Chapter 3

Wireless Signal Propagation

In the previous [illegible]d how the bits are transmitted to the wireless channel. In this [illegible]g to discuss how these bits travel or propagate through the wireless channel before reaching to the receiver.

3.1 Wireless Radio Channel

Wireless radio channel is different than a wired channel. The radio channel is "open" in the sense that it does not have anything to protect or guide the signal as it travels from source to destination. As a result, the signal is subject to many issues, which we must be aware of to understand how the receiver will receive the signal. These issues will be discussed in this chapter.

3.2 Antenna

Transmitter converts electrical energy to electromagnetic waves and the receiver converts those electromagnetic waves back to electrical energy. It is important to note that the same antenna is used for both transmission and reception. Therefore a device can use the same antenna for both transmitting bits and receiving bits.

Depending on how the antennas radiate or receive power, there can be three types of antennas as illustrated in Figure 3.1. An antenna is called **omni-directional** if the power from it radiates in (or it receives power from) all directions. A **directional** antenna, on the other hand, can focus most of its power in the desired direction. Finally, an **isotropic** antenna refers to a theoretical antenna that radiates or receives *uniformly* in each direction in space, without reflections and losses. Note that, due to reflections and losses in practical environments, the omni-directional antenna does not radiate or receive in all directions *uniformly*.

An isotropic transmitting antenna cannot produce much power at the receiver because the power is dissipated to all directions and wasted. Given that the receivers are likely to be contained in some space, for example in a horizontal plane rather than in a sphere, antennas are designed to control the power in a way so that the receivers receive more power compared to a theoretical isotropic antenna. Antenna **gain** refers to the ratio of the power at a particular point to the power with isotropic antenna, which gives a measure of power for the antenna. Antenna gain is expressed in dBi, which means "decibel relative to isotropic". For example, if an antenna is advertised as 3 dBi, it means that it will produce twice as much power than an isotropic antenna. Note that an isotropic antenna will have a gain of 0 dBi.

ifferent types of antennas

Example 3.1
How much stron receives (transmits) the signal compared to the isotropic antenna?

Solution
Let
Power of isotropic antenna = P_{iso}
Power of 17 dBi antenna = P
We have
$17 = 10\log_{10}(P/P_{iso})$
Thus $P/P_{iso} = 10^{1.7} = 50.12$, i.e., the 17 dBi antenna will receive (transmit) the signal 50.12 times stronger than the isotropic antenna albeit using the same transmit power.

Antennas are designed to transmit or receive a specific frequency band. For example, antennas used in wireless routers operating with 2.5/5 GHz are too small to receive TV signals operating with 700MHz. Fundamentally, end-to-end antenna length must be half the wavelength so electrons on the antenna can travel back and forth in one cycle. Small consumer devices, such as mobile phones, may hide their antennas within the device, but the fundamental relationship between antenna size and frequency exists, i.e., we would need larger antennas for lower frequencies, and vice versa.

3.3 Reflection, Diffraction, Scattering

When the transmitting antenna transmits a signal, the signal can reach the receiver antenna directly in a straight path if there is a line-of-sight (LOS) between the transmitter and the receiver. However, the signal also *bounces* from many other objects around us and the bounced signals reach the receiver by traveling different paths.

Figure 3.2 shows that there are three types of bouncing that can happen for the signal transmitted by a car antenna on the street. **Reflection** happens when the signal hits a large solid object such as a wall. **Diffraction** happens when the signal bounces off a sharp edge, such as a corner of a block. Finally, a signal may hit very small objects, such as a thin light post or even dust particles in the air, which causes **scattering**. Note that reflection and diffraction are more directional, but scattering is more omni-directional. There are complex mathematical formulas to capture the effect of reflection, diffraction, and scattering on the received signal at the receiving antenna, but those are outside the scope of this book. Our main objective here is to be aware of the fact that the transmitted signal can reach the receiver in many different ways, which may cause certain issues when designing the communication protocols.

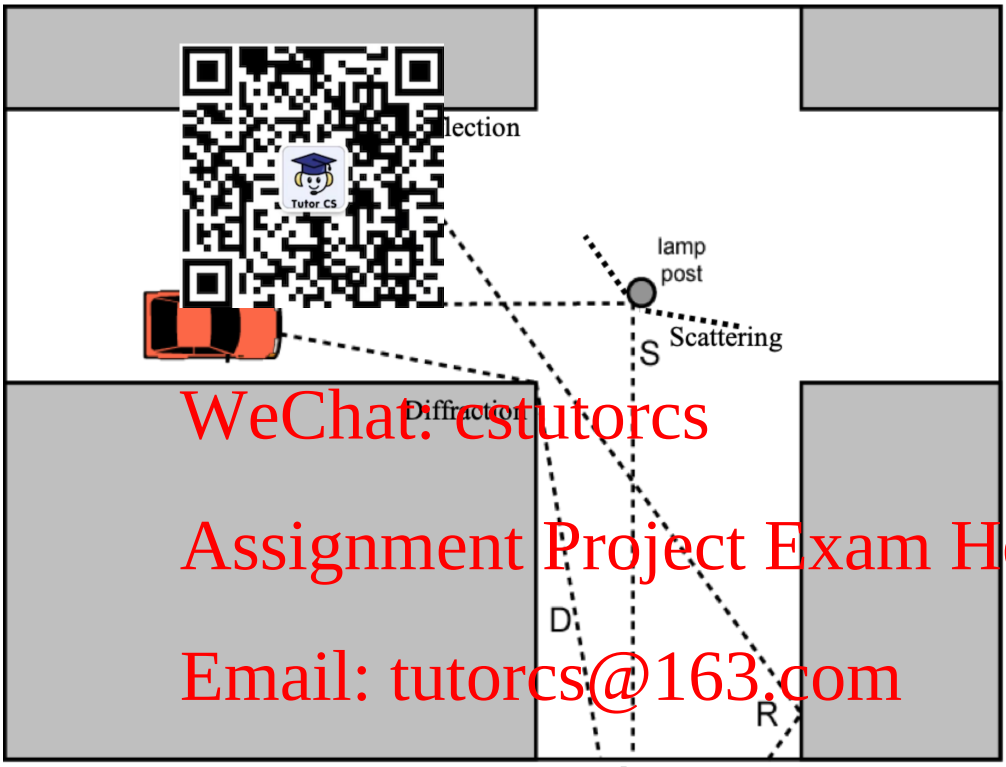


Figure 3.2 Reflection, Diffraction, and Scattering

Now let us try to understand the effect of these signal bouncing phenomena on wireless communication. Reflection happens when the surface is large relative to the wavelength of the signal. When the reflected signal reaches the receiver, it may have a phase shift. Depending on the phase shift, the reflected signal may actually cancel out the original signal (destructive), or strengthen it (constructive).

