

Chapter 3

Wireless Signal Propagation

In the previous chapter, we learned how the bits are transmitted to the wireless channel. In this chapter we are going 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 those electrical signals into radio waves that the same antenna can use the same antenna for both transmitting

and the receiver. It is important to note that a device

Depending on how the antennas radiate or receive, there are three types of antennas as illustrated in Figure 3.1. An **omni-directional** antenna radiates power from it in all directions (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.



Figure 3.1 Different types of antennas

Example 3.1

How much stronger a 17 dBi antenna 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

$$17 = 10 \log_{10}(P/P_{\text{iso}})$$

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

Antennas are designed to be as small as possible. For example, antennas used in mobile phones are small. To receive TV signals, the antenna length must be half the wavelength so electrons on the antenna can move back and forth in one cycle. Small consumer devices, such as mobile phones, have antennas within the device, but the fundamental relationship between frequency and wavelength 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 omnidirectional. 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.

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Now let us try to understand reflection on wireless communication. Reflection happens when the size of the object is large relative to the wavelength of the signal. When the reflected signal has a phase shift, it may have a phase shift. Depending on the phase shift, the reflected signal may 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 or estimate the signal that may be received at a given location given certain transmissions. This is called channel modeling.

Figure 3.3 shows that there is a transmitter mounted on a tower to transmit signals to subscriber devices, which may be located at anywhere around the tower. Power profile of the received signal at the subscriber station can be obtained by *convolving* the power profile of the transmitted 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.,

$$y(f) = H(f) \cdot x(f) + n(f) \quad (3.1)$$

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 .

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Figure 3.3 Chann

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:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2 = P_T G_T G_R \left(\frac{c}{4\pi f d} \right)^2 \quad (3.2)$$

Where P_R and P_T are the received and transmitted powers (in Watts), respectively, while G_T and G_R are transmitter and receiver antenna gains in linear scale, respectively. We see that, for a given 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.

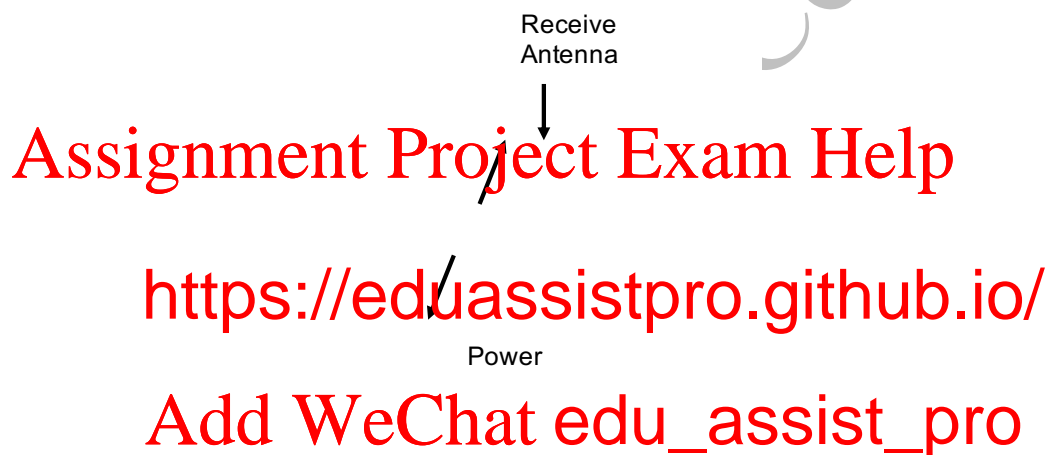


Figure 3.4 Power spreading in space and received power calculation for Frii's Law

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:

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

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:

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

For isotropic antennas (G_T^{dB} and G_R^{dB} are both 0 dB), path loss is reduced to the following simple formula:

$$\begin{aligned} Pathloss(dB) &= -10 \log_{10} \left(\frac{\lambda}{4\pi d} \right)^2 = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) = 20 \log_{10} \left(\frac{4\pi f d}{c} \right) \\ &= 20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10} \left(\frac{4\pi}{c} \right) \\ &= 20 \log_{10}(d) + 20 \log_{10}(f) - 147.55 \end{aligned} \quad (3.5)$$

