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 travel 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. Specifically, we need to be aware of the following issues:

- Path loss: Depends upon distance and frequency
- Noise
- Shadowing: Obstructions
- Frequency Dispersion (Doppler Spread) due to motion
- Interference
- Multipath: Multiple reflected waves
- Inter-symbol interference (ISI) due to dispersion

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 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.

Figure 3.1 Different types of antennas

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.

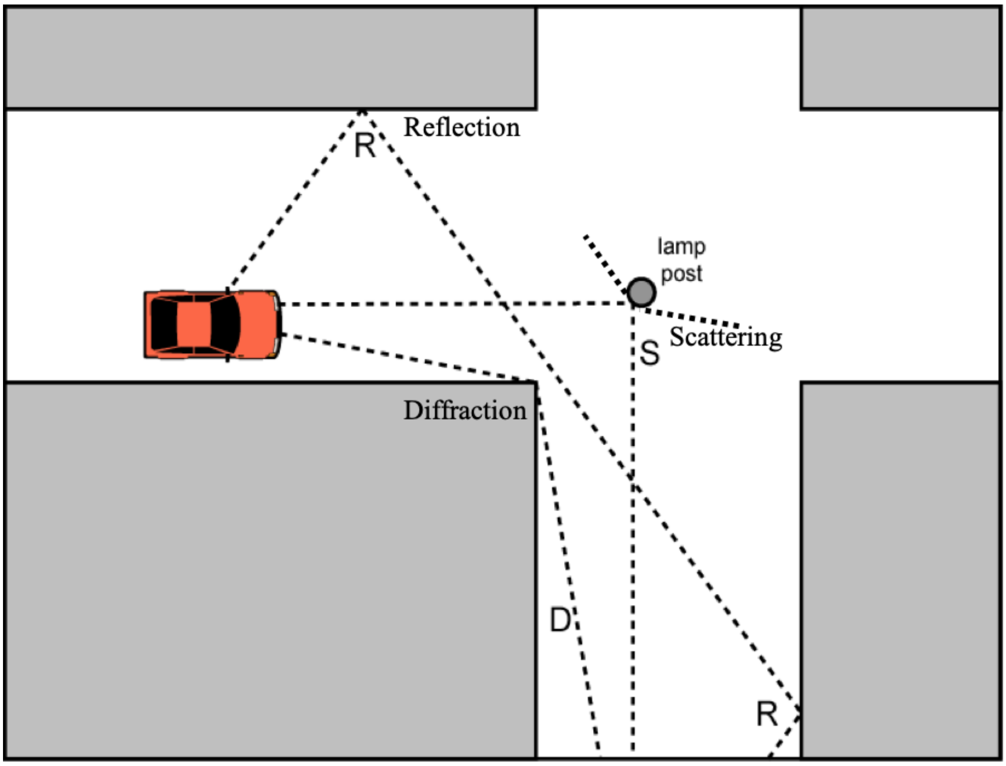


Figure 3.2 Reflection, Diffraction, and Scattering

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 implementable 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 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.,*

$$y(f) = H(f).x(f) + n(f) \tag{3.1}$$

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*.

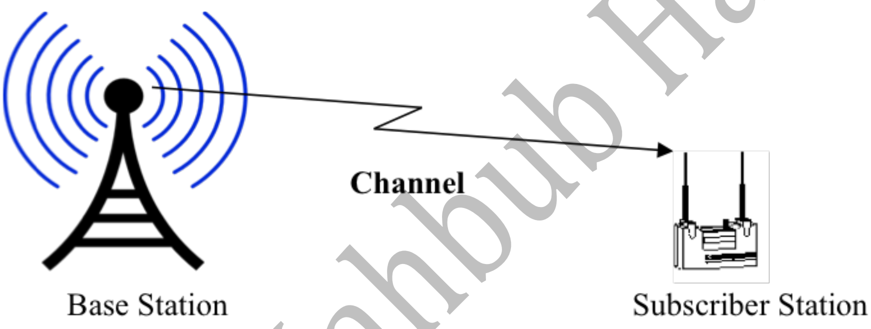


Figure 3.3 Channel model

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. 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:

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

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.

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:

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

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

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

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.

3.6 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 3.4 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 3.4 as it illustrates the signals only as simple impulses.

