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

Lecture 6: Computer Networks – January 21, 2020

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In the last lecture we discussed the baseband modulation. In this lecture we will discuss following topics:

- Passband Modulation
- Advantages of using digital signal for data transmission.
- Nyguist Sampling Theorem
- Shannon Channel Capacity Theorem
- Introduction to Link Layer

6.1 Passband Modulation

In digital transmission it is desirable to transmit signals at higer frequencies, but the signal output of baseband modulation is usually of lower frequencies. To achieve the task we use passband modulation to translate baseband modulated signals onto the medium via **Carrier** signals.

Carrier is a signal which has a *high* frequency.

6.1.1 Different types of Passband Modulation

Let's say we have carrier signal represented by some equation, for instance $A_c \cos(w_c t)$ and the baseband signal represented by $s(t)$, then we define following modulations as follows:

Amplitude Modulation

In Amplitude Modulation, the amplitude of the carrier wave is varied in proportion to the baseband signal. For instance, the Amplitude Modulated signal would be $A_c s(t) \cos(w_c t)$.

Frequency Modulation

In Frequency Modulation, the frequency of the carrier wave is varied in accordance with the baseband signal. For instance, the Frequency modulated signal would be $A_c \cos((w_c + s(t))t)$.

Phase Modulation

In Phase Modulation, the phase of the carrier wave is varied in proportion to instantaneous amplitude of the baseband signal. For instance, the Phase Modulated signal would be $A_c \cos(w_c t + s(t))$.

