Wireless Communication Networks & Systems

Spring 2025

Week # 06

Course Learning Outcomes (CLOs):

CLO # 01	Demonstrate an in-depth understanding of wireless network system's architecture, protocols, and Services.	**Cog. 3**
CLO # 02	Explore advanced technologies and features in wireless networks related to coverage, capacity, interference management, and mobility.	**Cog. 3**
CLO # 03	Examine the evolution of Wi-Fi networks, highlighting architectural differences across its various standards.	**Cog. 4**
CLO # 04	Analyze key cellular concepts used in cellular networks and the architectural advancements in 5G and beyond.	**Cog. 4**

Assessment Roadmap till Midterm:

- HW –I(5%): Wireless channel Modeling, 12^{th} Feb 2025
- Research Part – I (5%): Wk7
- Midterm Exam (20%): Wk8, 24^{th} Feb 2025

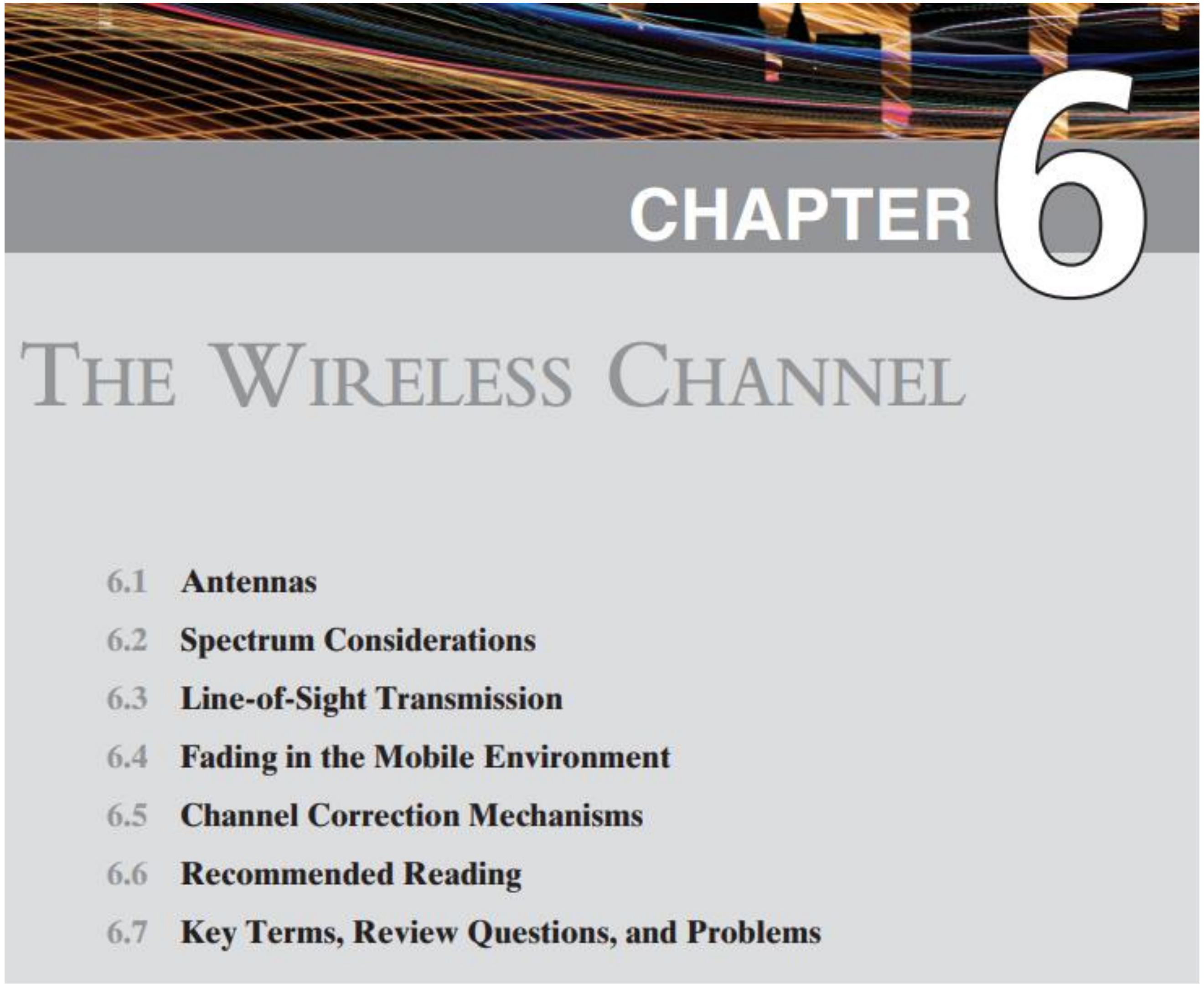
Homework:	20%	Inclusive Recitation session
Quiz:	20%	Inclusive Class participation
Midterm Exam:	20%	
Final Exam:	20%	
Research:	20%	Four milestones (5% each)

Wireless Communication Technology:

<u>CLO 02 :</u>

- Chapter 05 – Overview of Wireless Communications
- Chapter 06 – The wireless channel
- Chapter 07 – Signal Encoding Techniques
- Chapter 08 – Orthogonal Frequency division multiplexing
- Chapter 09 – Spread Spectrum
- Chapter 10 – Coding and Error Control

Wireless Communication Technology:



CHAPTER 6

THE WIRELESS CHANNEL

Wireless Communication Technology:

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Describe antenna patterns and the operation of MIMO directional antennas.
- Explain the importance of unlicensed frequencies.
- Compute path loss for free space and real-world environments using the path loss exponent.
- Compute path loss based on the Okumura–Hata model.
- Characterize the multipath and Doppler spreading characteristics of channels.
- Describe the approaches used to correct channel impairments.

Wireless Channel Impairments:
Attenuation (Path Loss)
Noise
Multipath & Fading

Noise modeling and its impact

Noise :

- For any data transmission event, the received signal will consist of the transmitted signal, modified by the various distortions imposed by the transmission system.
- Moreover, additional unwanted signals are inserted between transmission and reception, this unwanted signal is referred to as noise.
- Noise is the major limiting factor in communications system performance.