Similarly, diffraction happens when the edge of an impenetrable body is large relative to signal wavelength, but the phase shift is calculated differently than a reflection.

Finally, scattering happens when the size of the object is in the order of the wavelength. This means a light post can cause scattering for low frequency signals (large wavelength), but would cause reflection for very high frequency signals, such as 60 GHz. However, for 60 GHz, very tiny objects, such as snowflakes, hailstones, can cause scattering.

An interesting outcome of reflection, diffraction, and scattering is that the receiver can still receive the signal even if there is no LOS between the transmitter and the receiver. This is a great advantage for wireless communications. For example, it is not possible to have a LOS to the wifi access point or router located in the garage or in a central location from every room in the house. We however can still receive signals from the AP. It is because of this bouncing property of wireless signals. On the other hand, when we have LOS, we do not have to depend on signal bouncing, but the reflection, diffraction and scattering then actually cause some form of interference with the LOS signal.

3.4 Channel Model

Now that we have some appreciation of the signal propagation through the radio channel and how it can get affected by different physical phenomena, we need to find a way to predict [illegible]al that may be received at a given location given certain transmiss[illegible]hannel modeling.

Figure 3.3 show[illegible]smitter mounted on a tower to transmit signals to subscriber devic[illegible] located at anywhere around the tower. Power profile of the re[illegible]subscriber station can be obtained by *convolving* the power profil[illegible] signal with the impulse response of the channel. Note that *convolution* in time is *multiplication* in frequency.

Mathematically, after propagating through the channel *H*, transmitted signal *x* becomes *y*, *i.e.*,

$$y(f) = H(f).x(f) + n(f) \qquad (3.1)$$

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

Figure 3.3 Channel model

3.5 Path Loss

When a signal travels through space, it loses power. This is called path loss or signal attenuation. As a result of path loss, the power of a signal at the receiver (received power) is usually only a fraction of the original or input power used at the transmitter to generate the signal.

Path loss depends on the length of the path travelled by the signal. The larger the distance between the transmitter and receiver, the higher the path loss, and vice versa. Clearly, the path loss must be estimated and factored in properly when a wireless link is designed. Different path loss models are used for estimating path loss for different scenarios. Two popular path loss models are the Frii's model designed for free space with no reflections, and the 2-ray model that takes reflections from the ground into consideration. Frii's model is used as a guide for ideal scenarios whereas 2-ray is a more practical model used widely in wireless communications. We will examine 2-ray later in the chapter after discussing multipath reflections.

In free space without any absorbing or reflecting objects, the path loss depends on the distance as well as on the frequency (or wavelength) according to the following Frii's law:

$$P_R = P_T G_T \text{[illegible]} G_T G_R \left(\frac{c}{4\pi f d}\right)^2 \qquad (3.2)$$

Where P_R and [illegible] and transmitted powers (in Watts), respectively, while G_T and [illegible] and receiver antenna gains in linear scale, respectively. We [illegible] frequency, path loss increases as *inverse square of distance*, which is sometimes referred to as the d^{-2} law (path loss exponent = 2). It is also observed that path loss increases as inverse square of the frequency, which means that the signal power attenuates more rapidly for higher frequency signals, and vice versa.

Figure 3.4 Power spreading in space and received power calculation for Frii's Law

Equation (3.2) shows path loss in linear scale. For the convenience of calculating the link budget, however, path loss is actually measured in dB. By converting Equation (3.2) in dB, we obtain:

$$P_R^{dB} = P_T^{dB} + G_T^{dB} + G_R^{dB} + 10log_{10}\left(\frac{\lambda}{4\pi d}\right)^2 \qquad (3.3)$$

Where P_R^{dB} and P_T^{dB} refer to receive and transmit powers, respectively, in dBm, while G_T^{dB} and G_R^{dB} are the antenna gains in dBi. Thus, the path loss is obtained as:

$$Path\ Loss = P_T^{dB} - P_R^{dB} = -G_T^{dB} - G_R^{dB} - 10log_{10}\left(\frac{\lambda}{4\pi d}\right)^2 \quad (3.4)$$

For isotropic ant[illegible] (G^{dB} [illegible] G^{dB} are both 0 dB), path loss is reduced to the following simple[illegible]

$$\text{Pathloss}(dB) = [illegible] = 20log_{10}\left(\frac{4\pi d}{\lambda}\right) = 20log_{10}\left(\frac{4\pi f d}{c}\right)$$
$$= [illegible]g_{10}(d) + [illegible]g_{10}(f) + 20log_{10}\left(\frac{4\pi}{c}\right)$$
$$= 20log_{10}(d) + 20log_{10}(f) - 147.55 \quad (3.5)$$

where d is in meter, f in Hz, and $c = 3 \times 10^8\ m/s$. Equation (3.5) implies that for free-space propagation, the received power decays with distance (transmitter-receiver separation) or frequency at a rate of 20 dB/decade, i.e., the signal loses 20 dB for every decade (tenfold) increase in distance or frequency.

