Unit=1

🌐 **What is Path Loss?**

Path loss refers to the weakening of a radio signal as it propagates through space. This weakening is due to various factors, including:

- Distance: As the distance between the transmitter and receiver increases, the signal spreads out, resulting in a decrease in power density.
- Frequency: Higher frequencies generally experience greater path loss.
- Obstacles: Buildings, trees, and other obstructions can cause signal reflections, diffractions, and absorptions, leading to further attenuation.
- It is measured in **decibels (dB)** and is affected by distance, frequency, obstacles, environment, and antenna characteristics.

Path loss models are essential for:

- Network Planning:

By accurately predicting path loss, engineers can optimize the placement of base stations and antennas to ensure adequate signal coverage and minimize dead spot.

- Performance Prediction:

Path loss models help estimate the received signal strength at various locations, allowing for the prediction of network performance and the identification of potential issues like dropped calls or slow data speeds.

- Interference Mitigation:

Understanding path loss helps in designing strategies to minimize interference from other sources, ensuring reliable communication.

📉 **Causes of Path Loss**

1. **Free Space Attenuation**
   The natural spreading of the signal as it travels farther from the source.
2. **Reflection**
   When signals bounce off surfaces like buildings or water, causing interference.
3. **Diffraction**
   When the signal bends around obstacles.

4. **Scattering**
   When small objects (like trees, cars, dust) cause the signal to scatter in many directions.
5. **Absorption**
   When energy is absorbed by materials like walls, rain, or the atmosphere.

📐 Path Loss Model

A **Path Loss Model** is a mathematical model that **predicts the signal strength** or **path loss** for given distances and environmental conditions.
It is represented in **decibels (dB)**.

🔹 **General Path Loss Equation**

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

Where:

Symbol	Meaning
PL(d)	Path loss (in dB) at distance **d**
$PL(d_0)$	Path loss (in dB) at a reference distance **d_0** (usually 1 m)
n	Path loss exponent (depends on the environment)
d	Distance between transmitter and receiver
$X\sigma$	Shadowing factor (a random variable, usually Gaussian distributed)

🧮 Free Space Path Loss (FSPL) Model

Used when there are **no obstacles** — ideal line-of-sight (LOS) condition.

$$PL_{FS}(d) = 20\log_{10}(d) + 20\log_{10}(f) + 32.44$$

Where:

Symbol	Meaning
d	Distance between transmitter and receiver (in km)

Symbol	Meaning
f	Frequency of the signal (in MHz)
32.44	Constant (accounts for units of km and MHz)

👉 Example:
If **f** = **2000 MHz** and **d** = **2 km**,

$$PL = 20\log_{10}(2) + 20\log_{10}(2000) + 32.44 = 6.02 + 66.02 + 32.44 = 104.48\,dB$$

📡 Path Loss Models Overview

In wireless communication, signal strength changes due to **distance**, **obstacles**, and **environmental factors**.
Based on **how the signal varies**, path loss models are divided into two main categories:

1. **Large-Scale Path Loss Models**
2. **Small-Scale Path Loss (or Fading) Models**

🌍 1. Large-Scale Path Loss Model

🔹 **Definition:**

Large-scale path loss refers to the **average signal power reduction** that occurs **over large distances** — typically **hundreds or thousands of meters**.

It represents the **mean signal attenuation** due to distance, obstacles (like buildings, hills), and terrain type.

🧭 Purpose:

Used to **predict coverage area**, **cell planning**, and **average signal power** over a region — not short-term variations.

📏 Characteristics:

Property	Description
Distance Range	Large (100 m – several km)

Property	Description
Variation Speed	Slow changes with distance
Cause	Path loss due to distance, terrain, and environment
Output	Average received power
Time Sensitivity	Low (changes slowly over time)

⚙️ **Common Large-Scale Models:**

A) Log-Distance Path Loss Model

- It is used to **estimate how much a signal weakens (path loss) as it travels over distance**.
- Unlike the **free-space model** (ideal conditions), this model adds the effect of **real environments** (like urban, suburban, rural).
- It uses a value called the **path loss exponent (n)**, which shows how quickly the signal decreases depending on surroundings.
- It also includes **shadowing ($X\sigma$)**, which represents random obstacles (like buildings, trees) that cause extra signal variation.

