CS 425: Computer Networks **Jan-Apr 2020**

Lecture 5: Computer Networks – January 17, 2020

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Physical Layer is the lowest layer in our protocol model. It defines the electrical, timing and other interfaces by which bits are sent as signals over channels. It involves Media, Signal Transmission, Modulation and Limits of Communication.

In this lecture, we will broadly discuss these topics:

1. Theoretical Basis of Data Communication
2. Guided Transmission Media
3. Wireless Transmission
4. Digital Modulation

5.1 Theoretical Basis of Data Communication

In this section, we will try to understand how bits (Ex. audio signals) are sent over links. We define a **signal** as an electrical or electromagnetic current that is used for carrying data from one device or network to another. Physical links are designed to carry analog signals.

Fourier Series

Information can be transmitted on wires by varying some physical property such as voltage or current. By representing the value of this voltage or current as a single-valued function of time, $f(t)$, we can model the behavior of the signal and analyze it mathematically. We can split the signal as sum of multiple harmonics.

$$f(t) = c_o + \sum_{n=1}^{\infty} a_n cos(n\omega_0 t) + \sum_{n=1}^{\infty} b_n sin(n\omega_0 t)$$

Signals can be viewed in time domain as well as in frequency domain. **Fourier transform** takes the signal from time domain to frequency domain. The medium can transmit upto some frequency value, also known as **bandwidth**. So, some of the components of Fourier series will disappear. If the medium has a very low bandwidth, then we will get a simple and distorted version of our original signal.

Suppose bandwidth of our medium is 8ω. Then, the distorted version of our above signal will look like following

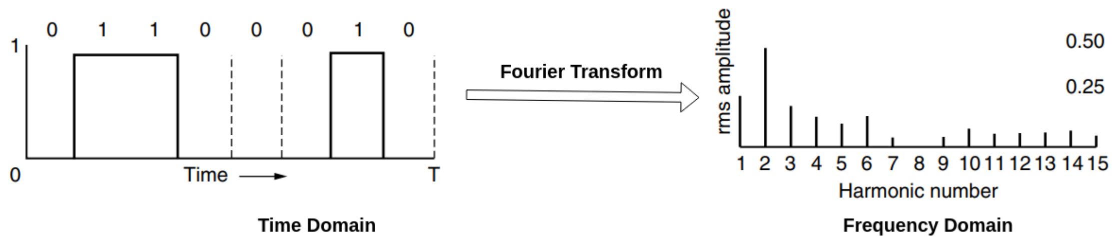

Figure 5.1: Time Domain to Frequency Domain Conversion

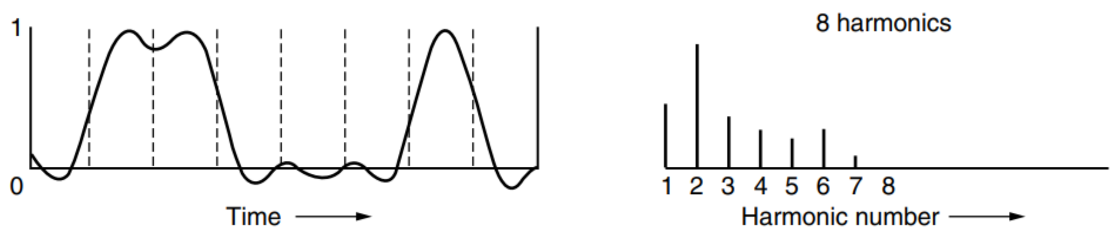

Figure 5.2: Distortion due to Limited Bandwidth

5.2 Guided Transmission Media

5.2.1 Wire Transmission

We know from the above sections that digital signals can be passed through wire using Fourier Series. However, in real life, this signal gets distorted due to various reasons:

1. Time delay

As transmission wires are typically several km long, signals suffer a time delay.

2. Frequency limited version

Wires have a limited range of supported frequencies [Bandwidth (communication)] to prevent data loss. Thus, when we make a signal consisting of frequencies not supported by a wire, they get cut-off before transmission. This leads to distortion of the signal as these frequencies may be important in Fourier Transform of the data signal.

3. Additive Noise

It refers to unwanted signals that get added during capture, storage, transmission, processing, or conversion.

4. Attenuation

It refers to any loss in signal strength (measured in dB). E.g. Power of signal decreases due to long wires.

Here, **Bandwidth (Communication)** refers to the frequency range between the lowest and highest attainable frequency (measured in Hz). **Bandwidth (Computer Science)** refers to maximum rate of data transfer across a given path (measured in bits/sec).

