# Concepts of Bandwidth & Capacity

* A communication channel is characterized by two main (related) attributes i.e. BANDWIDTH and CHANNEL CAPACITY.
* BANDWIDTH indicates the range of frequencies (expressed in Hz or cycles/per second) that can be successfully communicated over the communication channel. For example, the bandwidth of the human ear is 400-4000 Hz. This is also the bandwidth of most basic telephone lines.
* CHANNEL CAPACITY indicates the maximum rate at which data can be transmitted over a communication channel.

Quantifying Channel Capacity

* For noiseless channel (ideal case, not realized in practice due to signal attenuation and external interference), Nyquist Law defines the channel capacity:

**C = 2 W Log2V**

Where C = Channel capacity(bits per second)

W = Bandwidth (Hz)

V = Number of discrete signal levels (voltages, symbols)

Example of Nyquist Law

* Assuming a simple telephone line is noise free within a bandwidth of 3000 Hz (range: 1000-4000), and only two(2) discrete signal levels can be distinguished on a simple telephone line, the maximum data rate or channel capacity is :

C = 2 \* 3000 \* Log22

= 6000 bits/sec

Improving Channel Capacity

* For a fixed Bandwidth channel, its capacity can be improved by increasing V, i.e. introducing more discrete signal levels by using modulation techniques (amplitude, frequency) and data compression. This requires better hardware at the sending and receiving end of the channel.

If V = 8, C = 18 Kbps.

Data compression techniques may be used to further increase the channel capacity.

Capacity of a Noisy Channel

The capacity of a channel with random thermodynamic noise is defined by Shannon’s Law which states that

**C = W log2 (1 + S/N)**

where C = capacity(bits per second)

W = Bandwidth (Hz)

S/N = signal power/noise power

Example of Shannon’s Law

* A 3000 Hz channel with S/N = 1023 (typical S/N for a telephone line) has capacity

C = 3000 \* Log2 (1 + 1023)

C = 3000 \* 10

C = 30 Kbps

* Observe that Shannon’s Law establishes the maximum possible capacity regardless of number of signal levels used.

Capacity: data rate or baud rate

* Baud rate is the number of signal elements transmitted on a channel per second. The signal element may be discrete voltage, phase or frequency value, which identifies a unique symbol transmitted on the channel. Shannon’s Law establishes the maximum baud rate for a channel (i.e. symbols per second).
* Data rate is the maximum rate at which information bits may be transmitted on a channel. This may exceed the baud rate if a signal element represents more than one bit.

Example: data rate vs. baud rate

* If only two voltage levels are used, a signal element can represent a 1 or 0 i.e. only one bit. In this case, baud rate is the same as data rate.
* If 8 voltage levels are used, a signal element can represent 3 bits (v1=000, v2=001, v3=111). In this case, the data rate is three times the baud rate.

# Characteristics of Signals

Signals

Signals are a burst of energy characterized by a set of frequency components. In general, a signal may be Digital or Analog.

* + A continuous (or Analog) signal is one in which signal intensity varies in a smooth fashion over time, without breaks or discontinuities.
  + A discrete (or Digital) signal is one in which signal intensity maintains a constant level for some period of time and then changes to another constant level. Used to represent discrete values.
  + A periodic signal is one in which a signal pattern repeats over time. An example of a periodic analog signal is a sine wave. An example of a periodic digital signal is a square wave.

360° = 2π

A

A sin (2πft + Ø)

Time

Period (secs) = T = 1/f

* + Amplitude (A) is the peak value or strength of the signal over time.
  + Frequency (f) is the rate (in Hz or cycles/sec) at which the signal repeats.
  + Period (T) is the time (secs) duration of each repetition, i.e. 1/frequency.
  + Phase (Ø) is the relative position (0°-360°) in time within a single period of a signal.
  + If a signal is traveling at a velocity ν, it covers a distance νT during one period. This distance is called Wavelength (λ).

λ = νT = ν/f

λf = ν

A

Distance

λ = νT

A source of information may be analog in nature (e.g. voice) or digital (e.g. bits of data from a PC). This information may be transmitted as either digital or analog signal. A modem is used to transmit digital data as an analog signal. A codec is often used to transmit analog data (e.g. voice) as a digital signal e.g. with ISDN (64Kbps or DSØ ).

The presence of noise causes values of bits in a digital signal to get modified (1’s become 0’s and vice-versa). These “bit errors” are often scattered.

Signal-to-Noise (S/N) may be expressed using decibels (dBs) where:

(S/N) dB = 10 log10 (Signal power / Noise power)

So an S/N ratio of 1000 implies (S/N) dB = 10 log10 (1000)

= 10 \* 3

= 30 dB

frequency f, or a range f1-f2

Amplitude

t

Analog Signal (Continuous w.r.t. time, may take any value within a range)

6

5

4

3

Discrete set of values

2

t

Discrete Signal (Discontinuous w.r.t. time, may take only one of a set of values)

# The Digital Telephone Exchange Network

Example of a Telephone System

Digital source

Computer 010101…..