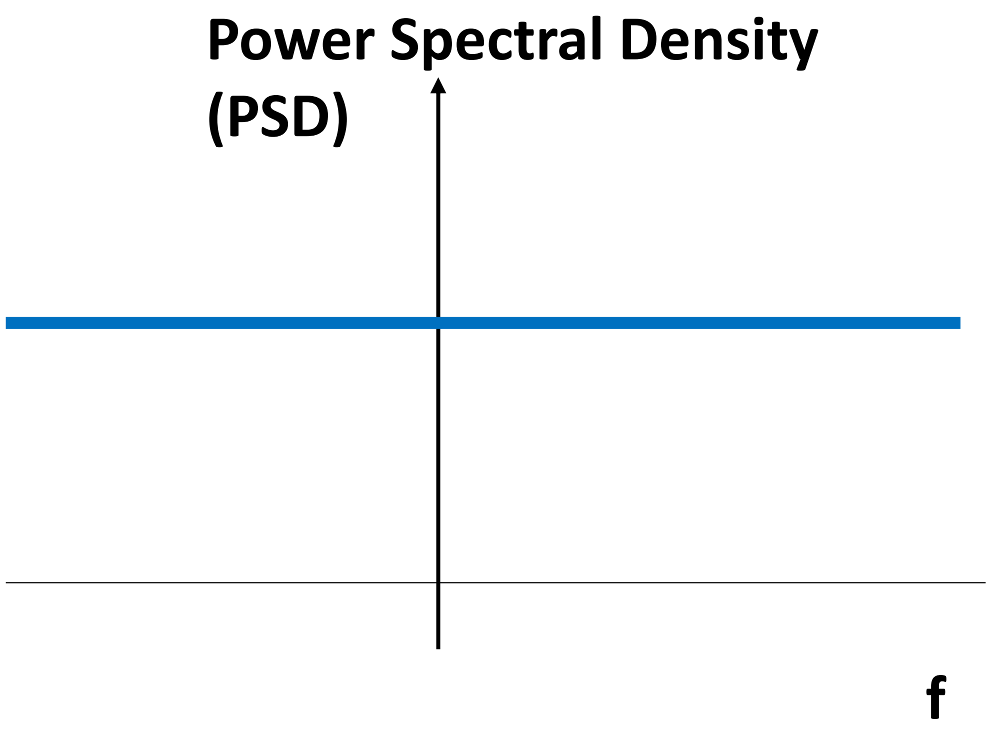
$$C = B \log_2 (1 + SNR)$$

Noise :

- Thermal noise is due to the random motion of electrons and it is present in all electronic devices and transmission media and is a function of temperature.

- Thermal noise is uniformly distributed across the frequency spectrum and hence is often referred to as White Noise

- Thermal noise cannot be eliminated and therefore places an upper bound on the performance of the communications system.



Noise :

The amount of thermal noise to be found in a bandwidth of 1 Hz in any device or conductor is as follows:

$$N_0 = kT\,(\mathrm{W/Hz})$$

N_0 = noise power density in watts per 1 Hz of bandwidth
k = Boltzmann's constant = 1.3803×10^{-23} J/K
T = temperature, in Kelvins (absolute temperature)

Example 6.7 Room temperature is usually specified as $T = 17°\text{C}$, or 290 K. At this temperature, the thermal noise power density is

$$N_0 = (1.3803 \times 10^{-23}) \times 290 = 4 \times 10^{-21}\ \mathrm{W/Hz} = -204\ \mathrm{dBW/Hz}$$

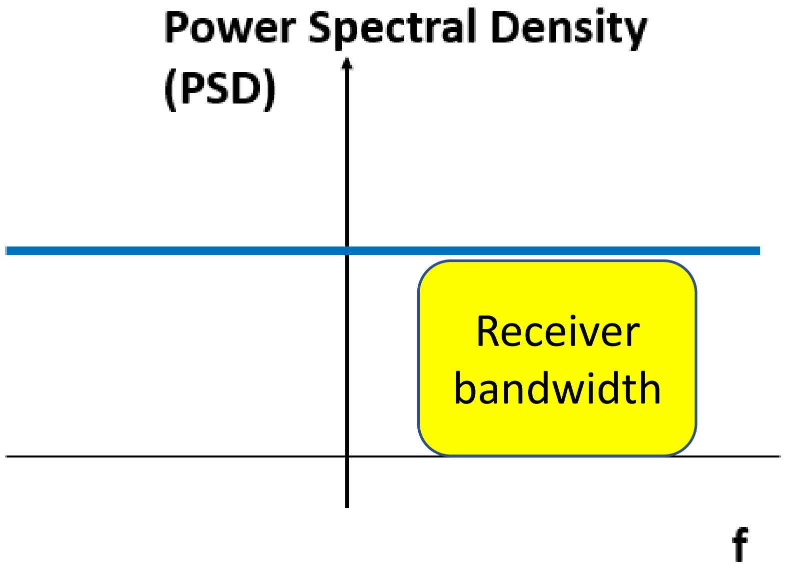
Noise :

$$N_0 = kT\left(\mathrm{W/Hz}\right)$$

- The noise is assumed to be independent of frequency. Thus, the thermal noise in watts present in a bandwidth of B Hertz can be expressed as:

$$N = kTB$$

$$\begin{aligned} N &= 10\log \mathrm{k} + 10\log T + 10\log B \\ &= -228.6\,\mathrm{dBW} + 10\log T + 10\log B \end{aligned}$$



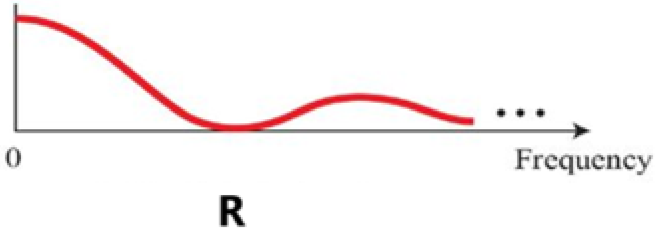
Noise :

Example 6.8 Given a receiver with an effective noise temperature of 294 K and a 10-MHz bandwidth, the thermal noise level at the receiver's output is

$$\begin{aligned} N &= -228.6 \text{ dBW} + 10 \log(294) + 10 \log 10^7 \\ &= -228.6 + 24.7 + 70 \\ &= -133.9 \text{ dBW} \end{aligned}$$

Noise :

E_b/N_O: The ratio of signal energy per bit (E_b) to noise power density per Hertz



$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{kTR}$$

where

- S is the signal power ; $E_b = S\,T_b$
- T_b is the time required to send one bit. ; $R = 1/T_b$
- R is the bit rate of a signal

