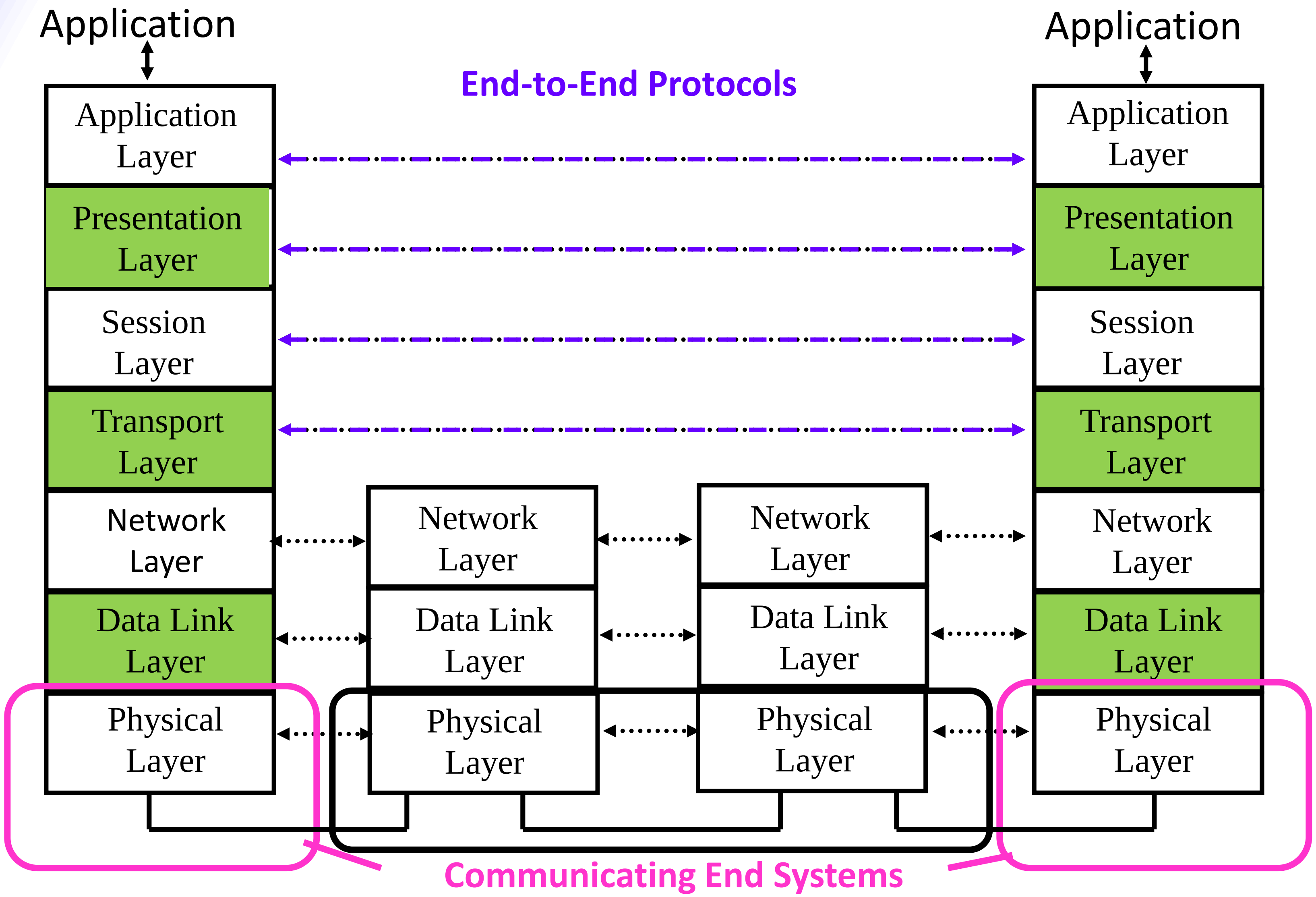