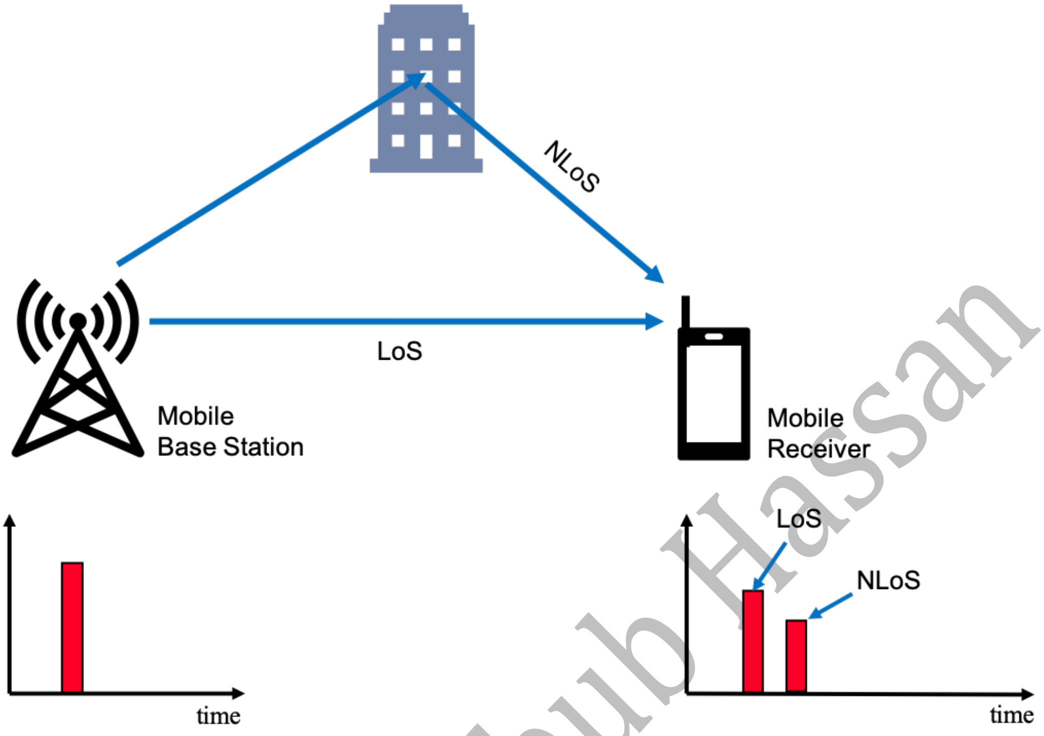


Figure 3.4 Effect of multipath

3.7 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 with two short pulses, blue and red at the transmitter, which become much wider at the receiver due to multipath. We can see that the blue symbol, which was transmitted before the red, is interfering with the red 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 the inverse of the symbol length.

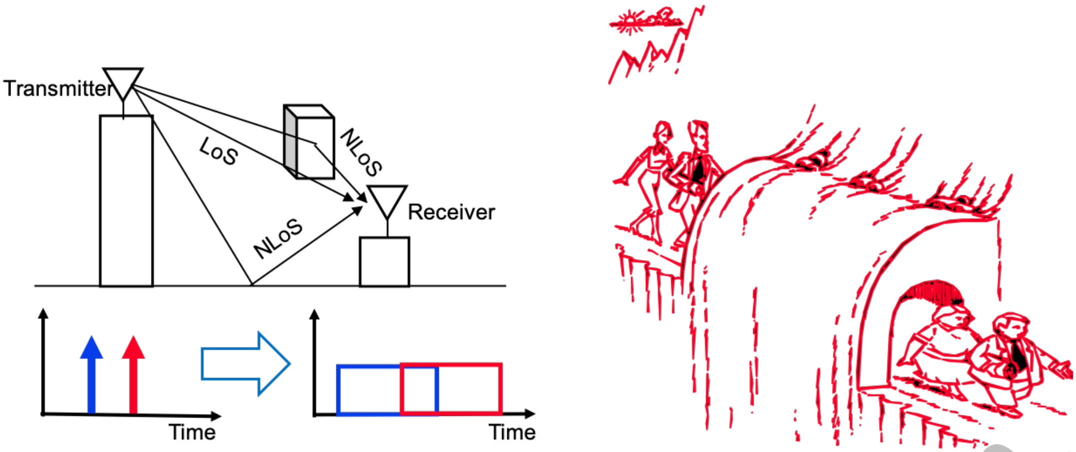


Figure 3.5 Inter-symbol interference

3.8 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 3.6. One thing to notice here is that the amplitude of the late arrivals can actually fluctuate, although they on average consistently diminish with time.