D-to-A conversion

Modem

A-to-D Modem

~analog signal

~analog signal

Digital Exchange

Digital Exchange

Long distance links carrying digital data

Reconstruction of Analog Signal

Sampling

Telephone (analog source)

Telephone (analog destination)

Telephone signal which is analog up to exchange is sampled at the exchange by taking 5 samples per second. Each sample value is represented by b bits/sample. So s \* b bits/second are generated.

7

e.g.

b=3

s=10

30 bits/sec

0

Sample Interval = 1/s seconds

**Sampling**

These bits are transmitted via a digital link (dedicated to a conversation) between the source and destination telephone exchanges. At the destination exchange the analog signal is reconstructed from the sample bits, and sent to the receiving telephone.

Analog-to-Digital Conversion

* Voice and video signals are inherently analog in nature. These signals must be converted to digital form before transmission over a channel. This is accomplished in two steps:
  1. Sampling
  2. Pulse Code Modulation (PCM)

Nyquist Criterion for Sampling

* + - The Nyquist criterion for sampling states that an analog signal which contains frequency components no higher than H can be completely reconstructed by obtaining only 2H samples per second.
    - For example, an analog signal containing frequencies within 4000 Hz can be reconstructed by taking samples at a rate of 2 \* 4000 samples per second.

Sampling Techniques

W = 4 KHz, Ts 1/8000 = 125μs

Sampling Interval = 1/2W seconds

Some Information Sources, Frequencies, and Sampling Rates

|  |  |  |
| --- | --- | --- |
| Information Type | Frequency Range (BW) | Sampling Rate |
| Telephone Speech | 4KHz | 8000/sec |
| Hi-Fidelity Audio | 20KHz | 40,000/sec |
| Video Signal | 6MHz | 12 million/sec |

Pulse Code modulation (PCM)

The value of each sample (i.e. the amplitude of the signal at the sampling point) is represented by certain number of bits. This set of bits is then transmitted over a digital transmission line-a technique called PCM. For example, when analog voice signal is received at a digital exchange, it is sampled using 8 bits per sample. This requires that inter-exchange digital channel support 8000 samples/sec \* 8 bits/sample, or, 64 Kbps. This channel capacity (also called as DSØ signal) is the most basic building block of digital telephone lines.

# Points to Ponder………..

* Bandwidth, Channel Capacity.
* Nyquist Law for noise-free channel.
* Shannon’s Law for noisy channel.
* Data rate versus Baud rate.
* Analog to Digital conversion-sampling.
* Nyquist Criterion for sampling.
* Pulse Code Modulation (PCM).

# Organization & Structure of Data Communication Systems

Data Communication Systems are a complex structure consisting of components implementing a collection of key functions:

* Interfacing.
* Signal Generation (EM, Light WLs).
* Synchronization & Exchange Management & Flow Control.
* Error Detection & Correction (Parity, CRC, Check Sum).
* Addressing (unique source & destination) & Routing (via network).
* Receiving.
* Message Formatting (machine architecture, same binary code, ASCII, EBCDIC).
* Security (encryption).
* Network Management (configure, monitor, account).
* Transmission System Utilization (best allocation of facilities among users)

The collection of the above communication functions is organized into a structured model called the OSI Model

Simplified Data Communications Model

Analog signal

Digital bit signal

Analog signal

Digital bit signal

Received signal r (t)

Recovered data g (t)'

Destination

Text

Receiver

Transmitted signal s (t)

Transmitter

Trans-mission

System

Generated data g (t)

Source Text

The Transmission System in this model could be a “do nothing” pass-through channel, or an elaborate channel performing A-to-D and D-to-A conversion, and transmitting the digital data over long distances. Since dedicated point-to-point links connecting the transmitter and receiver are impractical, the Transmission System in the above model takes the form of a communication network which allows communicating nodes (receivers, transmitters) to “attach” themselves to the network. This network may be a LAN or a WAN.

Some Fundamental Data Transmission Concepts

* Data transmission between transmitter and receiver may occur over a Guided or Unguided Medium. Guided medium guides the transmission along a physical path e.g. twisted pair, coaxial or fiber-optic cable. Unguided medium supports transmission of EM waves (but without guiding) through air, vacuum or water.
* Transmission of data may be

1. Simplex: Signals are transmitted only in one direction; the role of transmitter and receiver is fixed.
2. Half-Duplex: Both stations may transmit or receive, but neither can perform both functions simultaneously.

A (T)

A (R)

B (T)

B (R)

A (R)

B (T)

A (T)

B (R)

A (R)

B (T)

A (T)

B (R)

Not Possible

t

1. Full-Duplex: Both stations may transmit and receive simultaneously, like during a telephone conversation.