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

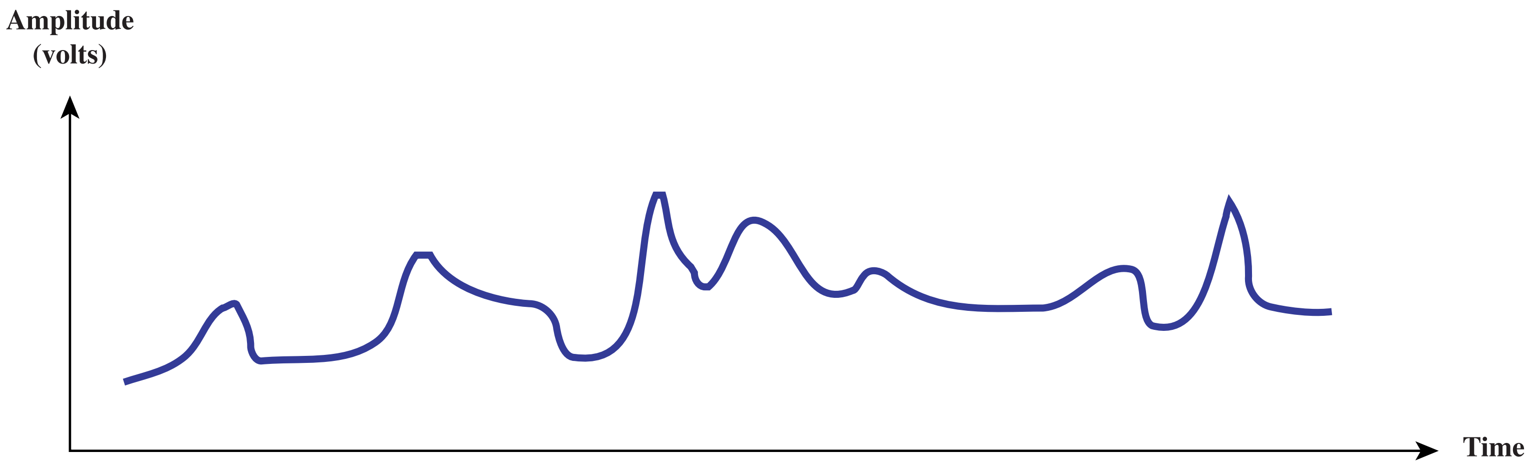
Terminology (3)