A simple explanation for Frii's path loss formula in Equation (3.2) can be given using a sphere around an isotropic point power source at the center radiating a power of P_T as shown in Figure 3.4. Basically, the power from the source spreads in space in all directions equally. As such, the power density on the surface of the sphere decreases with increasing sphere radius, d. With $4\pi d^2$ being the area of the sphere, we have a power density of $P_T/4\pi d^2$. Therefore, the total power received at an antenna located at the sphere surface becomes equal to the power density times the antenna area. We have learned that antennas size is dependent on the frequency or the wavelength. Given that the ideal antenna has an area of $\lambda^2/4\pi$, the received power at the antenna is equal to $P_T\left(\frac{\lambda}{4\pi d}\right)^2$, which is given by the Frii's law in Equation (3.2) for isotropic antennas with unit gains.

Example 3.2
If 50W power is applied to a 900 MHz frequency at a transmitter, find the receive power at a distance of 100 meter from the transmitter (assume free space path loss with unit antenna gains).

Solution
Unit antenna gain means: G_T=G_R=1.
We have d=100m, f=900x10^6 Hz, P_T=50W, c=3x10^8 m/sec, and $\pi = 3.14$

$$P_R = P_T\left(\frac{c}{4\pi f d}\right)^2 = 3.5\mu W$$

Example 3.3
What is the received power in dBm at 10 meters from a 2.4GHz wifi router transmitting with 100mW of power (assume free space path loss with unit antenna gains)?

Solution
Unit antenna gai ... Bm.
We have d=10m, ... 00mW=20dBm, c=3x10^8 m/sec, and $\pi = 3.14$
... $log_{10}\left(\frac{4\pi f d}{c}\right) dB = 60\ dB$
... $loss = 20 - 60 = -40dBm$

3.6 Receiver Sensitivity

If the path loss is too much, the SNR at the receiver could be too low for decoding the data. The noise at the receiver is a function of the channel bandwidth, i.e., larger the bandwidth, the higher the total noise power, and vice versa. The noise is also sensitive to the circuits and hardware of the receiver and the operating temperature, which is called the noise figure of the receiver. Receiver sensitivity refers to the minimum received signal strength (RSS) required for that receiver to be able to decode information. Noise, bandwidth and modulation affect the receiver sensitivity. For example, Bluetooth specifies that, at room temperature, devices must be able to achieve a minimum receiver sensitivity of -70dBm to -82dBm [BTBLOG].

Example 3.4
increase the coverage with low transmit power, a manufacturer produced Bluetooth chipsets with a receiver sensitivity of -80 dBm. What is the maximum communication range that could be achieved for this chipset for a transmit power of 1 mW? Assume Free Space Path Loss with unit antenna gains.

Solution
Bluetooth frequency f = 2.4 GHz, P_T= 1 mW, P_R=-80 dBm=10^{-8} mW
We have

$$P_R = P_T\left(\frac{c}{4\pi df}\right)^2$$

$$d = \frac{c}{4\pi f}\sqrt{P_T / P_R}$$

= 99.5 meter

3.7 Multipath Propagation

As wireless signals reflect from typical objects and surfaces around us, they can reach the receiver through multiple paths. Figure 3.4 illustrates the multipath phenomenon and explains its effect at the receiver. Here we have a cellular tower transmitting radio signals omnidirectionally. A mobile phone antenna is receiving not just one copy of the signal (the LoS), but another copy of the same signal that is reflected from a nearby high-rise building (NLoS). We make two observations:

- The LoS signal reaches the receiver first followed by the NLoS copy. This is due to th[illegible] of the NLoS signal compared to the LoS path.
- The sign[illegible] is higher compared to that of NLoS. This is because [illegible]vels further distance and hence attenuates more compare[illegible]

Figure 3.5 consi[illegible]LoS path. In reality, there are many NLoS paths due to many refl[illegible] multipath, there are also phase differences among the received signals copies due to the differences in their travelling time (different paths have different lengths). Such phase differences, however, are not shown in Figure 3.5 as it illustrates the signals only as simple impulses.

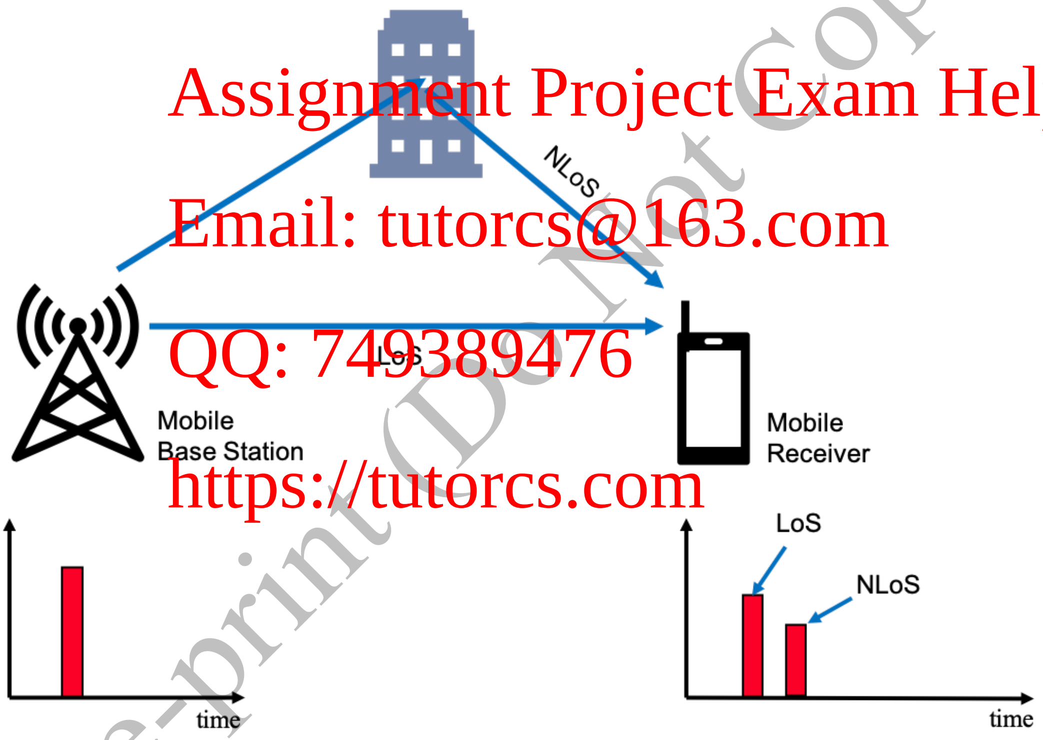


Figure 3.5 Effect of multipath

3.8 Inter-Symbol Interference

One problem with multipath is that the receiver continues to receive the signal well after the transmitter has finished transmitting the signal. This increases the time the receiver has to dedicate to decode one symbol or one bit, i.e., the symbol interval has to be longer than the ideal case when no NLoS paths exist. If we do not adjust the symbol interval adequately, then the signals from the previous symbol will enter into the next symbol interval and interfere with the new symbol. As a result, even if there were no other transmitters, the same transmitter would interfere with its *own* signal at the receiver. This phenomenon is called **inter-symbol interference**.

