Lecture 4
CS 598

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1 Introduction

In this lecture, Rate Adaptation, Frequency vs Bandwidth, Wireless Channel Recap and Multipath Channel were the topics covered.

2 Rate Adaptation

In wireless systems data is transmitted between devices at rates determined by both the hardware and the protocol in use. This rate is referred to as the **Symbol Rate**, which defines how quickly symbols, representing groups of bits, can be sent across a medium. For example, a symbol rate of 10 MHz means you can transmit up to 10^7 symbols per second. Each symbol can represent multiple bits, depending on the modulation scheme being used.

Modulation Schemes Modulation is the process of mapping bits to symbols, which are complex-valued. Different modulation schemes map different number of bits to each symbol. As an example

- 2 bits mapped to 1 symbol → $2 * 10^7$ bits
- 4 bits mapped to 1 symbol → $4 * 10^7$ bits
- 8 bits mapped to 1 symbol → $8 * 10^7$ bits

From the example above where 8 bits are mapped to a single symbol, the system is able to transmit 8×10^7 bits per second. The higher the modulation schemes, more bits that are mapped to each symbol. This can increase the data rate but also increases the potential for errors.

Trade-offs in Data Rate There is a trade-off between increasing data rates and the probability of errors in transmission.

- A **higher data rate** may cause you to lose throughput
- A **lower data rate** also can cause you to lose throughput

Therefore, the goal is to select an optimal rate that balances throughput and reliability. Choosing too high a rate may lead to more errors, reducing the effective data rate due to the need for re-transmissions. On the other hand, choosing too low a rate sacrifices throughput, even though the transmission may be error-free.

Coding and Error Correction There is also the concept of **coding**, which is used alongside modulation to help manage errors. Coding schemes introduce redundancy into the transmitted data, which allows the receiver to detect and correct certain errors without the need for re-transmissions.

Modulation and Coding Schemes (MCS) Wi-Fi uses a standardized **Modulation and Coding Scheme (MCS)** table to determine the appropriate combination of modulation and coding for a given communication link. The MCS table specifies various data rates, taking into account both modulation techniques and error-correcting codes to optimize performance across different conditions.

3 Frequency vs Bandwidth

Wireless systems rely on fundamental concepts that specifies how data is transmitted and received. The two main concepts are **frequency** and **bandwidth**.

Frequency The **frequency** refers to how fast the wave oscillates per second, measured in Hertz (Hz). It describes the number of cycles the wave completes in one second. Wi-Fi operates at frequencies of 2.4 GHz and 5 GHz, meaning the wave oscillates 2.4×10^9 or 5×10^9 times per second. The higher the frequency, the faster the data transmission. However, the higher the frequency the more susceptible the waves are to obstacles such as walls or interference from other devices.

Bandwidth **Bandwidth** describes how many symbols can be transmitted per second. The more bandwidth available, the more data that can be sent. For Wi-Fi, bandwidth options vary based on the specific configuration being used:

- 20 MHz $\rightarrow 20 \times 10^6$ symbols/second
- 40 MHz $\rightarrow 40 \times 10^6$ symbols/second
- 80 MHz $\rightarrow 80 \times 10^6$ symbols/second
- 160 MHz $\rightarrow 160 \times 10^6$ symbols/second

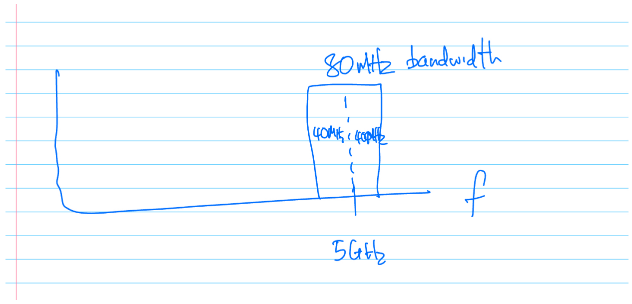

Figure 1: 5 GHz with 80 MHz bandwidth

For example, an 80 MHz bandwidth operating at a 5 GHz frequency means that the system is utilizing frequencies ranging from 5 GHz - 40 MHz to 5 GHz + 40 MHz. This range defines the channel in which data is being transmitted.

Sampling and Frequency Conversion There needs to be hardware capable of sampling the signal. If the sampling needs to be done at the rate of transmission, the sampling would be very expensive and requires power-hungry hardware components.

To mitigate this challenges, there are **frequency conversion techniques**, which reduce the need for such high sampling rates. There is up conversion and down conversion.

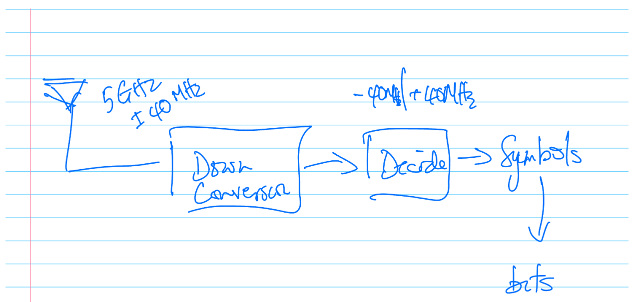

Figure 2: Down Conversion Illustration

- **Up Conversion**: This process shifts a signal from a lower frequency to a higher frequency and is typically used by the transmitter.
- **Down Conversion**: This process shifts a signal from a higher frequency to a lower frequency and is usually used at the receiver.