<u>The bit error rate (BER) is a function of E_b/N_0</u>

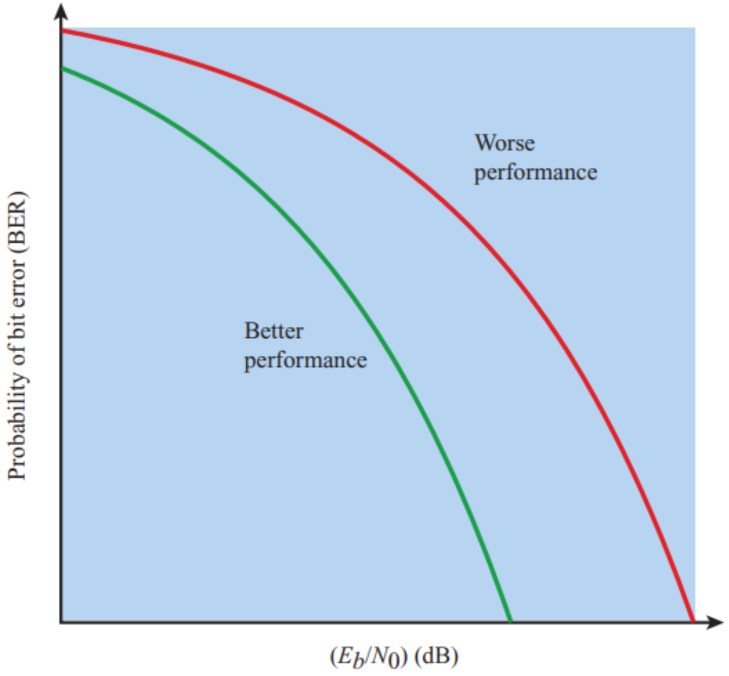


Figure 6.9 General Shape of BER versus E_b/N_0 Curves

Noise :

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{kTR}$$

$$\left(\frac{E_b}{N_0}\right)_{\text{dB}} = S_{\text{dBW}} - 10\log R - 10\log \text{k} - 10\log T$$
$$= S_{\text{dBW}} - 10\log R + 228.6\ \text{dBW} - 10\log T$$

Example 6.9 Suppose a signal encoding technique requires that $E_b/N_0 = 8.4$ dB for a bit error rate of 10^{-4} (one bit error out of every 10,000). If the effective noise temperature is 290 K (room temperature) and the data rate is 100 kbps, what received signal level is required to overcome thermal noise?

We have

$$8.4 = S_{\text{dBW}} - 10\log 100000 + 228.6\ \text{dBW} - 10\log 290$$
$$= S_{\text{dBW}} - (10)(5) + 228.6 - (10)(2.46)$$
$$S = -145.6\ \text{dBW}$$

Noise :

Eb/No vs SNR

We can relate E_b/N_0 to SNR as follows. We have

$$\frac{E_b}{N_0} = \frac{S}{N_0 R}$$

The parameter N_0 is the noise power density in watts/hertz. Hence, the noise in a signal with bandwidth B is $N = N_0 B$. Substituting, we have

$$\frac{E_b}{N_0} = \frac{S\,B}{N\,R}$$

Used in Digital communication
(Energy signal)

Used in Analog communication
(Power signal)

Noise :

Eb/No and Spectrum Efficiency:

$$C = B \log_2(1 + S/N)$$

where C is the capacity of the channel in bits per second and B is the bandwidth of the channel in hertz. This can be rewritten as

$$\frac{S}{N} = 2^{C/B} - 1$$

$$\frac{E_b}{N_0} = \frac{S\,B}{N\,R}$$

Using Equation (6.10), and R with C, we have

$$\frac{E_b}{N_0} = \frac{B}{C}(2^{C/B} - 1)$$

$$R \leq C$$

This is a useful formula that relates the achievable spectral efficiency C/B to E_b/N_0.

Example 6.10. Suppose we want to find the minimum E_b/N_0 required to achieve a spectral efficiency of 6 bps/Hz. Then, $E_b/N_0 = (1/6)(2^6 - 1) = 10.5 = 10.21$ dB.

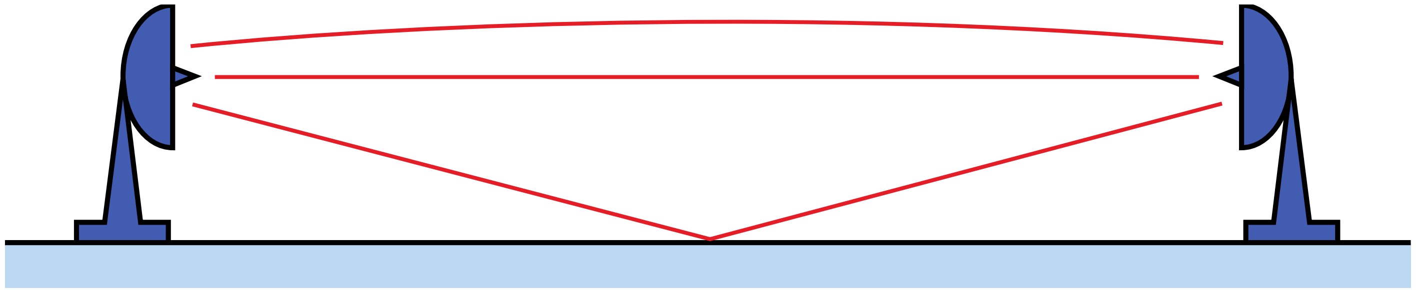
Wireless Channel Impairments:
Attenuation (Path Loss)
Noise
Multipath & Fading