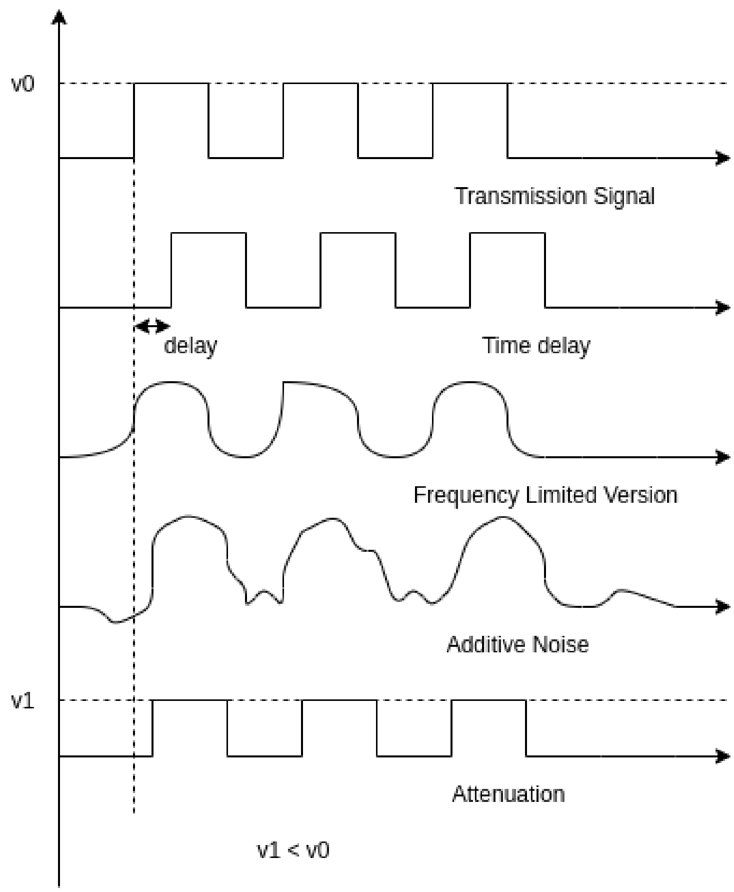

Figure 5.3: Reasons for signal deterioration

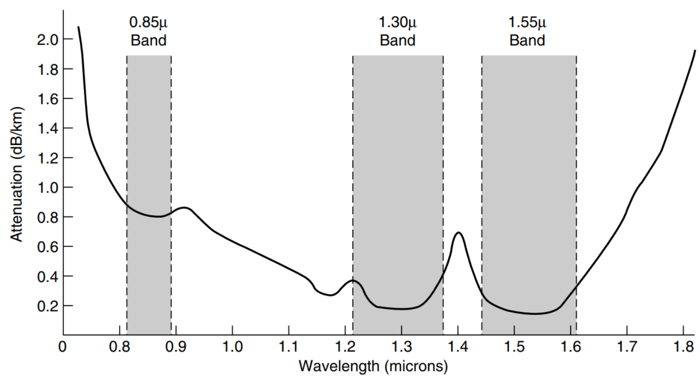

Figure 5.4: Attenuation coefficient of glass vs wavelength

5.2.2 Optical Fibre Transmission

An optical fiber is a thin fiber of glass or plastic that can carry light from one end to the other. This is helpful as light suffers very little attenuation in glass. This mode of transmission generally has a high data transfer rate.

Measuring Attenuation

The total attenuation is a function of the wavelength λ of the light. The total attenuation A(dB or decibels) between two arbitrary points X and Y on the fiber is

$$A(dB) = 10 \log_{10}(P_x/P_y)$$

P_x, P_y are the power outputs at points X and Y resp.

Attenuation in Fiber

The bands colored in grey are used for commercial purposes as they have relatively low attenuation.
Let the frequency of light that is used is f. Then,

$$f\lambda = c$$

$$f = 3 * 10^8/\lambda$$

λ is around $10^{-6}m$ in optical fibers. We get, $f = 3 * 10^{14}$. As the frequency is very high, data transmission is faster.

5.3 Wireless Transmission

This is the most interesting mode of signal transmission. The property of the wireless channel may change over time, so wireless communication must be adaptive. We need a high frequency "carrier" signal to transmit the original signal in the wireless medium.

