on measurements in specific environments

Modelling of wireless systems:

➢ **Common Wireless Impairments**

- **Path Loss:** Signal strength decreases with distance
- **Shadowing:** Signal blockage by large objects
- **Multipath Fading:** Multiple delayed versions of the signal arrive at the receiver
- **Doppler Effect:** Frequency shift due to relative motion

➢ **Fading Models**

- **Rayleigh Fading:** No line-of-sight (LOS); used in urban settings
- **Rician Fading:** LOS plus scattered signals
- **Nakagami-m Model:** Generalized fading model for flexible environments

Modelling of wireless systems:

➢ Importance of Modelling

- Enables:
  - System simulation
  - Performance evaluation under various conditions
  - Design of robust communication techniques (e.g., diversity, coding)

➢ Summary

- Wireless system modelling is essential for understanding real-world performance.
- Different models are used based on environment, frequency, and mobility.
- Accurate modelling leads to better design, capacity planning, and coverage analysis.

System model for narrowband Signals

➢ **Baseband System Model**

- The received signal can be modeled as:
- $r(t)=h(t)\cdot s(t)+n(t)$
- Where:
- $s(t)$: transmitted baseband signal
- $h(t)$: complex channel gain (includes amplitude fading + phase shift)
- $n(t)$: additive white Gaussian noise (AWGN)

System model for narrowband Signals

➢ **Channel Characteristics**

- **Fading**: caused by multipath components arriving with different delays and phases.
- **Doppler Shift**: due to mobility, causes phase variations in h(t)h(t)h(t).
- **Assumption**: No intersymbol interference (ISI) due to narrow bandwidth.

System model for narrowband Signals

➢ **Key Assumptions in Narrowband Modeling**

- **Single-tap channel**: only one path is considered, or all multipaths are assumed to combine into one.
- **Coherence bandwidth** $B_c \gg B$: ensures flat fading.
- Channel varies slowly with time: quasi-static or slow-fading channel.

Rayleigh Fading Wireless Channel

➢ Introduction to Rayleigh Fading

- Rayleigh fading occurs when **multiple reflected paths** (multipath) exist **without a dominant line-of-sight (LOS)** path.
- Common in **urban environments**, especially when the receiver is **moving**.
- The **amplitude** of the received signal follows a **Rayleigh distribution**.

Rayleigh Fading Wireless Channel

- **Rayleigh Probability Distribution**
- The envelope of the received signal r has the PDF:

$$f(r) = \frac{r}{\sigma^2} e^{-r^2/(2\sigma^2)}, \quad r \geq 0$$

- Where:
- σ2: variance of in-phase or quadrature components

Rayleigh Fading Wireless Channel

➢ **Channel Model**

- Channel gain h(t) is a **complex Gaussian random process** with:
  - Zero mean
  - Uncorrelated real and imaginary parts
- Received signal:
- $r(t)=h(t)\cdot s(t)+n(t)$

- **Characteristics**
- Rapid **amplitude fluctuations** due to constructive and destructive interference
- **Phase changes** due to motion or environmental dynamics
- **Doppler spread** from mobility causes **frequency broadening**

Rayleigh Fading Wireless Channel

➢ **Key Parameters**

- **Doppler Shift (fDf_DfD)**: Caused by relative velocity between Tx and Rx
- **Coherence Time (TcT_cTc)**: Time duration over which channel remains roughly constant
- **Level Crossing Rate (LCR)** and **Average Fade Duration (AFD)**: Measure fading dynamics

Rayleigh Fading Wireless Channel

➢ **Use in Wireless System Design**

- Used to simulate **non-LOS channels**
- Helps evaluate:
  - Bit Error Rate (BER)
  - Performance of diversity schemes (e.g., MRC, selection combining)
  - Adaptive modulation and coding
- **When to Use Rayleigh Model**
- No direct path (LOS)
- Dense scattering environment
- Common in mobile scenarios: city streets, indoor environments, and tunnels

Rayleigh Fading Wireless Channel

➢ **Summary**

- Rayleigh fading is fundamental in wireless modeling.
- Models signal strength variations due to multipath interference.
- Critical for designing robust receivers in mobile and urban environments.

The Wireless Channel: Basics of Wireless Channel Modelling

➢ Introduction to Wireless Channels

- The **wireless channel** represents the medium through which radio signals propagate from transmitter to receiver.
- Affected by various phenomena like:
  - Reflection
  - Diffraction
  - Scattering
  - Fading and shadowing

Basics of Wireless Channel Modelling

➢ Why Channel Modelling?

- Helps understand how signals degrade or distort.
- Crucial for:
  - **Performance prediction**
  - **Design of modulation and coding schemes**
  - **Simulation of real-world environments**

➢ Wireless Channel Characteristics

- **Time-varying**: Due to motion of transmitter, receiver, or objects.
- **Random**: Channel gain and phase vary due to multipath.
- **Bandwidth-dependent**: Wideband vs narrowband response varies.

