Data and Signals - Theoretical Concepts

Reference:
Chapter 3 - Stallings
Chapter 3 - Forouzan
Study Guide 3

Review of Lecture 2

- What are the major functions of the network access layer?

Review of Lecture 2

- What are the major functions of the network access layer?

Answer - source-to-destination delivery of a packet possibly across multiple networks, providing logical address details of sender and receiver, and to provide the mechanism for connection of networks through connecting devices (i.e. routers and switches).

Review of Lecture 2

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Review of Lecture 2

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Answer - The transport layer is responsible for the process-to-process delivery of the entire message. This requires: port addressing, segmentation and re-assembly (including replacing packets lost in communication), connection control, flow control and error control.

Review of Lecture 2

- Name the advantages of a layered network architecture.

Review of Lecture 2

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Answer - By localising functions into layers the protocol architecture is comprehensive and flexible. Provide boundaries between layers are well defined, changes to the software in one layer will not effect other layers. Development of layers can be defined independently and simultaneously. Independent of vendors and model variations.

Review of Lecture 2

- Name the disadvantages of a layered network architecture.

Answer - Each layer causes addition of a PDU header, which increases the size of the original packet to be transmitted. The greater the number of layers, the greater the overheads to the network.

Review of Lecture 2

- Which layers in the Internet model are the network support layers?

Review of Lecture 2

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Answer - Physical, Data-link and Network.

Review of Lecture 2

- Which layer in the Internet model is the user support layer?

Review of Lecture 2

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Answer - Application.

Lecture 3 Objectives

- To understand the meaning of data and signal;
- To understand the difference between digital and analog signals;
- Identify the amplitude, frequency and phase of a sine wave;
- Understand the meaning of bandwidth;
- To understand the relationship between bandwidth and data rate;
- Understand different types of transmission impairments;

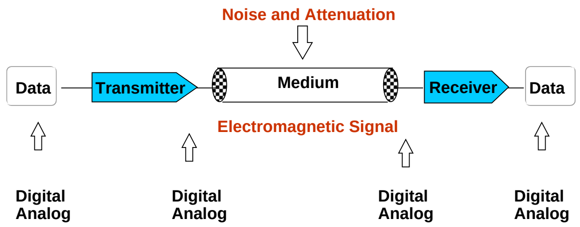
Lecture 3 Objectives Contd.

- To understand the meaning of SNR and its role in measuring noise in data transmission channels;
- To understand the meaning of decibel as a unit of noise measurement; and
- To calculate and determine the maximum capacity of a communication channel using Nyquist or Shannon theory.

Communication System

- Transmitter
- Receiver
- Medium
  - Guided medium
    - Waves are guided along a physical path, e.g. twisted pair, optical fiber
  - Unguided medium
    - Provides a means for transmitting but does not guide them, e.g. air, water, vacuum

Communications



Communication Link

- Direct link
  - No intermediate devices other than repeaters or amplifiers, can be applied to guided or unguided media
- Point-to-point
  - Direct link
  - Only 2 devices share link
- Multi-point
  - More than two devices share the link

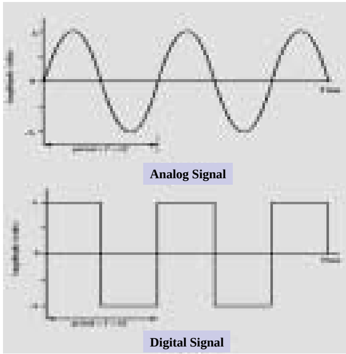
Communication Modes

- The direction of information flow over a transmission path
  - **Simplex - allows unidirectional information flow**
    - radio & TV broadcast, one-way streets, printers.
  - **Half Duplex - allows information flow alternatively in both directions**
    - press-to-talk radio systems, terminals
  - **Full Duplex - allows simultaneous information flow in both directions (common in computer communications)**

Modes of Signal Representation

- Data/information can be in the form of analog or digital
- These data can be transmitted as
  - analog signal
  - digital signal
- Signals are usually periodic
  - same signal pattern repeats over time
- Signals can be
  - continuous - varies in a smooth way over time
  - discrete - varies between constant levels
  - aperiodic - not repeated over time