Multipath & Fading in Wireless Communication

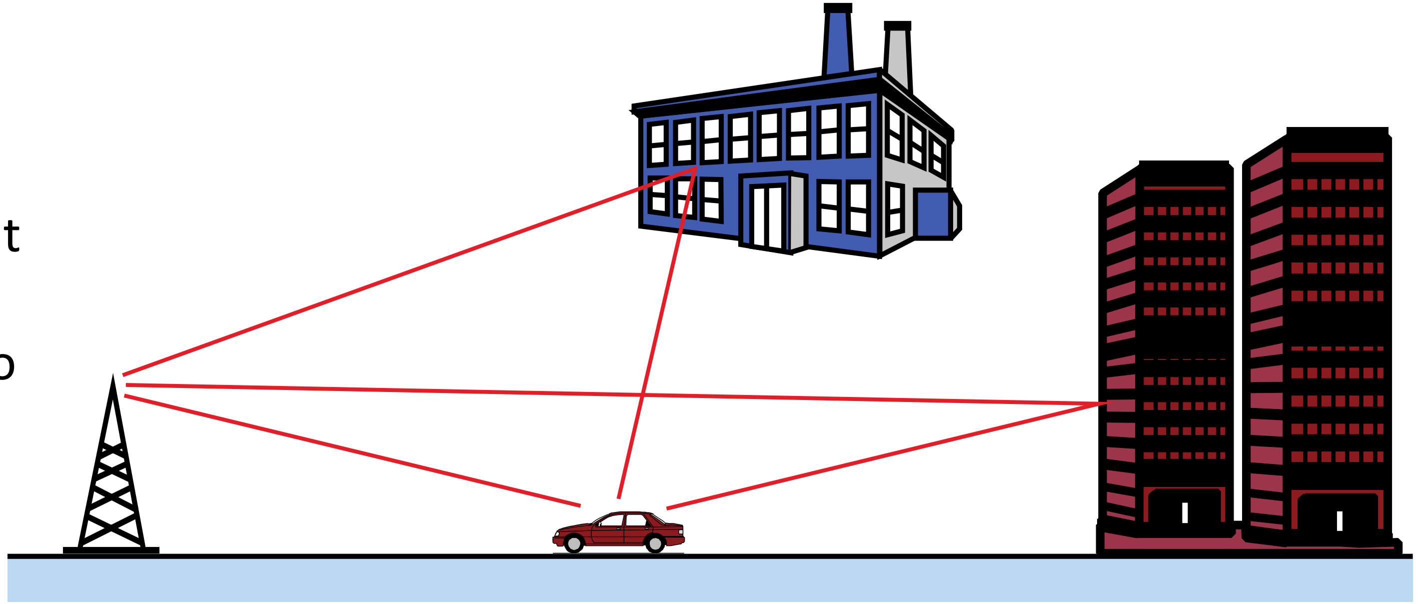
Multipath :

Obstacles can reflect the wireless signal, allowing multiple copies of the signal with varying delays to be received. The phenomenon of wireless is called the <u>Multipath Effect.</u>

Multiple copies of a signal may arrive at different phases, so if phases add destructively, the signal level relative to noise declines, making detection more difficult.



(a) Microwave line of sight



(b) Mobile radio

Multipath :

- Three of the three main propagation mechanisms:
  - Reflection: Reflection occurs when an electromagnetic signal encounters a surface that is large relative to its wavelength.
  - Diffraction: Diffraction occurs at the edge of a surface that is large compared to the wavelength of the radio wave. When a radio wave encounters such an edge, waves propagate in different directions with the edge as the source.
  - Scattering: If the size of an obstacle is on the order of the signal's wavelength or less, scattering occurs. An incoming signal is scattered into several weaker outgoing signals.

Multipath :

- These three propagation effects influence system performance in various ways depending on local conditions (terrain) and as the Tx/Rx moves.

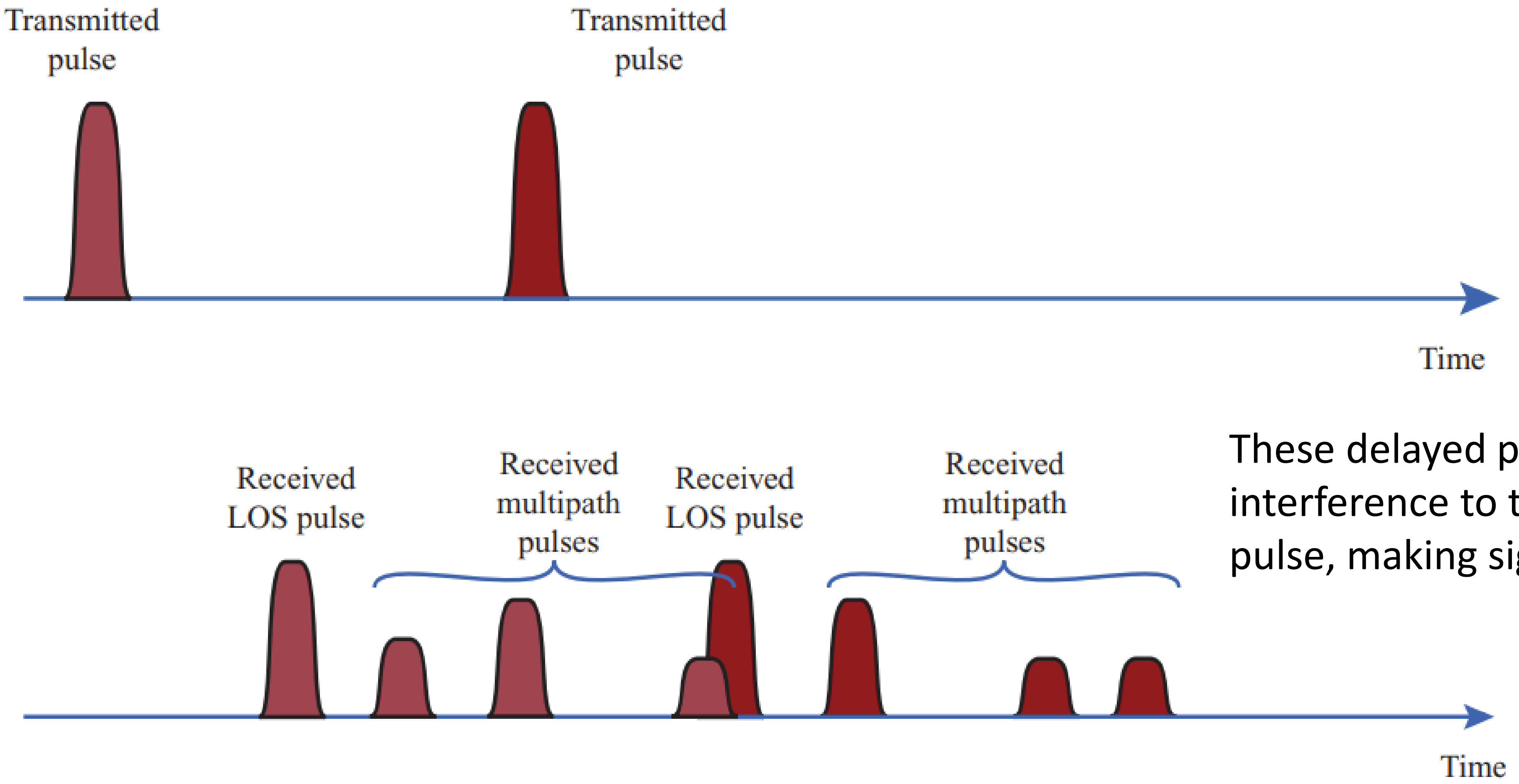
- If a mobile unit has a clear LOS to the transmitter (Open or rural area), then diffraction and scattering are generally minor effects, although reflection may have a significant impact.