B) Hata Model

The **Hata model** is an **empirical path loss model** (based on real-world measurements). It is a simplified version of the **Okumura model** and is widely used for **cellular network planning**

C) COST-231 Hata Model

The **COST-231 Hata model** is an **extension of the Hata model** to cover **higher frequencies** used in modern cellular systems (like GSM 1800, PCS, LTE).

- Frequency range: **1500 – 2000 MHz**
- Distance: **1 – 20 km**
- Base station antenna height: **30 – 200 m**
- Mobile antenna height: **1 – 10 m**
- Environments: **Urban, Suburban, Rural**

🏙️ **Where Used:**

- Mobile network coverage estimation
- Satellite communication
- Wi-Fi range calculation
- Base station placement

⚡ 2. Small-Scale Path Loss (Fading) Model

🔹 **Definition:**

Small-scale path loss (or fading) represents **rapid fluctuations** of signal strength over **short distances** (a few wavelengths) or **short time durations**.

It happens due to **multipath propagation** — the signal reaches the receiver by multiple paths because of reflection, diffraction, and scattering.

🧭 **Purpose:**

Used to model **instantaneous variations** of signal power around the average path loss predicted by large-scale models.

📏 **Characteristics:**

Property	**Description**
Distance Range	Very small (a few centimeters to meters)
Variation Speed	Rapid (due to movement of transmitter, receiver, or objects)
Cause	Multipath reflection, scattering, Doppler effect
Output	Instantaneous received signal strength
Time Sensitivity	High (changes quickly with movement)

⚙️ **Types of Small-Scale Fading:**

1. Multipath Fading

When multiple copies of the same signal (with different phases and amplitudes) interfere — causing **constructive or destructive interference**.

2. Doppler Shift

If the transmitter or receiver is moving, frequency changes due to motion → causes time variation in the received signal.

📊 Small-Scale Fading Models:

Model	Environment	Description
Rayleigh Fading Model	No line-of-sight	Amplitude of signal follows **Rayleigh distribution**
Rician Fading Model	With line-of-sight	Amplitude follows **Rician distribution**
Nakagami Fading Model	General case	More flexible for different fading environments

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🚗 Where Used:

- Mobile communication while moving
- Wi-Fi in buildings
- Vehicle-to-vehicle (V2V) communication
- IoT networks

📡 What is Fading?

🔹 Definition

Fading refers to the **variation or fluctuation of signal strength** (amplitude, phase, or power) over time and space when a radio signal travels from the transmitter to the receiver.

In simple words:
Fading means the **signal gets stronger or weaker** due to changes in the environment, reflections, motion, or interference of multiple signals.

💡 Why Fading Happens

When a wireless signal travels through air, it doesn't go in a straight line — it:

- **Reflects** from buildings or walls,
- **Diffracts** around obstacles,
- **Scatters** due to small objects like cars, trees, etc.

These cause **multiple copies** of the same signal to reach the receiver **at slightly different times and with different phases** — this is called **multipath propagation**.
When these copies combine, they cause **fading** (constructive or destructive interference).

⚙️ Types of Fading

Fading can be categorized based on **time**, **frequency**, and **space**.

Now, fading is mainly divided into **two broad categories**:

1. **Large-Scale Fading**
2. **Small-Scale Fading**

Then, **Small-Scale Fading** is further divided into **types based on causes** (multipath, Doppler) and **characteristics** (flat, frequency-selective, slow, fast, etc.).

🌍 1. Large-Scale Fading

Large-scale fading refers to **average signal power variations** over long distances (hundreds of meters to kilometers).

It mainly includes:

a) Path Loss

- The **average reduction** in signal strength as the signal travels away from the transmitter.
- Depends on distance and frequency.
- Example: Signal strength reduces as you move farther from a mobile tower.

b) Shadowing (Log-Normal Fading)

- Caused by **obstacles** (buildings, trees, hills) that block or reflect signals.
- Even at the same distance, two receivers can get different signal levels due to objects in between.
- Typically modeled as a **log-normal distribution** (Gaussian in dB scale).