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 Fig. The power density decreases with increasing distance from the source. In space in all directions equal where decreases with increasing sphere, we have a power density of $P_T/4\pi d^2$. Therefore, the total power density at the antenna located at the sphere surface becomes equal to the power density. We have learned that antenna size is dependent on the frequency. Given that the ideal antenna has an area of $\lambda^2/4$ and 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 $d = 100$ m, $f = 900 \times 10^6$ Hz, $P_T = 50$ W, $c = 3 \times 10^8$ 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 gain means: $G_T=G_R=0\text{dBm}$.

We have $d=10\text{m}$, $f=2.4\times 10^9\text{ Hz}$, $P_T=100\text{mW}=20\text{dBm}$, $c=3\times 10^8\text{ m/sec}$, and $\pi = 3.14$

$$\text{Pathloss} = 20\log_{10}\left(\frac{4\pi fd}{c}\right) \text{ dB} = 60 \text{ dB}$$

$$P_R = P_T - \text{pathloss} = 20 - 60 = -40\text{dBm}$$

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 is able to achieve a minimum RSS of -80 dBm.

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Example 3.4

increase the coverage with low transmit power. 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 $f = 2.4\text{ GHz}$, $P_T = 1\text{ mW}$, $P_R = -80\text{ dBm} = 10^{-8}\text{ mW}$

We have

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

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

$$= 99.5\text{ meter}$$

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 the longer path length of the NLoS signal compared to the LoS path.
- The signal strength for LoS is higher compared to that of NLoS. This is because the NLoS signal travels further distance and hence attenuates more compared to the LoS.

Figure 3.5 considers only a single NLoS path. In reality, there are many NLoS paths due to many reflecting surfaces. For 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.

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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 inverse of the symbol length.

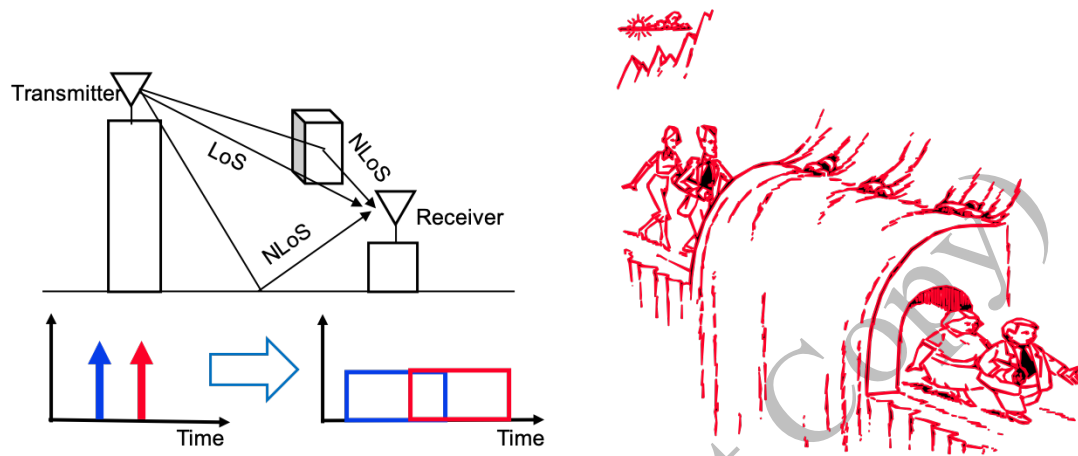


Figure 3.6 Inter-symbol interference

3.9 Delay Spread Assignment Project Exam Help

Now let us examine what happens when a single pulse is transmitted. When a single pulse is transmitted, the transmitter cannot transmit again until the previous pulse has arrived. If the late arrivals will collide with the new transmission.