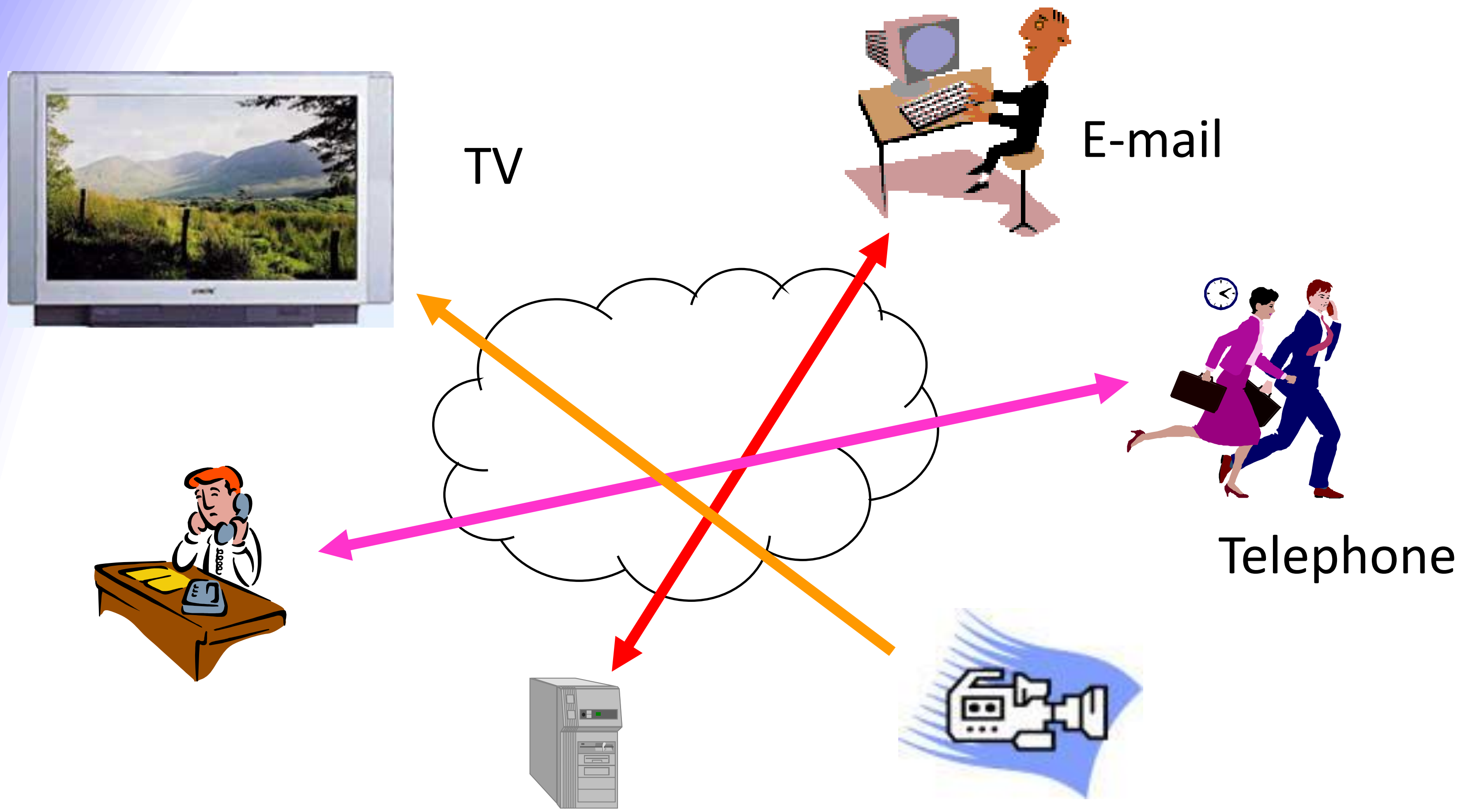
# 6. Data transmission