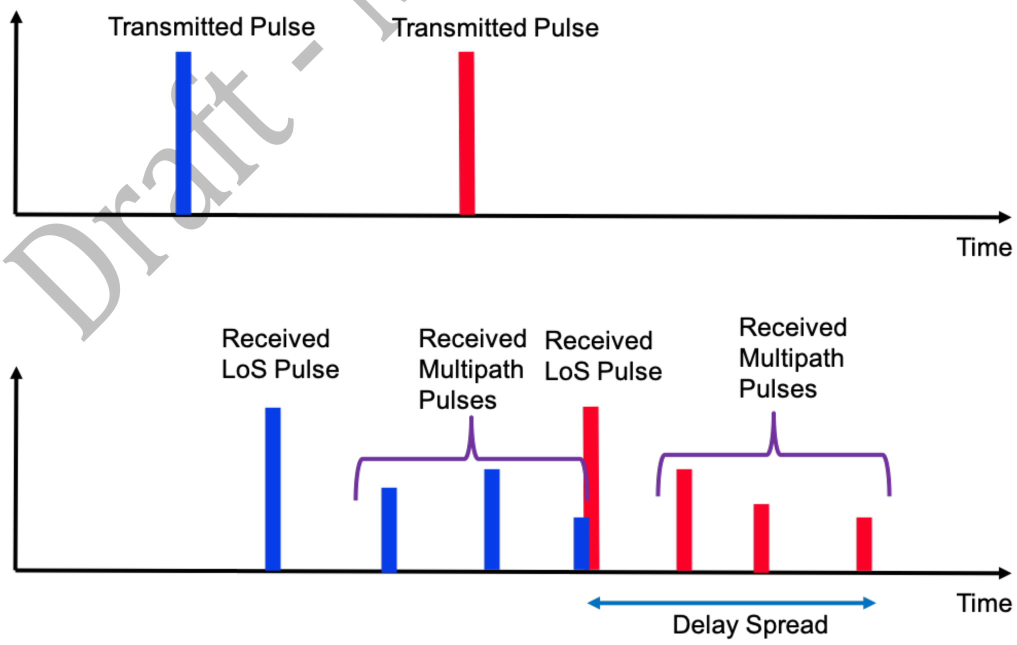


Figure 3.6 Multipath Propagation and Delay Spread

3.9 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 5.5 with a typical value of 4.

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 3.7. 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, 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 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.

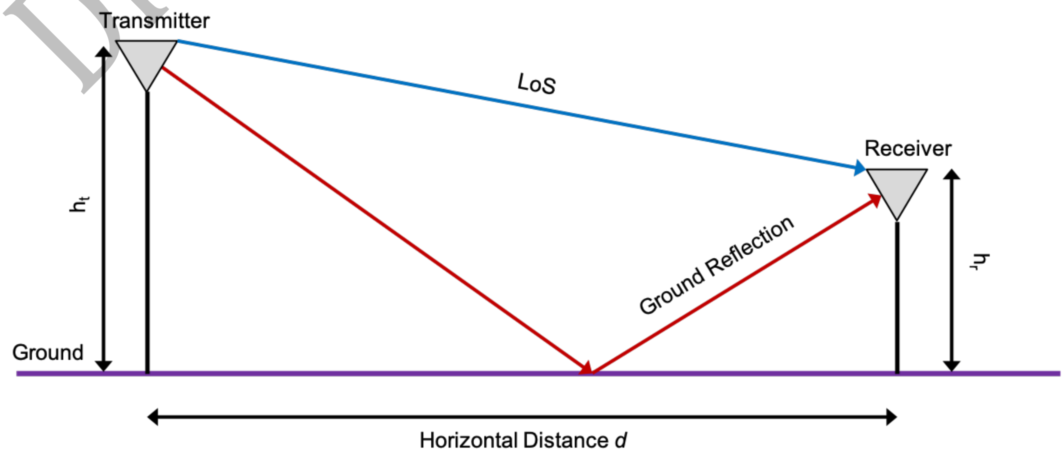


Figure 3.7 2-ray propagation model and d^{-4} power law

3.10 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 phse changes happen due to reflection. As Figure 3.8 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 slight only a few centimeter can cause big differences in signal amplitude die to changes in multipath. This is called *small scale fading*.

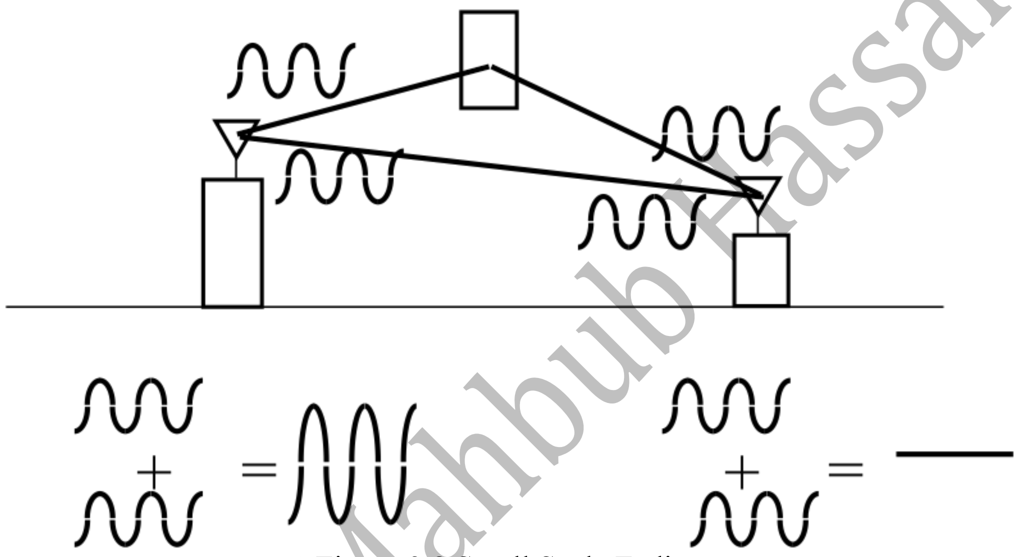


Figure 3.8 Small Scale Fading

3.11 Shadowing

If there is an object blocking the LoS, then the power received will be much lower due to the blockage. Figure 3.9 shows how the power suddenly decreased due to to the shadowing effect when the received is moved.

