Chapter 3: Data Transmission

Terminology (1)

- Transmitter
- Receiver
- Medium
  - —Guided medium
    - e.g. twisted pair, optical fiber
  - —Unguided medium
    - e.g. air, water, vacuum

Terminology (2)

- Direct link
  - —No intermediate devices
- Point-to-point
  - —Direct link
  - —Only 2 devices share link
- Multi-point
  - —More than two devices share the link

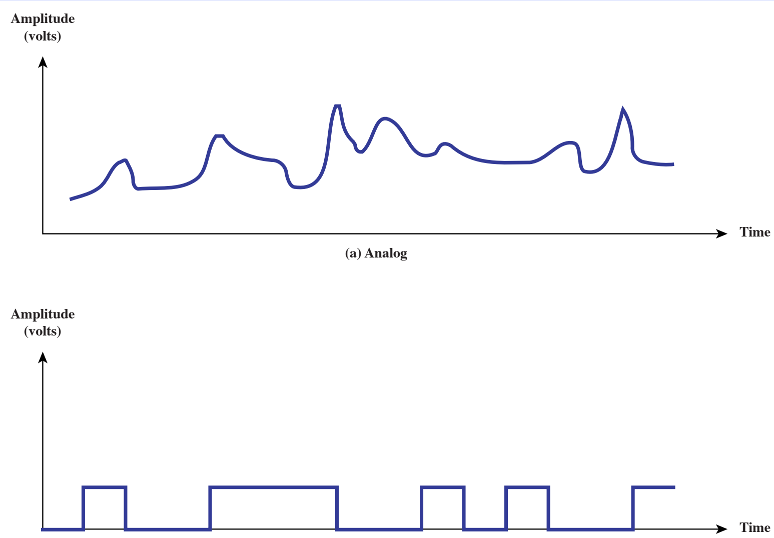
Terminology (3)

- Simplex
  - —One direction
    - e.g. Television
- Half duplex
  - —Either direction, but only one way at a time
    - e.g. police radio
- Full duplex
  - —Both directions at the same time
    - e.g. telephone

Frequency, Spectrum and Bandwidth

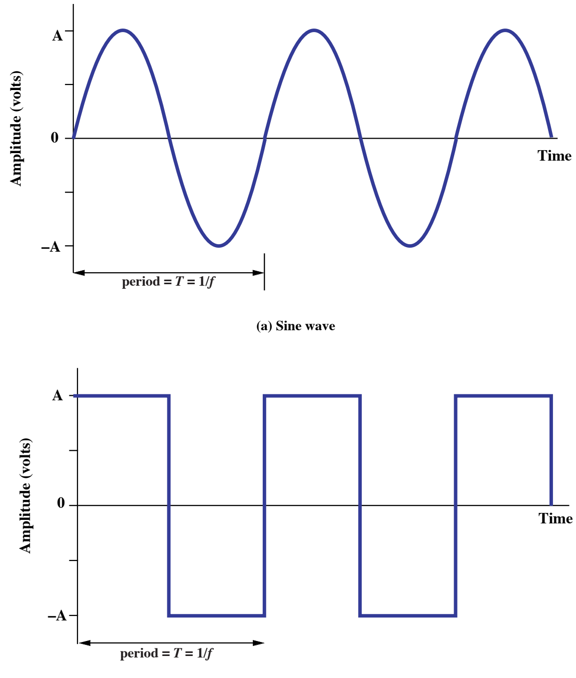
- Time domain concepts
  - —Analog signal
    - Varies in a smooth way over time
  - —Digital signal
    - Maintains a constant level then changes to another constant level
  - —Periodic signal
    - Pattern repeated over time
  - —Aperiodic signal
    - Pattern not repeated over time