* digital representation
* digital and analog transmission
* asynchronous and synchronous communications
* transmission media

# 7-Layer OSI Reference Model



# Digital transmission enables networks to support many services



## 6.1 Digital representation

- Bit: number with value 0 or 1
  - $n$ bits: digital representation for 0, 1, … , $2^n$
  - byte or octet, $n = 8$
  - computer word, $n = 16$, 32, or 64
- $n$ bits allows enumeration of $2^n$ possibilities
  - $n$-bit field in a header
  - $n$-bit representation of a voice sample
  - message consisting of $n$ bits
- *The number of bits required to represent a message is a measure of its information content*
  - more bits → more content

**Block**

- Information that occurs in a single block
  - text message
  - data file
  - JPEG image
- size = bits / block

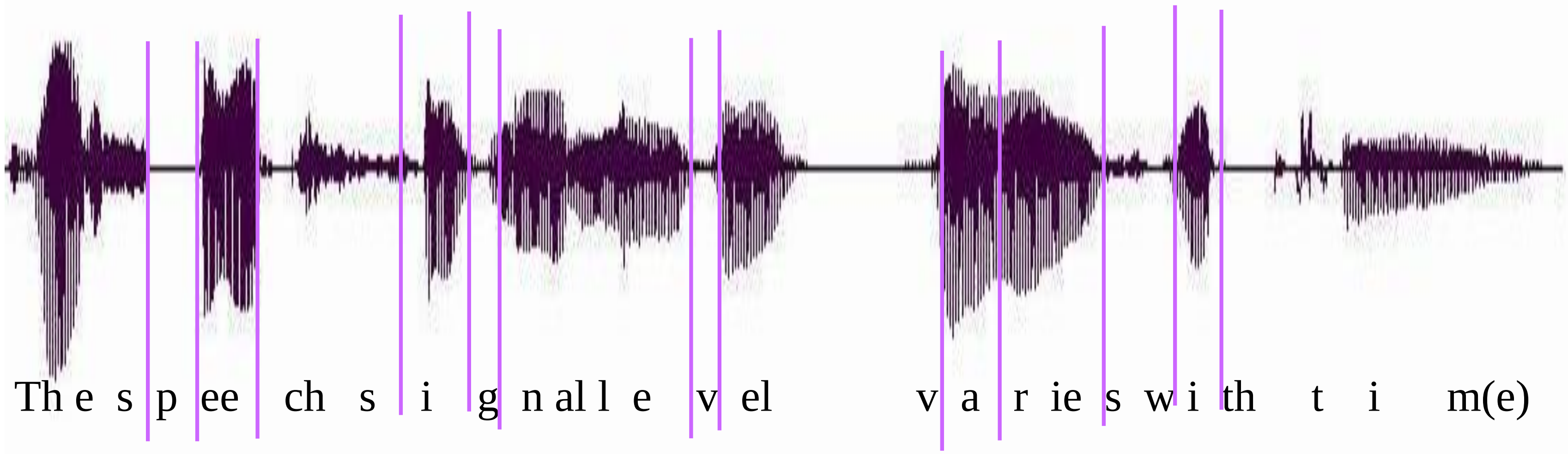
  or bytes/block
  - 1 Kbyte = $2^{10}$ bytes
  - 1 Mbyte = $2^{20}$ bytes
  - 1 Gbyte = $2^{30}$ bytes

**Stream**

- Information that is produced & transmitted *continuously*
  - real-time voice
  - MP3 audio
  - streaming video (H.261, MPEG-2)
- Bit rate = bits / second (bps)
  - 1 Kbps = $10^3$ bps
  - 1 Mbps = $10^6$ bps
  - 1 Gbps = $10^9$ bps