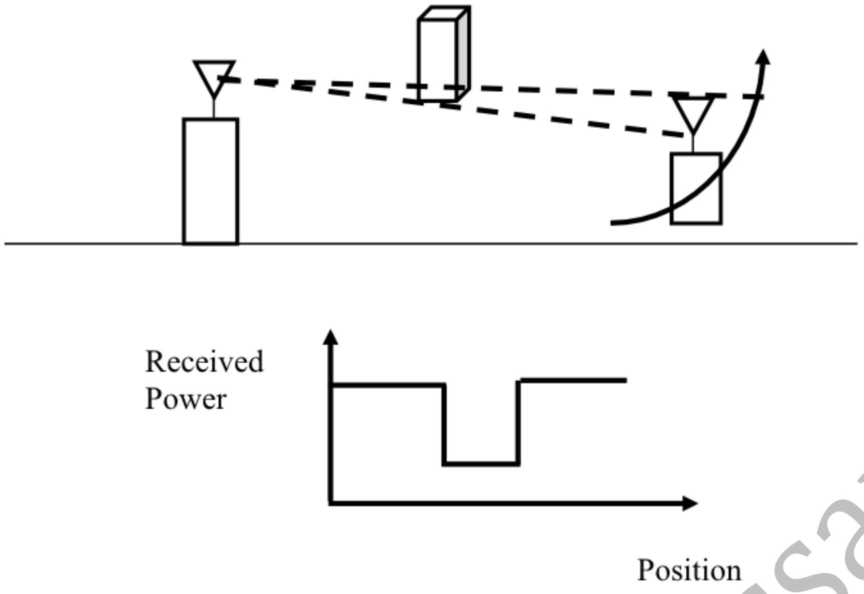


Figure 3.9 Shadowing

3.12 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 3.10 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 do consistently decrease with increasing distance.

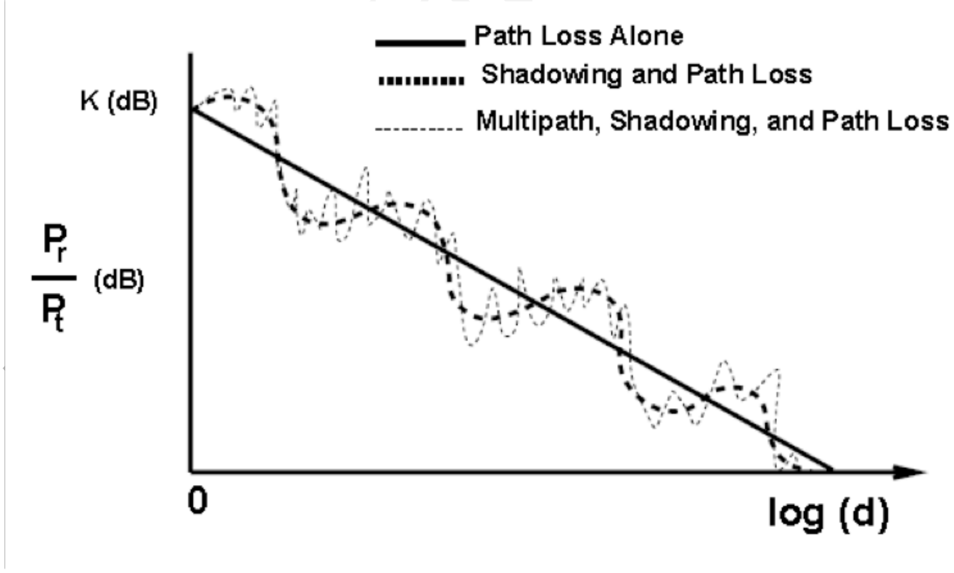


Figure 3.10 Total path loss

3.14 Multi-Antenna Systems

In the past, we had only single antennas on a wireless product. These days, many wireless systems are fitted with multiple antennas? What are the benefits of having multiple antennas?

Having multiple antennas provide diversity for wireless signals. These diversities can be exploited to control the focus of a transmitter to a particular direction (beamforming) and increase the data rate by combining the signals from multiple antennas (MIMO).

3.15 Receiver Diversity

Diversity due to multiple antenna has different meaning for the transmitter and the receiver. Let is first understand the reciver diversity.

Figure 3.12 shows a receiver fitted with M antennas. So the receiver is receiving M different signaling coming from M antennas. How can it take advantage from these M signals?

There many different ways the receiver can benefit from the multiple antennas. Here we discuss three different options that are often used:
Selection combining: Receiver compares the SNR of all M signals and selects the antenna with the highest SNR. It does that each time it receives the signal, so the actual antennas used changes over time.

Threshold combining: Instead of comparing all antenna outputs, it checks them one by one and selects the first antenna with SNR above a threshold.

Maximal Ratio Combining: It turns out that the receiver can process the output signal to adjust the phase. The phase is adjusted so that all signals have the same phase. Then weighted sum is used to maximize SNR

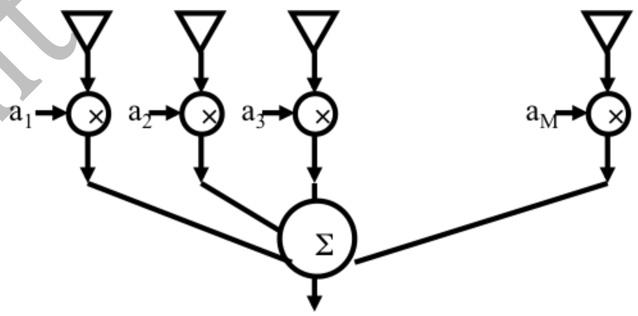


Figure 3.12 Receiver diversity with multiple antennas

3.16 Transmitter Diversity

Now let is examine the antenna diversity at the transmitter.