Analogue & Digital Signals



(b) Digital

Periodic Signals



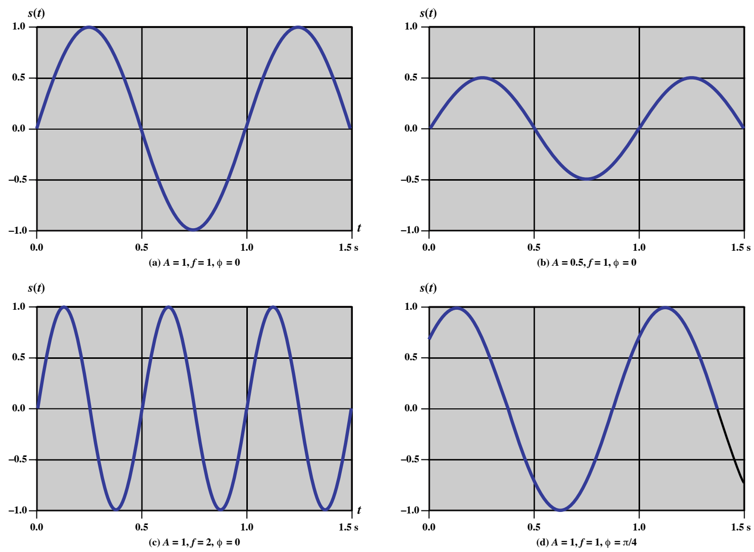
(a) Sine wave

(b) Square wave

Sine Wave

- Peak Amplitude (*A*)
  - —maximum strength of signal, in volts
- Frequency (*f*)
  - —Rate of change of signal, in Hertz (Hz) or cycles per second
  - —Period = time for one repetition (T), $T = 1/f$
- Phase (ϕ)
  - —Relative position in time
- Periodic signal $s(t+T) = s(t)$
- General wave $s(t) = A\sin(2\pi ft + \Phi)$

Periodic Signal: e.g. Sine Waves $s(t) = A \sin(2\pi ft + \Phi)$



Wavelength

- Distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- Wavelength λ
- Assuming signal velocity v

$\lambda = vT$ [unit is m]

$\lambda f = v$

$c = 3*10^8$ m/s (speed of light in free space)

Frequency Domain Concepts

- Signal is usually made up of many frequencies
- Components are sine waves
- It can be shown (Fourier analysis) that any signal is made up of component sine waves
- One can plot frequency domain functions

Building block for waves

- What is a square wave?
  - —What frequency components are digital signals composed of?
  - —How many components do I need to recreate a square wave?
  - —What is a realistic spectrum?
  - —Where is the main energy of the signal?
  - —Below is a representation of a square wave with amplitude A:

$$s(t) = \frac{A4}{\pi} \sum_{k\ odd, k=1}^{\infty} \frac{1}{k} \sin(2\pi k f t)$$

Physical Aspects

- Limited Bandwidth
  - —Fourier Analysis

$$v(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t$$

$$a_0 = \frac{1}{T}\int_0^T v(t)dt$$

$$a_n = \frac{2}{T}\int_0^T v(t)\cos(n\omega_0 t)dt$$

$$b_n = \frac{2}{T}\int_0^T v(t)\sin(n\omega_0 t)dt$$

$v(t)$ = voltage as a function of time
ω_0 = fundamental frequency component in radians / second
f_0 = fundamental frequency in Hz
$T = 1/f_0$ = period in seconds

Physical Aspects

- Limited Bandwidth (cont.)
  - —Unipolar

$$v(t) = \frac{V}{2} + \frac{2V}{\pi}\{\cos\omega_0 t - \frac{1}{3}\cos 3\omega_0 t + \frac{1}{5}\cos 5\omega_0 t - \ldots\}$$

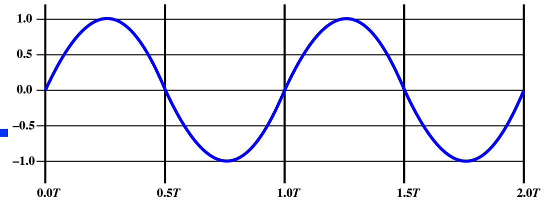
  - —Bipolar

$$v(t) = \frac{4V}{\pi}\{\cos\omega_0 t - \frac{1}{3}\cos 3\omega_0 t + \frac{1}{5}\cos 5\omega_0 t - \ldots\}$$

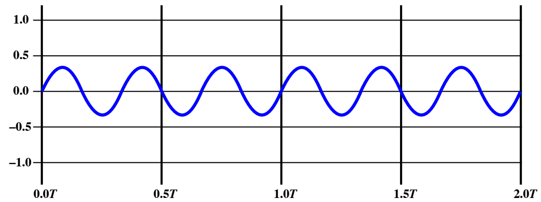
How much bandwidth do we need?