One good thing, however, is that the subsequent arrivals are attenuated further and further. So we really do not have to worry about them. They are just not 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.



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

And, the path loss in decibel,

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

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 $d \geq d_{break}$:

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

The 2-ray model shows that the higher the base station antenna, the higher the received power at the mobile device on the ground. This explains why the radio base stations are mounted on high towers, on the roof top, and so on.

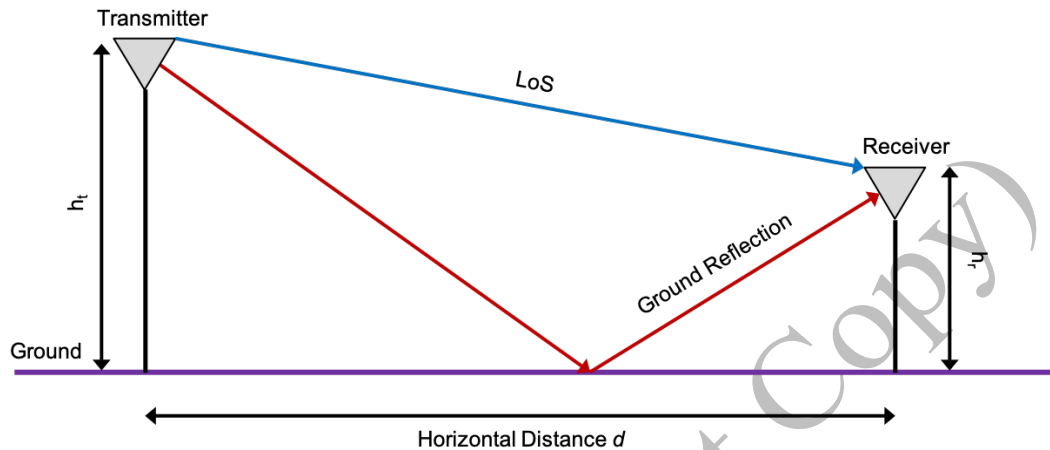


Figure 3.8 2-ray propagation model and d^{-4} power law

Example 3.5

A 2m tall user is from a 10m high transmission point smartphone? Assume *unit gain* antennas.

hile standing 800m GHz signal using a

Solution

We have $h_t = 10\text{m}$, $h_r = 2\text{m}$, $d = 800\text{m}$, $f = 1.8 \times 10^9$

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

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

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

The received power = $30 - 87.96 = -57.96\text{dBm}$ (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*.

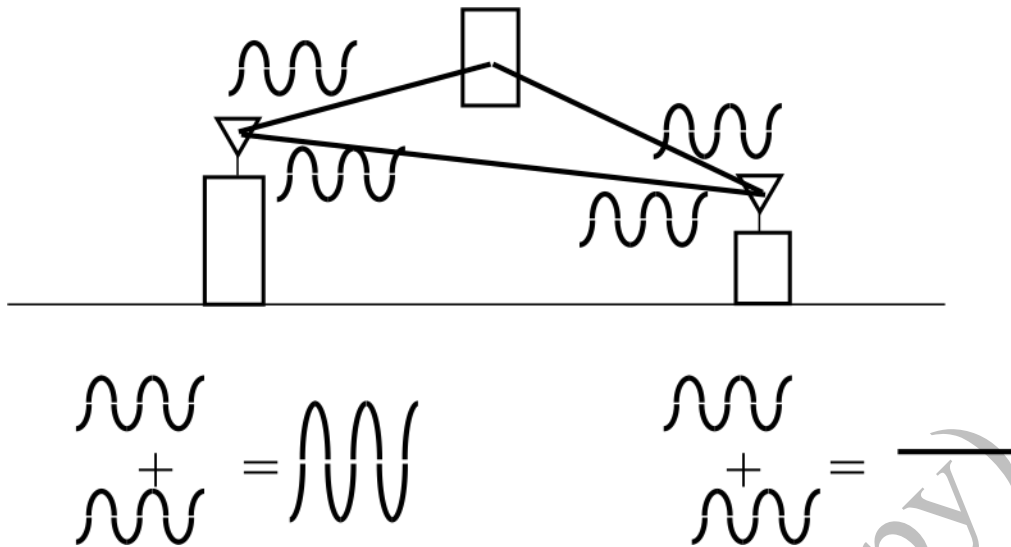


Figure 3.9 Small Scale Fading

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 receiver is moved.

