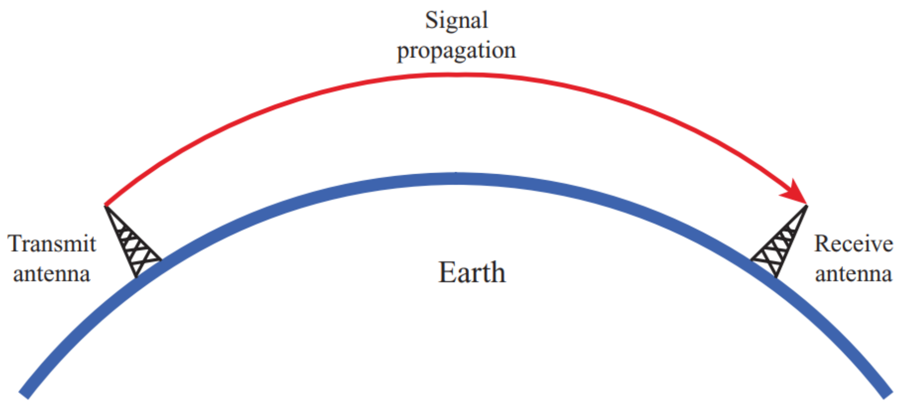
Chapter 1: Introduction to Wireless Environment

A water channel directs water from a source to a destination. Smooth channels produce easily predictable laminar flow. Obstacles like rocks induce turbulence that makes flow predictions in the channel difficult. A similar situation exists for the flow or channelling of a radio frequency (RF) signal from a transmitter to a receiver.

A.1 Propagation Modes

A signal radiated from an antenna travels along one of three routes: ground wave, sky wave, or line of sight (LOS).

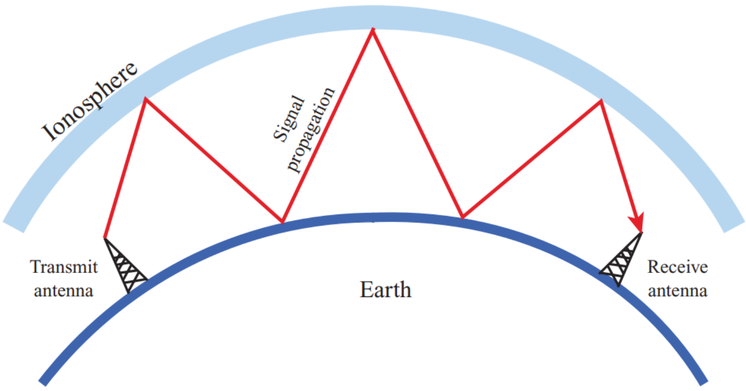
Ground wave propagation (Figure a) more or less follows the contour of the earth and can propagate considerable distances, well over the visual horizon. This effect is found in frequencies up to about 3 MHz. Electromagnetic waves in this frequency range are scattered by the atmosphere in such a way that they do not penetrate the upper atmosphere. The best-known example of ground wave communication is AM radio



(a) Ground wave propagation (below 2 MHz)

With **sky wave propagation** (Figure b) a signal from an earth-based antenna is refracted from the ionized layer of the upper atmosphere (ionosphere) back down to earth. A sky-wave signal can travel through a number of hops, bouncing back and forth between the ionosphere and the earth's surface.

With this propagation mode, a signal can be picked up thousands of kilometers from the transmitter. Sky waves generally operate between 3 and 30 MHz

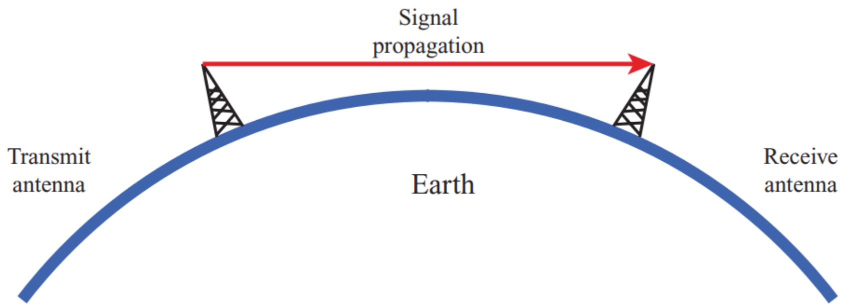


(b) Sky wave propagation (2 to 30 MHz)

Line-of-sight propagation (LOS) (Figure c) is necessary when neither ground wave nor sky wave propagation modes can operate. This generally occurs above 30 MHz. Most of the technologies we will discuss operate from 100s of MHz to a few GHz, so they operate in a line-of-sight mode.

This does not mean that line of sight always requires complete free space between transmitters and receivers, however. Different frequencies will be attenuated by atmospheric effects or have capabilities for penetrating through surfaces (e.g., through walls, buildings, cars, etc.).

For most materials, the ability to transmit through an object significantly degrades as frequency increases.



(c) Line-of-sight (LOS) propagation (above 30 MHz)

A.2 Basic Concepts

A.2.1 Channel

The term channel refers to the medium between the transmitting antenna and the receiving antenna as shown in Figure A.1.1

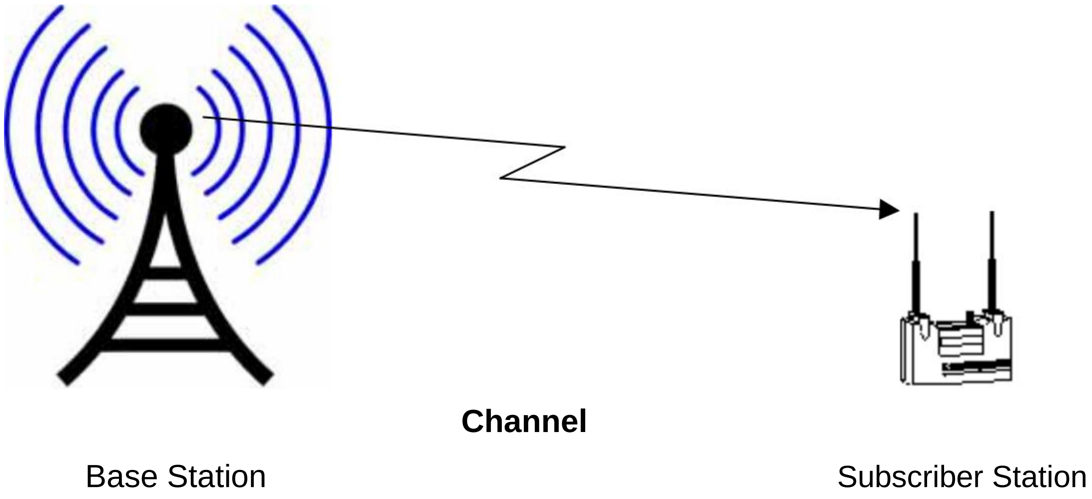


Figure A.1.1: Channel

The characteristics of wireless signal changes as it travels from the transmitter antenna to the receiver antenna. These characteristics depend upon the distance between the two antennas, the path(s) taken by the signal, and the environment (buildings and other objects) around the path. The profile of received signal can be obtained from that of the transmitted signal if we have a model of the medium between the two. This model of the medium is called **channel model**.