- 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

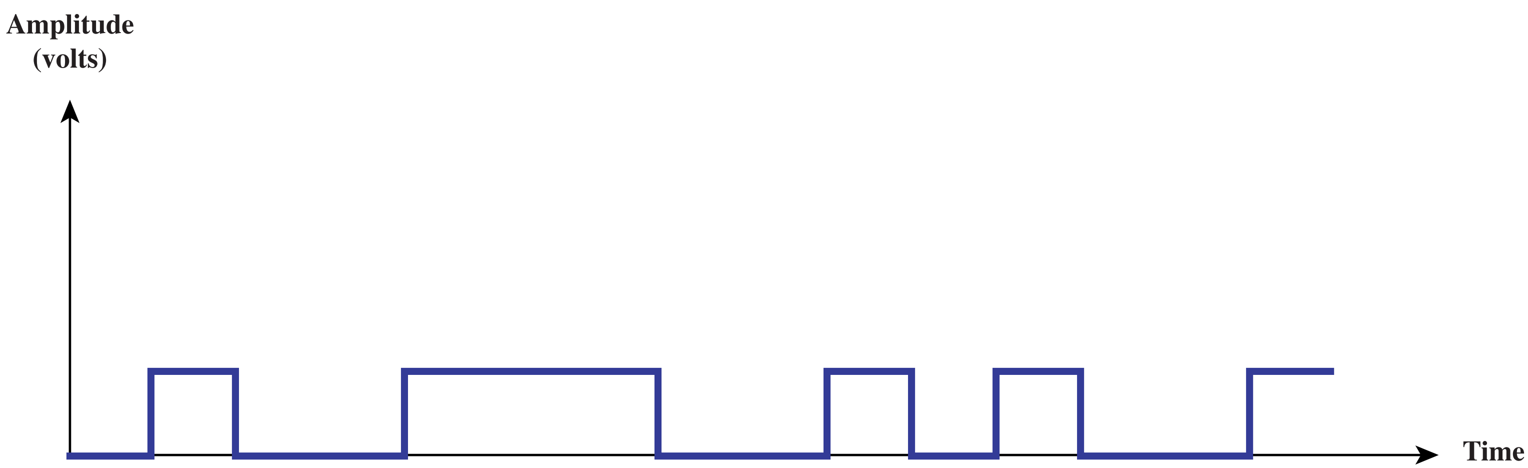
Frequency, Spectrum and Bandwidth

- 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

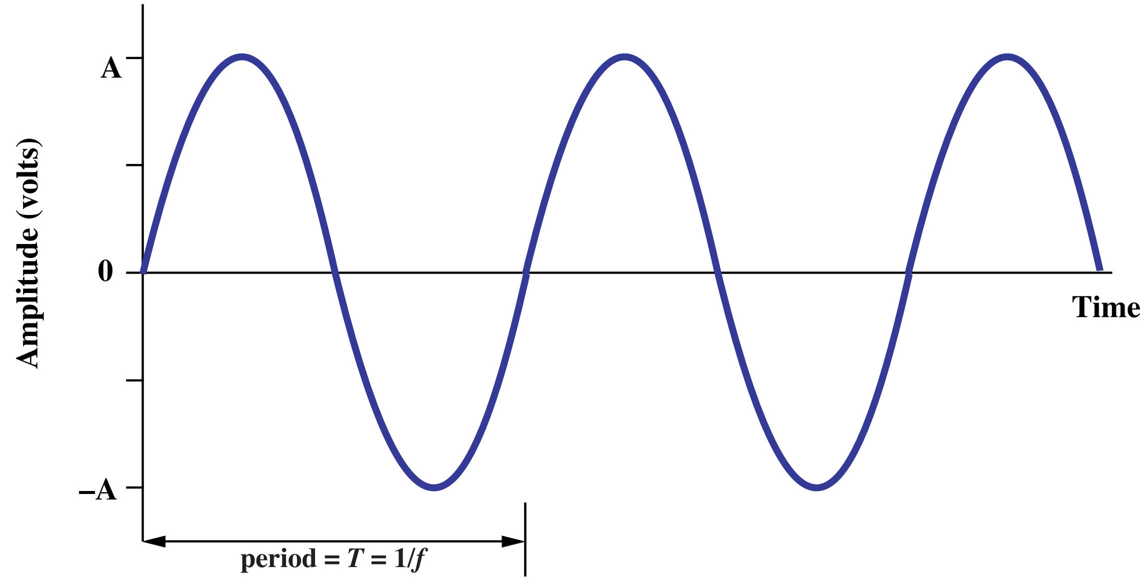


(a) Analog

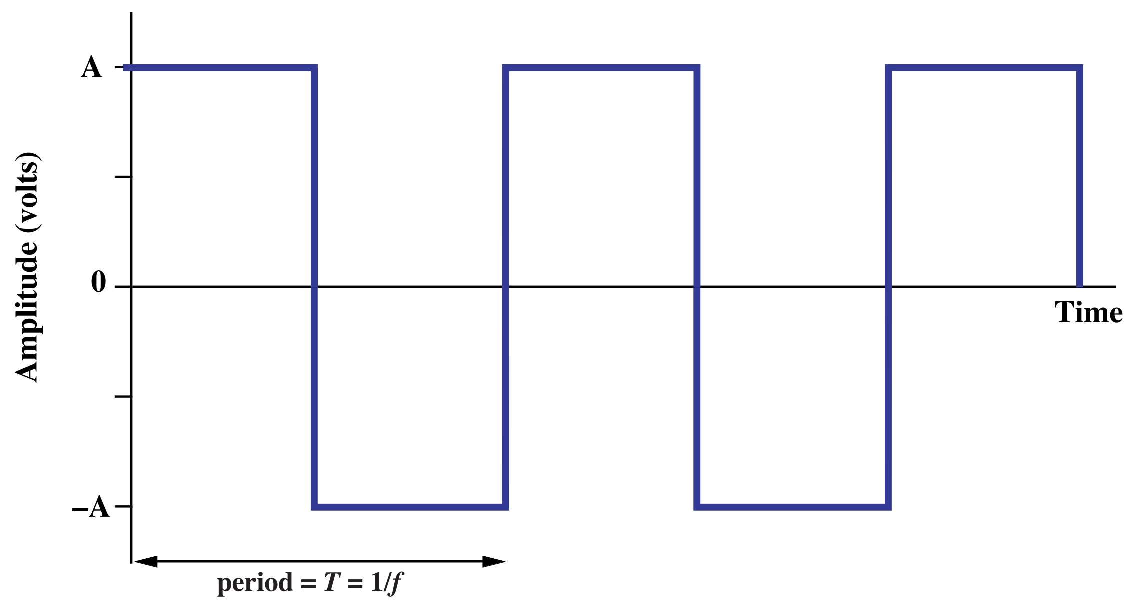


(b) Digital

Periodic Signals



(a) Sine wave

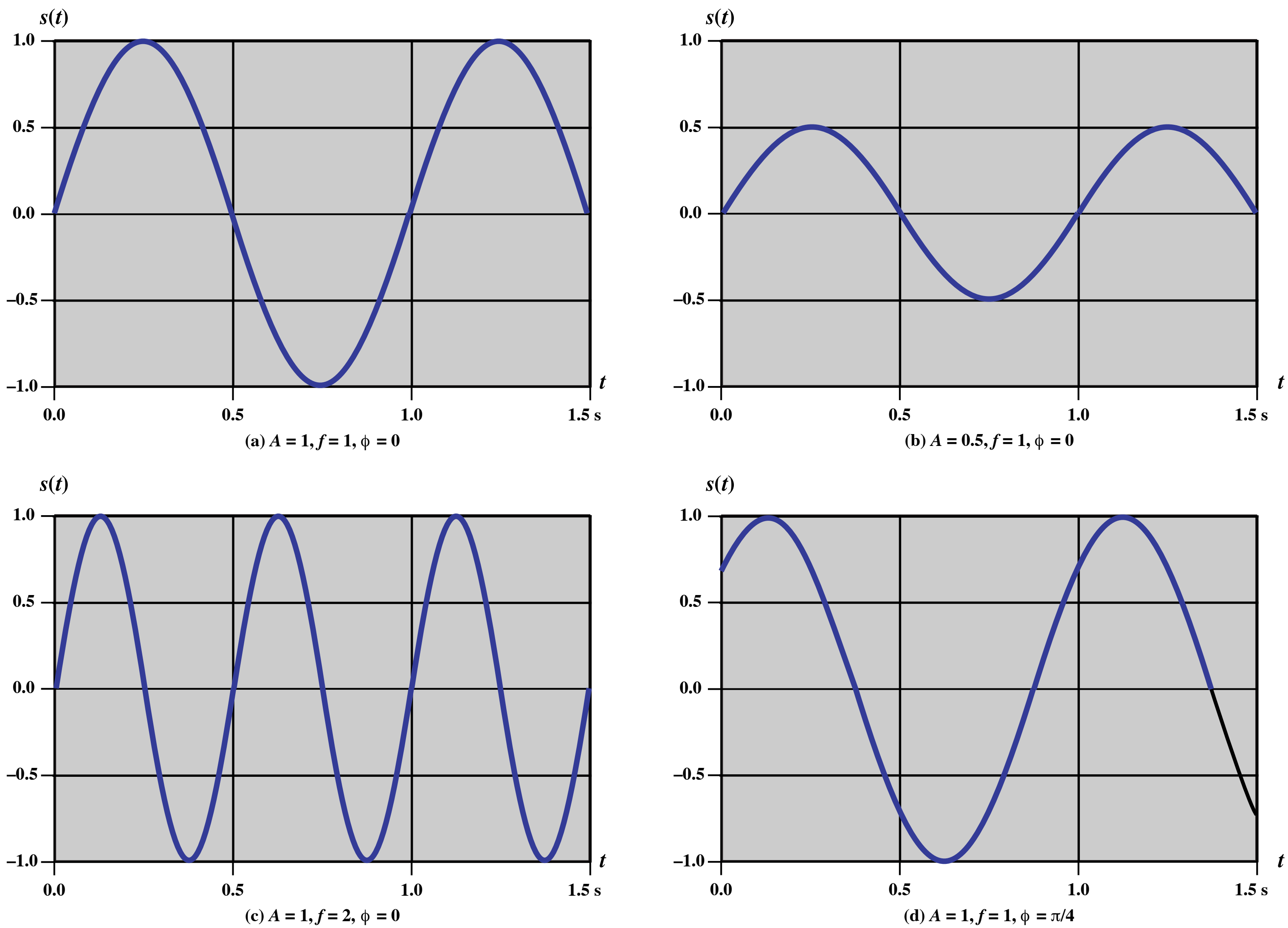


(b) Square wave