What are the trade-offs if we compromise bandwidth?

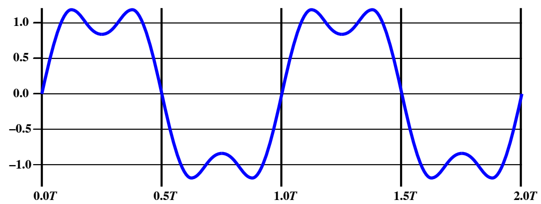
Addition of Frequency Components (T=1/f)



(a) sin (2πft)

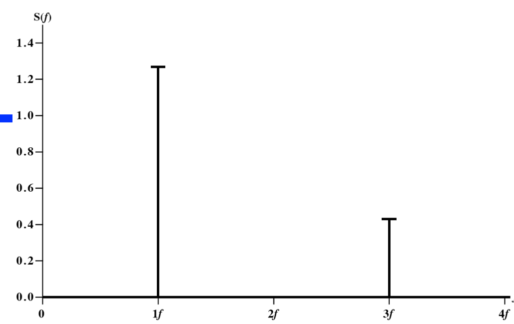


(b) (1/3) sin (2π(3f)t)



(c) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]

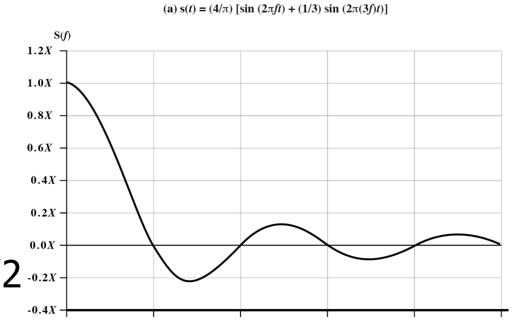
Spectrum of previous example



(a) s(t) = (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]

Single pulse:

between -X/2 and X/2

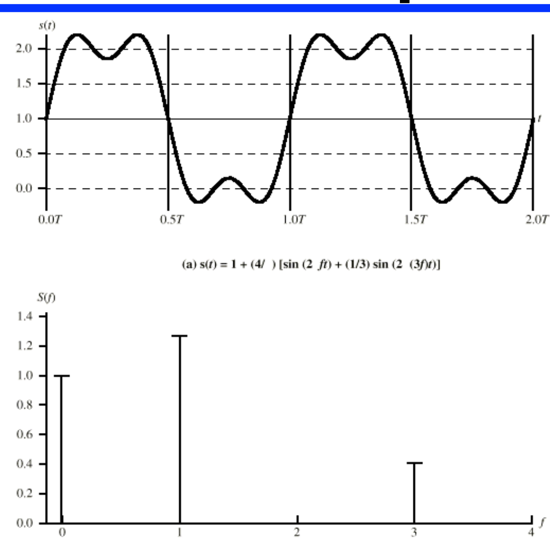


(b) s(t) = 1 − X/2 ≤ t ≤ X/2

Spectrum & Bandwidth

- Spectrum
  - —range of frequencies contained in signal
- Absolute bandwidth
  - —width of spectrum
- Effective bandwidth
  - —Often just *bandwidth*
  - —Narrow band of frequencies containing most of the energy
- DC Component
  - —Component of zero frequency

Signal with DC Component



(a) s(t) = 1 + (4/) [sin (2 ft) + (1/3) sin (2 (3f)t)]

(b) S(f)

Data Rate and Bandwidth

- Any transmission system has a limited band of frequencies
- This limits the data rate that can be carried
- Issues
  - —The more bandwidth the less distortion
  - —Where is the bulk of the energy?