In general, the power profile of the received signal can be obtained by *convolving* the power profile of the transmitted signal with the impulse response of the channel. Convolution in time domain is equivalent to multiplication in the frequency domain. Therefore, the transmitted signal x, after propagation through the channel *H* becomes *y*:

$$y(f) = H(f)x(f) + n(f)$$

Here $H(f)$ is **channel response**, and $n(f)$ is the noise. Note that *x*, *y*, *H*, and *n* are all functions of the signal frequency *f*.

The three key components of the channel response are **path loss**, **shadowing**, and **multipath** as explained below.

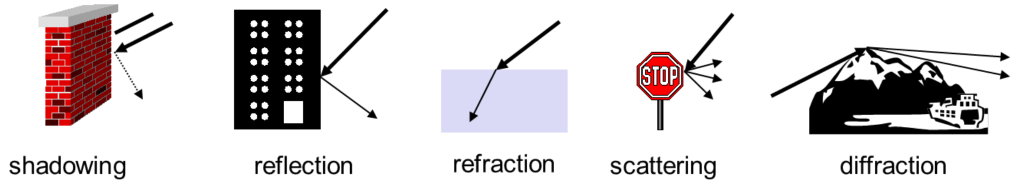
With any communications system, the signal that is received will differ from the signal that is transmitted, due to various transmission impairments.

There are five different mechanisms by which electromagnetic signals can transfer information from a transmitter to a receiver:

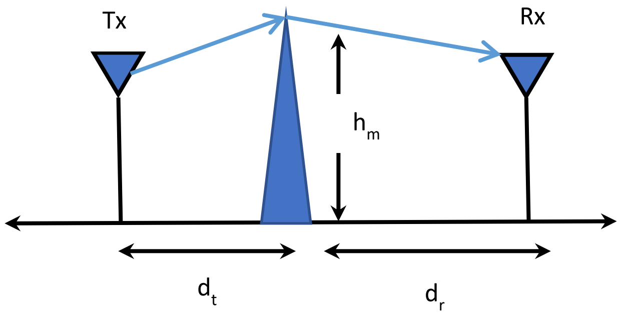
1. Free-space propagation transmits a wave when there are no obstructions. The signal strength decays as a function of distance.
2. Transmission propagates a signal as it penetrates in and through a medium. The signal is refracted at the surface of the medium to a different angle of transmission.
3. Reflections
4. Diffraction.
5. Scattering.

- **Reflection**
  - Occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal. For example, suppose a ground-reflected wave near the mobile unit is received.
  - The ground-reflected wave and the line-of-sight (LOS) wave may tend to cancel, resulting in high signal loss.
  - Further, because the mobile antenna is lower than most human-made structures in the area, multipath interference occurs.
  - These reflected waves may interfere constructively or destructively at the receiver.
- **Diffraction**
  - **O**ccurs at the edge of a solid body 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.

Thus, signals can be received even when there is no unobstructed LOS from the transmitter



A.2.2 Diffraction loss:



The diffraction loss can be estimated in dB by:

$$L_d = \begin{cases} 6 + 9v - 1.27v^2 & 0 < v < 2.4 \\ 13 + 20 logv & v > 2.4 \end{cases}$$

The diffraction parameter v is defined as:

$$v = h_m \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_t} + \frac{1}{d_r}\right)}$$

h_m is the height of the obstacle

d_t is distance transmitter - obstacle

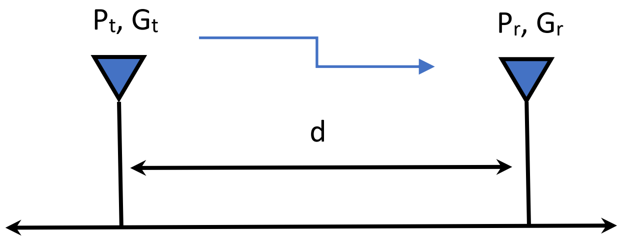
d_r is distance receiver - obstacle

A.2.3 Path Loss

The simplest channel is the free space line of sight channel with no objects between the receiver and the transmitter or around the path between them. In this simple case, the transmitted signal attenuates since the energy is spread spherically around the transmitting antenna, the received signal power P_r follow the inverse square law:

$$P_r \propto \frac{1}{d^2}$$

Where d is the distance between the transmitter and the receiver.



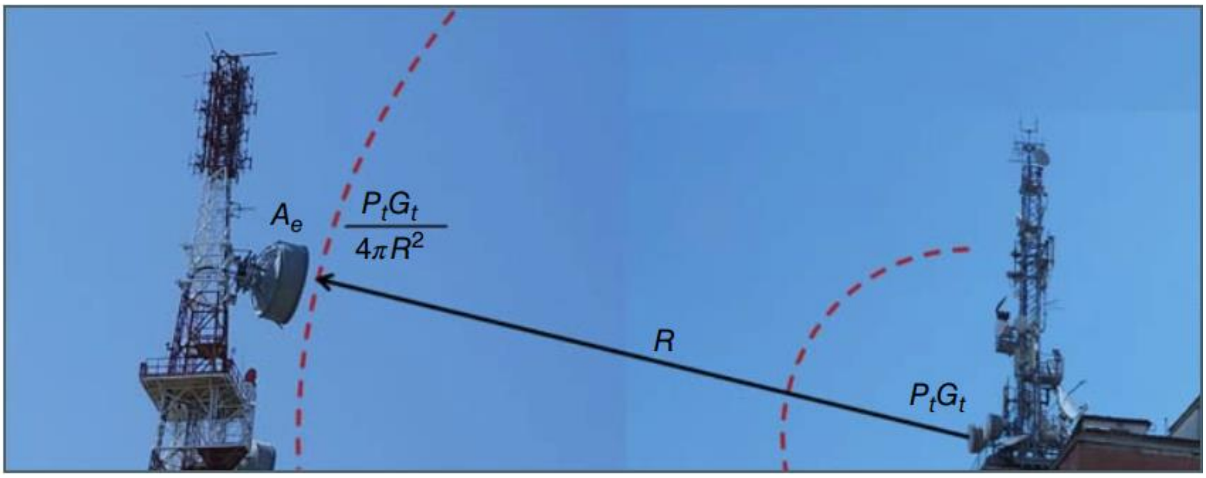


Figure A.1.2: Free Space Propagation Geometry

For this line of sight (LOS) channel, the received power is given by:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2}$$

Where G_t, and G_r are the transmitter and the receiver gains. P_t and P_r are the transmitted and received powers.