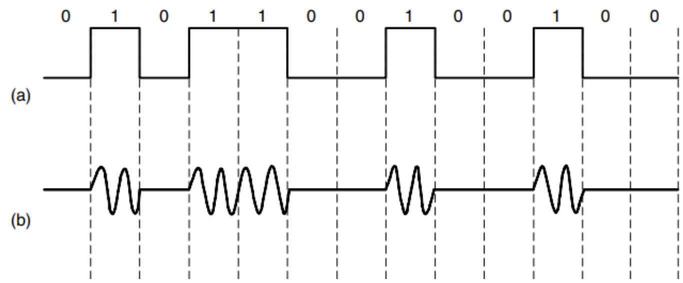

Figure 5.5: (a) Original signal (b) Carrier multiplied signal (transmitted)

5.3.1 Need for carrier signal:

- Generally our signals have very limited bandwidth like our voice signal. Since these signals have the same frequency band, if we want communication among multiple individuals simultaneously, these signals will superimpose on each other and make no sense.

- To overcome this, the individual signals are transmitted at different frequency levels by superimposing data on signals having very high frequencies (order of GHz or more). These very high frequencies are called carrier frequencies and corresponding signals carrier signals.

- Carrier signals are used in optical fibers as well. To accommodate multiple users, the same fiber can transmit various frequencies of light signal and different carrier frequencies can be allocated to different pairs of users.

5.3.2 Reason of high frequency of carrier signal

- Antenna size for transmission of the wireless signal is directly proportional to wavelength. So to have a reasonable antenna size, we need low wavelength, i.e. high-frequency signal.

- We need to accommodate multiple signals, i.e. sender-receiver pair, and communicating on high frequency gives us a lot of such slots.

5.3.3 Carrier multiplied signal

Suppose we want to send an original signal and we have a very high-frequency carrier signal.

- We change the amplitude of the carrier signal according to the signal that we want to send as we can see in the figure below. The amplitude of the final signal will reflect whether the signal is transmitting 1 or 0.

- We can achieve this by just multiplying the original signal with the carrier signal, and this carrier multiplied signal is finally transmitted.

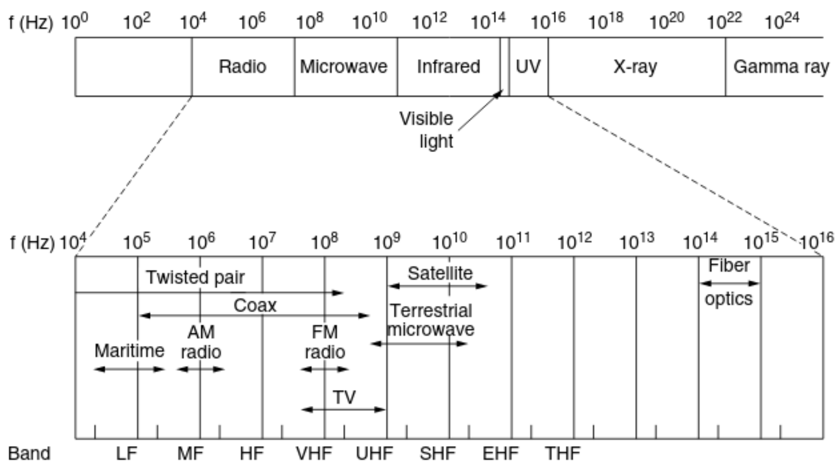

Figure 5.6: The electromagnetic spectrum and its uses for communication.

5.3.4 The electromagnetic spectrum

5.3.5 Attenuation in wireless signals

Visible light has less attenuation and high frequency, but wireless signals have very high attenuation in-spite of operating at microwave length. It turns out that signal power falls as distance increases.

$$\text{Signal power} \propto \frac{1}{distance^2}$$

Apart from the attenuation, which is only impacting amplitude, it also can impact frequencies. Some frequencies are attenuated more than other frequency, and this is called **frequency selective attenuation**.

5.3.6 Spatial reuse and cellular model

- Consider the user trying to get information for source signal A. Here signals of other transmitters B and C are also interfering with the original signal from A.
- We can't communicate using wireless signals over large distance due to its rapid attenuation, but at the same time, there are some advantages of this rapid attenuation as spatial reuse.
- As B and C have higher attenuation due to large distance from the user, there would not be a reasonable amount of interference, and thus we can spatially reuse same frequency for transmission in wireless media.
- This idea of spatial reuse of frequencies is used by mobile service providers. They adopt a cellular model over the 2d plane, where the whole geographical region is sliced into hexagonal cells having a tower/antenna.