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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.

the coverage range and signal strength by exploiting multiple Tx antennas to focus the beam at a narrow angle, which is known as *beamforming*.

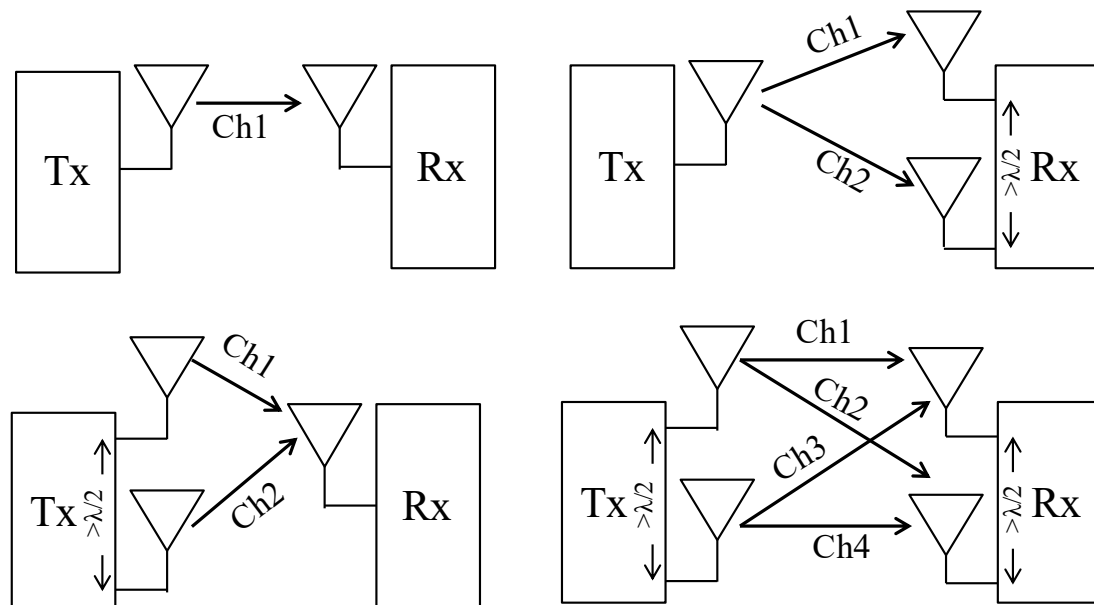


Figure 3.12 Examples of spatial channels.

3.14.1 Spatial

As we can see from the examples, independent spatial channels where N_T represents the number of transmit antennas and N_R represents the number of receive antennas. Spatial diversity refers to the technique of sending multiple copies of the same data over all of the $N_T \times N_R$ channels. Such redundancy increases 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 $\min(N_T, N_R)$.

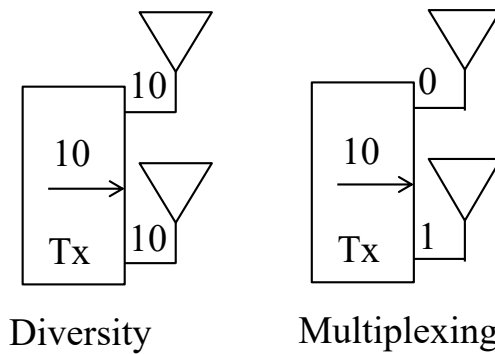


Figure 3.13 Diversity vs. multiplexing

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 create a strong beam towards intended receivers. Beamforming towers to direct beams to specific houses or in beamforming is to concentrate the transmit power in a specific direction. 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

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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 consumer electronics, such as in WiFi routers.