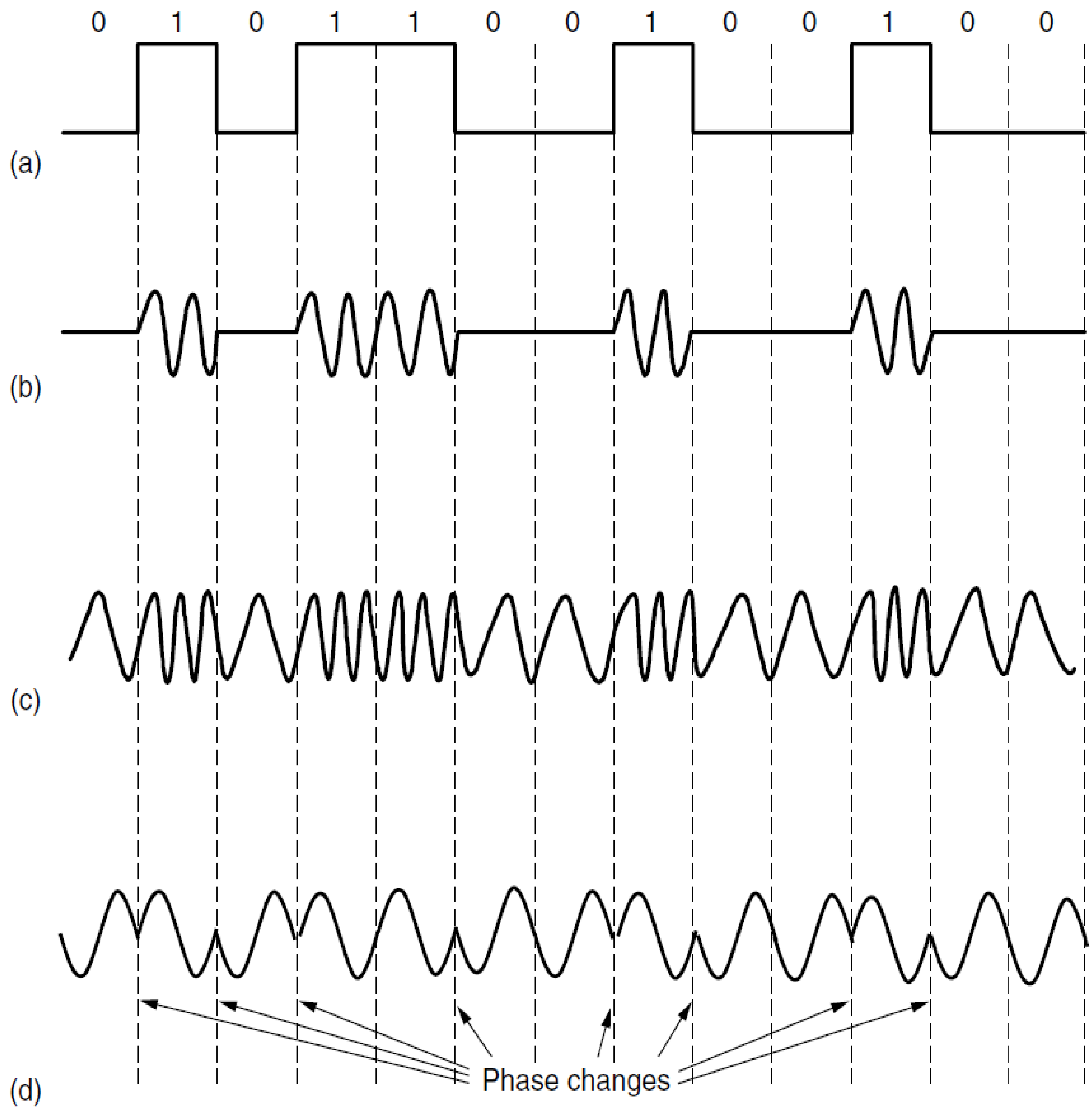

Figure 6.1: (a) Baseband Signal (b) Amplitude Modulation (c) Frequency Modulation (d) Phase Modulation

6.2 Why digital signals are preferred over analog signals?

Digital signals offer many advantages over analog signal :

- **Noise resistance** is high in case of digital signals. Since the information is stored as discrete level in a digital signal, therefore whenever the noise gets superimposed on original digital signal , even if it shifts amplitude by considerable amount, we can still correctly recover discrete level of digital signal.

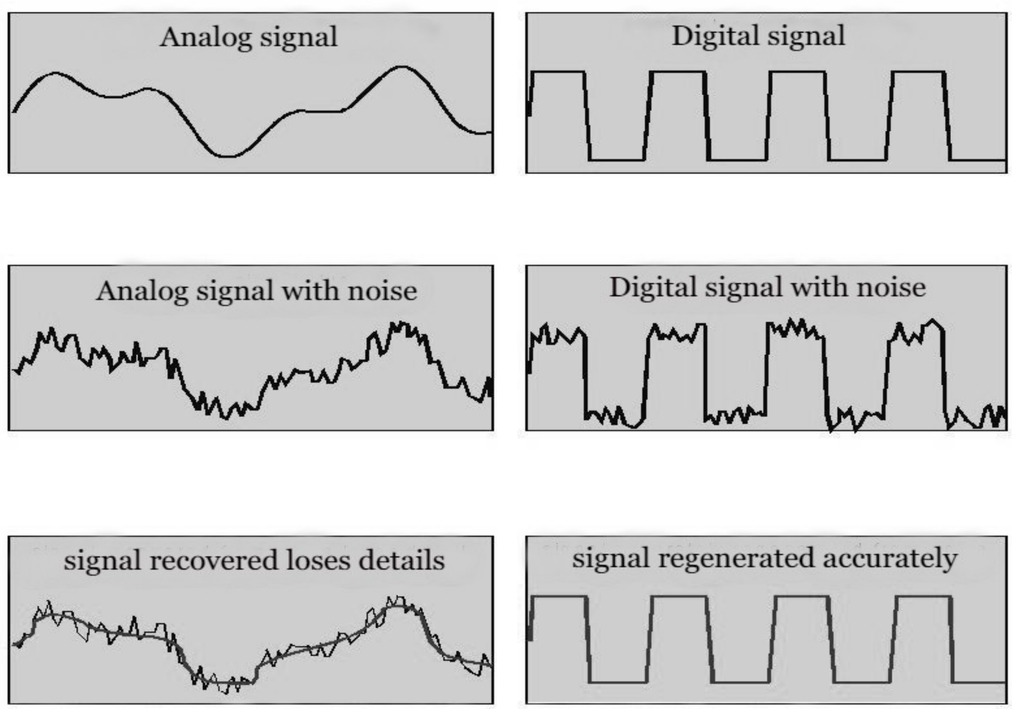

Figure 6.2: Noise resistance in case of analog and digital signal

- **Error detection and correction** is possible with the help of different error correction coding schemes.
- Digital signals are collection of bits and hence can be encrypted unlike the case of analog signals which are difficult to encrypt, hence serve the purpose of **Security**.

6.3 Limits of information transmission

6.3.1 Nyquist Sampling Theorem

- We can convert an analog signal to a digital signal by sampling at discrete points.

- Higher sample rate will increase the accuracy of signal reconstruction.
- If we sample at a very high rate, large amount of data has to be stored and processed which is time consuming. And if we sample at a lower rate, then we might not be able to reconstruct the original signal back.
- Therefore the question arises - what should be the minimum sampling rate for successful reconstruction of the original signal? This answer is given by Nyquist Theorem.

It states that : **the minimum sampling frequency of a signal that it will not distort its underlying information, should be double the frequency of its highest frequency component.** If the baseband frequency is f_b, then the critical sampling frequency must be greater than $2f_b$.

Following figures illustrates the working of this theorem:

1. If we sample at the same frequency as that of baseband frequency, i.e. , $f_s = 1 * f_b$, then it is possible that the reconstructed signal is just a straight line signal which can be seen in the figure.

