Lecture 2
CS 598
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1 Introduction

In this class, we will address the following topics

- How do two wireless devices communicate with each other?
- Why do wireless devices experience poor service sometime?
- The Zigzag paper

2 Wireless signals as waves

Waves used for communication can be electromagnetic (requiring no medium for transmission) or acoustic. Waves are typically characterized by their wavelength (λ) and frequency (f). The wavelength is measured in units of distance (m/cm) and frequency using Hz (cycles/second). Wireless standards often specify the frequencies that different technologies should operate at. For instance,

- Wi-Fi uses the 2.4, 5 and 6 GHz frequency bands. This corresponds roughly to wavelengths of 12 cm, 6 cm and 5 cm respectively.
- Different generations of cellular technologies use frequency bands at 700 MHz ($\lambda \approx$ 40 cm), 1.8 GHz ($\lambda \approx$ 16 cm), 3.5 GHz ($\lambda \approx$ 8 cm) etc. With millimeter wave communication, these frequencies get even higher.

Note that higher frequencies travel lower distances as the amplitude of signals scales as

$$a \propto \frac{\lambda}{d} \tag{1}$$

where d is the distance from the transmitter. Therefore, using higher frequencies (lower wavelengths) reduces the range of communication for a given transmission power. Despite this, newer generations of wireless technologies (5G, Wi-Fi 6 or Wi-Fi 7) move to higher frequencies because

- higher frequencies allow wider channels to be used for transmission which in turn increases throughput. The trade-off is that denser deployments of access points and base stations are required.
- increased availability of spectrum implies more users can be accomodated
- in the case of Wi-Fi, the 2.4 GHz and 5 GHz bands are unlicensed and shared with other devices like microwave ovens, etc. that can cause contention whereas as the 6 GHz band is relatively contention free

There are some parts of the spectrum where users such as the military have priority. In cellular networks, spectrum is largely owned by telecom operators such as ATT. However, the Citizens Broadband Radio Service (CBRS) is unlicensed spectrum which individuals (as opposed to large spectrum owning corporations) can use to set up base stations and provide service.

The speed of waves is measured as

$$v = \lambda \times f \tag{2}$$

c is usually used to denote the speed of light and in vacuum it is roughly $3 \times 10^8 ms^{-1}$.

3 Using waves to communicate data

In this class, we will focus primarily on digital communication where the information to be transmitted is a series of bits. There exist a number of methods by which the information in bits can be captured by waves or symbols. The process of doing so is called **modulation**. At the receiver, the process of converting these symbols back to bits is called **demodulation**.

3.1 On-off keying

In this case, sending the wave can be equivalent to sending bit 1 and not sending anything is equivalent to bit 0. This is shown in Figure 1 where the reciever recevies a noisy version of the sent signal.

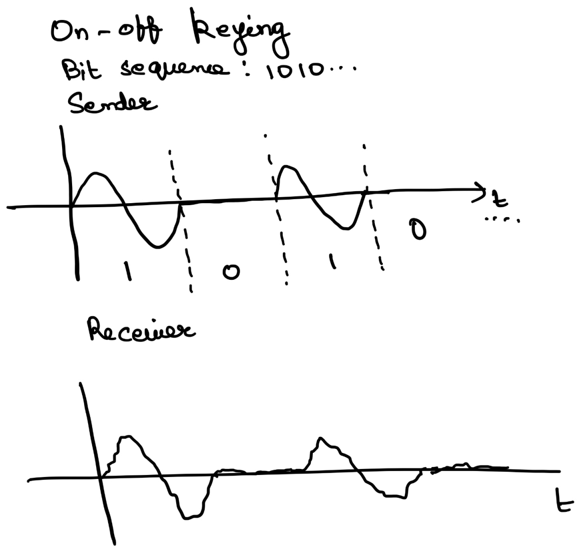

Figure 1: On-off keying

3.2 Amplitude modulation

Information can be captured in waves using their different attributes. In amplitude modulation, the amplitude of the wave is set to various levels depending on the message being sent. By using multiple values of amplitude, a symbol can capture more than one bit. Figure 2 presents two examples where the amplitude modulation is used to send 1 bit per symbol and 2 bits per symbol.

3.3 Frequency modulation

Here, the frequency of the wave is changed to capture different bits as shown in Figure 3.

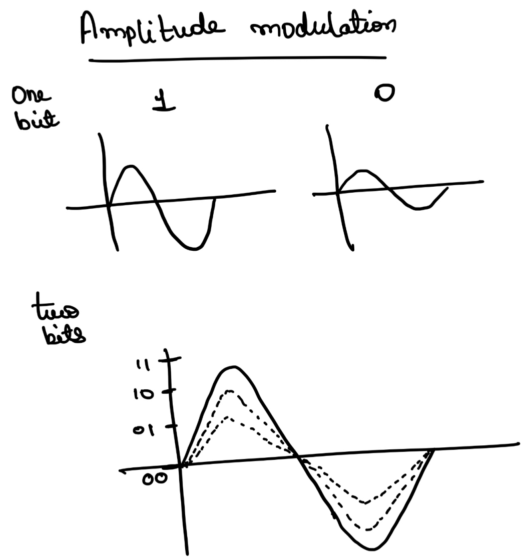

Figure 2: Amplitude modulation

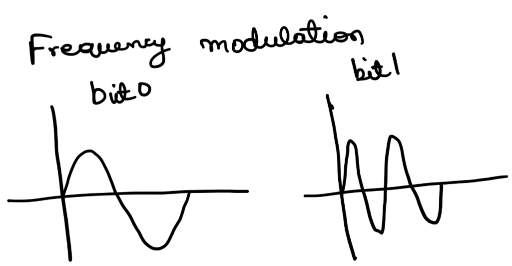

Figure 3: Frequency modulation

3.4 BPSK

The phase of the wave can also be varied according to the bit(s) being sent. The phase of a wave can vary from 0 to 360 degrees or 0 to 2π radians. At any point the phase is given by