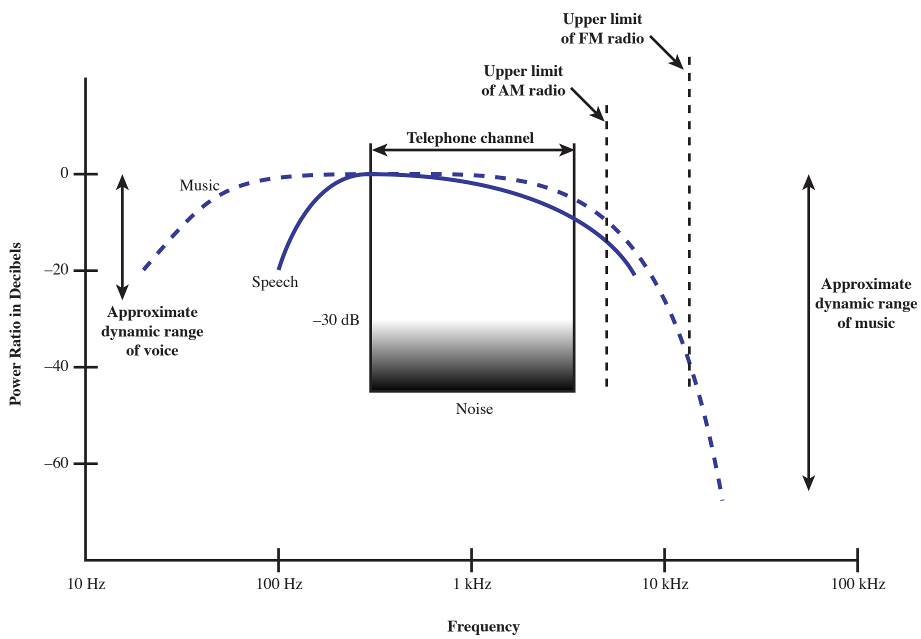
Analog and Digital Data Transmission

- Data
  - —Entities that convey meaning
- Signals
  - —Electric or electromagnetic representations of data
- Transmission
  - —Communication of data by propagation and processing of signals

Analog and Digital Data

- Analog
  - —Continuous values within some interval
  - —e.g. sound, video
- Digital
  - —Discrete values
  - —e.g. text, integers

Acoustic Spectrum (Analog)



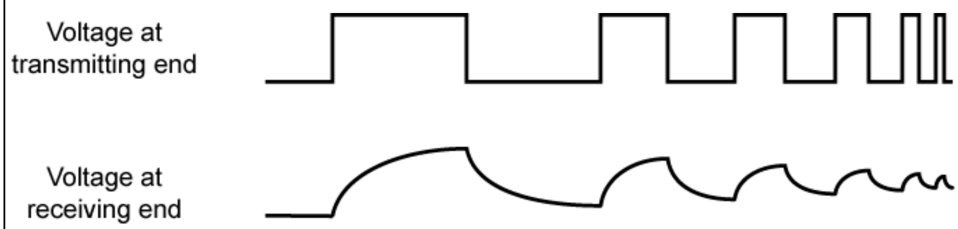
Analog and Digital Signals

- Means by which data are propagated
- Analog
  - —Continuously variable
  - —Various media
    - wire, fiber optic, space
  - —Speech bandwidth 100Hz to 7kHz
  - —Telephone bandwidth 300Hz to 3400Hz
  - —Video bandwidth 4MHz
- Digital
  - —Use two DC components

Advantages & Disadvantages of Digital

- Cheaper
- Less susceptible to noise
- Greater attenuation
  - —Pulses become rounded and smaller
  - —Leads to loss of information

Attenuation of Digital Signals

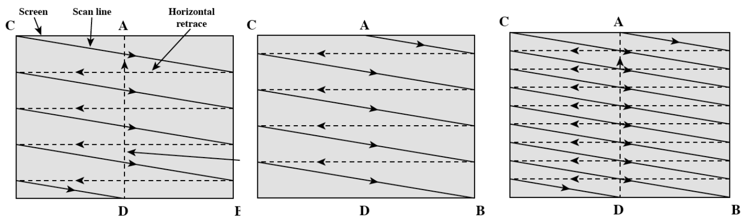


Components of Speech

- Frequency range (of hearing) 20Hz-20kHz
  - Speech 100Hz-7kHz
- Easily converted into electromagnetic signal for transmission
- Sound frequencies with varying volume converted into electromagnetic frequencies with varying voltage
- Limit frequency range for voice channel
  - 300-3400Hz