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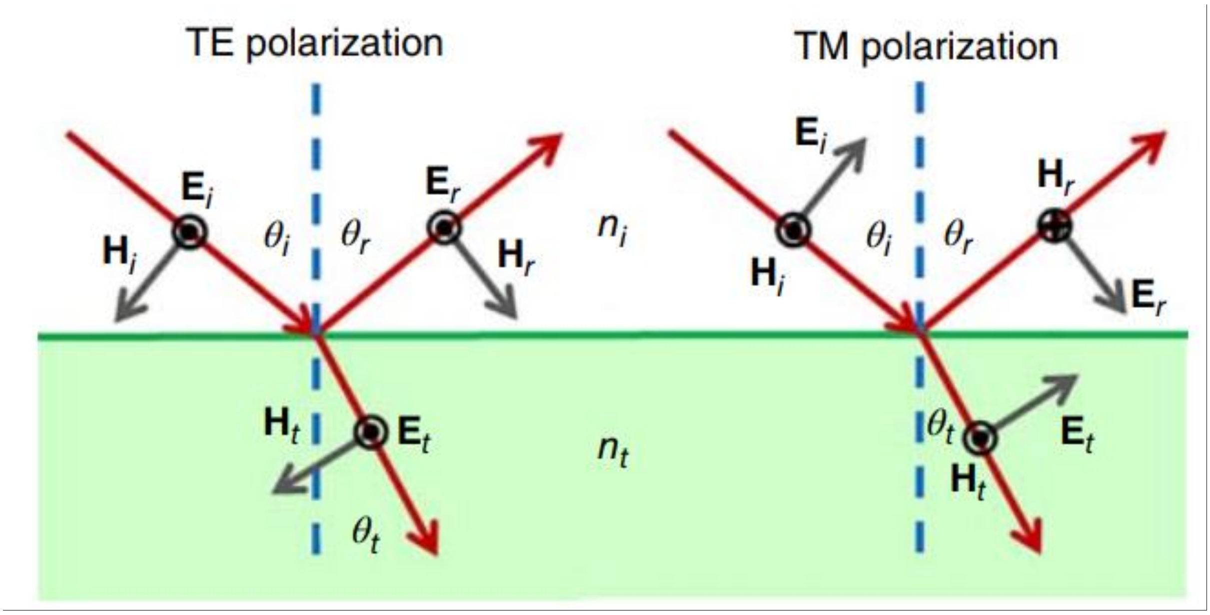

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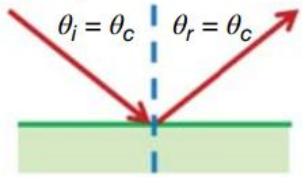
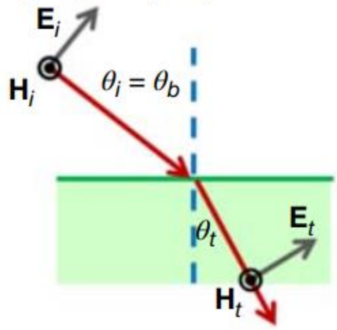
	Critical angle	Brewster angle
Characteristic	Total reflection when $\theta \geq \theta_c$	Total transmission when $\theta = \theta_b$
Polarization	TE and TM	TM
Index of refraction	$n_i > n_t$	$n_i \geq n_t$ or $n_i \leq n_t$
Diagram		

A.3 Multipath

When the reflected signal interacts with the LOS signal, interference patterns form. In-phase signals add in amplitude as shown in Figure A.1.4, otherwise the resulting sum is less than the sum of the two amplitudes.

In fact, when they are out of phase by 180◦, they cancel or fade. Theoretically, the power falls off in proportion to the square of the distance. In practice, the power falls off more quickly, typically 3rd or 4th power of distance.

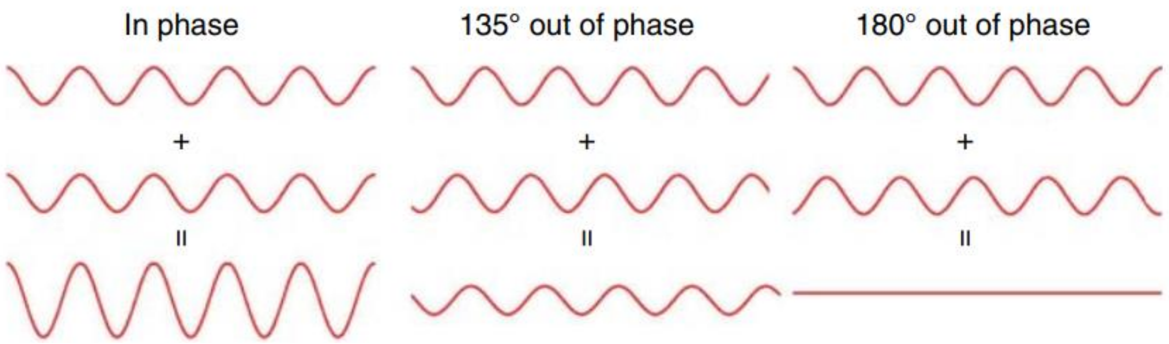


Figure A.1.4 Adding one signal to another of the same frequency but different phases.

Multipath means that a transmitted signal arrives at the receiver by more than one route. Figure A1.4 depicts a communication channel with a direct or LOS signal plus one reflected or multipath signal. Since the signals take different paths to the receiver, they have different amplitudes due to reflections and diffractions as well as additional free space loss. The phase and time of arrival of each signal at the receiver differ, because their paths have different lengths. All the signals sum to create a dispersed signal (longer duration than transmitted signal) resulting from the time delays of the various paths

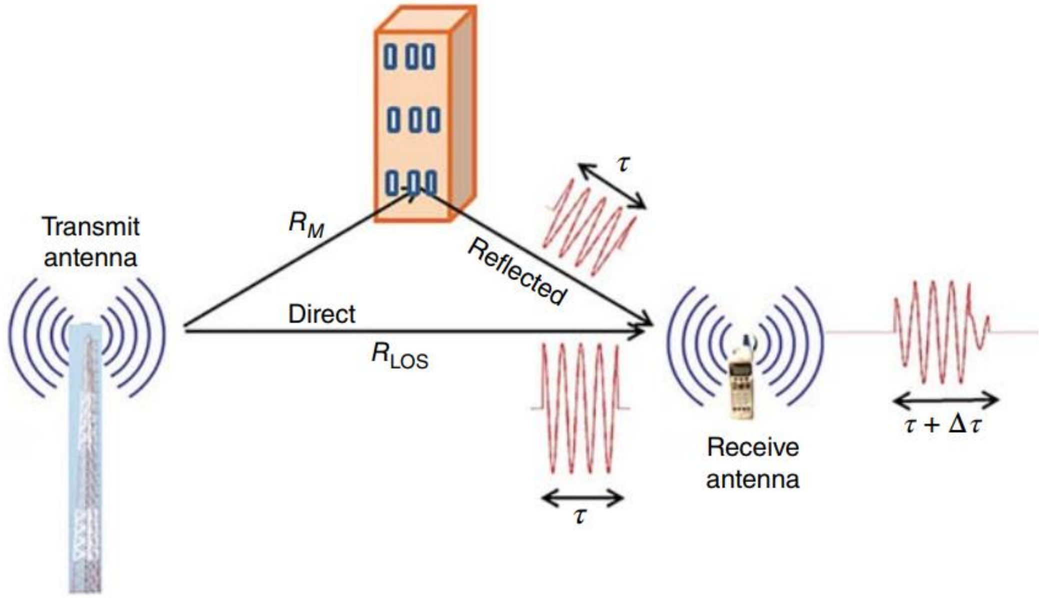


Figure A.1.4 Multipath occurs when the signal takes more than one route to get to the receiver. The received signal shows dispersion or broadening of the pulse.

If the signal takes two paths of length R_{LOS} and R_M ($R_M > R_{LOS}$), then the multipath signal arrives $\Delta\tau = (R_M - R_{LOS})/c$ after the LOS signal.

A.3.1 Antennas over the Earth

Figure A.1.5 presents a microwave link between transmit and receive antennas placed on towers. The LOS path (R_{LOS}) starts at the transmitter mounted h_t above the ground and ends at the receiver mounted h_r above the ground.

The transmit antenna appears to have an image antenna beneath the ground that radiates the reflected signal. Since the ground is not a perfect reflector, the image antenna radiates a reduced amplitude compared to the actual antenna.

Using the Friis transmission formula, the received signal, $s_r(t)$, equals the sum of the electric fields of the LOS and image (reflected) signals.