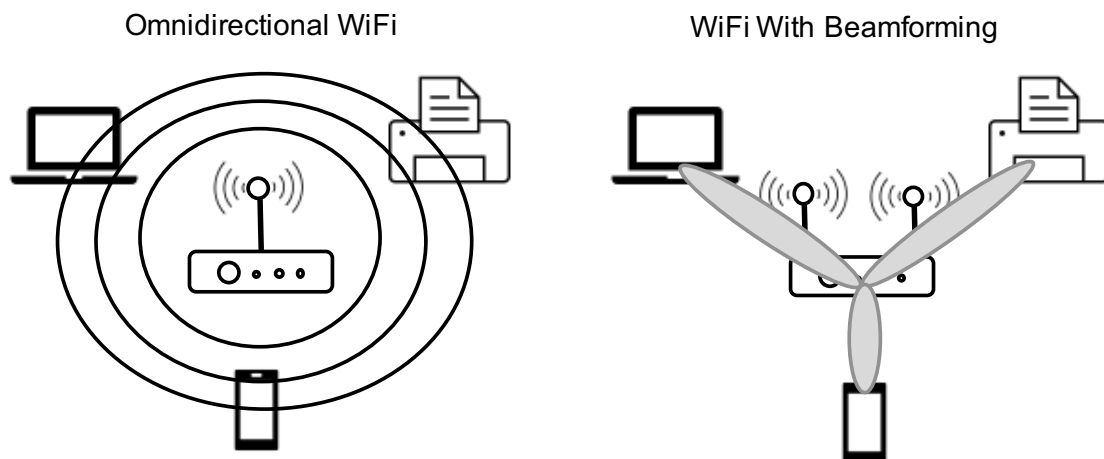


Figure 3.14 Beamforming with WiFi

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 efficient to divide it into many narrower orthogonal subbands/subcarriers of equal bandwidth. Each subchannel is modulated independently with a BPSK, QPSK, 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.