- If there is no clear LOS, such as in an urban area at street level, then diffraction and scattering are the primary means of signal reception.

- The first effect of multipath propagation is that the multiple copies of a signal may arrive at different signal phases. If these phases add destructively, the resulting signal power can be lower by a factor of 100 or 1000 (20 or 30 dB). The signal level relative to noise declines, making signal detection at the receiver more difficult.

Multipath :

- The second effect of Multipath is inter-symbol interference (ISI).



These delayed pulses act as a form of interference to the subsequent primary pulse, making signal recovery difficult.

Fading:

- In wireless communication, fading refers to the variation or fluctuation of the received signal strength due to various environmental factors, such <u>as obstacles, interference, and the movement of the transmitter or receiver.</u>

- Specifically in the mobile environment, where one of the two antennas is moving relative to the other, the relative location of various obstacles changes over time, creating varying transmission effects.

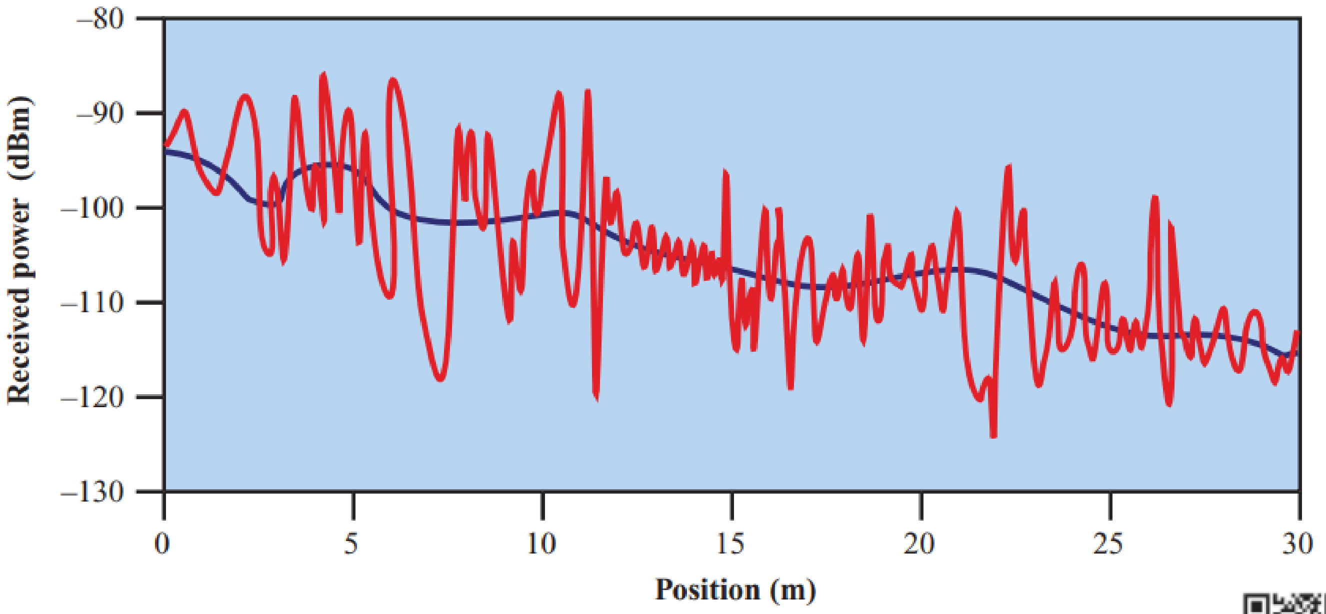
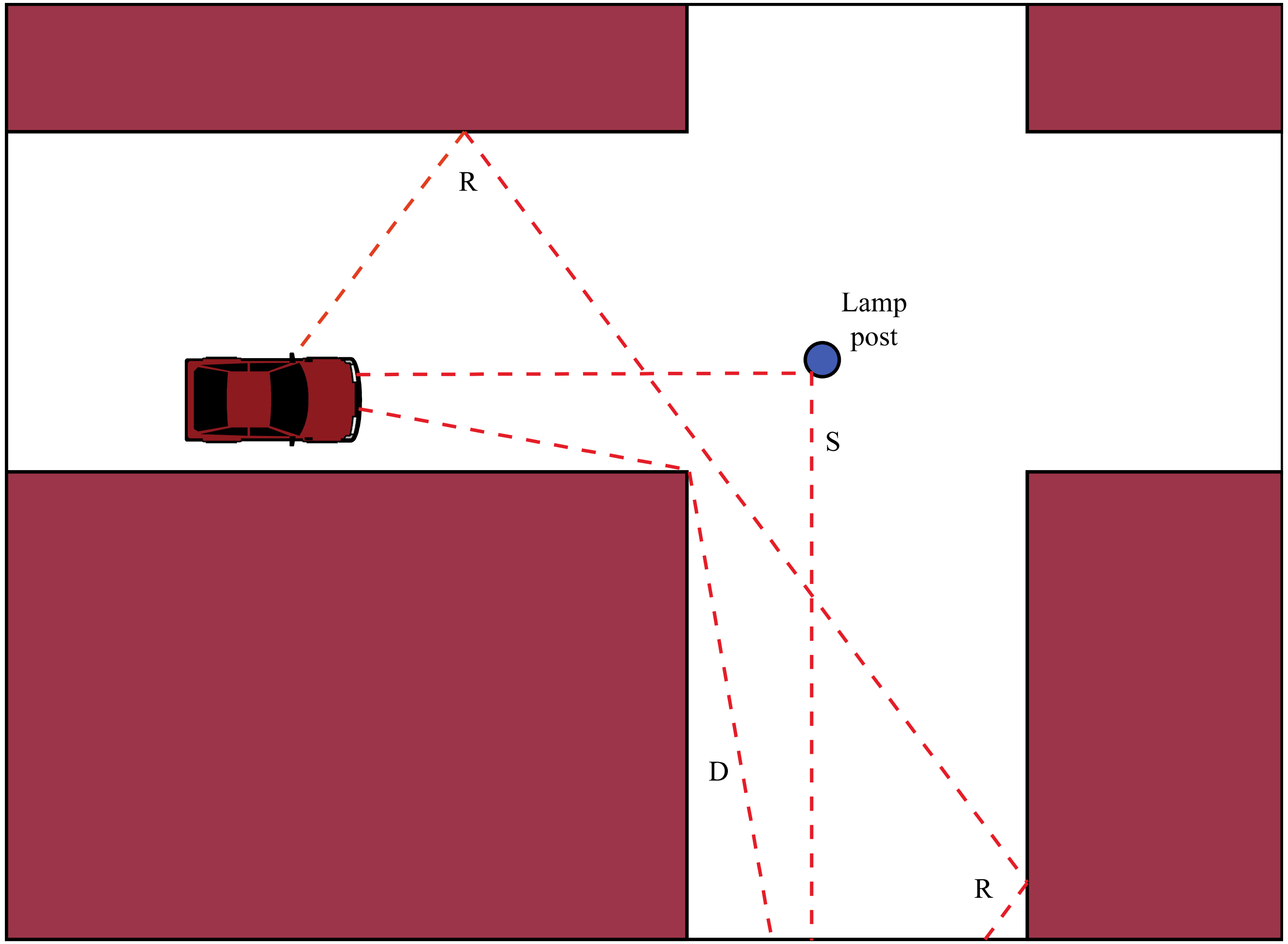