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

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

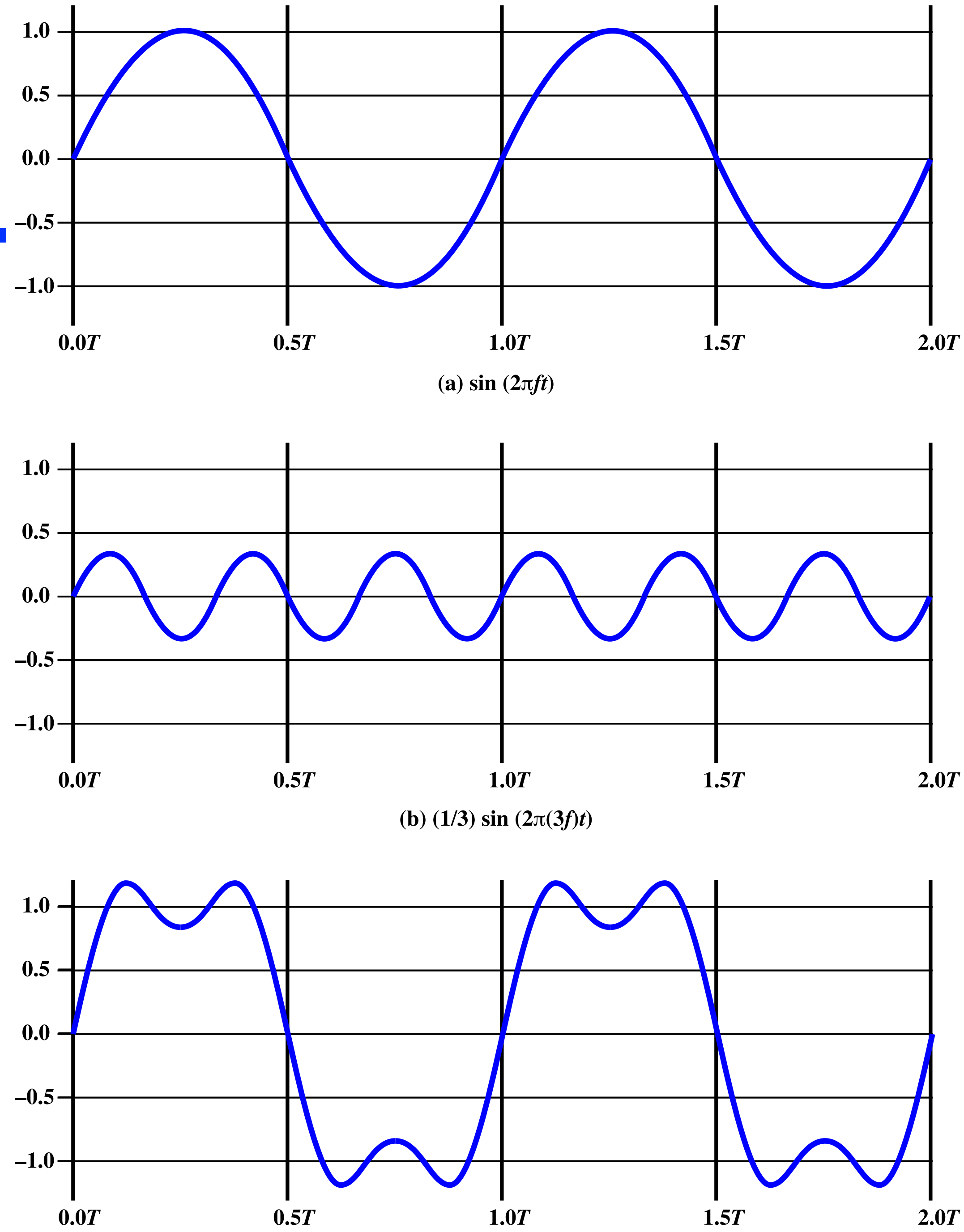
  - Bipolar

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

How much bandwidth do we need?

What are the trade-offs if we compromise bandwidth?

Addition of Frequency Components (T=1/f)

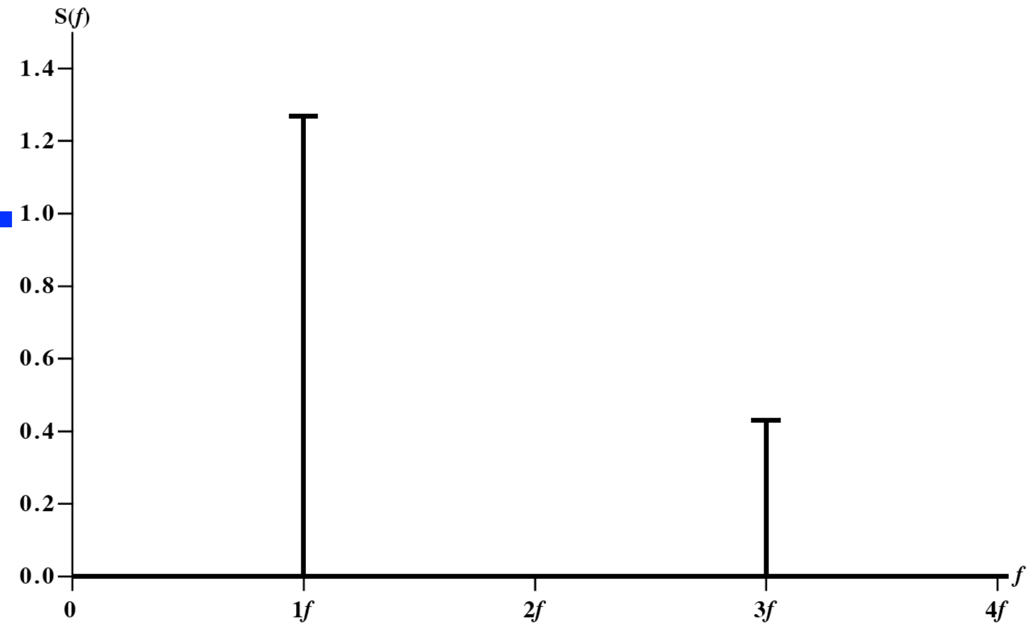


(a) sin (2πft)