The process of inter-symbol interference is illustrated in Figure 3.6 with two short pulses, dark and light at the transmitter, which become much wider at the receiver due to multipath. We can see that the dark symbol, which was transmitted before the light, is interfering with the light symbol. To reduce this interference at the receiver, the transmitter has to use much wider symbol intervals. As a result of having to widen the bit intervals at the receiver, we have to reduce the data rate or bits per second as the data rate is inver[illegible]gth.

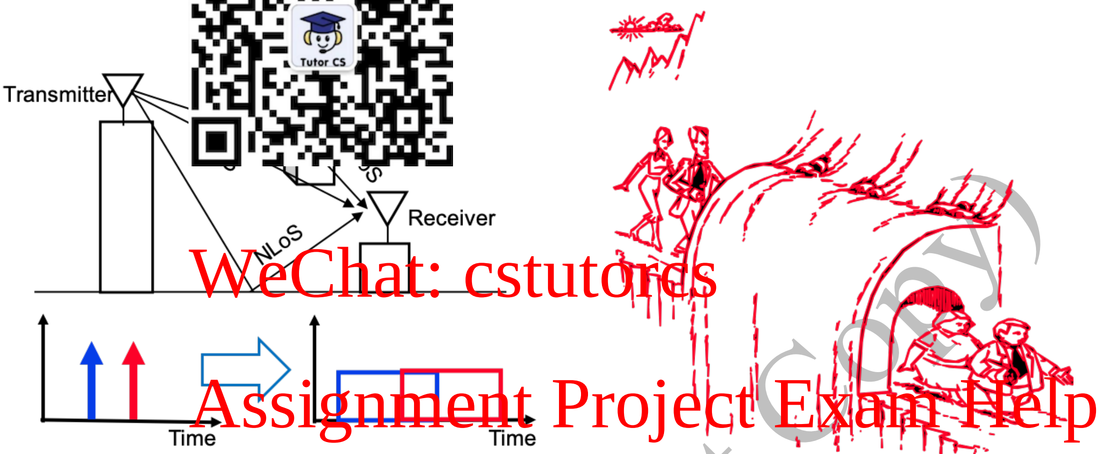


Figure 3.6 Inter-symbol interference

3.9 Delay Spread

Now let us examine the effect of multipath more closely. Recall that when a single pulse is transmitted, multiple pulses arrive at the receiver. As a result, the transmitter cannot transmit two pulses quickly one after the other. Otherwise the late arrivals will collide with the new transmission.

One good thing, however, is that the subsequent arrival of the signal copies are attenuated further and further. So we really do not have to wait too long, but just enough so the next arrivals are below some threshold power.

The time between the first and the last versions of the signal above the power threshold is called the *delay spread*. The concept of delay spread is illustrated in Figure 3.7. One thing to notice here is that the amplitude of the late arrivals can actually fluctuate, although they on average consistently diminish with time.

Figure 3.7 Multipath Propagation and Delay Spread

3.10 2-ray Propagation Model and d^{-4} Power Law

Earlier we learned that, in the absence of any multipath (no reflector), Frii's formula can be used to estimate the received power at the receiver where the power decreases as square of distance, which is the d^{-2} law. Later, significant measurements were done in real environments, which revealed that the attenuation follows a d^{-n} law where n is called the path loss exponent and varies from 1.5 to 5 [Munoz2009].

It was also found that the antenna heights significantly affect the received power when multipaths are present. Based on this observation, a new propagation law was derived, which is called the 2-ray model or d^{-4} Power Law, which is illustrated in Figure 3.8. This model, which considers 1 LoS and 1 reflection from the ground, considers a transmitter at height h_t and a receiver at height h_r separated by distance d. The received power is then described as:

$$P_R = P_T G_T G_R \left(\frac{h_t h_r}{d^2}\right)^2 \qquad (3.6)$$

And, the path loss in decibel,

$$pathloss\ (dB) = 40log_{10}(d) - 20log_{10}(h_t h_r) \qquad (3.7)$$

From Equation (3.7), we see that with the 2-ray model, the received power decays with distance (transmitter-receiver separation) at a rate of 40 dB/decade. It is interesting to note that the 2-ray model is independent of the frequency. However, the 2-ray pathloss of Equation (3.7) is valid only when the distance is greater than a threshold (cross-over distance), i.e., when $d \geq d_{break}$:

$$d_{break} = 4\left(\frac{h_t h_r}{\lambda}\right) = 4\left(\frac{h_t h_r f}{c}\right) \qquad (3.8)$$

The 2-ray model shows that the higher the base station antenna, the higher the received power a[illegible] on the ground. This explains why the radio base stations are mou[illegible] on the roof top, and so on.