Note that transmitters usually have more space and more expensive equipment, so they can afford more antennas and sophisticated algorithms. For example, cellular towers and wifi routers can put more antennas. So even if the receiving equipment cannot afford to have many antennas die to space and cost of the equipment, the wireless communication benefit.

Figure 3.13 shows that a transmitter is transmitting the same signal using M different antennas. It also continuously estimates the channel. If it has a good channel estimation, then it can phase each component and weight it before transmission so that they all arrive *in phase* at the receiver and maximize SNR.
If, on the other hand, the channel is not known, the transmitter can still benefit from having multiple antennas by using a special type of coding called *space time block codes.*

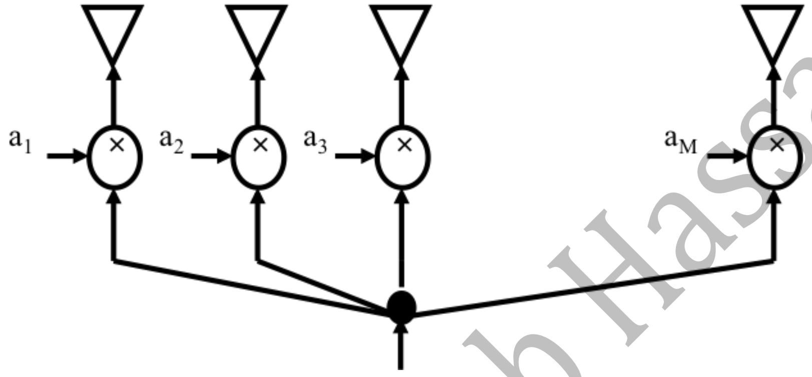


Figure 3.13 Transmitter diversity with multiple antennas

3.17 Beam Forming

The idea of beamforming is to make the signal directional to increase the reception power and quality at a single point. Figure 3.14 shows that the tower can form the beam dynamically so the signal is pointed to each house at different time. Beamforming is also applicable to a receiver. Figure 3.15 shows that the receiver can somehow adjust its anetnna (ear in this case) to focus its receotion to aparticular direction.

The beamforming can be done with multiple Phased Antenna Arrays. By phase-shifting various antenna signals the transmitter can focus on a narrow directional beam. Digital Signal Processing (DSP) is used for signal processing.

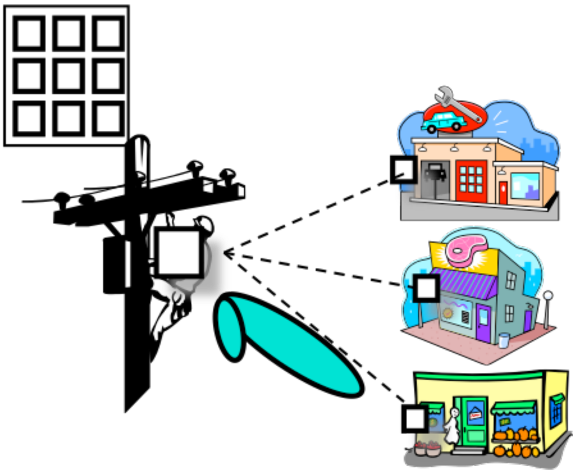


Figure 3.14 Transmitter diversity with multiple antennas

Figure 3.15 Transmitter diversity with multiple antennas

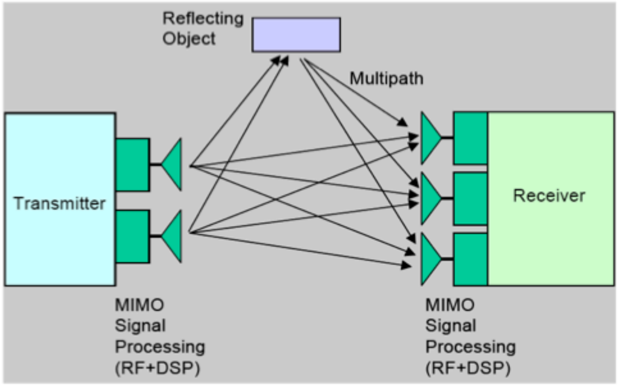
3.18 MIMO

Now we know that having multiple antennas at the transmitter and the receiver helps. Another way to refer to such systems is Multiple Input and Multiple Output (MIMO). Here the 'input' refers to the antennas at the receiver and 'output' refers to the transmitter antennas. So if the transmitter has 2 antennas and the receiver has 3, then it is called a 2x3 MIMO, as shown in Figure 3.16.