(b) (1/3) sin (2π(3f)t)

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

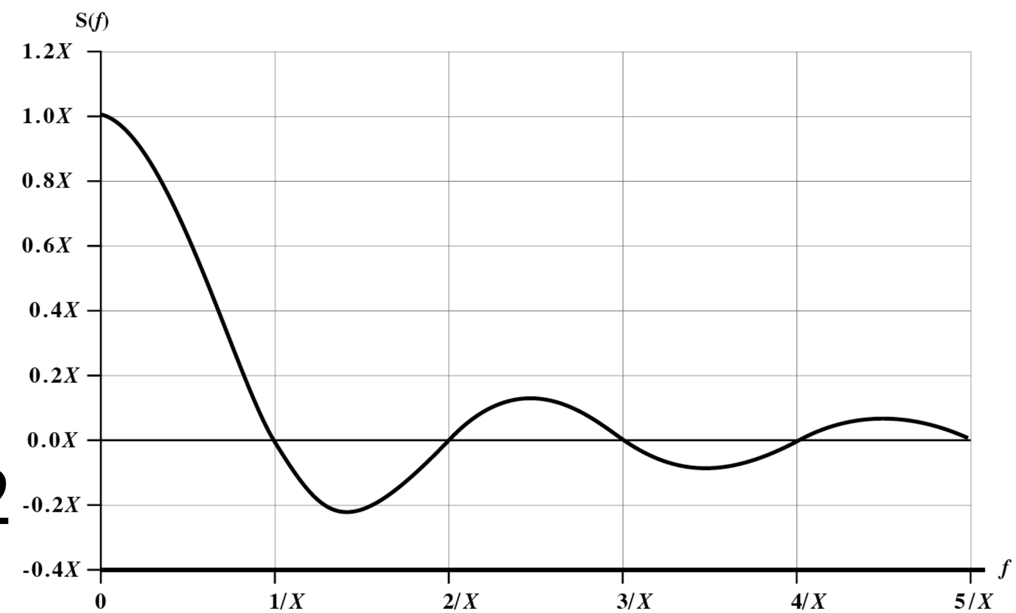
Spectrum of previous example



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

Single pulse:

between -X/2 and X/2

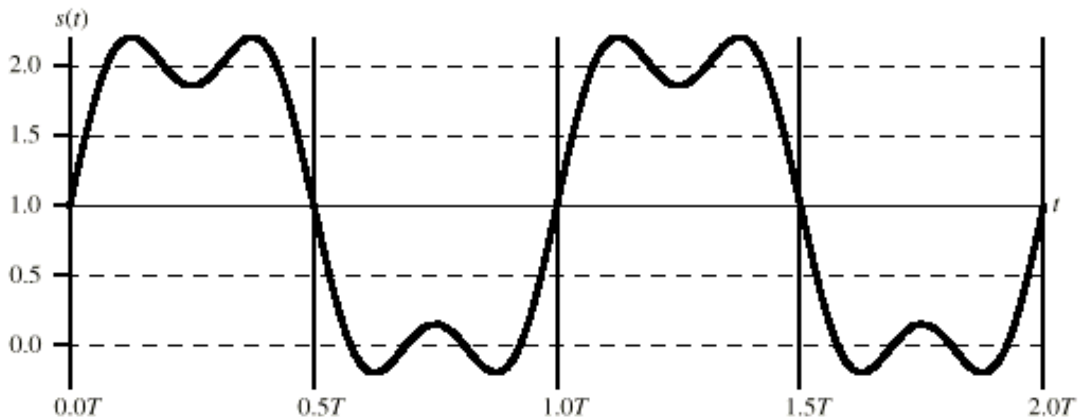


(b) s(t) = 1 − X/2 ≤ t ≤ X/2

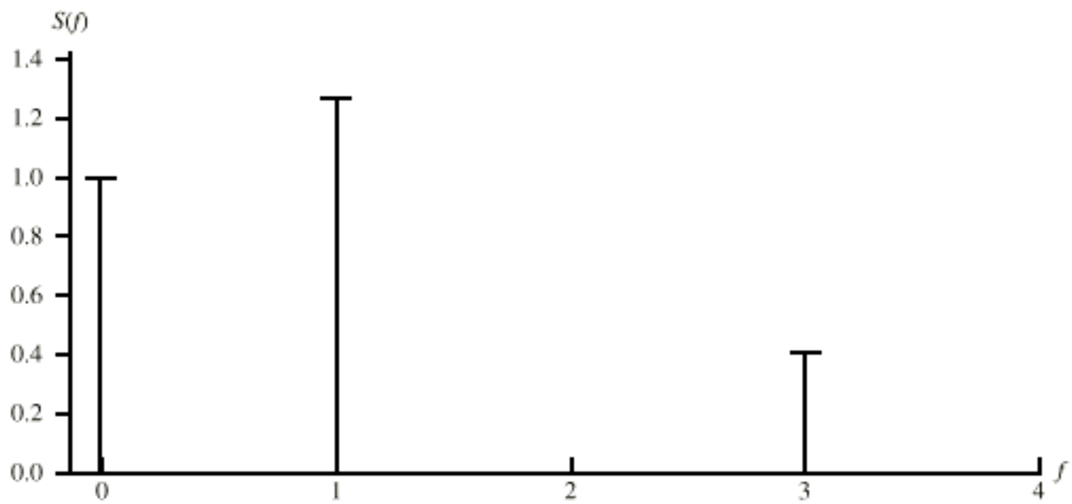
Spectrum & Bandwidth

- 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?