Example: Analog and Digital Signal

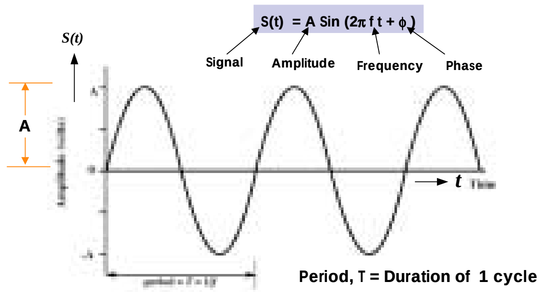


Both signals in this example are periodic

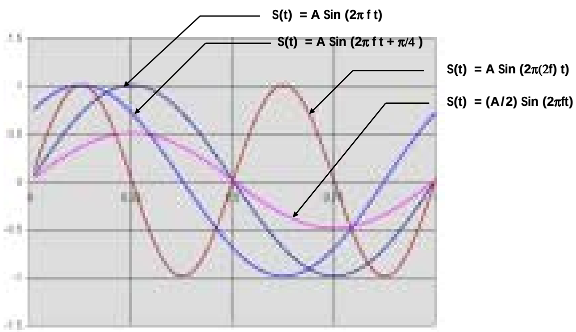
Characteristics of Analog Signal

- Continuous
- May be periodic, e.g., sine wave
- Components
  - Amplitude
  - Phase
  - Frequency

Characteristics of Analog Signal



Characteristics of Analog Signal



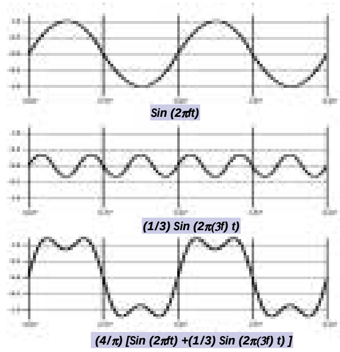
Domain Concepts

- Time domain concept
  - Signals viewed as a function of time
  - what we have seen so far
- Frequency domain concept
  - Signals viewed to be made of many constituent frequencies
  - More important to the understanding of data transmission

Frequency Domain

- A signal can be viewed as a function of frequency
- Any signal is made up of a number of sinusoidal waveforms of different frequencies
  - All frequency components are integer multiples of one frequency called **fundamental frequency**
  - multiples of fundamental frequency called **harmonics**
- Some examples: rainbow - combination of lightwave frequencies, musical sound - combination of different acoustic frequencies
- It is important to observe signal in the frequency domain because using Fourier analysis, we can illustrate the relationship between data rate and bandwith

Frequency Domain: Harmonics

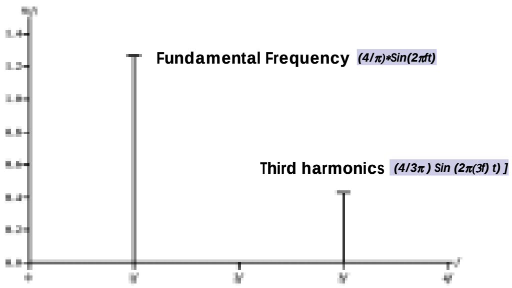


Fundamental Frequency

Third harmonics

Using Fourier analysis this signal can be decomposed into signals of above frequencies

Frequency Domain: Harmonics



Harmonics-example ...

- We can add more sine waves to our fundamental frequency wave to our example, and as more waves are added, the waves will create a smooth square wave (just like the digital signal shown in slide#20)
- A perfect square wave has infinite number of sinusoidal waves

$$s(t) = A \times \sum_{k=1,3,\ldots}^{\infty} \frac{1}{k} \sin(2\pi k f_1 t)$$

- Using Fourier analysis any signal can be decomposed into **fundamental frequency** and **harmonics**
- Higher harmonic has lesser contribution, hence, first few frequency components provide the most energy

Bandwidth

- Absolute bandwidth = $f_{highest} - f_{lowest}$
- Effective bandwidth = useful range of frequencies
  - where most of the energy of the signal is concentrated
  - only first few harmonics are used to reconstruct the signal
  - Normally communication medium should have effective bandwidth of signal and not absolute bandwidth
  - Note that the absolute bandwidth of a square wave is infinity
- Communication media can accommodate only a limited bandwidth

Bandwidth ...

Examples

- Piano Sound 30-4200Hz
- Human ear 30-18,000Hz
- Normal telephone channel 200-3500Hz
- Voice grade channel 0-4000Hz

Bandwidth

- Knowing the effective bandwith and the fact that a square wave can be approximated using a number of sine waves, we can now calculate the potential data rate of a given effective bandwith

Bandwidth and Data Rate …

- In communications, data rate is what we really interested in because we want to know how much data we can transmit in any given time
- Consider, the waves in the harmonics-example and a fundamental frequency of 1MHz
- Effective bandwidth = 3x(1MHz)-1MHz = 2 MHz
- Period (T) = $1/10^6 = 1\mu$ sec
- If we treat the square wave form as representation of 1 and 0 (+A = 1, -A=0), we have one bit occurs every 0.5 μ sec, thus in a second we will have 1/ 0.5 μ = 2 Mbps

(Assuming square wave is reconstructed by the first two frequency components only)

Bandwidth and Data Rate …

- What happen to the data rate if we increase the fundamental freq into 2 MHz?
- Effective bandwidth=3x2MHz - 2 MHz = 4 MHz
- Period = $1/(2x\ 10^6)=0.5\ \mu$ sec
- Each bit occurs every 0.25 μ sec
- Data rate = 1/0.25 μ = 4 Mbps
- What conclusion can you make about the relationship of bandwidth and data rate?