Video Components

- USA - 483 lines scanned per frame at 30 frames per second
  - 525 lines but 42 lost during vertical retrace
- So 525 lines x 30 scans = 15750 lines per second
  - 63.5μs per line, (11μs for retrace, so 52.5 μs per video line)
- Max frequency if line alternates black and white
- Horizontal resolution is about 450 lines giving 225 cycles of wave in 52.5 μs
- Max frequency of 4.2MHz



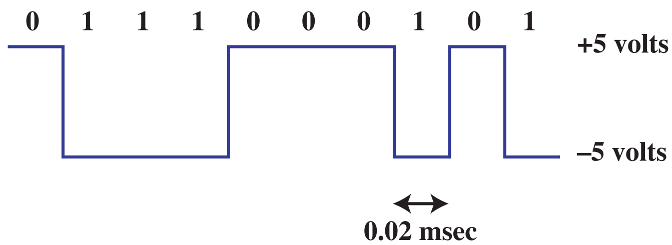
(a) Even field only (b) Odd field only (c) Odd and even fields

Binary Digital Data

- From computer terminals etc.
- Two dc components
- Bandwidth depends on data rate

Conversion of PC Input to Digital Signal

- as generated by computers etc.
- has two dc components
- bandwidth depends on data rate



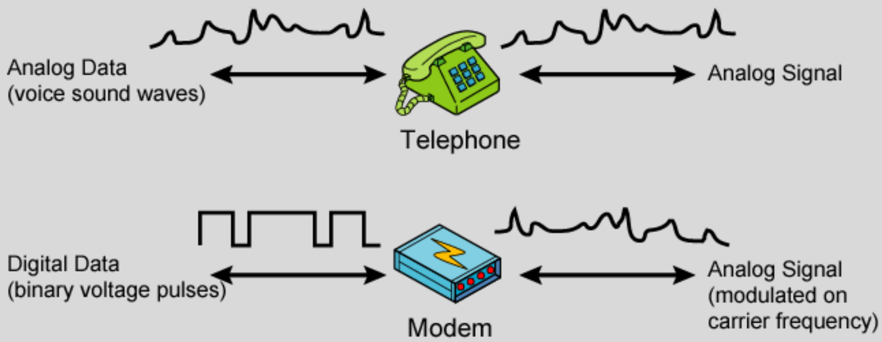
User input at a PC is converted into a stream of binary digits (1s and 0s). In this graph of a typical digital signal, binary one is represented by –5 volts and binary zero is represented by +5 volts. The signal for each bit has a duration of 0.02 msec, giving a data rate of 50,000 bits per second (50 kbps).

Data and Signals

- Usually use digital signals for digital data and analog signals for analog data
- Can use analog signal to carry digital data
  - —Modem
- Can use digital signal to carry analog data
  - —Compact Disc audio

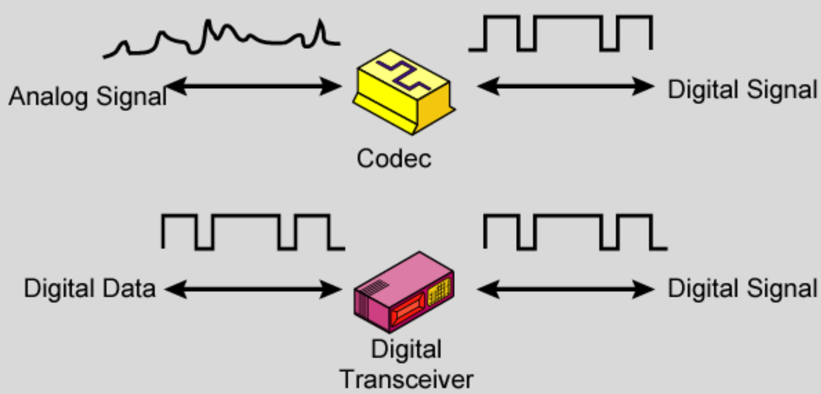
Analog Signals Carrying Analog and Digital Data

Analog Signals: Represent data with continuously varying electromagnetic wave



Digital Signals Carrying Analog and Digital Data

Digital Signals: Represent data with sequence of voltage pulses



Transmission Impairments

- Signal received may differ from signal transmitted causing:
  - —analog - degradation of signal quality
  - —digital - bit errors
- Most significant impairments are
  - —attenuation and attenuation distortion
  - —delay distortion
  - —noise