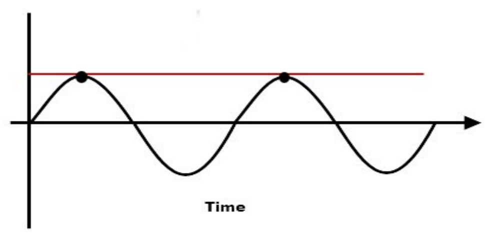

Figure 6.3: Sampling frequency is less than twice baseband frequency

2. If we sample at the frequency greater than twice the baseband frequency, then as we can see from following figure that we are able to approximate the analog signal.

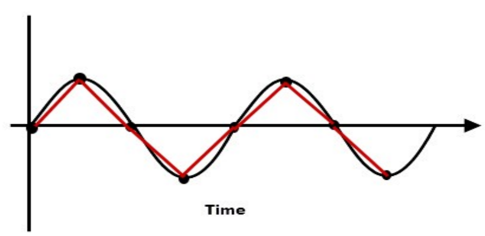

Figure 6.4: Sampling frequency is greater than twice baseband frequency

6.3.2 Shannon Channel Capacity Theorem

- Till now we have just looked at noiseless channels. Noise is present irrespective of the medium due to the motion of molecules in the system.
- The amount of thermal noise present is measured by the ratio of the signal power to the noise power, called the signal-to-noise ratio. If signal power is denoted by S and the noise power denoted by N, the signal-to-noise ratio is $\frac{S}{N}$.

- Sometimes the quantity $10\log_{10}(\frac{S}{N})$ is used. Its unit is decibels (dB).

The noise puts a limit on the rate at which data can be transmitted. **Shannon Channel Capacity Theorem** give the limit on maximum data rate in a channel of given bandwidth WHz and SNR of S/N.

$$\text{Maximum data rate } D_r = W\log_2(1+\frac{S}{N}) \text{ bits/sec}$$

So this implies :

- Keeping SNR fixed, data rate is proportional to bandwidth W.
- Lower noise $\implies$ Higher data rate.

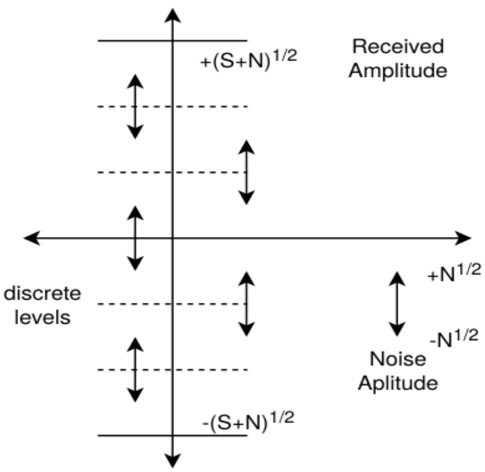

Figure 6.5: How to discretize amplitude of signal ?

The intuition behind this result is as follows :

- The power received at receiver is $(S+N)$ which means amplitude of final signal is $\sqrt{S+N}$. Signal strength varies between $\pm\sqrt{S+N}$.
- Amplitude of noise signal is $\sqrt{N}$. Noise signal strength varies between $\pm\sqrt{N}$. So the number of distinguishable levels is $\frac{2\sqrt{S+N}}{2\sqrt{N}}$.
- Number of bits required for the final signal will be $\log_2(\frac{2\sqrt{S+N}}{2\sqrt{N}}) = \frac{1}{2}\log_2(1+\frac{S}{N})$.

Nyquist Bandwidth Formula = $2W\log_2 M$ bits/sec. M is the # of distinguishable levels.

Question : Suppose the signal power at a receiver is S and the noise per unit bandwidth is η. If the bandwidth of the channel W $\to\infty$, what will be the capacity of the channel?

Answer :

$$N = \eta W$$

$$C = \lim_{W\to\infty} W\log_2(1+\frac{S}{\eta W}) = (W\log_2 e)\lim_{W\to\infty}\ln(1+\frac{S}{\eta W})$$

$$\text{Result : } \lim_{x\to\infty}(1+\frac{1}{x})^x = e$$

$$\text{Hence, } C = \lim_{W \to \infty} \frac{S}{\eta} \ln \left((1 + \frac{1}{\frac{\eta}{S}W})^{\frac{\eta}{S}W} \right) \log_2 e = \frac{S}{\eta} e \log_2 e$$

Switches are used to maintain the S/N ratio over larger distances. They in operate both physical layer and link layer.