Bandwidth and Data Rate …

- Any transmission system has a limited band of frequencies
- Practically digital information is reconstruct-ed by signal of limited bandwidth
- Limited bandwidth of transmission system limits the data rate that can be carried
- The greater the bandwidth of the transmission system, the higher the data rate and the higher the cost
- For a digital signal of data rate W bps, a very good representation can be achieved with a bandwidth of 2W Hz

Classification based on Bandwidth

- Broadband Signal
  - uses analog signal
  - has large bandwidth (MHz and GHz range)
  - use analog modulation (see later)
  - Uses frequency division multiplexing for channel sharing (see later)
- Baseband Signal
  - uses digital signal
  - bandwidth is limited
  - Does not use modulation
  - Use time division multiplexing

Digital Signal

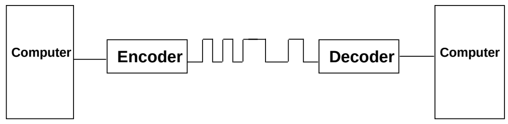
- Square wave forms
  - Periodic waveforms
  - Repetition rate
- Infinite harmonic (odd multiples of fundamental frequency)
- The principal advantages of digital signalling are that it is generally cheaper than analog signalling and it is less susceptible to noise interference
- The principal disadvantage is that digital signals suffer more from attenuation or reduction of signal strength

Digital Data

- Data is coded as binary digits (bits)
- A message is coded into a string of 0's and 1's
  - minimum message coding scheme, ...
- popular coding schemes for alpha and numeric characters are ASCII and EBCDIC

Digital Signal

- For transmission, binary information has to be converted into electrical signal (as square wave)



Baud Rate vs Bit Rate

- Rate of transmission can be expressed as:
  - baud rate- rate at which the condition of the circuit changes
  - bits/sec - rate at which information can be transmitted
    - known as channel capacity

Transmission Impairment

- Signal received may differ from signal transmitted
- Analog - degradation of signal quality
- Digital - bit errors
- Caused by
  - Attenuation and attenuation distortion
  - Delay distortion
  - Noise

Attenuation

- signal's strength reduces as it travels over a distance
- signal's strength can be boosted using amplifier or repeater
- amplifier (used in analog transmission) does not retransmit a new signal, i.e. it will boost not just the signal but also the noise
- Repeater (used in digital transmission) retransmit a new signal, when a repeater receive a signal, it recovers the bit pattern and retransmit a new signal

Delay distortion

- Caused by different Fourier components traveling at different speed
- Various frequency components arrive at receiver at different times
- Delay distortion causes intersymbol interference - one bit position spill into/overlap with other bit position
- Only applied to guided transmission media
- Limits maximum bit rate over a transmission channel

Noise

- Noise
  - sometime some unwanted signals are mixed into the intended signals
  - Unwanted signals = noise
- Type of noise
  - Thermal noise
    - caused by thermal agitation of electrons
    - cannot be eliminated - white noise
    - is a function of temperature
  - Crosstalk
    - unwanted coupling between signal paths

Noise ...

- Intermodulation noise
  - caused when signals at different frequencies share the same media
  - caused by nonlinear behavior of the system
  - example, mixing of f_1 and f_2 into $f_1 + f_2$ can cause interference with the intended signal with frequency of $f_1 + f_2$.
  - can be caused by component malfunction or excessive use of signal strength
- Impulse noise
  - short bursts of noise of high amplitude
  - caused by external electromagnetic interference or fault in communication system
  - not much of a problem for analog data but causes bit errors in digital data

Some Math Backgrounds-1

- Intensity level of a given sound is measured in decibels (dB)

$$\beta = 10\log_{10}\frac{I}{I_0}$$

I = intensity level

I_0 = an arbitrary reference intensity

- Originally, a scale of intensity levels in defined as *bels* (in the honour of Alexander Graham Bell)
- one-tenth of a bel is used => decibel

Some Math Backgrounds-2

- $\log_{10} X = Y \iff 10^y = X$
- $\log_{10} 1000 = 3 \iff 10^3=1000$
- $\log_{10} 0.001= -3 \iff 10^{-3}=0.001$
- $\log_{10} a/b = \log a - \log b$
- $10 \log_{10} a/b = 10 (\log_{10} a - \log_{10} b)$
  $= 10 \log_{10} a - 10 \log_{10} b$
- $\log_2 X = Y \iff 2^y=X$
- $\log_2 32 = 5 \iff 2^5=32$