$$\phi = 2\pi ft \bmod 2\pi \tag{3}$$

where f is the frequency of the wave and t is time. In binary phase shift keying, bit 0 has a phase of 0 and bit 1 has a phase offset of π as shown in Figure 4.

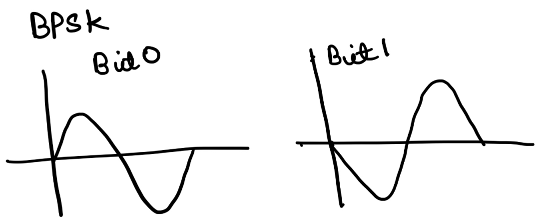

Figure 4: BPSK

4 Complex number representation of symbols

Complex numbers are a convenient way to represent symbols. A complex number C is written as

$$C = Re + j \times Im = ae^{j\phi} \tag{4}$$

where $j = \sqrt{-1}$, Re is the real part, Im is the imaginary part, a is the magnitude and ϕ is the phase. Communication symbols can correspond to complex numbers as below

- **On-off keying** Bit 0 : 0 and Bit 1 : 1
- **AM** Bit 0: 0.5 and Bit 1 : 1
- **BPSK** Bit 0: -1 = $e^{j\pi}$ and Bit 1 : 1

In Figure 5, QPSK (Quadrature Phase Shift Keying) is introduced where phase is divided into four instead of two like in BPSK.

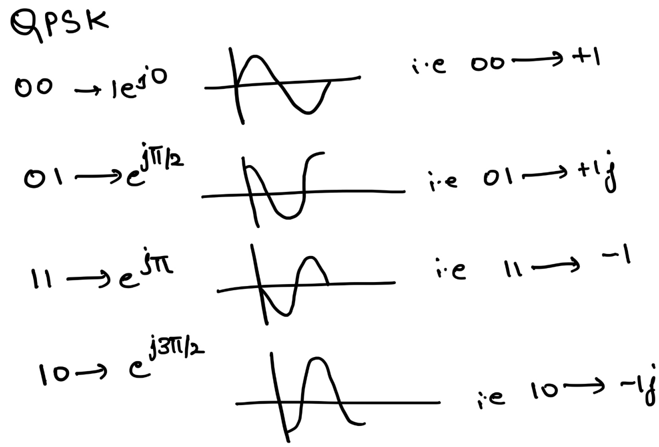

Figure 5: QPSK

5 The wireless channel

The process of communication entails

- a sender with some sequence of bits to transmit converting them to symbols x_1, x_2, x_3, x_4 and so on and the radio transmitting them
- propagation over the wireless channel which brings in effects like fading, interference, noise, etc.
- the receiver's radio capturing these waves, converting them to symbols y_1, y_2, y_3, y_4 and so on (y_i can be different from x_i because of the wireless medium) and converting those symbols to bits, perhaps with some errors

The received symbols can be modelled with the equation

$$y = hx + n \tag{5}$$

where h captures the effect of the channel and affects the amplitude and phase of the received signal and n is the additive noise. The model considered here is simple and assumes that the channel remains constant with time and for all symbols. Consider the following example: +1, -1, -1j, +1j are the transmitted symbols

- if $h = 0.5$, the received symbols are 0.5, -0.5, -0.5j, 0.5j with only the amplitude affected
- if $h = 0.5j$, the received symbols are 0.5j, -0.5j, +0.5, -0.5 with both the amplitude and phase effected

Therefore, an estimate of h is necessary at the receiver to recover the transmitted symbols. This is where a **preamble** is effective. A preamble is a sequence of symbols transmitted at the start of, say, every packet that is agreed upon by both the receiver and transmitter in advance (during the formation of wireless standards). This preamble is used to estimate the channel (h') as

$$h' = \frac{y}{x} \tag{6}$$

where x is the known preamble symbol that was transmitted and y is the corresponding received symbol. Typically, the packet lengths are configured so that the assumption of channel being constant for the duration of the packet's transmission holds true.

5.1 SNR and SINR

The Signal to Noise Ratio is an indication of channel quality and can be computed as

$$\text{SNR} = \frac{|hx|^2}{|n|^2} \tag{7}$$

It is often measured in dB as below

$$\text{SNR in dB} = 10 \log_{10}(\text{SNR}) \tag{8}$$

Therefore, 10 dB corresponds to a ratio of 10, 30 dB to 1000 and so on.

SINR is the Signal to Interference and Noise Ratio and is measured as

$$\text{SINR} = \frac{\text{Signal power}}{\text{Interfernce + Noise power}} \tag{9}$$

6 Zigzag paper

We will cover this in the next class.