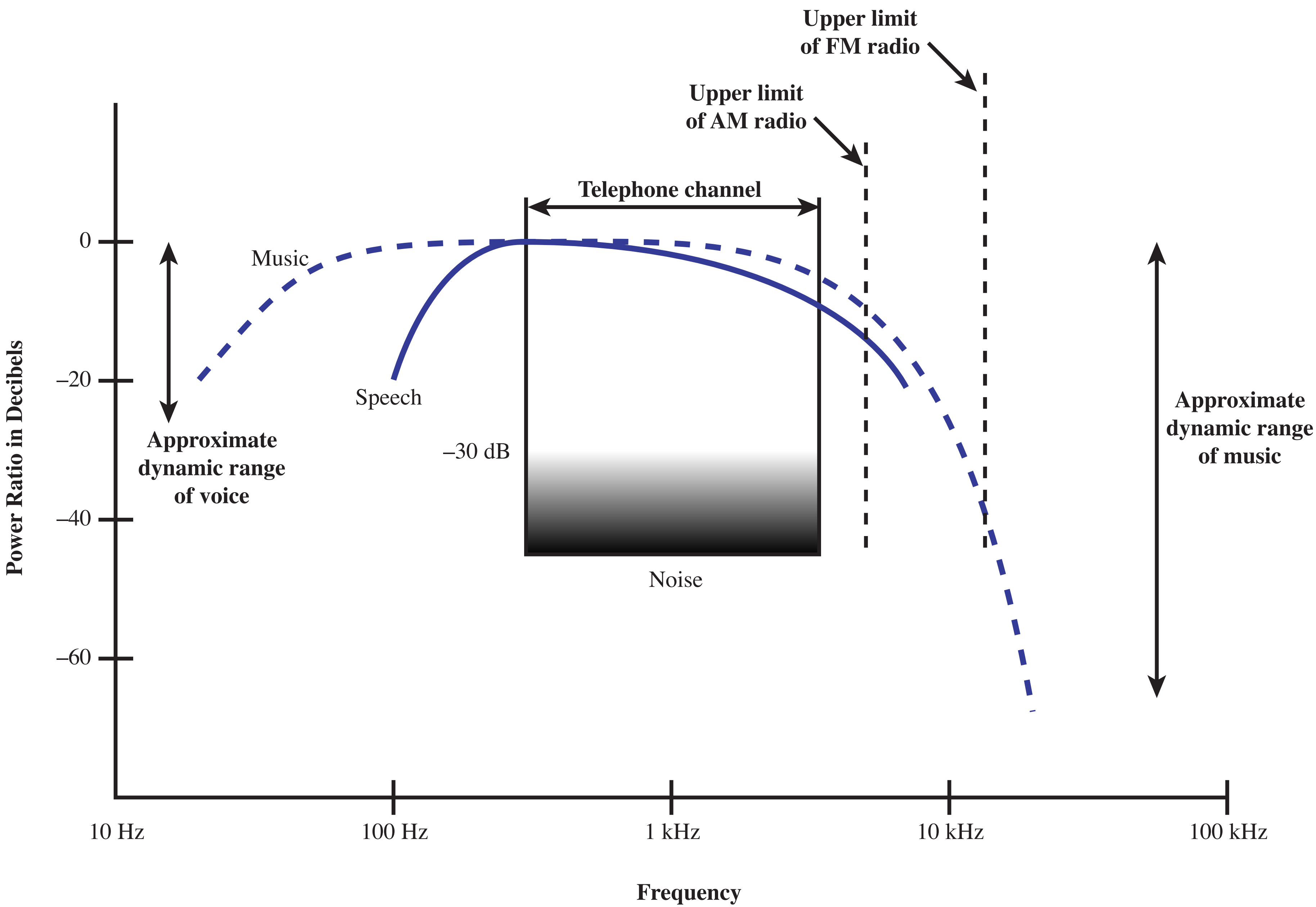
Analog and Digital Data Transmission

- 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)