Attenuation

- Signal strength falls off with distance
- Depends on medium
- Received signal strength:
  - —must be enough to be detected
  - —must be sufficiently higher than noise to be received without error
- Attenuation is an increasing function of frequency

Delay Distortion

- Only in guided media
- Propagation velocity varies with frequency

Noise (1)

- Additional signals inserted between transmitter and receiver
- Thermal
  - Due to thermal agitation of electrons
  - Uniformly distributed
  - White noise
- Intermodulation
  - Signals that are the sum and difference of original frequencies sharing a medium

Noise (2)

- Crosstalk
  - —A signal from one line is picked up by another
- Impulse
  - —Irregular pulses or spikes
  - —e.g. External electromagnetic interference
  - —Short duration
  - —High amplitude

Digital Transmission

- Concerned with content
- Integrity endangered by noise, attenuation etc.
- Repeaters
  - —Repeater receives signal
  - —Extracts bit pattern
  - —Retransmits
  - —Attenuation is overcome
  - —Noise is not amplified

Analog Transmission

- Analog signal transmitted without regard to content
- May be analog or digital data
- Attenuated over distance
- Use amplifiers to boost signal
- Also amplifies noise

Advantages of Digital Transmission

- Digital technology
  - Low cost LSI/VLSI technology
- Data integrity
  - Longer distances over lower quality lines
- Capacity utilization
  - High bandwidth links economical
  - High degree of multiplexing easier with digital techniques
- Security & Privacy
  - Encryption
- Integration
  - Can treat analog and digital data similarly

Channel Capacity

- Data rate
  - —In bits per second, bps (not Bps)
  - —Rate at which data can be communicated
- Bandwidth
  - —In cycles per second of Hertz, Hz
  - —Constrained by transmitter and medium
- Convention: not all k's are equal
  - — data rates are given as power of 10
    - e.g., kHz is 1000Hz
  - — data is given in terms of power of 2
    - e.g., KByte is 1024 Bytes

Nyquist Bandwidth

- If rate of signal transmission is 2B then a signal with frequencies no greater than B is sufficient to carry the signal rate.
  - —Why? Assume we have a square wave of repeating 101010. If a positive pulse is a 1 and a negative pulse is 0, then each pulse lasts 1/2 T_1 ($T_1 = 1/f_1$) and the data rate is $2f_1$ bits per second.

Nyquist Bandwidth

- If we limit the components to a maximum frequency (restrict the bandwidth) we need to make sure the signal is accurately represented.
- Based on the accuracy we require, the bandwidth can carry a particular data rate. The theoretical maximum communication limit is given by the **Nyquist** formula:

$$C = 2B \log_2 M$$

C = capacity or data transfer rate in bps
B = bandwidth (in hertz)
M = number of possible signaling levels

Signal Strength

—An important parameter in communication is the strength of the signal transmitted. Even more important is the strength being received.

—As signal propagates it will be *attenuated* (decreased)

—*Amplifiers* are inserted to increase signal strength

—Gains, losses and relative levels of signals are expressed in decibels

- This is a logarithmic scale, but strength usually falls logarithmically
- Calculation of gains and losses involves simple addition and subtraction

—Decibel measure of difference in two power levels is

$$N_{dB} = 10 \log_{10} \frac{P_1}{P_2}$$

Physical Aspects

- Signal Attenuation and Distortion
  - —As a signal propagates across a transmission medium its amplitude decreases. This is known as **signal attenuation.**
  - —A typical signal consists of a composition of many frequency components (Fourier Analysis). Due to the limited transmission bandwidth of a medium, the higher frequency components may not be able to be transmitted.
    - Recall the **Nyquist** formula

$$C = 2B\log_2 M \qquad \log_2(x) = \frac{\ln\,(x)}{\ln\,(2)}$$

Delay Distortion

- —Different frequency components of a signal
  - are attenuated differently, and
  - travel at different speeds through guided media
- —This may lead to **delay distortion**

Shannon capacity

—A transmission line may experience interference from a number of sources, called **noise**. Noise is measured in terms of signal to noise power ratio, expressed in decibels:

$$\left(\frac{S}{N}\right)_{dB} = 10\log_{10}\left(\frac{S}{N}\right)\text{dB}$$

—The effects of noise on channel capacity can be seen using the **Shannon-Hartley Law:**