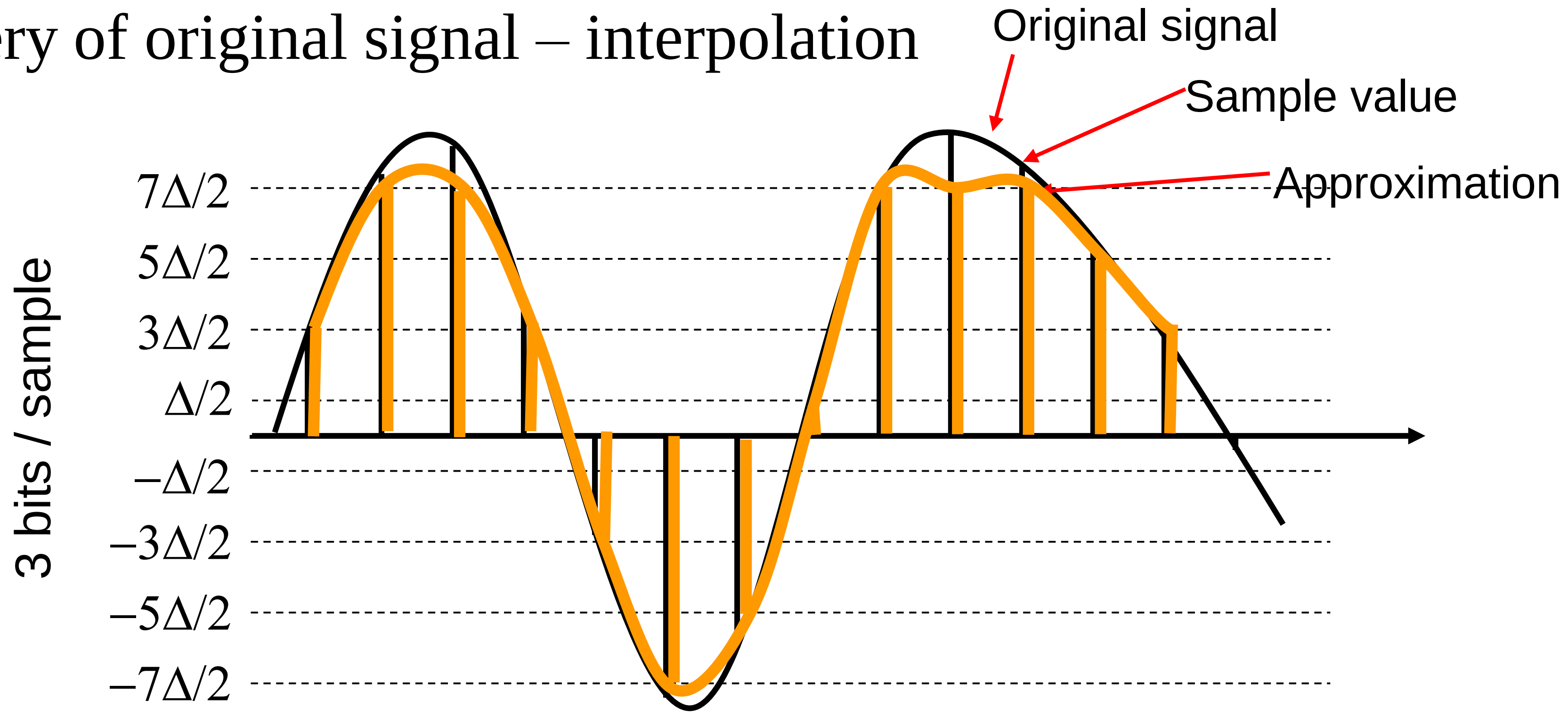
# Stream information

- a real-time voice signal must be digitized & transmitted as it is produced
- analog signal level varies continuously in time



# Digitization of analog signal

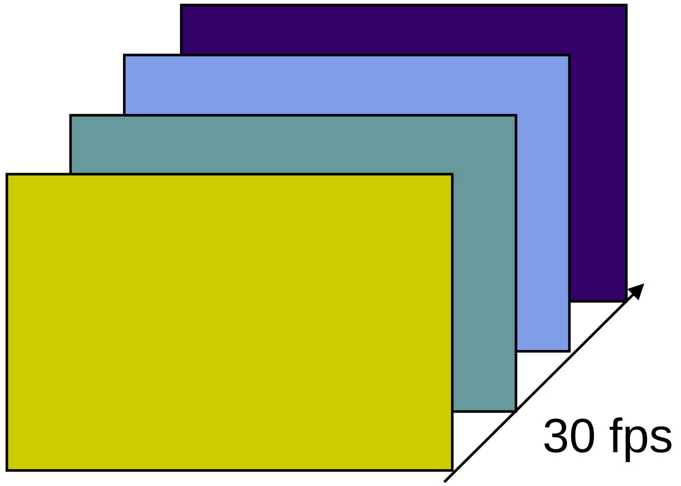
- sample analog signal in time
- find closest approximation – quantization
- recovery of original signal – interpolation