🧠 Example: You're walking on a street. When you go behind a tall building, your phone signal drops — that's **shadow fading**.

⚡ 2. Small-Scale Fading

Small-scale fading occurs due to **rapid fluctuations** in signal strength over **short distances** (a few wavelengths) or **short time periods**.

It happens mainly because of:

- **Multipath propagation** (multiple copies of the signal arrive with different delays)
- **Doppler effect** (frequency change due to relative motion)

Let's see the **types of small-scale fading** in detail 👇

A. Based on Multipath Delay Spread

1️⃣ Flat Fading

- The **bandwidth of the signal** is **less than the coherence bandwidth** of the channel.
- All frequency components of the signal experience **the same fading**.
- There is **no distortion**, only the amplitude of the signal changes.
- Example: Narrowband systems.

Key Points:

- Channel acts like a single tap (constant gain + phase shift).
- Occurs when multipath delay is **much smaller** than the symbol duration.

2️⃣ Frequency-Selective Fading

- The **signal bandwidth** is **greater than the coherence bandwidth**.
- Different frequency components **fade differently**.
- Causes **inter-symbol interference (ISI)** because multipath components arrive at different times.

Key Points:

- Channel acts as **multiple taps** (each with its own delay and gain).
- Occurs in **wideband systems** (like OFDM, LTE, Wi-Fi).

📶 Example: In a wideband system, a reflection from a nearby wall and another from a distant building can interfere differently with different parts of the signal.

B. Based on Doppler Spread

1️⃣ Slow Fading

- Channel conditions **change slowly** compared to the signal symbol duration.
- Caused by **slow movement** of the receiver or obstacles.
- The channel can be considered **constant** for several symbols.

Example: A pedestrian using a mobile phone—slow movement means the fading varies gradually.

2️⃣ Fast Fading

- Channel conditions **change rapidly** compared to symbol duration.
- Caused by **high mobility** (car, train, airplane).
- Leads to **rapid signal strength fluctuations** over time.

Example: A person in a fast-moving vehicle passing through multiple reflections — signal strength changes quickly.

C. Based on Line-of-Sight (LOS) Condition

1️⃣ Rayleigh Fading

- Occurs when there is **no Line-of-Sight (LOS)** path between transmitter and receiver.
- The received signal is the sum of **many reflected and scattered paths**.
- The amplitude follows a **Rayleigh distribution**.

Example: Urban areas with high buildings where direct path is blocked.

2️⃣ Rician Fading

- Occurs when there **is a strong LOS path** along with multiple reflected paths.
- The received signal has one dominant component (LOS) and many weaker reflected ones.
- Amplitude follows a **Rician distribution**.

Example: Open areas where direct tower visibility exists.

Coherence Time (Tc)

The time duration over which the channel's impulse response is essentially unchanged.

If the symbol period (reciprocal of symbol rate) is longer than the coherence time, the channel will change significantly during the transmission of a single symbol, leading to distortion.

Coherence time and Doppler spread are inversely proportional, as a faster-changing channel (higher Doppler spread) has a shorter coherence time.

Coherence Bandwidth (Bc)

The range of frequencies over which two frequency components have a strong likelihood of being correlated, meaning the channel can be considered "flat" over that frequency range.

If the signal bandwidth is much larger than the coherence bandwidth, the channel is considered to be frequency-selective, and different frequency components will be affected differently, leading to distortion and ISI.

If the signal bandwidth is much smaller than the coherence bandwidth, the channel is flat fading, and no distortion or ISI occurs.

Coherence bandwidth is the inverse of the delay spread.

Doppler Spread (fD)

A measure of the spectral broadening in the received signal caused by time-varying multipath effects, indicating the range of frequencies over which the received Doppler spectrum is non-zero.

It quantifies how much the mobile channel changes over time.

A high Doppler spread indicates a fast-fading channel, whereas a low Doppler spread indicates a slow-fading channel.

Time Dispersion Parameters in Context

- These parameters help characterize the time-varying nature of mobile multipath channels.
- They are crucial for designing wireless systems, as they determine the effects of the channel on the transmitted signals. For instance, understanding these parameters is key to avoiding distortion and inter-symbol interference.