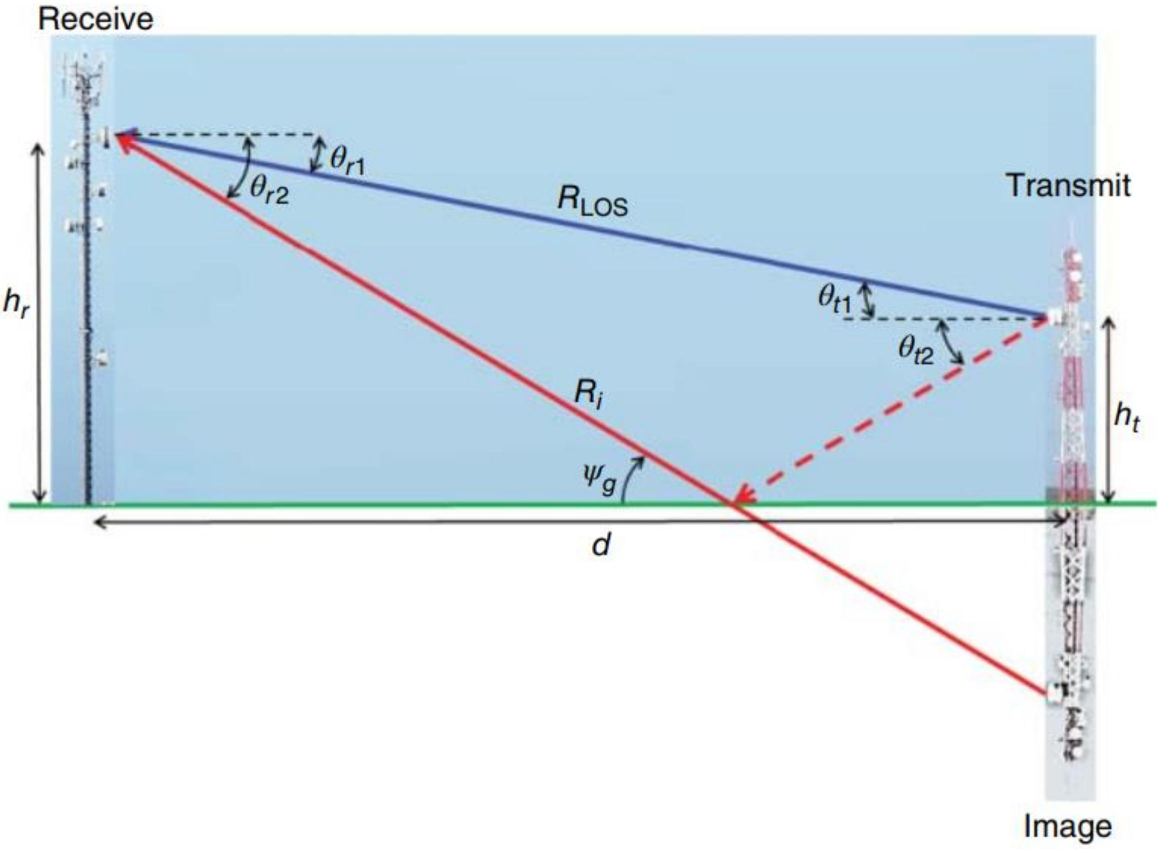


Figure A.1.5 Diagram of direct and reflected rays.

When considering the reflection from ground, we can use the two-ray ground reflection model as follows:

$$P_r = P_t G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2$$

where h_t and h_r denote the transmitter antenna height and receiver antenna height, respectively. Unlike Friis transmission equation, the received power is affected by the antenna
heights.
The fourth power of the distance, d^4, is included in the equation so that the received power decreases more quickly according to the distance. This equation does not depend on the wavelength.

In practical systems, we use empirical path loss models. The received power of the empirical models is expressed as follows:

$$P_r = P_r P_0 \left(\frac{d_0}{d}\right)^{\gamma}$$

where P_0 is the power at the reference distance, d_0, and γ is the path loss exponent which typically has 2–8 according to carrier frequency, environment, and so on.

The path loss is defined as the difference between the transmitted power and the received power as follows:

$$PL = P_t - P_r = 10log_{10}\left(\frac{P_t}{1mW}\right) - 10log_{10}\left(\frac{P_r}{1mW}\right) = 10log_{10}\frac{P_t}{P_r}$$

where PL, P_t, and P_r are the path loss (dB), transmitted power (W), and received power (W), respectively

Thus, the path loss can be defined as:

$$PL(d) = PL_0 + 10\gamma log_{10}\left(\frac{d}{d_0}\right)$$

where PL_0 is the path loss at the reference distance d_0 (dB). When a propagating electromagnetic wave encounters some obstruction such as wall, building, and tree, reflection, diffraction, and scattering happen and the electromagnetic wave is distorted. We call this effect shadowing or slow fading and use the modified path loss model as follows:

$$PL(d) = PL_0 + 10\gamma log_{10}\left(\frac{d}{d_0}\right) + x$$

where x denotes a Gaussian distributed random variable with standard deviation, σ, and represents shadowing effect.

A.3.2 Earth Surface

Earth curvature blocks the LOS signal when the transmitter and receiver are many kilometers apart. Figure A.1.6 shows two towers separated by d_{max}, the sum of the distances from the transmit (d_{th}) and receive antennas (d_{rh}) to the horizon.

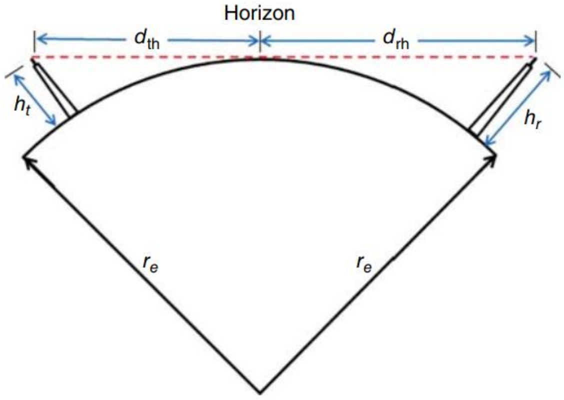


Figure A.1.6 The Earth curvature limits the maximum range of LOS signals.

A LOS formula that assumes a smooth Earth with no obstructions estimates d_{max} as

$$d_{max} = \sqrt{2h_t r_e} + \sqrt{2h_r r_e}$$

where the radius of the Earth is approximately $r_e = 6.378 \times 10^6 m$. In real life, many natural and manmade obstructions between the transmitter and receiver reduce d_{max}, so the LOS is much less than d_{max}.

A.4 Signal Fading

Fading occurs when the receive signal level drops below the minimum detectable level of the receiver due to

- **Path loss**
- **Fluctuations in the received signal power**
- **Fluctuations in signal phase**
- **Variations in the angle of arrival of the received signal**
- **Reflection and diffractions from objects**
- **Frequency shift due to the Doppler effect**

The fade margin equals the difference in dB between the received signal strength and the receiver sensitivity. A reliable link has a high fade margin.