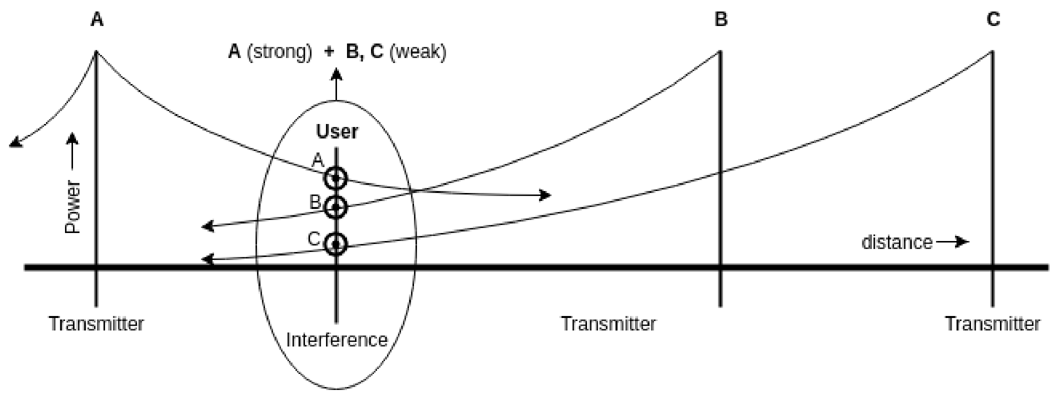

Figure 5.7: Interference of signals from various transmitter

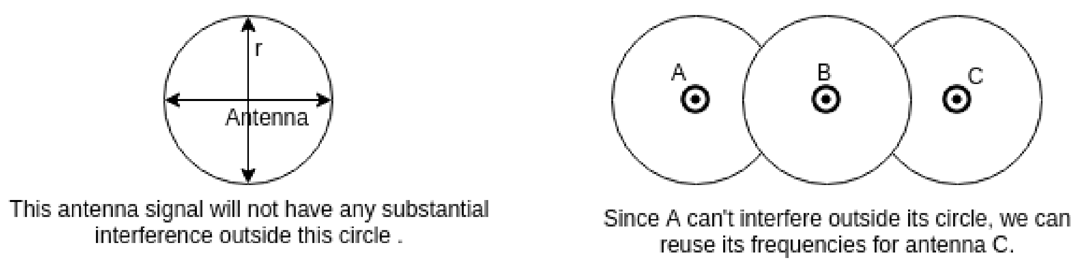

Figure 5.8: Spatial reuse of frequencies

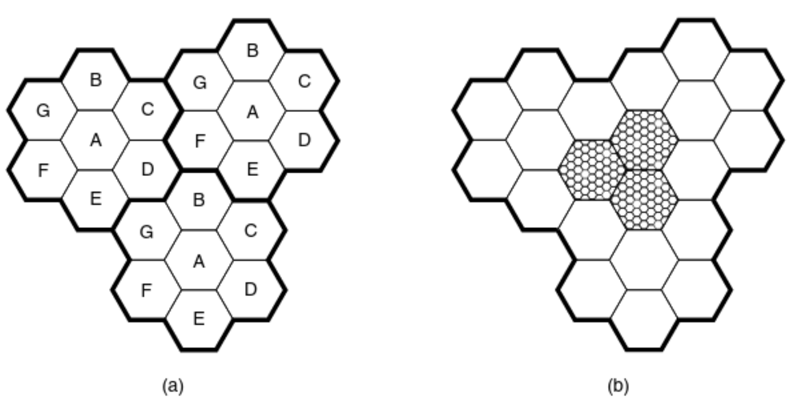

Figure 5.9: Cellular model over geographical region

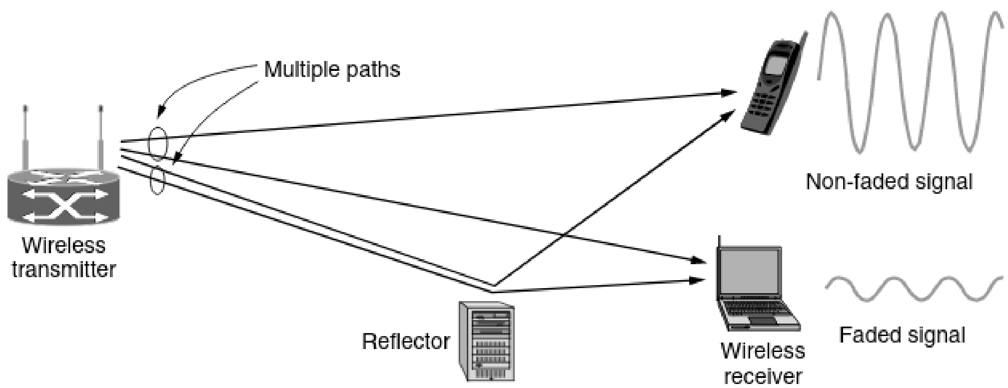

Figure 5.10: Multi-path fading

- In the cellular grid, frequencies are not reused in adjacent cells, as shown in fig 9(a), so we need only 7 different frequency bands. To add more users, local smaller cells using different frequency can be used, as shown in fig 9(b).