$R_s$ = bit rate = # bits/sample x # samples/second

# Video signal

- sequence of picture frames
  - each picture digitized & compressed
- frame repetition rate
  - 10-30-60 frames/second (fps), depending on quality
- frame resolution
  - small frames for videoconferencing
  - standard frames for conventional broadcast TV
  - HDTV frames




Rate = M bits/pixel **x** (WxH) pixels/frame **x** F frames/second

# Video frames

QCIF videoconferencing

at 30 frames/sec =

760,000 pixels/sec

Broadcast TV

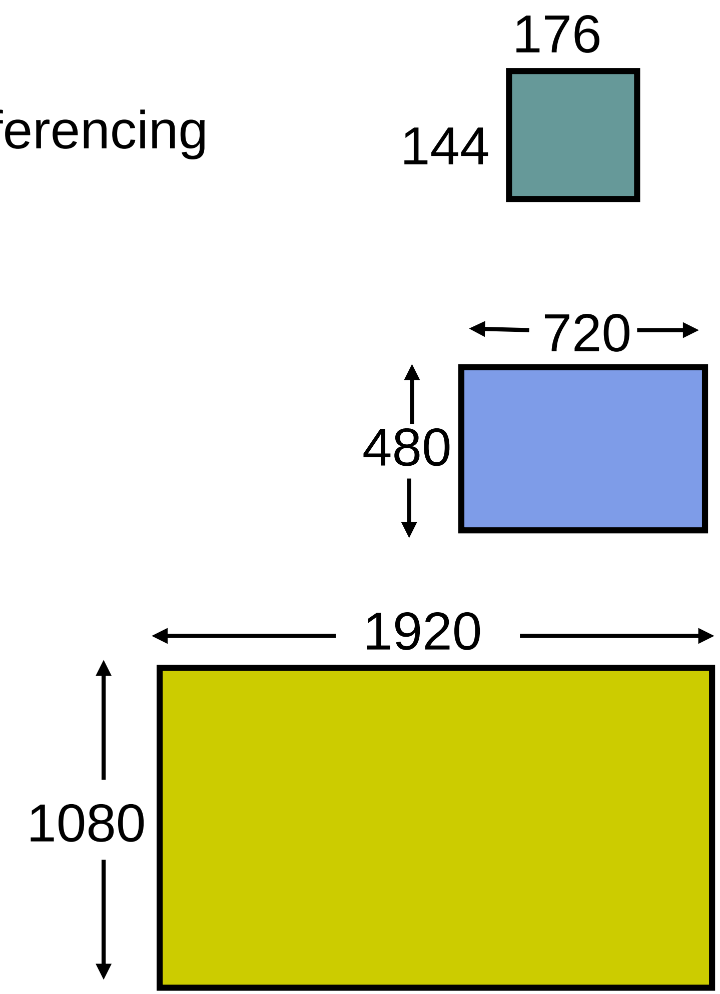
at 30 frames/sec =

$10.4 \times 10^6$ pixels/sec

HDTV

at 30 frames/sec =

$62 \times 10^6$ pixels/sec



# Digital video signals

| Type | Method | Format | Original | Compressed |
| --- | --- | --- | --- | --- |
| Video Conference | H.261 | 176x144 or 352x288 pix @10-30 fps | 2-36 Mbps | 64-1544 Kbps |
| Full Motion | MPEG-2 | 720x480 pix @30 fps | 249 Mbps | 2-6 Mbps |
| HDTV | MPEG-2 | 1920x1080 @30 fps | 1.6 Gbps | 19-38 Mbps |