These conversions allow for less expensive hardware while maintaining the transmitted signal.

Antennas and Wavelengths An antenna is a critical component in any wireless system. The size and design of the antenna are directly related to the wavelength of the signal, which is inversely proportional to the frequency:

$$\lambda = \frac{c}{f}$$

Where:

- λ is the wavelength
- c is the speed of light (3×10^8 m/s)
- f is the frequency

A 5 GHz frequency has a wavelength of approximately 6 cm.

Carrier Frequency Offset and Sampling Frequency Offset The transmitter and receiver can generate slightly different frequencies. The difference between the frequency at the transmitter (f_c) and the frequency at the receiver (f'_c) is called the **carrier frequency offset**. Since no two hardware can generate at the identical rate, this offset can cause synchronization issues between the two devices which can lead to errors.

In addition to carrier frequency offsets, there can also be discrepancies in the **sampling frequency**. The difference between the sampling frequencies at the transmitter and receiver is known as the **sampling frequency offset**, which can also lead to errors.

4 Wireless Channel Recap

Data is transmitted by converting it into symbols that are sent from the transmitter to the receiver over the air. However, due to the nature of the wireless medium, the transmitted symbols are affected by different factors before arriving at the receiver.

Sending Symbols A transmitter sends a sequence of symbols, $x_1, x_2, x_3, x_4, \ldots$. Each symbol carries information, and depending on the modulation scheme used, it can represent one or more bits of data. The transmission process is initiated by converting these symbols into radio waves and then transmitting them.

Receiving Symbols At the receiver, the symbols are captured after propagating through the air. However, what is received is not exactly the same as what was sent due to different factors, such as interference, noise, etc. The received symbols are denoted as $y_1, y_2, y_3, y_4, \ldots$, where each y_i corresponds to a version of the transmitted symbol x_i.

Mathematical Model of the Channel The relationship between the transmitted symbol x_i and the received symbol y_i can be modeled mathematically as:

$$y_i = h \cdot x_i + n_i$$

where:

- x_i is the transmitted symbol
- y_i is the received symbol

- h is the **wireless channel** coefficient, which represents the effect of the environment on the transmitted signal
- n_i is the **noise**, which represents random disturbances that affect the signal during transmission

The Wireless Channel (h) The coefficient h, referred to as the **wireless channel**, captures the effects of the environment on the transmitted signal. h can vary over time and space, leading to different levels of attenuation or amplification of the transmitted signal.

Noise (n_i) The received signal is also influenced by **noise** (n_i). Noise can originate from various sources, such as interference from other devices operating on the same frequency. This random noise adds uncertainty to the received signal, making it more difficult to recover the original transmitted symbols.

5 Multipath Channel

Wireless communication is subject to a variety of challenges due to the nature of the environment in which signals propagate. One of those is the **multipath** effect, which occurs when multiple copies of the same signal arrive at the receiver via different paths. This often results in **Inter-Symbol Interference (ISI)**, especially at higher bandwidths.

Multipath Propagation The transmitted signal can take multiple paths to reach the receiver. These paths can be created by the signal reflecting off objects such as wall, floor etc.. The receiver might capture two or more copies of the same signal, which can lead to signal interference or distortion. Consider two copies of the signal arriving at the receiver, the first copy travels a distance d_1 and the second copy travels a distance d_2

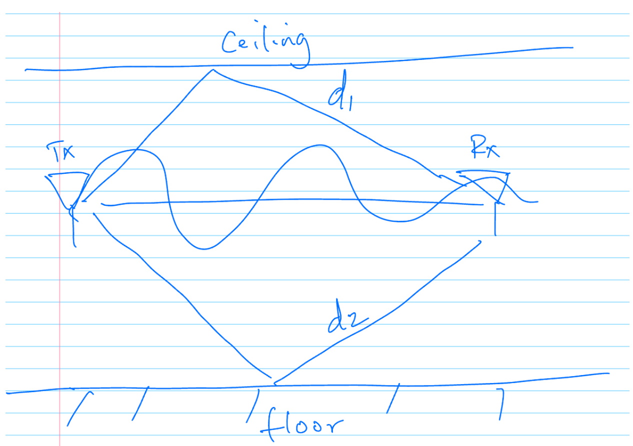

Figure 3: Multipath Illustration

Although the loss in signal strength for both signals might be nearly the same, the difference in path lengths (d_1 and d_2) introduces a time delay between the two signals. This time delay can result in overlapping symbols at the receiver, causing what is known as **Inter-Symbol Interference (ISI)**.

Inter-Symbol Interference (ISI) and Bandwidth The effect of **Inter-Symbol Interference (ISI)** becomes more pronounced when the system operates at higher bandwidths.

- **High Bandwidth**: At higher bandwidths, such as 100 MHz or more, symbols are transmitted at a faster rate. This increases the likelihood of inter-symbol interference because the delay caused by multipath propagation may result in overlap between symbols.
- **Low Bandwidth**: At lower bandwidths, such as 1 KHz, the symbols are transmitted more slowly, and the time delay between multipath signals is less likely to cause overlapping symbols. As a result, systems operating at lower bandwidths are less susceptible to ISI.