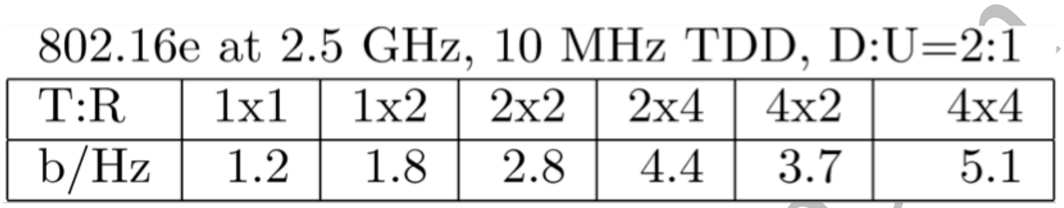
The reason that MIMO improves performance is because of the diversity we have discussed. How much performance can be improved with MIMO?

The performance is measured in bps/Hz. Theoretical, under perfect diversity, it is possible to achieve a linear increase in capacity. For example, if b bps/Hz is achieved with 1x1 system, i.e. if both transmitter and the receiver have 1 antenna each, the with a 2x2 MIMO, we can expect to achieve 4b bps, or with a 2x3 MIMO as shown in Figure 3.16, we should get a 6x performance increase from the single antenna system.

In practice, however, the maximum cannot be achieved. Nevertheless , improvements are always expected with higher orders of MIMO. Figure 3.16 shows some MIMO gains from practical experiments in Wimax (802.16e) system.



2x3



802.16e at 2.5 GHz, 10 MHz TDD, D:U=2:1

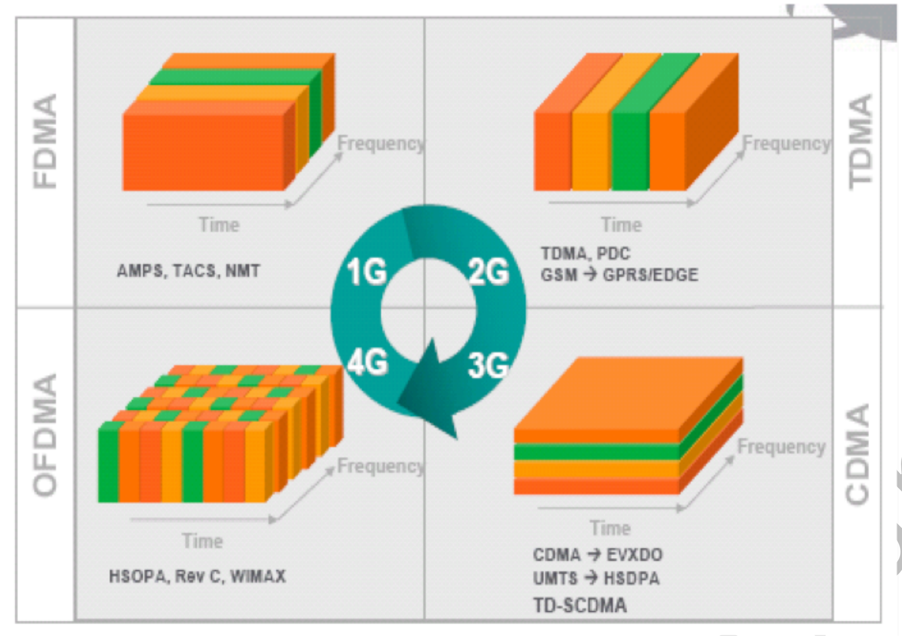
T:R	1x1	1x2	2x2	2x4	4x2	4x4
b/Hz	1.2	1.8	2.8	4.4	3.7	5.1

Figure 3.16 MIMO

3.19 Multiple Access Methods

Wireless providers or equipment have to share a limited allocated band for the service. For example, all WiFi equipment will have to share the 2.4 GHz band if they are working in that band. If there are many equipment within the interfering zone, how can they share the band?

Different multiple access methods have been used over the generations to address this problem. Figure 3.17 shows the use of different multiple access technologies used over the four generations of the telecommunications networks.
At first, in the first generation, frequency division multiple access (FDMA) was used to separate different users. Each user was allocated a different frequency, so they could not interference with each other. In 2G, it was time division multiple access (TDMA), where the users were separated in time. In the 3G, CDMA was used, where all users could share the same frequency and time, but use different codes. Now, in 4G, we are using a new method called Orthogonal Frequency Division Multiple Access (OFDMA), which allocates a time slot *and* a frequency to each user.



Source: Nortel

Figure 3.17 Multiple access methods in 4 generations

3.20 OFDM

OFDMA is based on Orthogonal Frequency Division Multiplexing (OFDM), which is a multiplexing technology. Let us have a look at the basic principles of OFDM and why it is increasingly being adopted in more and more systems.

It turns out that instead of using a big fat pipe or a large band on its entirely for modulation and coding, it is much more efficient to divide the band into many smaller sub-band or channels and then modulate each channel separately. This is illustrated in Figure 3.18. The multiplexing is then needed to put the data streams into all these channels at one end and then retrieve them from the individual channel at the other end.