Figure A.1.7 breaks down the different categories of fading that will be discussed in the following paragraphs

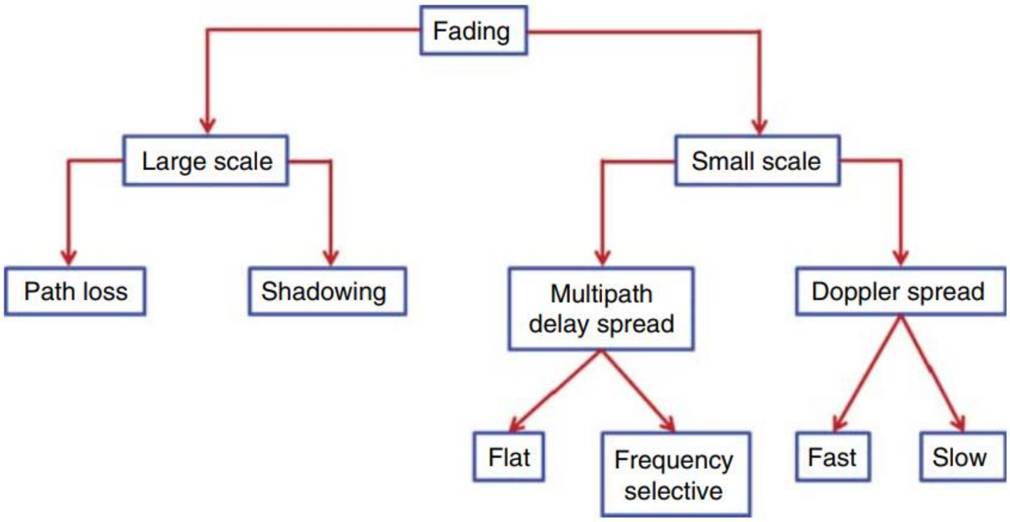


Figure A.1.7 Categories of fading.

Large-scale fading means that the signal amplitude slowly changes over distances greater than a wavelength.

Small-scale fading, on the other hand, implies that signal fades occur quickly over small distances on the order of a wavelength.

The differences between these two types of fading are shown by signal power plots at the bottom of Figure A.1.8. Small-scale and large-scale fading add together to get a total signal level shown in the top plot of Figure A.1.8.

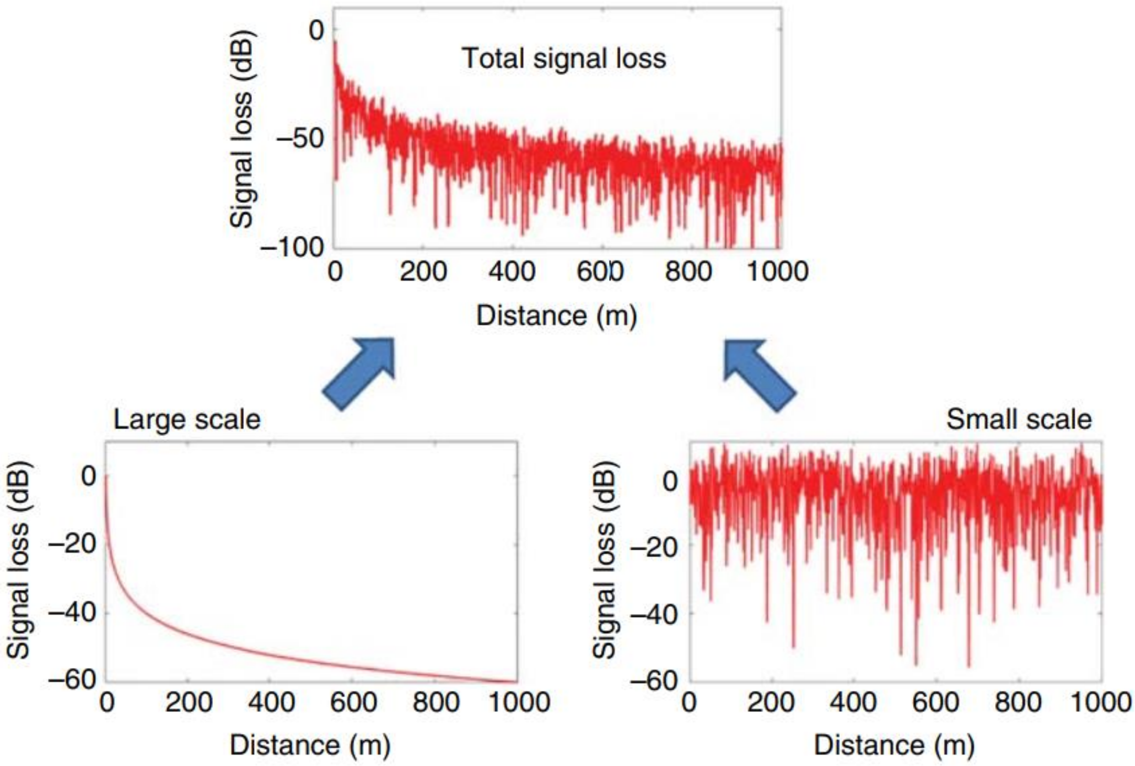
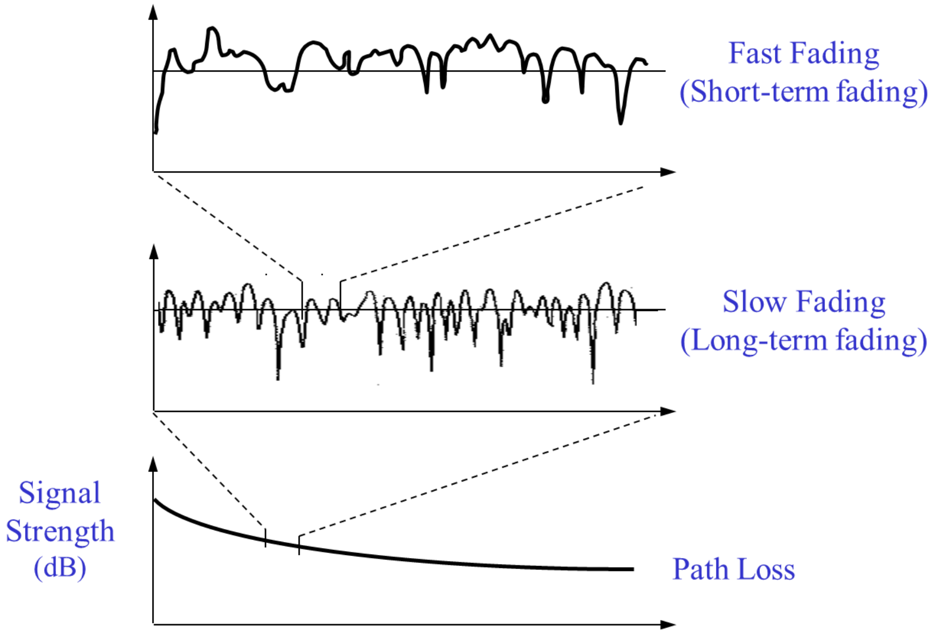


Figure A.1.8 The total signal is a combination of large-scale and small-scale fading



Two types of large-scale fading are path loss and shadowing. **Path loss** attenuates a signal by $1/R^{\gamma}$ as previously discussed. Eventually, a signal fades when R becomes large.

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 – 3.5
Urban area cellular (obstructed)	3 – 5
In-building line-of-sight	1.6 – 1.8
Obstructed in-building	4 – 6
Obstructed in-factories	2 – 3

Shadowing causes large-scale fading when a large object (e.g. building or mountain) blocks the LOS signal, but the diffracted signal exists and slowly decays in the shadow region.