Figure 6.13 Typical Slow and Fast Fading in an Urban Mobile Environment

Fading :

Fading effects in a mobile environment can be classified as either small scale or large scale.

- Large-scale fading, occurs over a longer timescale and is caused by factors that vary slowly, such as the distance between the transmitter and receiver, the terrain, and large obstacles like hills or buildings. Typically it is related with Path loss and Shadowing.

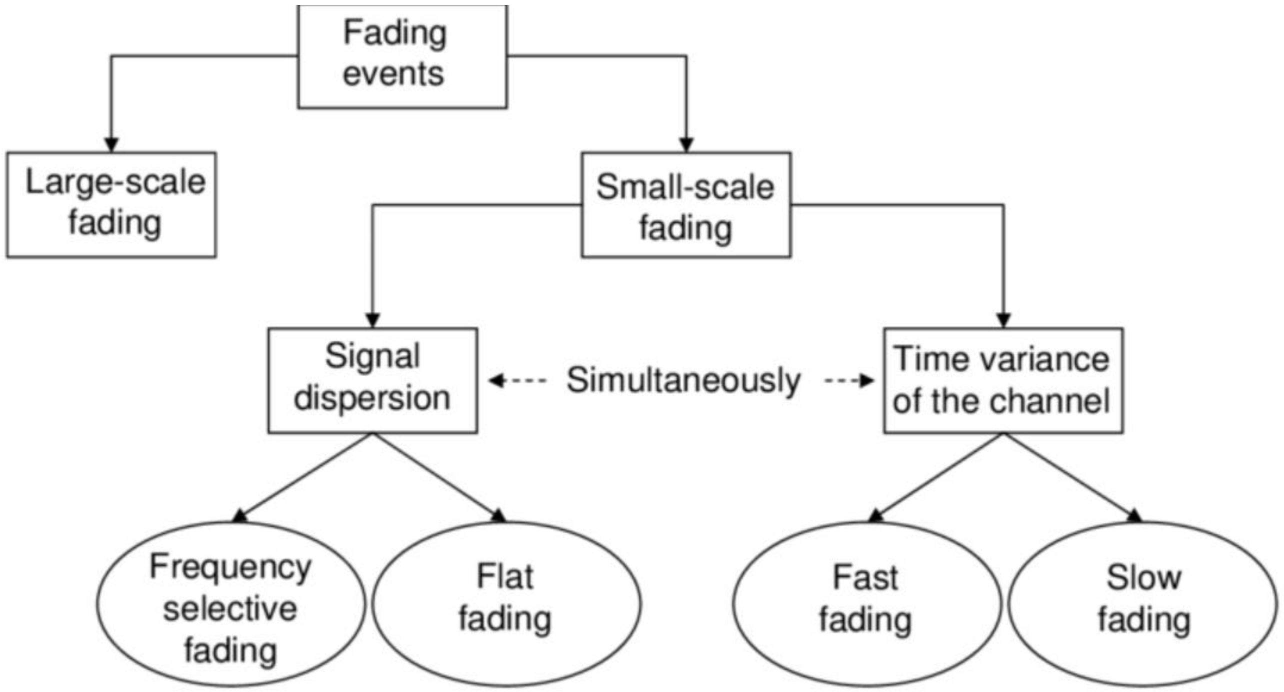


Fading :

- <u>Small Scale fading</u> occurs over a short period of time and is caused by rapid changes in the signal as the transmitter or receiver moves.

- In the case of small-scale fading, the received signal can fluctuate rapidly in amplitude or phase, leading to deep fades and occasional signal loss.

- There are four distinct types of small-scale fading effects.



Fading :

Coherence Bandwidth:

- Coherence bandwidth is the range of frequencies over which the channel response is nearly flat. Within this bandwidth, different frequency components of a signal experience similar fading.

- If the signal bandwidth is smaller than the coherence bandwidth, it will experience flat fading. If the signal bandwidth is larger than the coherence bandwidth, the signal will experience frequency-selective fading.