Some Math Backgrounds-3

- Given a sound with intensity of 20dB, what is the ratio of intensity in absolute magnitude?
- $20 = 10 \log_{10}$ (ratio)
- $\log_{10}$ (ratio) = 20/10=2
- remember we are using base-10 log, hence we have ratio = 10^2=100
- In absolute magnitude, the ratio is 100:1
- Decibel unit provides a shorter notation for the intensity ratio. It is useful because intensity ratio in absolute term can be a big number

Channel Capacity

- communication facilities is expensive
  - price is a function of bandwidth,
  - the greater the bandwidth, the higher the cost of the channel
- bandwidth can also be limited by the nature of the transmission media or deliberate limitation from the transmitter to prevent interference
- Hence, the main objective of any communication engineers is *how to get the highest possible data rate with acceptable error rate in a given bandwidth*

Channel Capacity

- The maximum rate at which data can be transmitted over a given communication channel
- Four concepts that relate to each other in calculating channel capacity:
  - Data rate - bps
  - Bandwidth - hertz
  - Noise - average level of noise over communication path
  - Error rate

Measuring Channel Capacity

- Theoretical capacity of a given channel can be calculated using Nyquist or/and Shannon laws

Noiseless Channel

- Nyquist established the relationship between the channel capacity and the bandwidth of a **noiseless** communication channel as

$$C = 2 W \log_2 M$$

where

C is the channel capacity (bit rate)
W is the bandwidth of the line
M is the number of discrete signal levels

Example: W = 3100 Hz, M = 4 (2 bits per signalling element) then C = 12, 400 bps

Nyquist Formula

- Channel capacity is related to the bandwidth of the medium
- The criteria gives the impression that for a given medium of fixed bandwidth, data rate can be increased by increasing the number of different signal levels e.g.: BW = 3KHz, M = 64, then C = 36,000 bps
- The above observation is not practical because
  - the receiver needs to recognize more levels and hence the circuitry is complex
  - Noise and other impairments on the transmission medium limit the practical value of M

Nyquist Example

- Given a channel with 9600 bps, signal elements encode 4 bits-word, ie each signal represent 4 bits What is the required bandwidth for the channel?
- 4 bits-word requires 2^4=16 signal levels, on other words, if we have 4 bits, we can have 16 different combinations of 1 and 0, eg 0000, 0001,0010,…,1111 (16 of them), each of the combination is represented by one signal level. Thus, in our example we have M=16.
- $C=2W\log_2 M$ => $9600=2\ W \log_2 16$
- => $W = 9600/(2\log_2 16) = 9600/(2x4)=1200$ Hz

Noisy Channel

- In practice, some amount of noise is always introduced
- Noise is the limiting factor in computer communications performance
- Hence channel capacity cannot be increased indefinitely by increasing the number of signal levels
- Shannon introduces way of calculating channel capacity in noisy environment

Signal-to-Noise Ration (SNR)

- Important parameter in determining the performance of a transmission system
- Measured in dB as

  $(SNR)_{dB}$ = $10\log_{10}$ (Signal Power/Noise Power)

- A relative not absolute measure
- A high SNR (also represented as S/N) means high quality signal reception
- To change SNR in decibel to ratio of signal power to noise power:
  - Let SNR = X dB
  - X = 10 log (absolute ratio)
  - log (absolute ratio) = X/10
  - absolute ratio = $10^{(x/10)}$

Signal-to-noise ratio

- Example, let SNR=40dB
  - 40 = 10 log (ratio)
  - log (ratio)=40/10=4
  - ratio = 10^4=10000
  - ratio of signal power/noise power = 10000:1

Shannon's Law

- Shannon's law gives the theoretical maximum that can be achieved for a given transmission medium
- Actual capacity will be much less as other noises and signal attenuation are involved

$$C = W\log_2(1 + SNR)$$

- The signal-to-noise ratio used in the calculation is the *absolute number*, NOT the decibel value (this may cause some confusion for students, but you have been warned here ;-)), eg if SNR=30 decibels, we will use 1000 because the ratio in absolute number is 1000:1

Shannon's Law

- Example, what is the maximum capacity for a channel with bandwidth = 3100 (voice line) and SNR = 30 dB?

  Answer:
  - change the SNR to a absolute ratio

    => 30 dB = 1000:1
  - calculate capacity

    => C_{max} = 3100 $\log_2$ (1 + 1000)

    = 30,894 bps

Shannon's Law

- Gives theoretical maximum capacity
- In practice, only much lower data rates are achieved
  - considers white noise only
  - other noises are not taken into account
- From formula it appears that data rate could be increased by increasing either W or SNR, but …
  - Increasing bandwidth increases noise and decreases SNR
  - Increasing signal power increases nonlinearity causing more noise