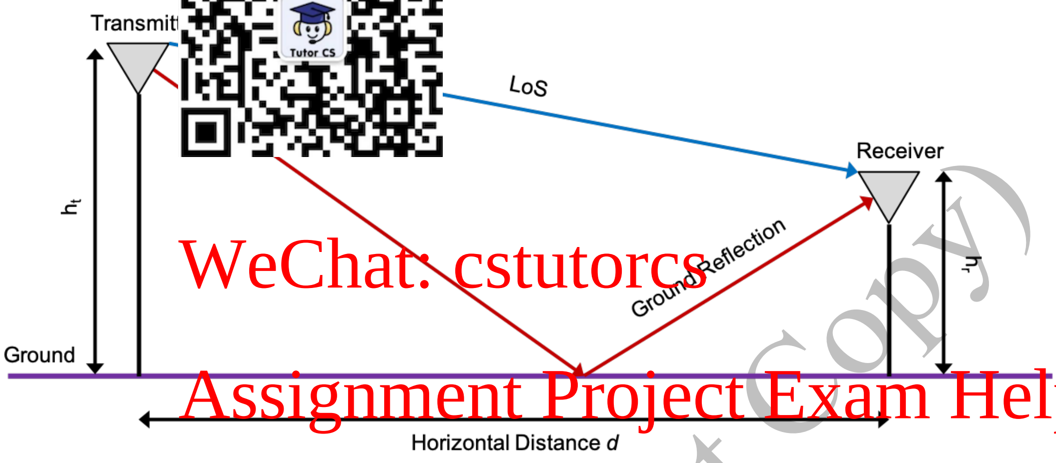


Figure 3.8 2-ray propagation model and d^{-4} power law

Example 3.5
A 2m tall user is holding his smartphone at half of his height while standing 800m from a 10m high base station. The base station is transmitting a 1.8GHz signal using a transmission power of 30dBm. What is the received power (in dBm) at the smartphone? Assume *unit gain* antennas.

Solution

We have h_t = 10m, h_r=*1m, d*=500m, f=1.8x10^9 Hz, P_T=30dBm, c=3x10^8 m/sec

$$d_{break} = 4\left(\frac{h_t h_r f}{c}\right) = 240m$$

This means that the 2-ray model can be applied to estimate the pathloss at 800m.

$$pathloss = 20log_{10}\left(\frac{d^2}{h_t h_r}\right) = 87.96\text{dB}$$

The received power = 30 – 87.96 = -57.96dBm (approx.)

3.11 Fading

One interesting aspect of multipath we discussed earlier is that the multipath signals can be either constructive or destructive. It depends on how the phase changes happen due to reflection. As Figure 3.9 shows, if the phases are aligned, multipath can increase the signal amplitude. On the other hand, the multipath can cancel out the signal if totally out of phase.

Sometimes by moving the receiver only a few centimetres can cause big differences in signal amplitude due to changes in multipath. This is called *small scale fading*.

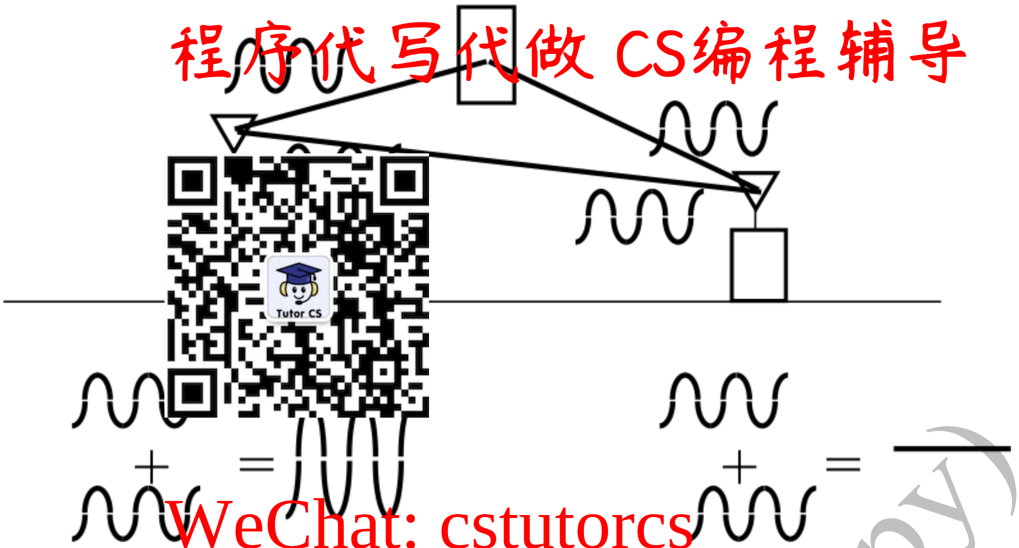


Figure 3.9 Small Scale Fading

3.12 Shadowing

If there is an object blocking the LoS, then the power received will be much lower due to the blockage. Figure 3.10 shows how the power suddenly decreased due to the shadowing effect when the received is moved.

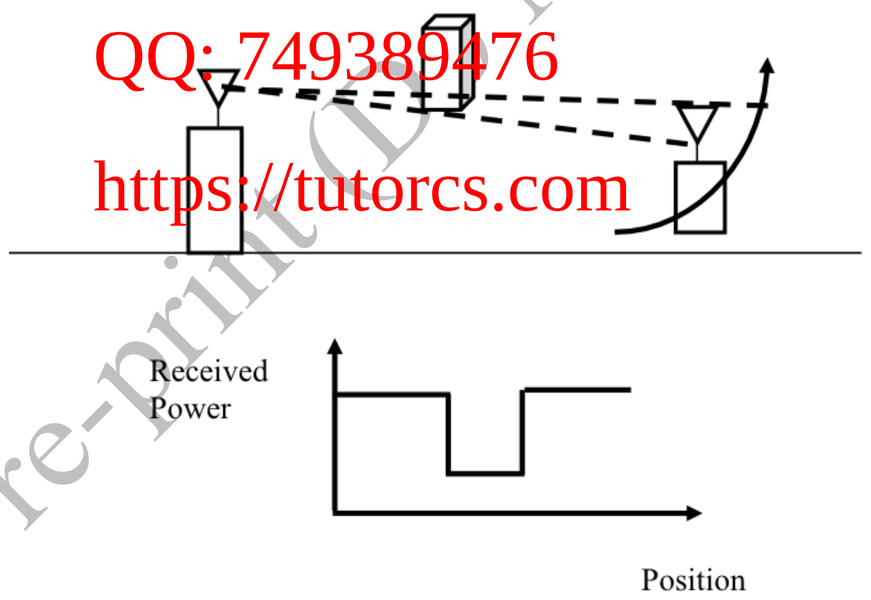


Figure 3.10 Shadowing

3.13 Total Path Loss

Now we see that there are many phenomena that affect the path loss. Multipath, shadowing, etc. all can cause path loss in some way. Figure 3.11 shows the total effect of all these phenomena on path loss. The y-axis shows the attenuation in dB and the x-axis the distance in log. If there is no multipath, shadow etc., then the path loss is a straight line. However, due to fading, actual path loss fluctuates, but does consistently decrease with increasing distance.