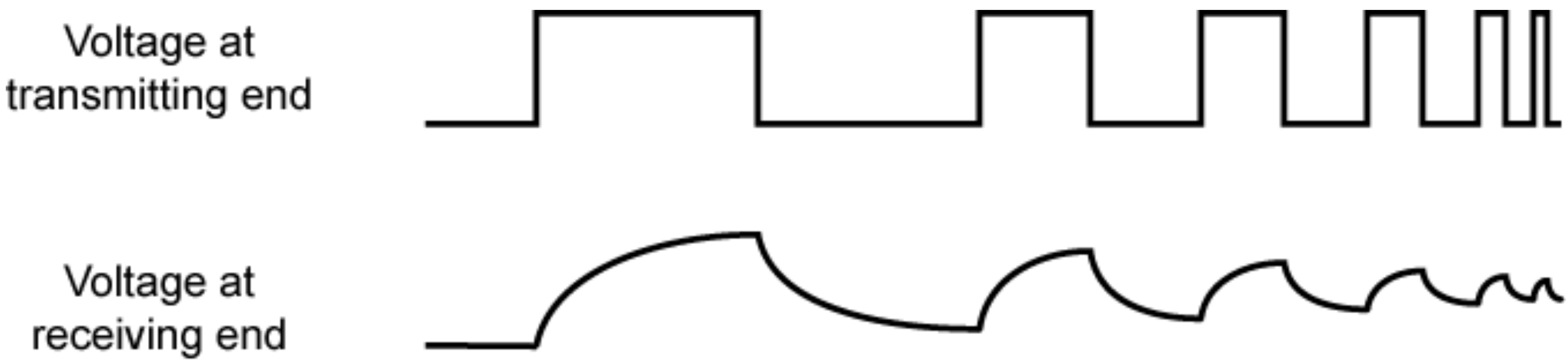
Analog and Digital Signals

- 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

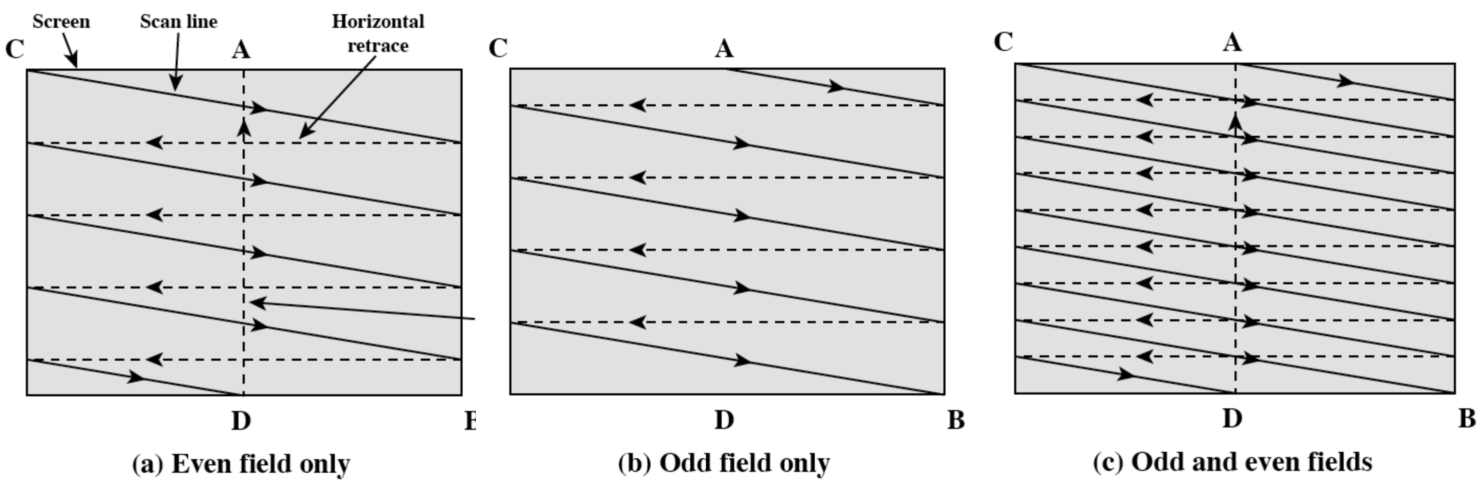


Components of Speech

- 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

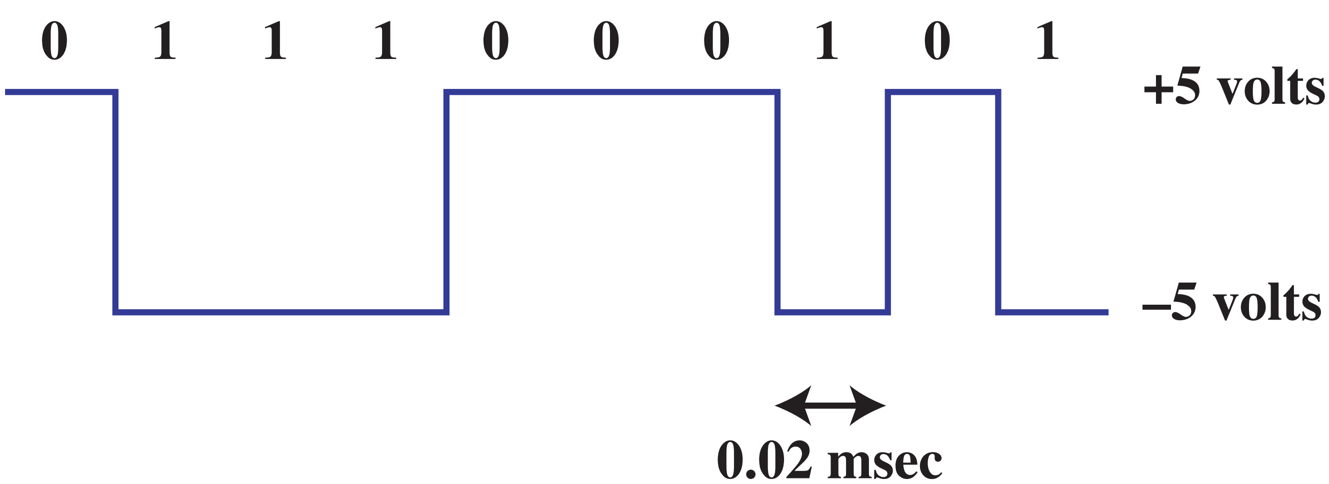


Binary Digital Data

- 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

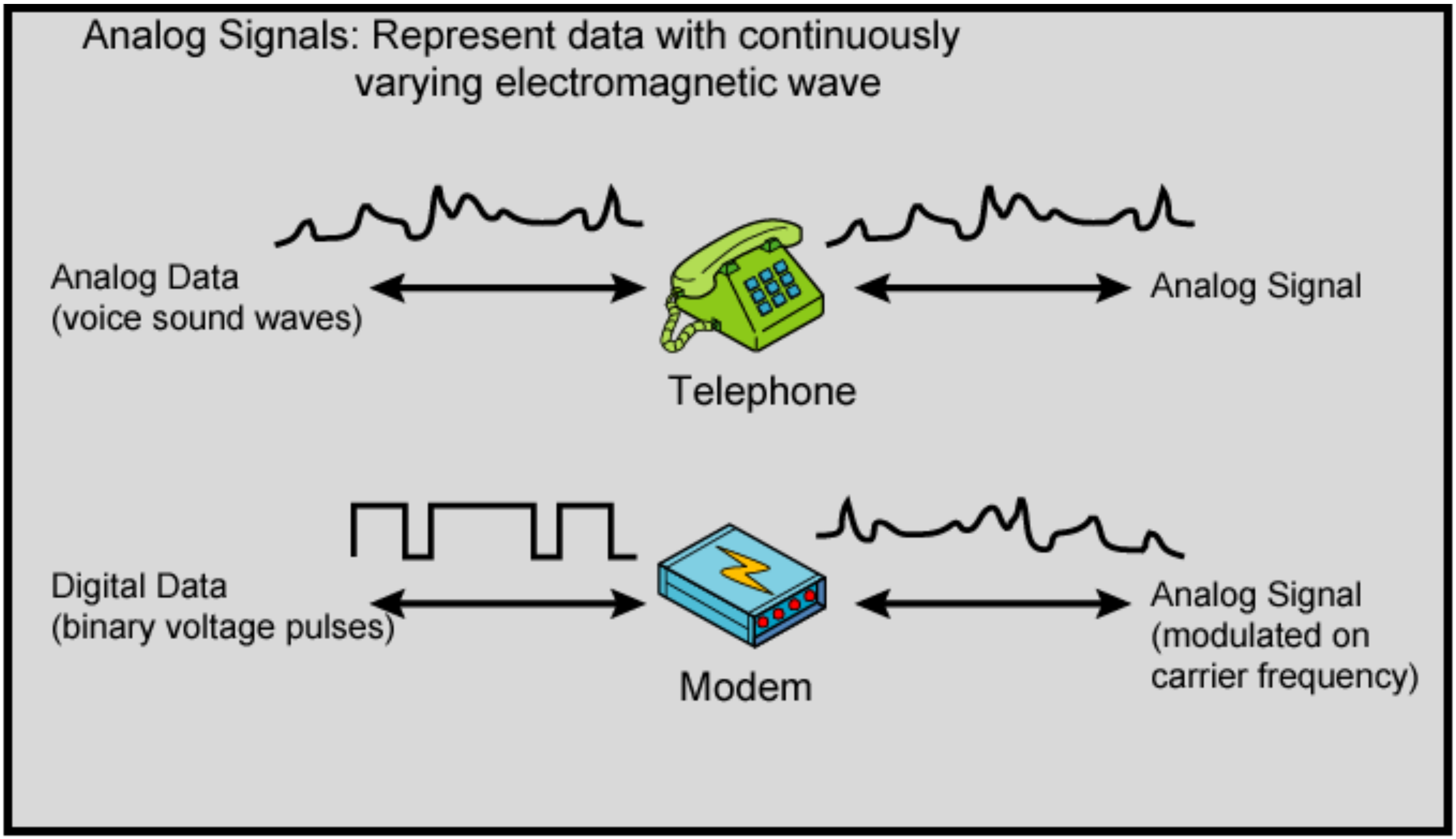


User input at a PC is converted into a stream of binary digits (1s and 0s). In this graph of a typical digital signal, binary one is represented by –5 volts and binary zero is represented by +5 volts. The signal for each bit has a duration