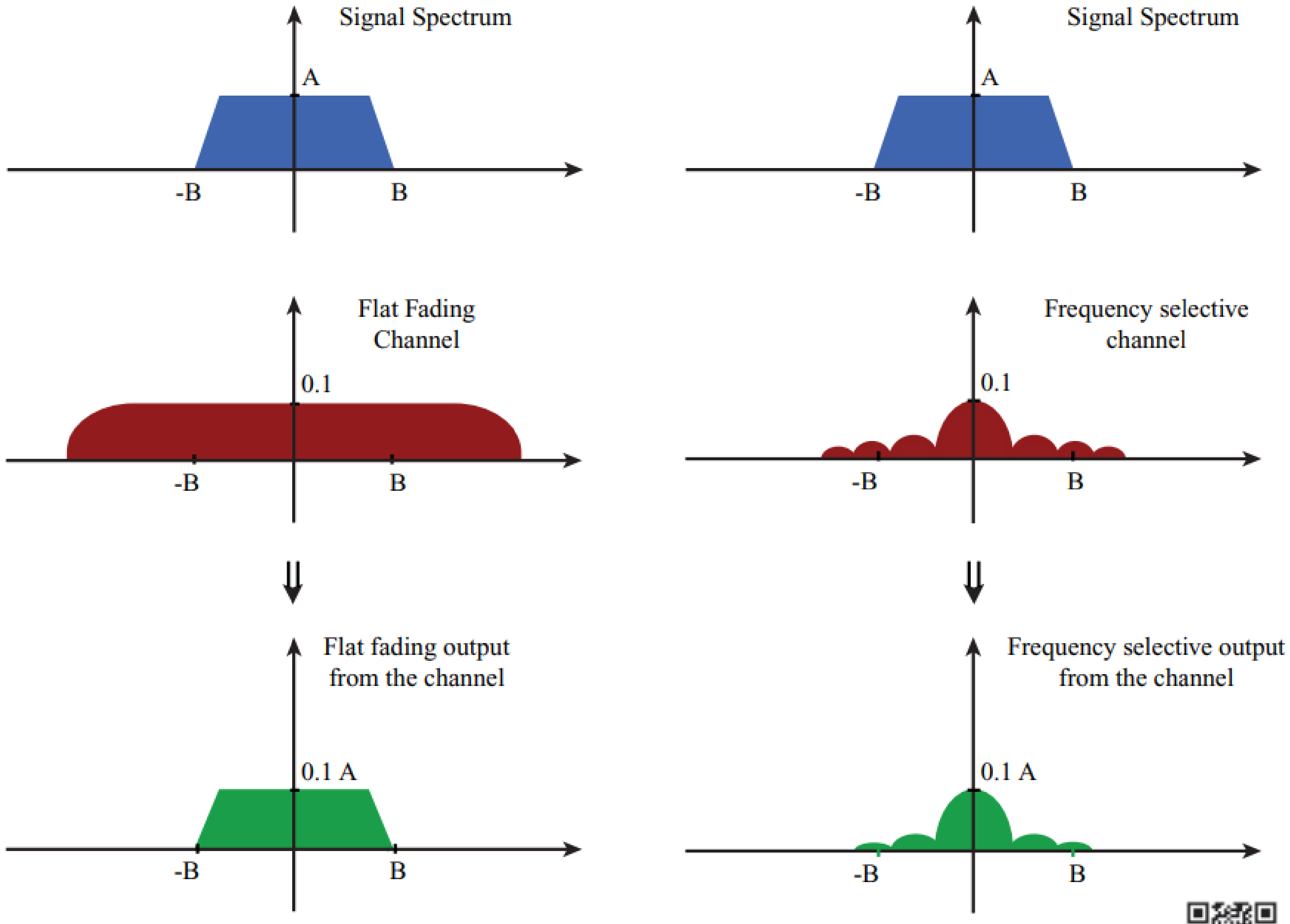


Figure 6.14 Flat and Frequency Selective Fading

$$B_C \gg B_S$$
$$B_C > 10B_S$$

B_c : Coherence Bandwidth
B_s : Signal Bandwidth
Condition for flat fading.

Fading :

Coherence Time:

- Coherence time is the time duration over which the channel's response remains relatively constant. During this time period, the received signal undergoes negligible changes.

- A longer coherence time means that the channel conditions are more stable for a longer period, whereas a shorter coherence time means that the channel conditions change rapidly, typically due to the movement of the transmitter, receiver, or surrounding objects.

- If the signal transmission duration is shorter than the coherence time, the channel conditions can be considered constant over that period i.e., slow fading. If the signal transmission duration is longer than the coherence time , the signal will undergo fast fading due to time-varying channel conditions.

$$T_C \gg T_b'$$
$$T_C > 10T_b'$$

T_c : Coherence Time
T_b : Signal duration
Condition for slow fading.

Fading :

$$B_C \gg B_S$$
$$B_C > 10B_S$$

B_c : Coherence Bandwidth
B_s : Signal Bandwidth
Condition for flat fading.

$$T_C \gg T_b'$$
$$T_C > 10T_b'$$

T_c : Coherence Time
T_b : Signal duration
Condition for slow fading.

Signal related information:

- Signal Bandwidth = B_s assume Bit rate (r_b) = Signal bandwidth (B_s)
- Signal Duration: T_b ; rb = $1/T_b$

Channel related information:

- B_c : Coherence Bandwidth
- T_c : Coherence Time

Example 6.11. Suppose that a pedestrian is moving in an urban environment that has a wireless channel with a coherence time of 70 ms and a coherence bandwidth of 150 kHz. The bit rate of the signal being used is 100 kbps.

a. How would the channel be characterized regarding Doppler spread and multipath fading?

To check for slow fading, test the following, using a factor of 10 for much, much greater.

$$T_b = 1/r_S = 10\ \mu s$$
$$T_C \gg T_b?$$
$$T_C > 10T_b?$$
$$\textit{Test condition}: 70\ ms > 100\ \mu s?$$

This is true, so *slow fading*.
To check for flat fading, test the following:

$$\text{Assume } B_S \approx r_S = 100\ kHz$$
$$B_C \gg B_S?$$
$$B_C > 10B_S?$$
$$\textit{Test condition: } 150\ kHz > 1\ Mbps?$$

This is not true, so *frequency selective fading*.
This channel is slow and frequency selective.

b. What range of bit rates can be supported to have flat fading?
This is the requirement

$$B_C \gg B_S$$
$$B_C > 10B_S$$
$$150\ kHz > 10B_S$$
$$B_S < 15\text{ kHz}$$
$$r_b < 15\text{ kbps}$$

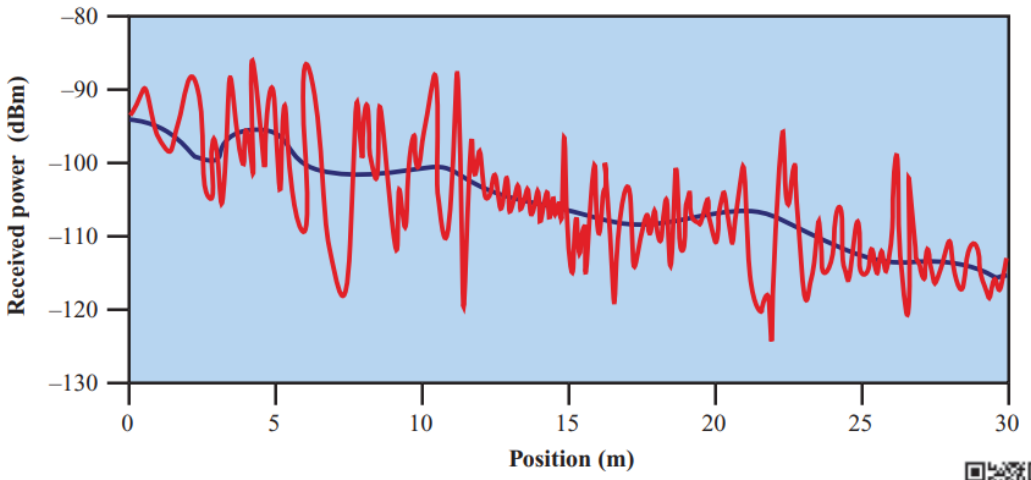


Figure 6.13 Typical Slow and Fast Fading in an Urban Mobile Environment

Fading :

6.15 Suppose that a student is walking through a university campus that has a wireless channel with a coherence time of 1 ms and a coherence bandwidth of 500 kHz. The bit rate of the signal being used is 10 kbps. Characterize the channel.

a. Is the channel slow or fast fading?

b. Is the channel flat or frequency-selective fading?