Figure 3.11 Total path loss

3.14 MIMO

Traditionally, single antennas were used for all types of wireless communications. In recent years, multiple antennas are increasingly being used to increase the quality, reliability, and capacity of wireless communication systems. Multiple Input Multiple Output (MIMO) is a framework used to describe such systems where 'multiple input' refers to multiple antennas at the transmitter while 'multiple output' refers to multiple antennas at the receiver. Under this framework, the transmitter or receiver could have single antennas, leading to four possible MIMO configurations as explained in Table 3.1.

Table 3.1 MIMO configurations

Configuration	Explanation
SISO	single input (1 Tx antenna) single output (1 Rx antenna)
SIMO	single input (1 Tx antenna) multiple output (>1 Rx antenna)
MISO	multiple input (>1 Tx antenna) single output (1 Rx antenna)
MIMO	multiple input (>1 Tx antenna) multiple output (>1 Rx antenna)

These configurations are typically enumerated using two numbers. For example, a 2x2 MIMO refers to a system with 2 Tx antennas and 2 Rx antennas while a 4x2 MIMO refers to 4 Tx antennas and 2 Rx antennas.

A fundamental benefit of MIMO comes from the fact that, if the antennas are spaced $\lambda/2$ or more apart, then the signals from different antennas can be uncorrelated creating multiple independent *spatial channels* over the same frequency as illustrated in Figure 3.12. These spatial channels can be exploited to either improve the reliability of the communication using a technique called *spatial diversity* or increase the data rate by exploiting *spatial multiplexing*. Finally, it is also possible to increase the coverage range and signal strength by exploiting multiple Tx antennas to focus the beam at a narrow angle, which is known as *beamforming*.

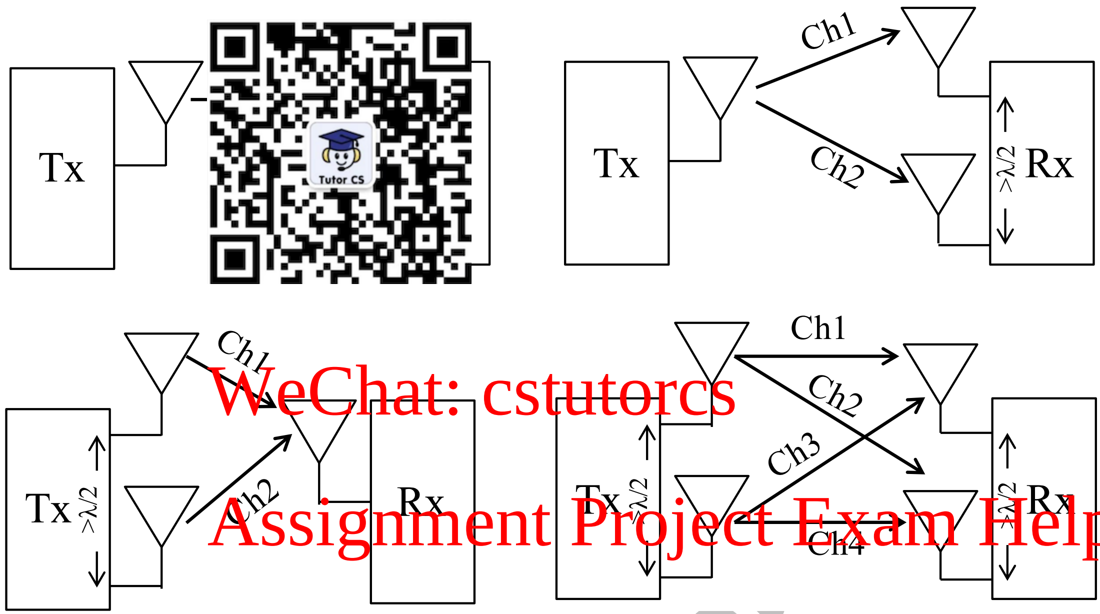


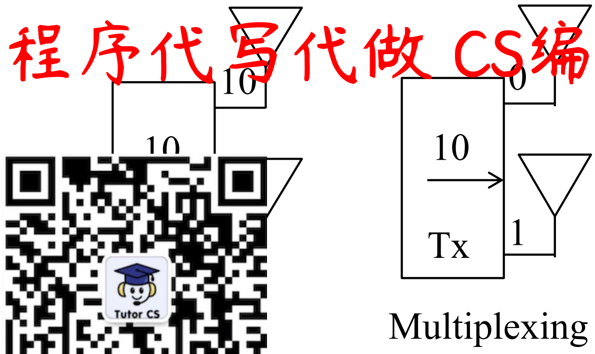
Figure 3.12 Examples of spatial channels.

3.14.1 Spatial Diversity

As we can see from Figure 3.12, there are a total of N_T x N_R independent spatial channels where N_T represents the number of transmit antennas and N_R the number of receive antennas. Spatial diversity refers to the technique that transmits every data bit over all of the N_T x N_R channels. Such redundant transmissions do not increase the data rate but improves the reliability of communication because the probability that all channels will experience severe fading simultaneously is low. The improved SNR at the receiver is called the *diversity gain*.

3.14.2 Spatial Multiplexing

The goal of spatial multiplexing is to send different bits in the data stream over different spatial channels to increase the effective data rate of the communication link. The difference between diversity and multiplexing is illustrated in Figure 3.13. The increase in data rate due to multiplexing is referred to as the *multiplexing gain*, which is limited by the degrees of freedom defined as the min(N_T,N_R).



Diversity vs. multiplexing

Example 3.6
What is the degrees of freedom for an 802.11ac WiFi system with the access point having 8 antennas and communicating to a laptop equipped with 2 antennas?