of 0.02 msec, giving a data rate of 50,000 bits per second (50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

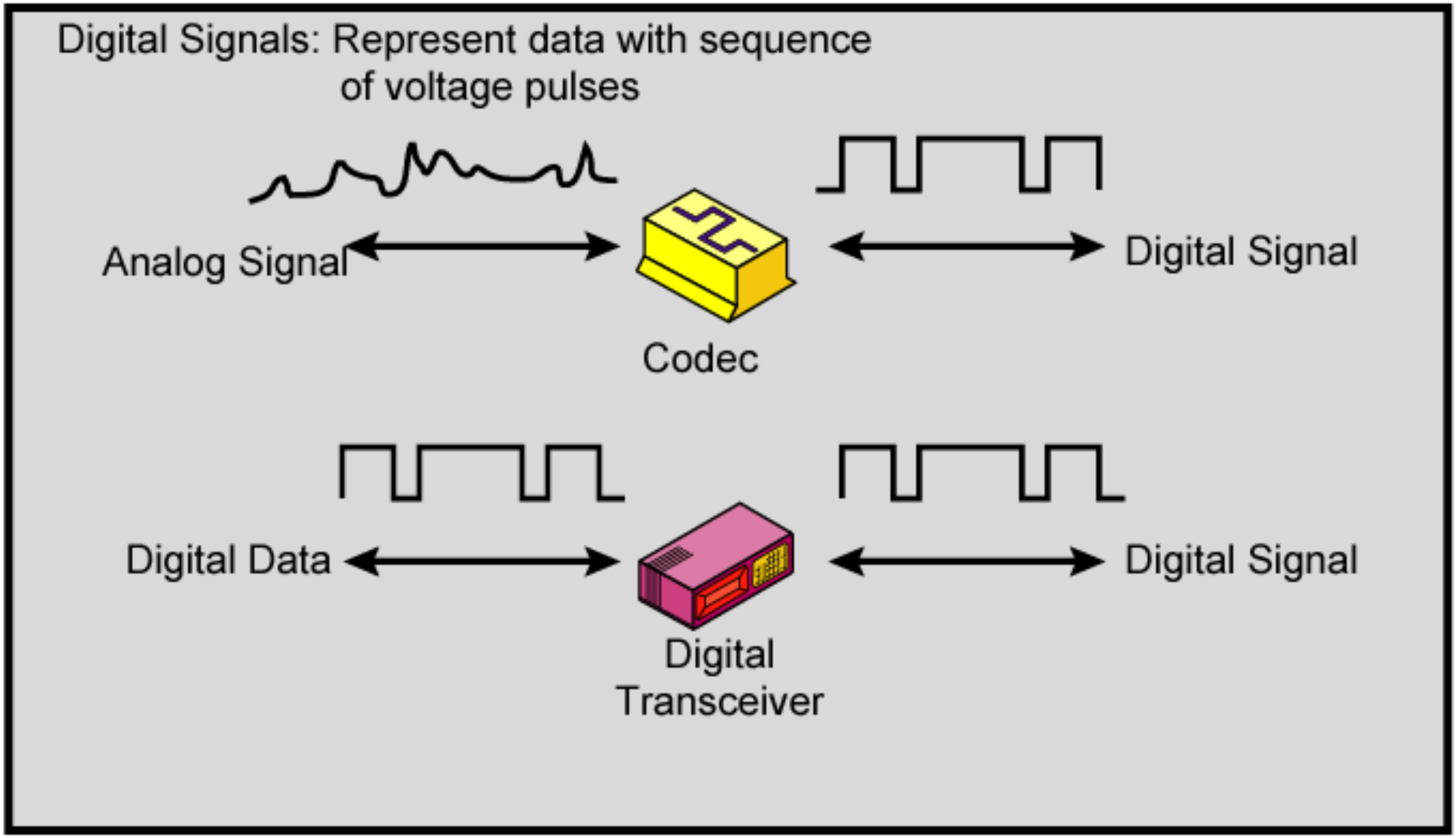
Data and Signals

- 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



Digital Signals Carrying Analog and Digital Data



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

$$C = 2B\log_2 M$$

$$\log_2(x) = \frac{\ln(x)}{\ln(2)}$$

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:

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

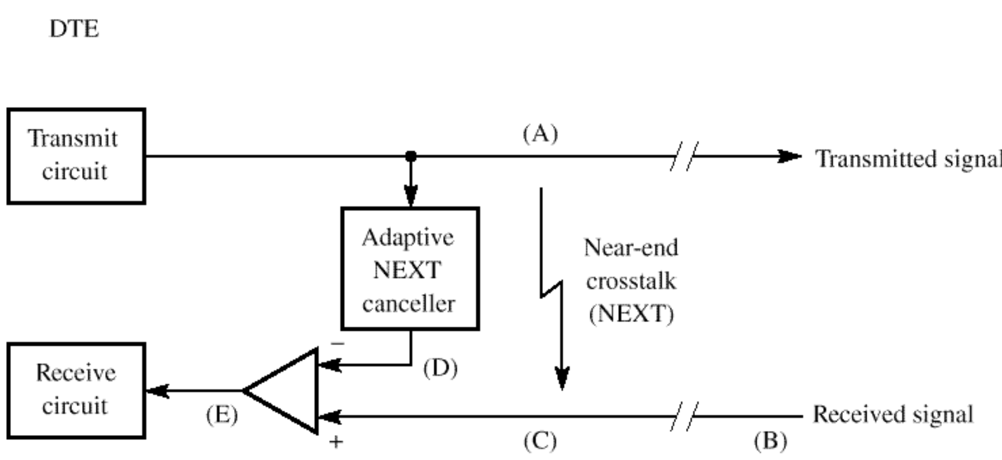
- The effects of noise on channel capacity can be seen using the **Shannon-Hartley Law:**