Basics of Wireless Channel Modelling

➢ **Types of Channel Models**

- **Deterministic Models**
  - Based on physical environment geometry (e.g., ray tracing)
- **Stochastic Models**
  - Use statistical descriptions of environment (e.g., Rayleigh, Rician)
- **Empirical Models**
  - Based on measurement data (e.g., Hata, Okumura)

Basics of Wireless Channel Modelling

➢ Key Channel Parameters

- **Delay spread**: Causes intersymbol interference (ISI)
- **Doppler spread**: Frequency variation due to motion
- **Coherence time & coherence bandwidth**

➢ Summary

- Wireless channel modelling is fundamental for designing efficient wireless systems.
- It captures the impact of the propagation environment on signal transmission.
- Different models are used depending on the application, frequency, and environment.

Average Delay Spread in Outdoor Cellular Channels

➢ What is Delay Spread?

- **Delay Spread (τ):** Measures the time dispersion of multipath signals arriving at the receiver.
- It reflects the **difference in arrival times** between the **earliest** and **latest significant multipath components**.

➢ Relevance in Outdoor Cellular Channels

- Outdoor environments, especially urban and suburban areas, involve:
  - Buildings, trees, and terrain causing reflection, diffraction, and scattering.
  - Result: multiple delayed signal copies reach the receiver.

Average Delay Spread in Outdoor Cellular Channels

➢ Average Delay Spread (ADS)

- **ADS** quantifies the **average time dispersion** of the channel:

$$\tau_{\text{rms}} = \sqrt{\frac{\sum P_i(\tau_i - \bar{\tau})^2}{\sum P_i}}$$

Where:

- P_i: Power of the i-th multipath component
- τ_i: Delay of the i-th component
- $\bar{\tau}$: Mean delay

Average Delay Spread in Outdoor Cellular Channels

➢Impact on System Performance

- Delay spread affects:
  - **Inter-symbol interference (ISI)** in digital systems
  - **Coherence bandwidth**: Inversely proportional to delay spread

$$B_c \approx \frac{1}{\tau_{\text{rms}}}$$

- Equalizer design and guard interval requirements in systems like OFDM

➢Summary

- Outdoor cellular channels typically experience **moderate to high delay spread**.
- Affects system **bandwidth efficiency**, **equalization**, and **data rate**.
- Accurate modeling is essential for reliable system design.

Coherence Bandwidth (Bc)

- **Coherence Bandwidth (Bc)** is a statistical measure of the frequency range over which the **channel's frequency response is flat** (i.e., the channel does not cause significant distortion).

Coherence Bandwidth (Bc)

➢ Relationship with Delay Spread

- Coherence bandwidth is **inversely proportional** to the **RMS delay spread (τrms)**:

$$B_c \approx \frac{1}{2\pi\tau_{\text{rms}}} \quad \text{or} \quad B_c \approx \frac{1}{5\tau_{\text{rms}}}$$

➢ **Interpretation**

- If signal bandwidth **B < Bc**:
  → Channel is **flat fading** (no frequency-selective distortion).
- If signal bandwidth **B > Bc**:
  → Channel is **frequency-selective**, causing **inter-symbol interference (ISI)**.

Relation between ISI and Coherence Bandwidth

- **What is ISI (Inter-Symbol Interference)?**

- ISI occurs when **multiple delayed copies of a signal** interfere with subsequent symbols.
- Caused by **multipath propagation** where reflections arrive with delays.

Relation between ISI and Coherence Bandwidth

- **Relationship Between ISI and Coherence Bandwidth**
- **If signal bandwidth B<Bc :**
  - The channel behaves as **flat fading**.
  - All frequency components are equally affected.
  - **ISI is negligible**.
- **If signal bandwidth B>Bc :**
  - The channel exhibits **frequency-selective fading**.
  - Different frequency components of the signal undergo different fading.
  - **ISI becomes significant** due to **time dispersion** caused by multipath.

Doppler Fading (Time-Selective Fading)

➢ **What is Doppler Fading?**

- Doppler fading occurs due to **relative motion** between the **transmitter**, **receiver**, or **scattering objects**.
- Causes a **shift in frequency** of the received signal known as the **Doppler shift**.

Doppler fading, Doppler Impact on a wireless Channel, Coherence Time

- Doppler Shift Formula

$$f_D = \frac{v}{\lambda} = \frac{v f_c}{c}$$

Where:

- f_D: Doppler shift
- v: Relative velocity
- λ: Wavelength
- f_c: Carrier frequency
- c: Speed of light

Doppler fading, Doppler Impact on a wireless Channel, Coherence Time

➢ Doppler Spread

- **Doppler Spread (Δf)**: Range of Doppler shifts due to multipath components.
- It causes **frequency broadening** of the received signal spectrum.

➢ Coherence Time (Tc)

- Time duration over which the channel impulse response is considered constant.
- Inversely related to Doppler spread:
- $Tc \approx 1/fD$

Doppler fading, Doppler Impact on a wireless Channel, Coherence Time

➢Types of Doppler Fading

- **Fast Fading**: Channel changes within one symbol duration (when $Ts>Tc$).
- **Slow Fading**: Channel remains constant over many symbols (when $Ts<Tc$).

➢Impact on Wireless Systems

- **Causes time variation** of channel amplitude and phase.
- **Degrades performance** of systems like OFDM and coherent detection.
- Requires **adaptive equalization**, **channel estimation**, or **diversity techniques**.