5.3.7 Fading of wireless signal

- In a wireless medium, we can't control how the signal is reaching to us. We can have a transmitter and a direct path via which we are receiving the signal, or there may be several reflectors from which the same signal may be getting reflected and coming to us.
- This reflected signal can come to us in exactly opposite phase, superimposed with the original one and thus nullifying/weakening the components of the signal. This is called **fading of signal**.

5.4 Digital Modulation

Wires and wireless channels carry analog signals. To send digital information, we must devise analog signals to represent bits. The process of converting between bits and signals that represent them is called **digital modulation**.

Baseband Modulation: This is a scheme for converting bits to signal. In this, the signal occupies frequencies from zero up to a maximum that depends on the signalling rate. This is mostly used in wires.

Passband Modulation: This scheme involves regulating the amplitude, phase, or frequency of a carrier signal to convey bits. In this, the signal occupies a band of frequencies around the frequency of the carrier signal. It is used for wireless and optical channels.

5.4.1 NRZ: Non-Return-to-Zero

The most straightforward form of digital modulation is to use a positive voltage to represent a 1 and a negative voltage to represent a 0. For an optical fiber, the presence of light might represent a 1, and the absence of light might represent a 0. This scheme is called **NRZ (Non-Return-to-Zero)**.

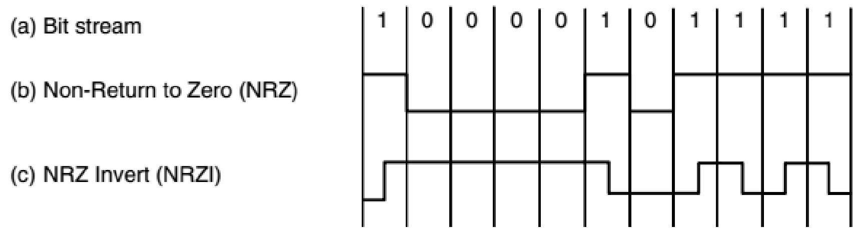

Figure 5.11: NRZ AND NRZI Coding Schemes

Once sent, the receiver converts the NRZ signal into bits by sampling the signal at regular intervals of time.

5.4.2 Drawbacks of NRZ

For all schemes that encode bits into symbols, the receiver must know when one symbol ends, and the next symbol begins to decode the bits correctly. With NRZ, in which the symbols are simply voltage levels, a long run of 0s or 1s leaves the signal unchanged. After a while, it is hard to tell the bits apart accurately, unless you have a very accurate clock which is expensive. This problem associated with the accuracy of clocks is called **Clock Recovery Problem**

We can overcome this drawback using NRZ-Inverted coding.

5.4.3 NRZI: Non-Return-to-Zero Inverted

In NRZI, we code a 1 as a transition and a 0 as no transition. With this coding scheme, long runs of 1s do not cause a problem as 1s appear during the transitions.

Drawback: Long runs of 0s still cause a problem, which is not solved in this scheme. To solve this problem, we can break up runs of 0s by mapping small groups of bits to be transmitted so that groups with successive 0s are mapped to slightly longer patterns that do not have too many consecutive 0s.

5.4.4 4B/5B Coding

This coding scheme overcomes the problem of a long sequence of consecutive bits by mapping every 4 bits into a 5-bit pattern with a fixed translation table. The five-bit patterns are chosen so that there will never be a run of more than three consecutive 0s.

Data (4B)	Codeword (5B)	Data (4B)	Codeword (5B)
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1001	10011
0010	10101	1011	10111
0100	01011	1100	11011
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

Table 5.1: 4B/5B Mapping

Since there are 16 input combinations and 32 output combinations, some of the output combinations are not used. Putting aside the combinations with too many successive 0s, there are still some codes left. These non-data codes are used to represent physical layer control signals. For example, in some uses 11111 represents an idle line and 11000 represents the start of a frame.

Question: How can one design a baseband modulation scheme which is immune to both long 1's and long 0's problem?

Answer: 4B/5B followed by NRZI. This sequence of coding will work because 4B/5B will remove long sequences of 0s and then NRZI will remove the long sequences of 1s. NRZI followed by 4B/5B will not work because after applying NRZI, long sequences of 1s will be removed, but after applying 4B/5B, they can reappear.

References

[1] JF Kurose, KW Ross, Computer Networking: A Top-Down Approach, 5th Ed., Addison-Wesley, 2009.

[2] AS Tanenbaum, DJ Wetherall, Computer Networks, 5th Ed., Prentice-Hall, 2014