6.16 Suppose a wireless channel has a coherence bandwidth of 500 kHz. What range of bit rates can be supported to have frequency-selective fading?

Wireless Channel Model incorporating all impairments:

Attenuation (Path Loss)

Noise

Multipath & Fading

The Wireless Channel:

- In designing a communications system, it is important to estimate the effects of multipath fading and noise on the wireless channel. For this, three main Wireless channel models are as follows:

- The simplest channel model, from the point of view of analysis, is the additive white Gaussian noise (AWGN) channel.

- In this channel, the desired signal is degraded by thermal noise associated with the physical channel itself as well as electronics at the transmitter and receiver (and any intermediate amplifiers or repeaters).

- This model is fairly accurate in some cases, such as space communications but for terrestrial wireless transmission, particularly in the mobile situation, AWGN is not a good guide for the designer.

The Wireless Channel:

- Rayleigh fading channel: this model is used when there are multiple indirect paths between the transmitter and the receiver and no distinct dominant path, such as a LOS path. This represents a worst-case scenario in the context of received signal degradation.

- The Rayleigh channel model provides insights into performance characteristics that can be used in difficult environments, such as downtown urban settings.

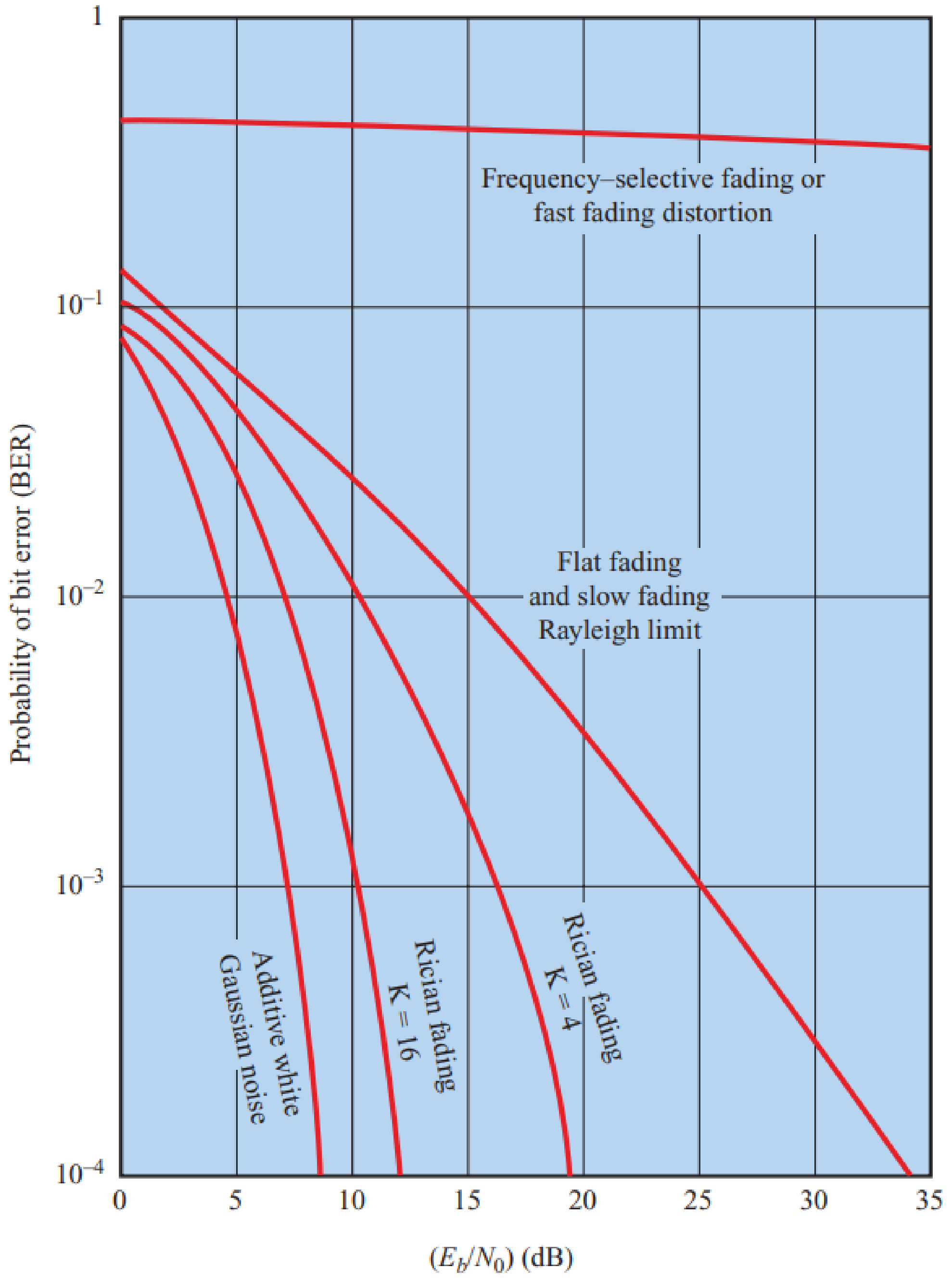
The Wireless Channel:

- <u>Rician fading model:</u> best characterizes a situation where there is a direct LOS path in addition to a number of indirect multipath signals.

- The <u>Rician fading</u> channels are characterized by a parameter K, defined as follows:

$$K = \frac{\text{power in the dominant path}}{\text{power in the scattered paths}}$$

- When K = 0, the channel is Rayleigh (i.e., the numerator is zero), and when K = ∞ , the channel is AWGN (i.e., the denominator is zero).



Next………..

Channel Correction Mechanism

The Wireless Channel: Correction Mechanism

The efforts to compensate for the errors and distortions introduced by multipath fading fall into four general categories:

- Error correction codes or Channel coding
- Equalization
- Adaptive modulation and coding
- Diversity techniques (MIMO)
- Orthogonal frequency division multiplexing (OFDM)
- Spread spectrum.

Thanks!