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

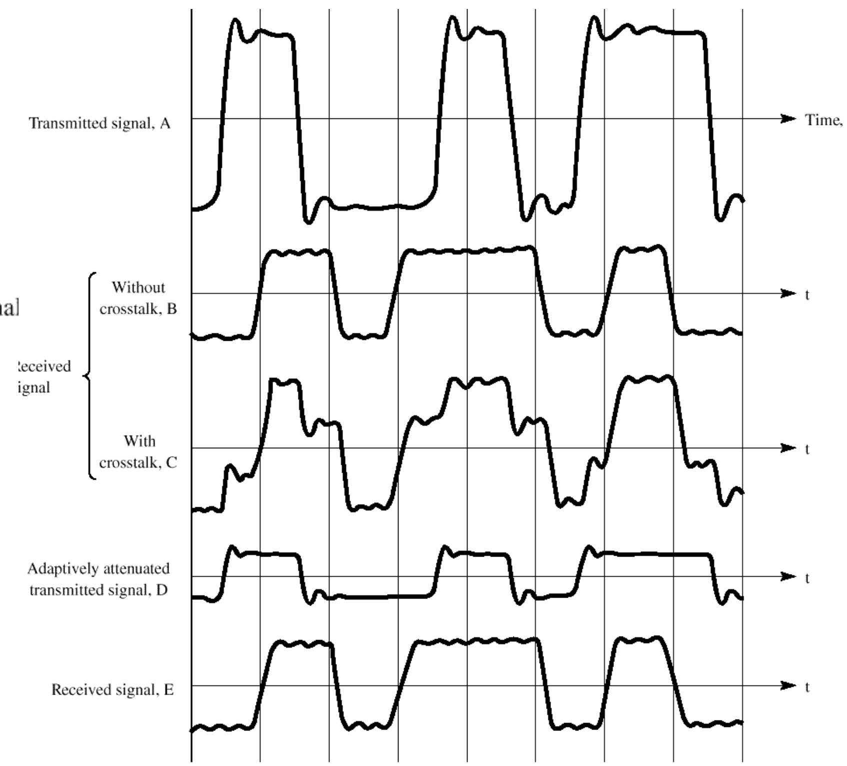
C = data transfer rate in bps
B = bandwidth (in hertz)

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

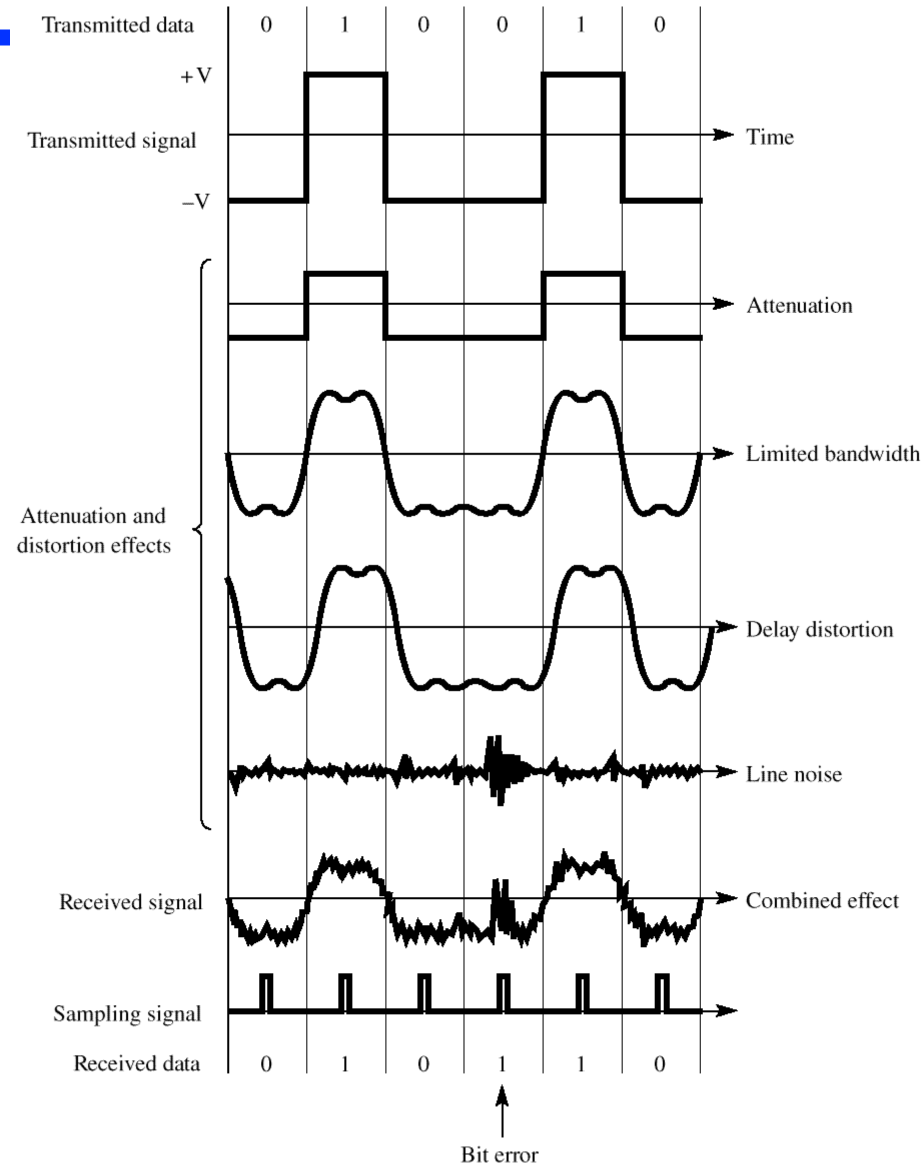
- White Noise
  - random noise – entire spectrum
- Pink Noise
  - "realistic spectrum"
  - the power spectral density is inversely proportional to the frequency

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 $3 \times 10^8\ ms^{-1}$
  - Speed of EM in cable/wire $2 \times 10^8\ ms^{-1}$
- 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 $\dfrac{T_P}{T_x}$

d = distance in meters
V = EM speed

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