So many how many subdivisions are good? Again, it turns out that higher the number of subdivisions the better, but they have to be orthogonal. Two channels are orthogonal if the peak power of channel is at the bottom of the other channel, i.e., the interference is minimized. This is shown in Figure 3.19 with different colors for different channel. We can see, for example, that the peak for black is at the bottom of red and the peak of red is at the bottom of black and blue, and so on.

At present, it is possible to divide a band into 256 or more channels.

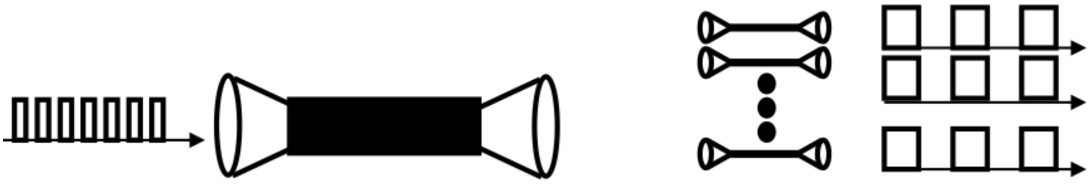


Figure 3.18 OFDM

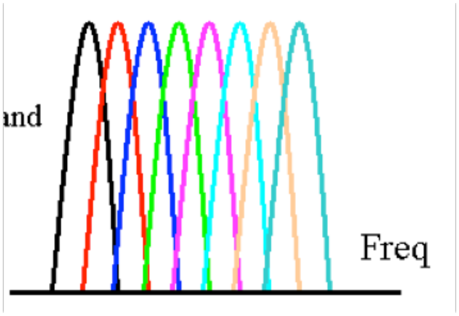


Figure 3.19 Orthogonal subcarriers in OFDM

3.21 Advantages of OFDM

We have just learned that OFDM is more efficient than using the whole band as a whole. Now let us see what are some of the benefits of OFDM and why it provides better efficiency.

First of all, it is easy to implement using FFT/IFFT. The computational complexity of OFDM is only O(B log BT) compared to previous O(B^2T) for Equalization, were B is the bandwidth and T is the delay spread.

OFDM provides graceful degradation if there is excess delay [needs better explanation]

OFDM is robust against frequency selective burst errors, because the data is modulated over many different orthogonal frequencies. For the same reason, it is also robust against narrowband interference.

OFDM allows adaptive modulation and coding of each individual channel or subcarriers (subbands).

Finally, OFDM allows pilot subcarriers for channel estimation. [needs better explanation]

3.22 OFDM: Design Considerations

The larger the number of subcarriers the better. This is because with larger number of subcarriers, the data rate per carrier is smaller, which means the symbol durations are larger. Larger symbol durations reduces *inter-symbol interference*. For example, we can see in Figure 3.20 that there is only 0.1 us for each symbol when 10 Mbps data rate is concerned, whereas the symbol duration can be extended by a factor of 10 for a 1 Mbps data rate.

One may wonder whether it becomes infeasible to computationally manage very large number of subcarriers. Fortunately, it easily implemented as Inverse Discrete Fourier Transform (IDFT) of data symbol block. Fast Fourier Transform (FFT) is a computationally efficient way of computing DFT, and there are DSP chips that can do these computations for us. So, having many subcarriers is not an issue.

Is there any disadvantage in increasing the number of subcarriers infinitely? There is. Note that, with larger number of subcarriers, the spacing between subcarriers are also reduced. This means that the power in one subcarrier can spill to the next which would increase *inter-carrier* interference. Also due to Doppler spread in mobile applications, carriers can actually shift a little bit. Such shift will bring one carrier inside the other increasing inter-carrier interference.

Figure 3.20 Relationship between data rate and symbol duration

3.23 OFDMA

OFDM, which is a multiplexing technology, can also be used as a multiple access technology. OFDMA, which stands for Orthogonal Frequency Division *Multiple Access*, 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 3.21 illustrates the difference between OFDM and OFDMA. In OFDM, all subcarriers given to the same user. Then using TDMA, OFDM subcarriers can be shared between different users, but that would be TDMA, not OFDMA. In the OFDMA, we see a 2D scheduling, where different users get a different 'block' allocations, where a block is defined by a subset of subcarriers over certain time slots.