Solution: degrees of freedom = min(8,2) = 2

3.14.3 Beamforming

The idea of beamforming is to direct the wireless signal towards a specific receiver, thus creating a strong signal at the intended receiver but no or weak signal elsewhere. Figures 3.14 shows an example of beamforming used by a WiFi router to create strong beams towards intended receivers. Beamforming is also used by cellular towers to direct beams to specific houses or mobile users. The primary advantage of beamforming is to concentrate the transmit power in narrow beams instead of radiating it in all directions. This in turn improves the signal quality and eventually the data rate and reliability of the communication links between the transmitter and the intended receivers.

Single antenna transmitters cannot realize beamforming. To create beams, a transmitter would need to transmit the signal via multiple closely spaced antennas. A typical way to achieve beamforming is to exploit an array of antennas where each antenna sends the same signal at slightly different times (phase shifted) to create constructive signal combinations at the target receiver (within the beam) and destructive interference elsewhere (outside the beam). We have already seen examples of such constructive and destructive signal combinations in the context of small scale fading due to multipath reflections (Figure 3.8). For beamforming, however, only line-of-sight signals transmitted by multiple antennas located at the transmitter are involved.

In practical wireless communication systems, the beam needs to be steered dynamically as the location of the receiver changes either because a new receiver is targeted, or the target receiver has moved to a new location. Even for a fixed beam, changes in the wireless propagation environment requires adjustment in antenna phase shifts and amplitudes to maintain the beam properties. The phase shifts and amplitudes for all individual antennas of the antenna array will thus have to be recomputed continuously, which is computationally complex. Special digital signal processing (DSP) chips are used to achieve this, which however leads to increased cost and power consumption for beamforming systems. Fortunately, with advancements in DSP and low-power electronics, beamforming is becoming widely available in cons[illegible]ch as in WiFi routers.

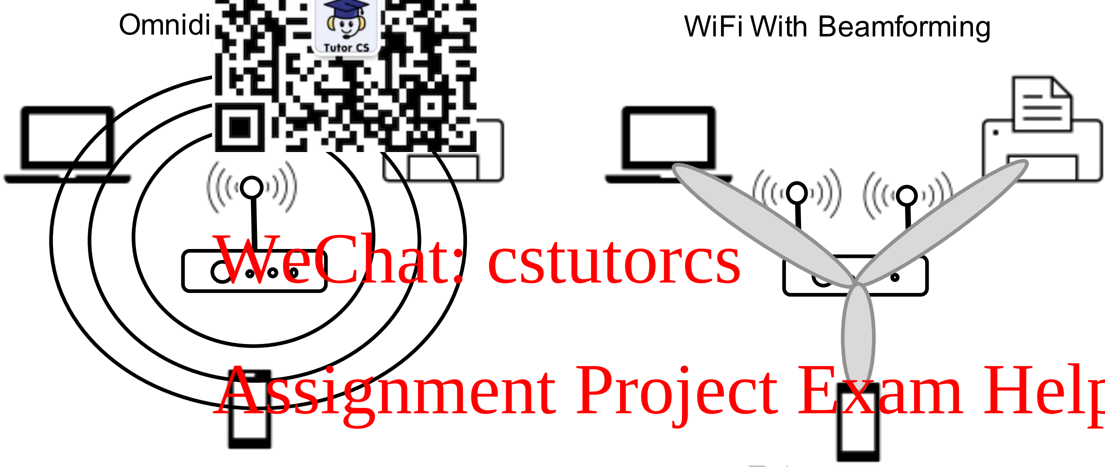


Figure 3.14 Beamforming with WiFi

3.15 OFDM

It turns out that instead of using a big fat pipe or a wide band/channel on its entirety for modulation and coding, it is much more effective to divide the band into many narrower orthogonal subbands/subcarriers or subchannels and then modulate each subchannel independently with a BPSK, QPSK, 16-QAM, 64-QAM etc. depending on the fading in the channel. The frequency selective modulation helps address the frequency selective fading experienced in typical environments, leading to many advantages such as better protection against frequency selective burst errors and narrowband interference which affect only a small fraction of subchannels. This process is called Orthogonal Frequency Division Multiplexing (OFDM). Figure 3.15 illustrates the OFDM process highlighting the fact that the symbol durations in OFDM get extended due to the lower data rates caused by narrower channels. Less inter-symbol interference due to longer symbols is therefore another added advantage of OFDM.

So how many subdivisions are good? The higher the number of subdivisions the better it can address the frequency selective fading and interference, but they have to be orthogonal to avoid inter-channel interference. Two channels are orthogonal if the peak power of a channel is at the bottom of the neighbouring channel as shown in Figure 3.16.

Due to its many benefits, both WiFi and cellular systems employ OFDM. Having many subcarriers allow OFDM to use some of them as *pilots* to help estimate the channel in real-time while data is being sent over the other subcarriers. For example, the basic 802.11a WiFi has a total of 64 OFDM subcarriers for each of its 20MHz channels where 4 of them are used as pilots. We will examine the details of WiFi OFDM in later chapters.