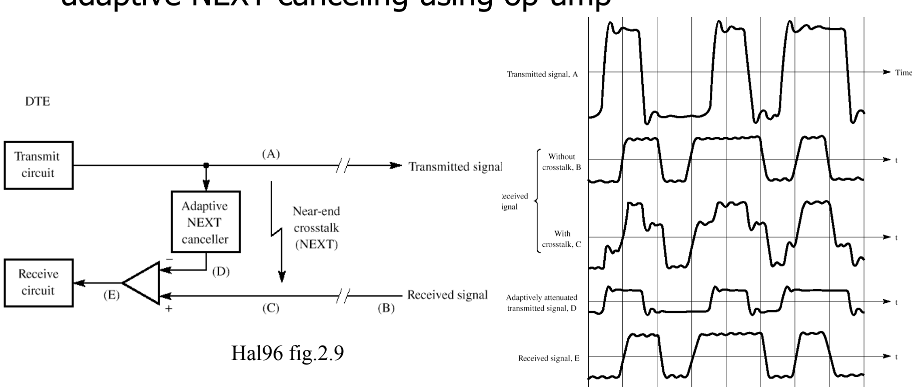
$$C = B\log_2\left(1+\frac{S}{N}\right)\text{ bps}$$

C = data transfer rate in bps
B = bandwidth (in hertz)

Cross Talk -- NEXT canceling

—near-end crosstalk (NEXT), cross talk of strong transmit (output) signal to weak receive (input) signal.

—adaptive NEXT canceling using op-amp



Hal96 fig.2.9

Noise

- Impulse Noise
  - impulse caused by switching, lightning etc.
- Thermal Noise
  - present irrespective of any external effects
  - caused by thermal agitation of electrons

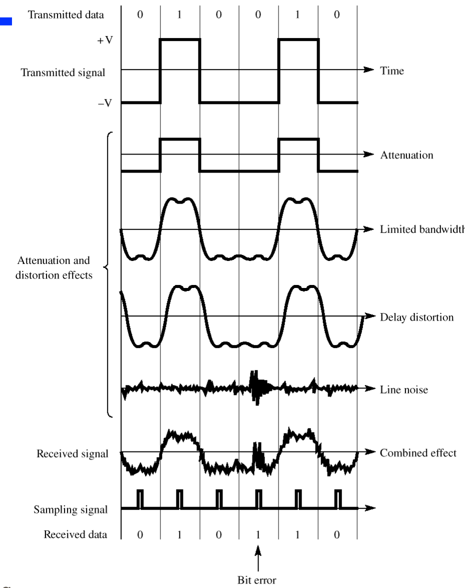
Noise

- White Noise
  - random noise – entire spectrum
- Pink Noise
  - "realistic spectrum"
  - the power spectral density is inversely proportional to the frequency

Combined Effects

- Attenuation
- Limited Bandwidth
- Noise

It all adds up!



Hal96 fig.2.6

Thermal Noise

—Energy (in joules = watts x seconds) per bit in a signal:

$$E_b = ST_b$$

S = signal power in watts
T_b = time period for 1 bit in seconds

—Data Transmission rate $R = 1/T_b$

—Thermal noise N_0 in a line is: (T is temperature in K)

$$N_0 = kTW \text{ where } \quad k = 1.3803 \times 10^{-23} \text{ joule K}^{-1}$$

k is Boltzmann constant

W is the bandwidth

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S/R}{kTW}$$

Signal Delay

—There exists a **transmission propagation delay** in any medium

- Speed of light 3 x 10^8 ms^{-1}
- Speed of EM in cable/wire 2 x 10^8 ms^{-1}

—Important parameter is **round-trip-delay** (time from first bit sent to last bit acknowledged)

Signal Delay

—Propagation delay T_p and transmission delay T_x

$$T_P = \frac{d}{V}, \; T_x = \frac{n}{R}$$

—Important ratio $\frac{T_P}{T_x}$

d = distance in meters
V = EM speed

n = number of bits transmitted
R = link bit rate in bits per second