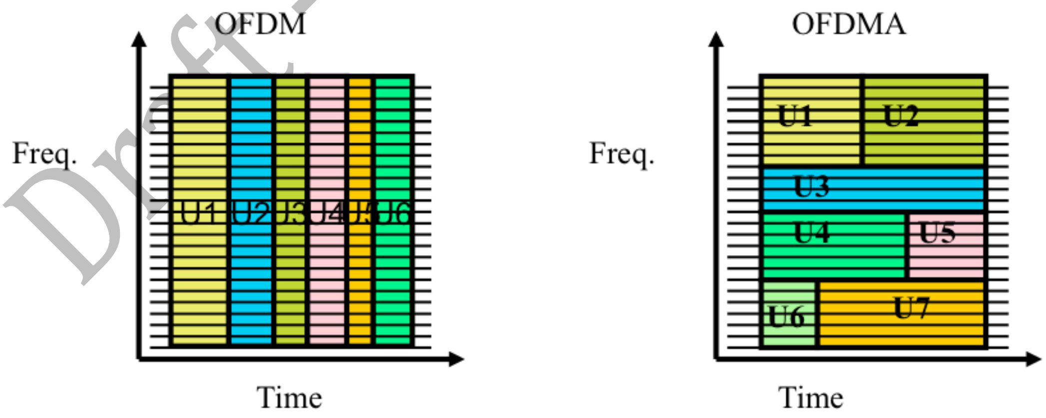


Figure 3.21 Principles of OFDMA

3.24 Scalable OFDMA (SOFDMA)

By now, we know that OFDM enjoys longer symbol duration due to smaller width and lower data rates of the subcarriers compared to the original large bandwidth of the entire allocated spectrum or band. However, the width of the subcarrier, which is the subcarrier spacing in other words, actually depends on the bandwidth of the original spectrum and the number of subcarriers created out of it. Clearly, for the same spectrum, the subcarrier spacing is narrower (symbol duration is larger) if we have more subcarrier, and vice versa. In fact, subcarrier spacing is simply obtained as the bandwidth of the original spectrum divided by the number of subcarriers.

One issue that arise is that the spectrum allocation for a given service is different in different countries. This would create unequal symbol durations. This means the OFDM technology will have to change for different countries. To address this issue, Scalable OFDMA (SOFDMA) was introduced, which keeps the symbol duration fixed to 102.9 us and the subcarrier spacing 10.94 kHz. The number of subcarriers then vary according to the bandwidth allocation in different countries. Larger the allocation, the more subcarriers.

Figure 3.22 shows how the number of subcarriers vary, but the spacing remains the same.

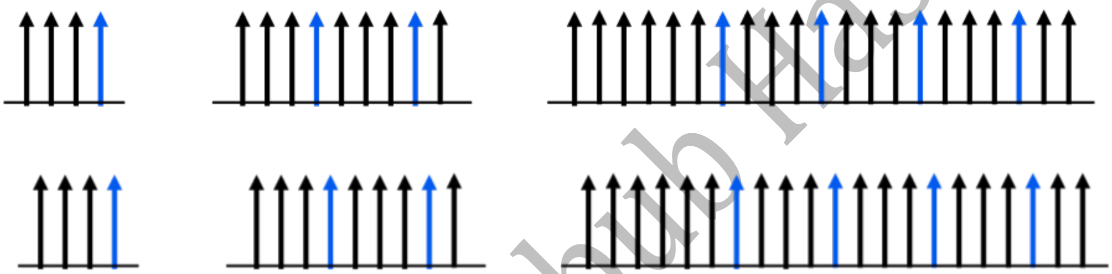


Figure 3.22 Constant spacing for scalable OFDMA

3.25 Effect of Frequency

There are many interesting effects of frequency. Figure 3.23 illustrates some differences between low and high frequency. Let us list the effects of frequency one by one:

1. Higher Frequencies have higher attenuation, e.g., 18 GHz has 20 dB/m more than 1.8 GHz
2. Higher frequencies need smaller antenna. Note that antenna length has to be greater than half the wavelength. For example, we need a 6 inch antenna to transmit data over 800 MHz.
3. Higher frequencies are affected more by weather. Higher than 10 GHz is affected by rainfall and 60 GHz affected by absorption of oxygen molecules
4. Higher frequencies have more bandwidth and higher data rate
5. Higher frequencies allow more frequency reuse, simply because they attenuate close to cell boundaries. They also travel more in straight line allowing better spatial reuse. Low frequencies propagate far and wide, spills over the cell boundaries and create interference with other cells.
6. Lower frequencies have longer reach
7. Lower frequencies require larger antenna and antenna spacing. This means that realizing MIMO is very difficult particularly on mobile devices
8. Lower frequencies mean smaller channel width, which in turn needs more aggressive MCS, e.g., 256-QAMto achieve good data rates.

9. 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.
10. Mobility can be easily supported below 10 GHz, but becomes very difficult at higher frequencies

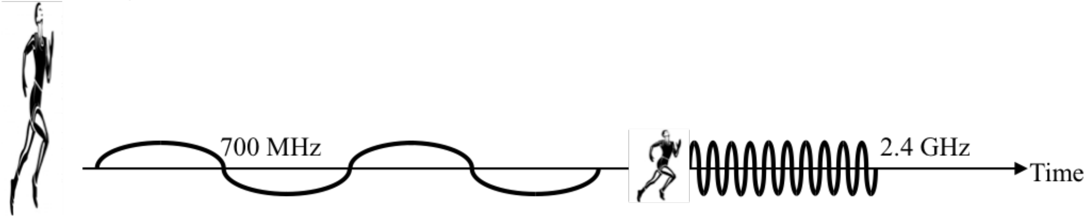


Figure 3.23 Effects of frequency

3.26 Chapter Summary

1. Path loss increase at a power of 2 to 5.5 with distance.
2. Fading = Changes in power changes in position
3. Fresnel zones = Ellipsoid with distance of LoS+il/2
   Any obstruction of the first zone will increase path loss
4. Multiple Antennas: Receive diversity, transmit diversity, Smart Antenna, MIMO
5. OFDM splits a band in to many orthogonal subcarriers.
   OFDMA = FDMA + TDMA