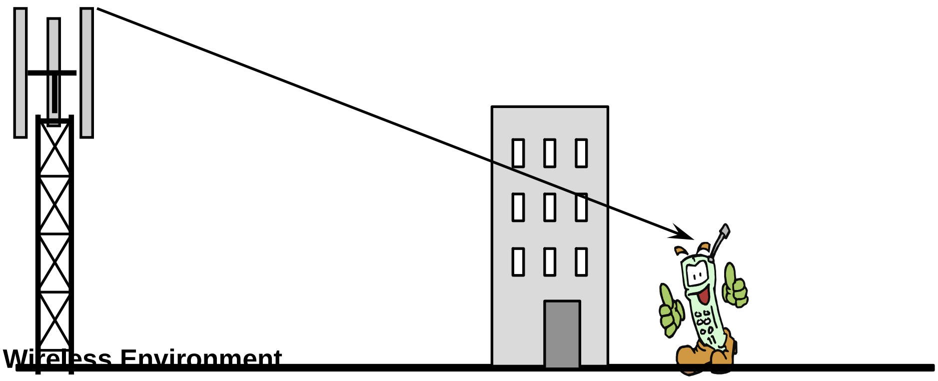


Figure A.1.9: Shadowing

Small-scale fading splits into two categories: multipath delay spread and Doppler spread.

Regarding Doppler spread, a channel may change over a short time span. This is caused by movement of mobiles and surrounding objects. This is characterized by the channel's coherence time, Tc, which is the time over which the channel stays relatively constant.

Coherence times for a pedestrian might be 70 ms, whereas times might be 5 ms for a vehicle moving at highway speeds.

This might have a significant effect on a signal, depending on its bit rate, r_b bits/second. This signal would have a bit time $T_b = 1/r_b$ second/bit. If the coherence time T_c is much, much longer than the bit time T_b, then the channel could be called **slow fading**

Fast fading if the coherence time T_c is less than, approximately equal, or even slightly greater than the bit time T_b

The other small-scale effect, multipath fading, can cause distortion and inter-symbol interference.

Multipath fading can be characterized by a coherence bandwidth, B_C, which is the range of frequencies over which the channel response is relatively constant.

Flat fading coherence bandwidth is much, much greater than the signal bandwidth, (**Figure A.1.10**). All frequency components in a flat-fading channel have the same amount of fading. Flat fading preserves the spectral characteristics of the transmitted signal. The signal bandwidth is less than the channel bandwidth.

Frequency-selective fading (time dispersion) occurs when coherence bandwidth is smaller than the signal bandwidth (**Figure A.1.10**). Not all signal frequencies experience the same fading. The signal passing through it spreads out in time and has a reduced bandwidth

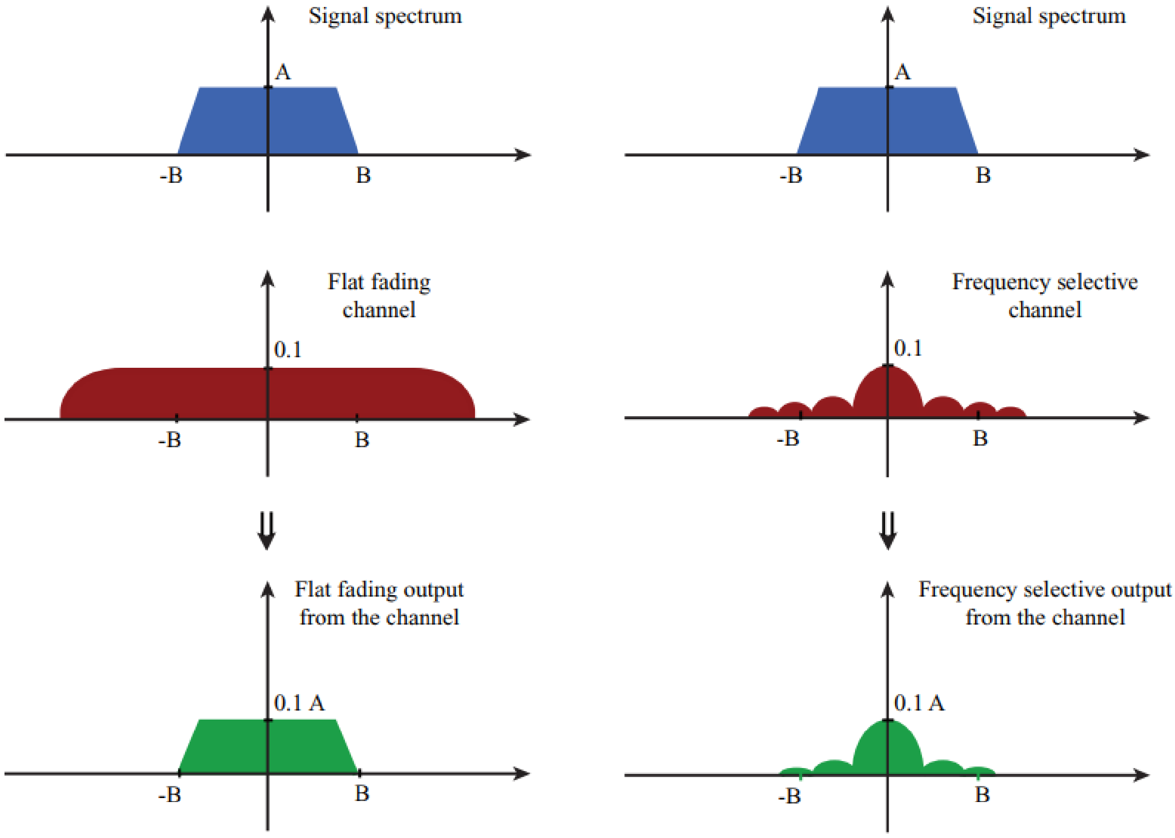
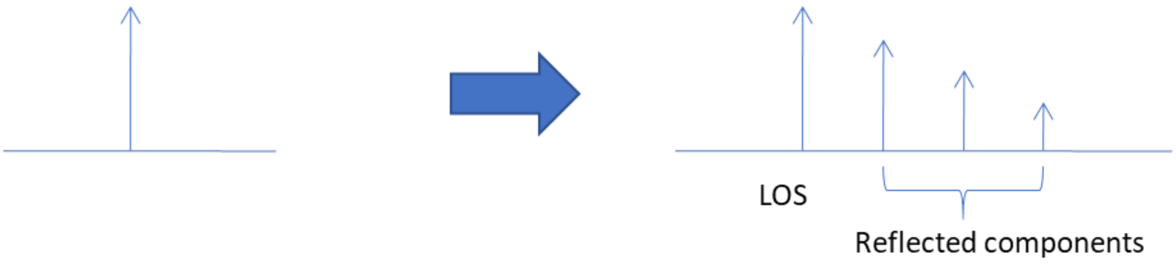


Figure A.1.10

These characterizations for Doppler spread and multipath fading do not depend on each other. Therefore, four combinations can occur: fast-flat, slow-flat, fast-frequency selective, and slow-frequency selective fading.

A.4.1 Delay spread

If a single pulse is transmitted in the multipath channel, it will yield a train of pulses with delay time



Delay spread (τ): the time delay between the arrival of the first received signal component and the last received signal component associated with a single transmitted pulse

Coherence bandwidth $B_c = {}^{1}/_{\tau}$

Example: 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, and it bandwidth is 1 MHz

1) How would the channel be characterized regarding Doppler spread and multipath fading?
2) What range of bit rates can be supported to have flat fading?