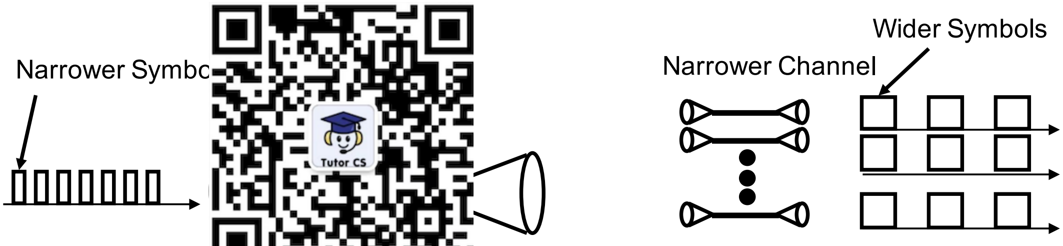


Figure 3.15 OFDM

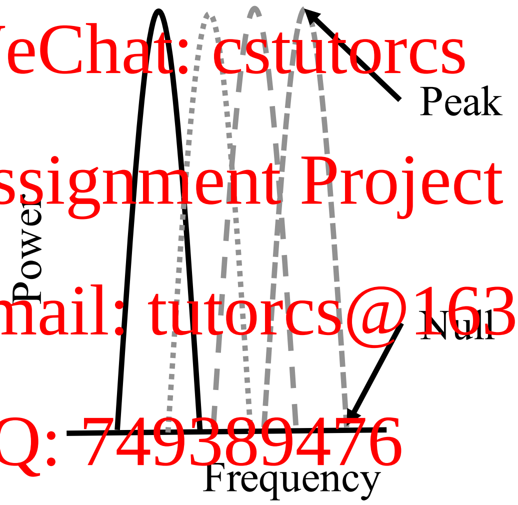


Figure 3.16 Orthogonal subcarriers in OFDM

Example 3.7 With a subcarrier spacing of 10kHz, how many subcarriers will be available in an OFDM system with 20MHz channel bandwidth?

Solution: #of subcarriers = channel bandwidth/subcarrier spacing = 20MHz/10kHz = 2000

3.16 OFDMA

OFDM, which is a multiplexing technology, can also be used as a multiple access technology. Orthogonal Frequency Division Multiple Access (OFDMA), is based on OFDM. Note that the 'M' in OFDM stands for *multiplexing*, but the 'M' in OFDMA stands for *multiple*.

In OFDM, the spectrum is divided into many subcarriers for multiplexing efficiency, such as longer symbol durations etc. Now we can do multiple access over OFDM by allocating different subsets of subcarriers to different users. We can even change the subcarrier subset over time to make more efficient allocation over time. Such dynamic allocation of subcarrier subsets of OFDM is called OFDMA.

Figure 3.17 illustrates the difference between OFDM and OFDMA. In OFDM, all subcarriers are given to the same user. Then using TDMA, OFDM subcarriers can be shared between different users, but that would be TDMA, not OFDMA. In OFDMA, we see a 2D sc[illegible], where different users are allocated a different 'block', i.e., a su[illegible]ver certain time slots. OFDMA has been used in cellular systems [illegible] currently being considered for the latest WiFi standard.

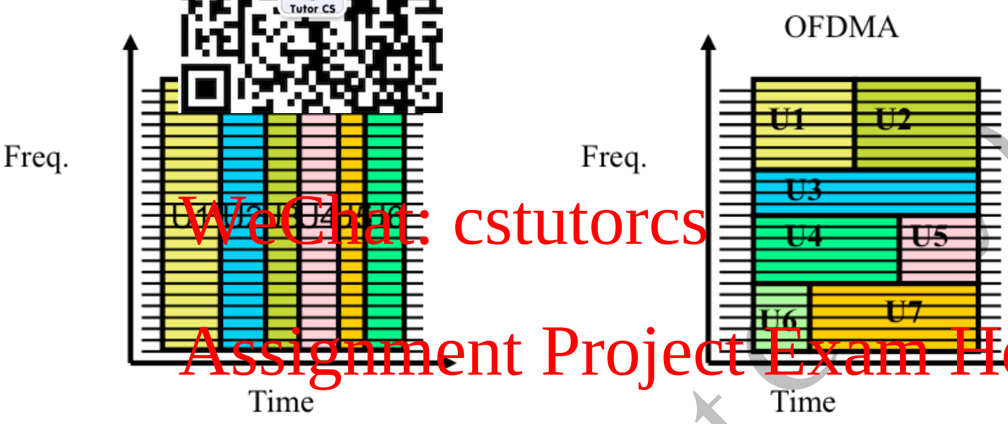


Figure 3.17 OFDM vs. OFDMA

3.17 Effect of Frequency

The choice of frequency has major impacts on wireless communications. Using a cartoon, Figure 3.18 illustrates the wavelength differences between low and high frequency communications. The other effects of frequency are discussed below:

- Higher Frequencies have higher attenuation, e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- Higher frequencies need smaller antennas. Note that antenna length has to be greater than half of the wavelength. For example, we need a 17cm antenna to transmit data over 900 MHz.
- Higher frequencies are affected more by weather. Higher than 10 GHz is affected by rainfall and 60 GHz affected by absorption of oxygen molecules
- Higher frequencies have more bandwidth and higher data rate
- Higher frequencies allow more spatial frequency reuse, because they attenuate close to cell boundaries. Low frequencies propagate far and wide, spills over the cell boundaries and create interference with other cells.
- Lower frequencies have longer reach
- Lower frequencies require larger antenna and antenna spacing. This means that realizing MIMO is very difficult particularly on mobile devices
- Lower frequencies mean smaller channel width, which in turn needs more aggressive MCS, e.g., 256-QAM to achieve good data rates.
- Doppler shift = vf/c = Velocity ×Frequency/(speed of light). This means that we have lower Doppler spread at lower frequencies. This allows supporting higher speed mobility more easily with lower frequencies.
- Mobility can be easily supported below 10 GHz, but becomes very difficult at higher frequencies

[illegible]8 Effects of frequency

3.18 Chapter Summary

1. An omnidirectional antenna radiates power in all directions, whereas a directional antenna focusses its power in a specific direction; isotropic antenna refers to a theoretical antenna that radiates *uniformly* in each direction in space, without reflections and losses.
2. In Frii's model, path loss increases at a power of 2 with distance as well as frequency
3. In 2-ray model, path loss increases at a power of 4 with distance but is not dependent on the frequency; it rather depends on the antenna heights
4. Fading = Changes in received signal power with changes in position or environment
5. Multipath effect can cause inter-symbol interference if symbol intervals are not adequately designed
6. Multiple antennas can help create multiple independent spatial channels over the same frequency.
7. An array of omnidirectional antennas can help realize directional transmissions by creating the so-called beams.
8. OFDM is a multiplexing technique which splits a wide channel into many narrow orthogonal subcarriers, where each subcarrier is modulated independently.
9. OFDMA is a multiple access technology which shares blocks of OFDM subcarriers between users dynamically over time.

References

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End of Chapter 3