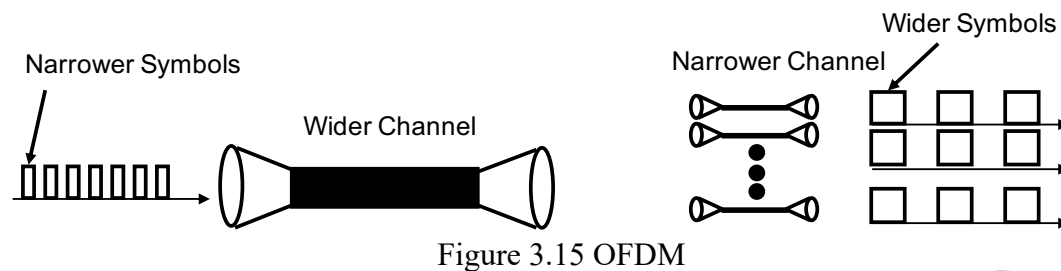


Figure 3.15 OFDM

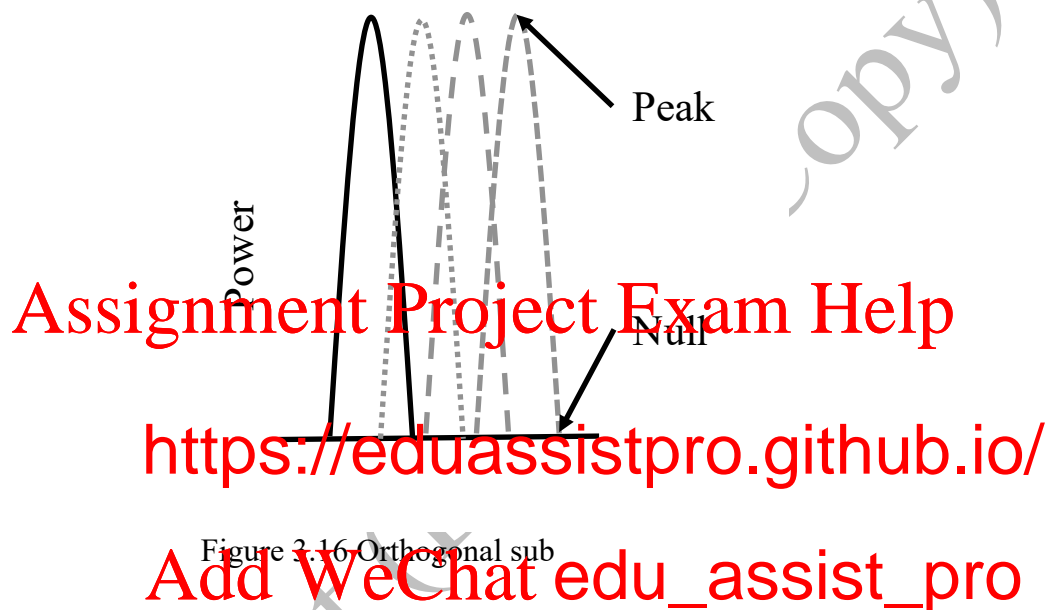


Figure 3.16 Orthogonal sub

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.

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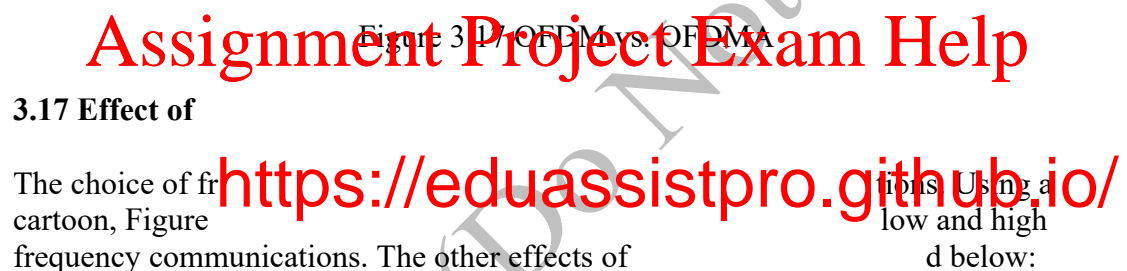
Figure 3.17 OFDM vs. OFDMA

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Figure 3.17 OFDM vs. OFDMA

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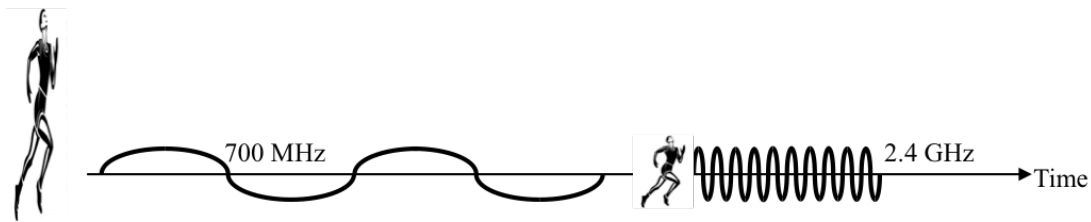


Figure 3.18 Effects of frequency

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
7. An array of antennas can realize directional transmission
8. OFDM is a multiplexing technique which splits a wide channel into many narrow orthogonal subcarriers, where each is modulated independently.
9. OFDMA is a multiple access technology that dynamically allocates OFDM subcarriers between users dynamically over time.

References

- [BTBLOG] Bluetooth Special Interest Group Blog. <https://www.bluetooth.com/blog/>. Accessed 18 October 2021.
- [Munoz2009] David Munoz, Frantz Bouchereau, Cesar Vargas, Rogerio Enriquez, "Position Location Techniques and Applications," Academic Press, 2009.

End of Chapter 3