Solution:

1) $T_b = \frac{1}{r_b} = \frac{1}{100kbps} = 10\ \mu s$

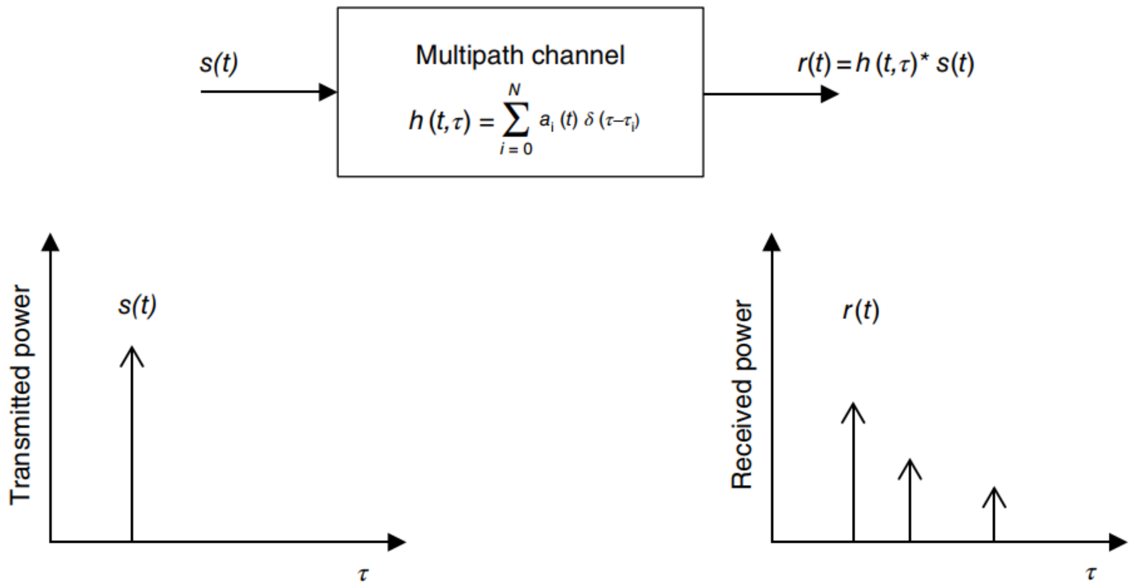
   Since the coherence time is much greater than the bit time $(70ms \gg 10\mu s)$ slow fading occurs
2) Since the coherence bandwidth (150 KHz)< signal bandwidth (1MHz)

Then, frequency selective fading occurs.

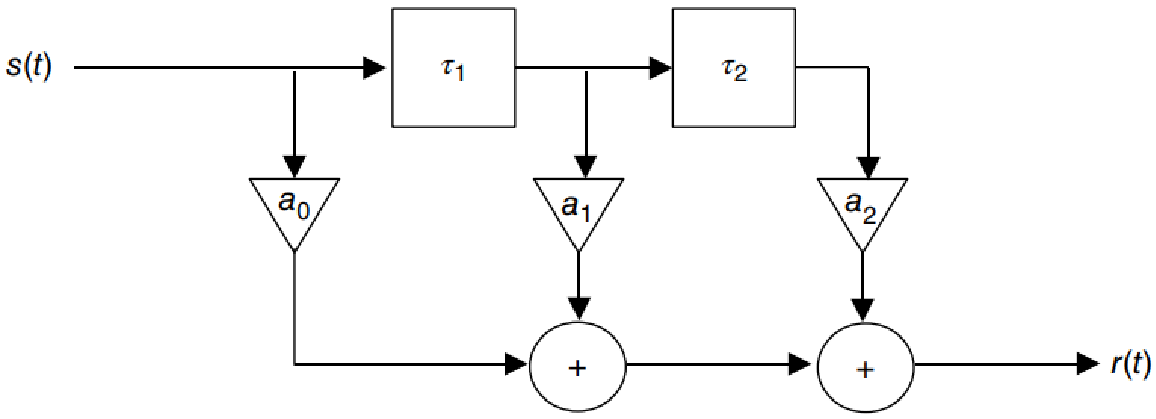
The multipath channel is modeled as a linear Finite Impulse Response (FIR) filter. The impulse response, h(t,τ), of the multipath channel is

$$h(t,\tau) = \sum_{i=1}^{N} a_i(t)\delta(\tau - \tau_i)$$

where $a_i(t)$ and $\delta(\tau - \tau_I)$ denote amplitude of a multipath and the Delta function, respectively. N means N different reflected paths



We can observe two different reflected paths in the delay profile and represent this using a three-tap FIR filter



A.5 The Fading Channel

In designing a communications system, the communications engineer needs to estimate the effects of multipath fading and noise on the mobile channel.

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 and some wire transmissions, such as coaxial cable. For terrestrial wireless transmission, particularly in the mobile situation, AWGN is not a good guide for the designer.

A.5.1 Small-Scale Fading Models

Rayleigh fading occurs 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.

Fortunately, Rayleigh fading can be dealt with analytically, providing insights into performance characteristics that can be used in difficult environments, such as downtown urban settings.

Rician fading best characterizes a situation where there is a direct LOS path in addition to a number of indirect multipath signals. The Rician model is often applicable in an indoor environment whereas the Rayleigh model characterizes outdoor settings. The Rician model also becomes more applicable in smaller cells or in more open outdoor environments. The channels can be characterized by a parameter K, defined as follows:

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

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

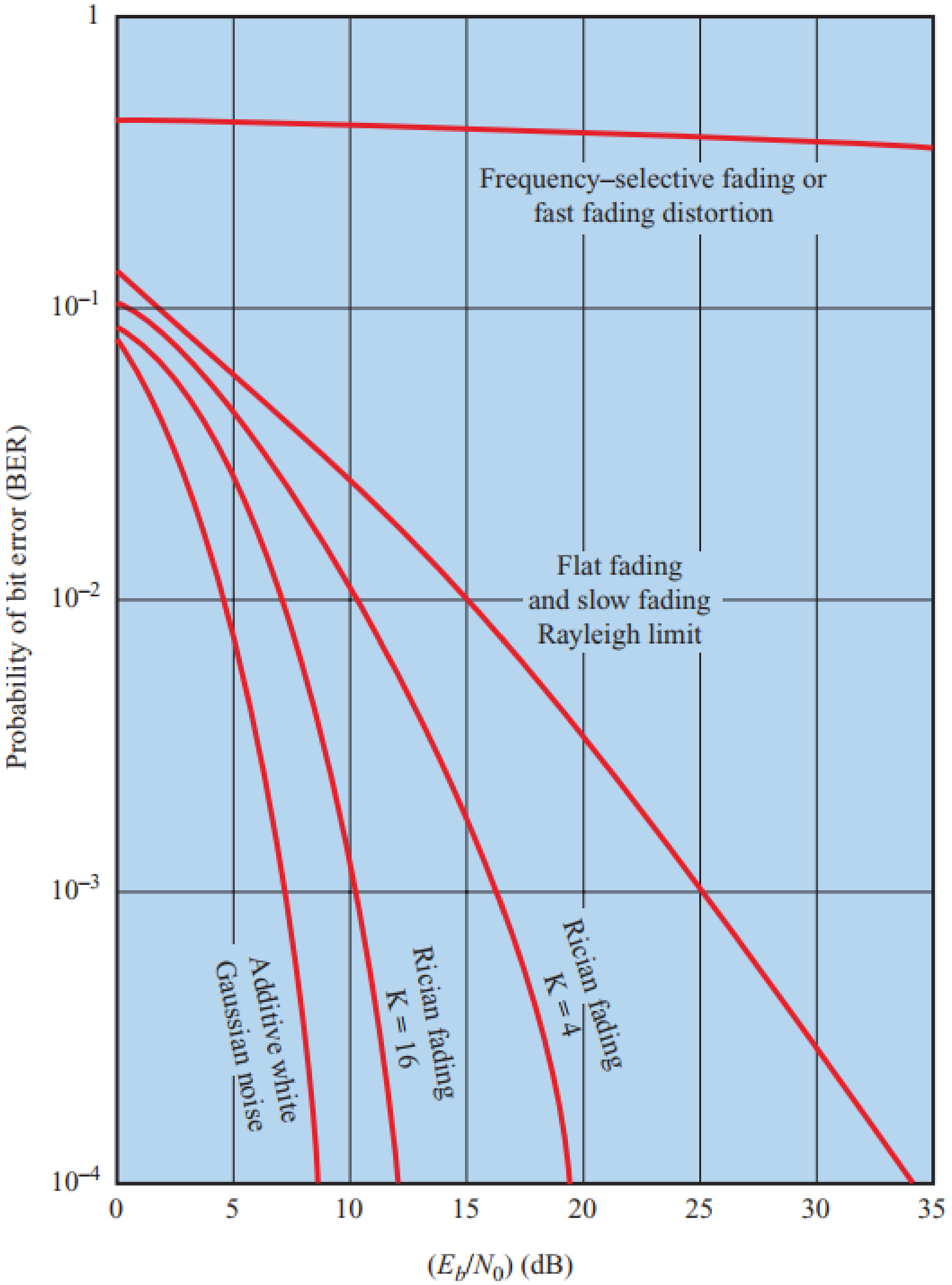


Figure Theoretical Bit Error Rate for Various Fading Conditions

A.5.2 Empirical Path Loss Models

In propagation studies a qualitative description of the environment is usually employed using terms such as rural, suburban, urban and dense urban. Dense urban areas are generally defined as dominated by tall buildings such as office blocks and other commercial buildings. On the other hand, suburban areas comprise residential areas, gardens and parks. The rural term defines open land with scattered buildings, woodland and forests

Actual environments are too complex to model accurately. In practice, most simulation studies use empirical models that have been developed based on measurements taken in various real environments. In this section we describe a number of commonly used empirical models.

Hata Model

In 1968, Okumura conducted extensive measurements of base station to mobile signal attenuation throughout Tokyo and developed a set of curves giving median attenuation relative to free space path loss. To use this model one needs to use the empirical plots given in his paper. This is not very convenient to use. So in 1980, Hata developed closed-form expressions for Okumura's data. According to Hata model the path l oss in an urban area at a distance d is:

$$PL_{urban}(d)dB = 69.55 + 26.16log_{10}(f_c) - 13.82log_{10}(h_r) - a(h_r) + (44.9 - 6.55log_{10}(h_t))log_{10}(d)$$

where

f_c is the ferquency in MHz

h_t is effective transmitter antenna height in meters (30-200m)

h_r is effective receiver antenna height in meters (1-10m)

d is T-R separation in km

$a(h_r)$ is the correction factor for effective mobile antenna height which is a function of coverage area

$a(h_r) = (1.1log_{10}(f_c) - 0.7)h_r - (1.56log_{10}(f_c) - 0.8)$ dB

- Note : Hata model is **valid** from 150MHz to 1500MHz

COST 231 Extension to Hata Mode

The European Cooperative for Scientific and Technical (COST) research extended the Hata model to 2 GHz as follows:

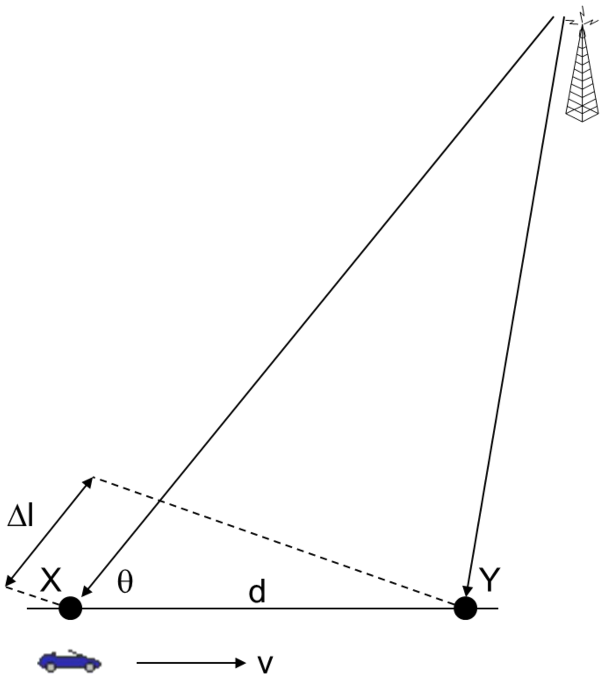
$$P_{L,urban}(d)dB = 46.3 + 33.9\log_{10}(f_c) - 13.82\log_{10}(h_t) - a(h_r) + (44.9 - 6.55\log_{10}(h_t))\log_{10}(d) + C_M$$

Here, C_M is 0 dB for medium sized cities and suburbs and is 3 dB for metropolitan areas. The remaining parameters are same as before. This model is restricted to the following range of parameters:

Carrier Frequency	1.5 GHz to 2 GHz
Base Antenna Height	30 m to 300 m
Mobile Antenna Height	1m to 10 m
Distance d	1 km to 20 km

A.5.3 Doppler Effects

When the transmitter and/or receiver moves the transmitted signal experiences a Doppler shift that translates the signal to a lower or higher frequency



$$d = |XY|$$

$$\Delta l = |SX| - |SY| = d\cos\theta$$

$$\Delta l = v\Delta t\cos\theta$$

the phase change in the received signal is:

$$\Delta\Phi = \frac{\Delta l}{\lambda}2\pi = \frac{2\pi v\Delta t}{\lambda}\cos\theta$$

the Doppler shift (The apparent change in frequency):

$$f_D = \frac{1}{2\pi}\frac{\Delta\Phi}{\Delta t} = \frac{v}{\lambda}\cos\theta$$

The Doppler frequency

$$f_D = \frac{V}{\lambda}\cos\theta = f_m\cos\theta$$

The received signal frequency

$$f_r = f_c - f_m\cos\theta$$

When $\theta = 0$ (mobile moving away from the transmitter)

$$f_r = f_c - f_m$$

When $\theta = 90$ (I.e. mobile circling around)

$$f_r = f_c$$

When $\theta = 180$ (mobile moving towards the transmitter)

$$f_r = f_c + f_m$$

Effects of Doppler shifts

- Bandwidth of the signal could increase or decrease leading to poor and/or missed reception.
- The effect in time is coherence time variation and signal distortion
  - *Coherence time:* **Time duration over which channel impulse response is invariant, and in which two signals have strong potential for amplitude correlation**
  - **Coherence time is expressed by:**

$$T_c = \sqrt{\frac{9}{16\pi f_{D\text{-}max}^2}}$$

  - **where $f_{D\text{-}max}$ is the maximum Doppler shift, which occurs when $\theta = 0$ degrees**
- To avoid distortion due to motion in the channel, the symbol rate must be greater than the inverse of coherence time.

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