Example

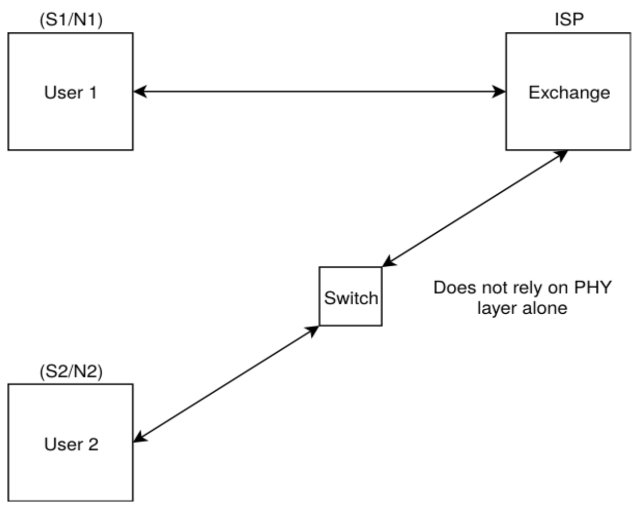

Figure 6.6: Use of switch to rectify signal

6.4 Pipeline for Signal Transmission

- The source signal which is analog signal containing the information is first passed through the source coder.
- The source coder converts the source analog signal to digital signal. This digital signal is such that it is sufficient enough to retrieve the analog signal on the receiver side (Nyquist Sampling Theorem).
- Now the digital signal is passed through the Channel Coder which uses the Shannon Channel Capacity Theorem to determine the max data rate for given bandwidth and noise.

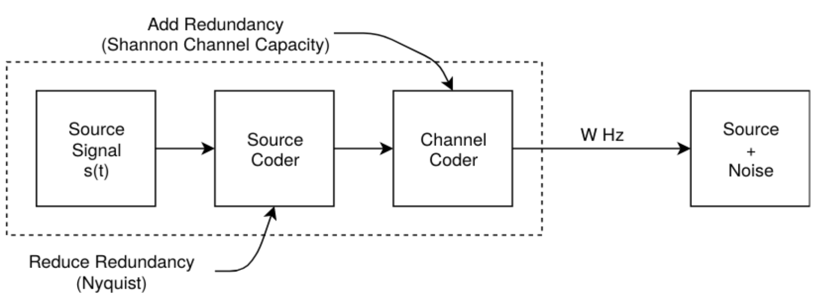

Figure 6.7: Pipeline for signal transmission

6.5 Link Layer

Goal : To provide reliable communication over a link.
To accomplish the goal, the data link layer takes the packets it gets from the network layer and encapsulates them into frames for transmission. Each frame contains a frame header, a payload field for holding the packet, and a frame trailer as shown in Figure 6.8

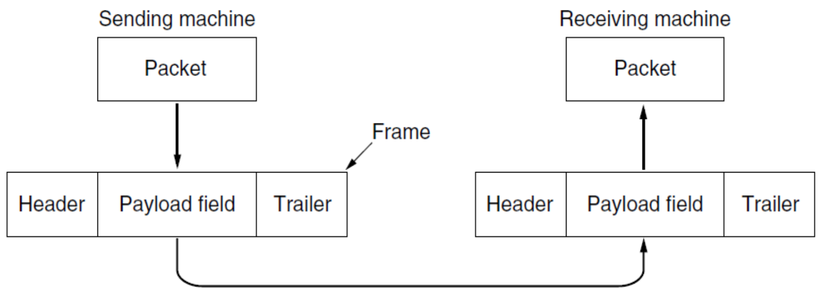

Figure 6.8: Relationship between packets and frames

6.5.1 How are layers implemented in a computer?

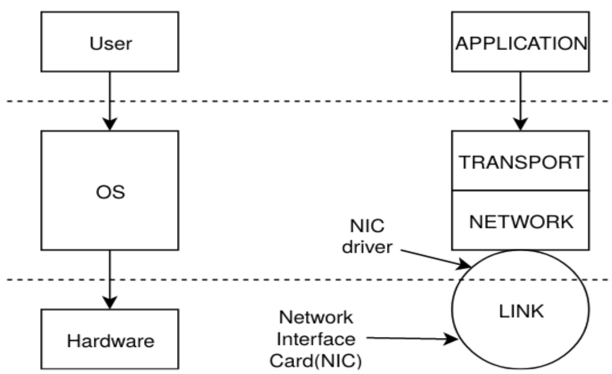

Figure 6.9: Link layer in computer

Link Layer has components both at OS as well as Hardware level. At OS level it is through Network Interface Card(NIC) driver whereas at Hardware level it is through NIC.

6.5.2 Topics in Link Layer

- Frames - construction.
- Error Detection and Correction.
- Retransmission.
- Multiple Access.
- Switching.

References

1. AS Tanenbaum, DJ Wetherall, Computer Networks, 5th Ed., Prentice-Hall, 2010
2. JF Kurose, KW Ross, Computer Networking: A Top-Down Approach, 5th Ed., Addison-Wesley, 2009.