# Transmission of stream information

- Constant bit-rate
  - Signals such as digitized telephone voice produce a steady stream:  e.g. 64 Kbps
  - Network must support steady transfer of signal, e.g. 64 Kbps circuit
- Variable bit-rate
  - Signals such as digitized video produce a stream that varies in bit rate, e.g. according to motion and detail in a scene
  - Network must support variable transfer rate of signal, e.g. packet switching or rate-smoothing with constant bit-rate circuit

# 6.2 Digital and analog transmission


Transmitter

- converts information into *signal* suitable for transmission
- injects energy into communications medium or channel
  - telephone converts voice into electric current
  - modem converts bits into tones

Receiver

- receives energy from medium
- converts received signal into form suitable for delivery to user
  - telephone converts current into voice
  - modem converts tones into bits

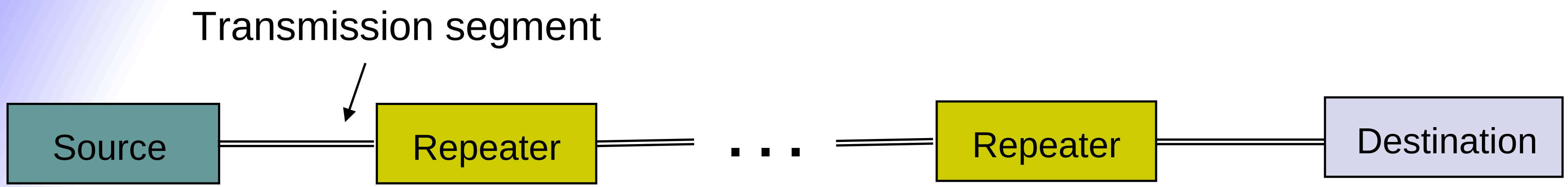

Communication Channel

- Pair of copper wires
- Coaxial cable
- Radio
- Light in optical fiber
- Light in air
- Infrared

Transmission Impairments

- Signal attenuation
- Signal distortion
- Spurious noise
- Interference from other signals

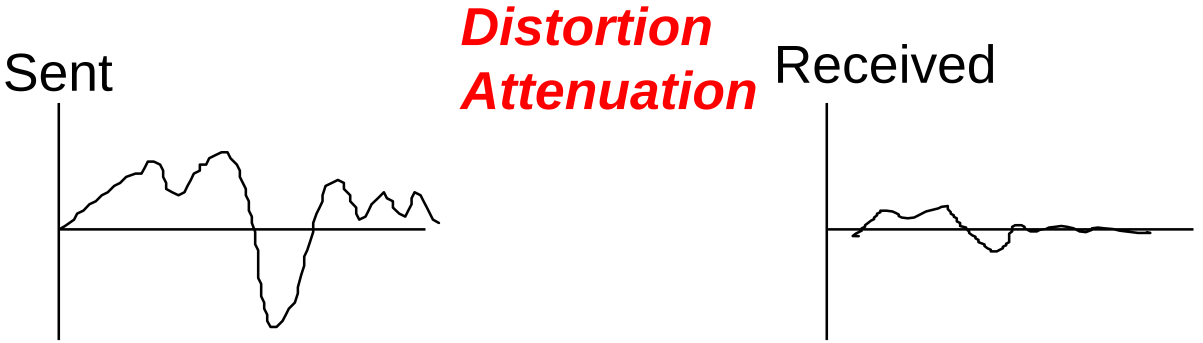
# Analog long-distance communication




- Each repeater attempts to restore analog signal to its original form
- Restoration is imperfect
  - Distortion is not completely eliminated
  - Noise and interference is only partially removed
- Signal quality decreases with number of repeaters
- Communication is distance-limited
- Analogy: copy a song using a cassette recorder

# Analog vs. digital transmission

**Analog transmission**: all details must be reproduced accurately




**Digital transmission**: only discrete levels need to be reproduced


Simple Receiver: Was original pulse positive or negative?

# Digital long-distance communication

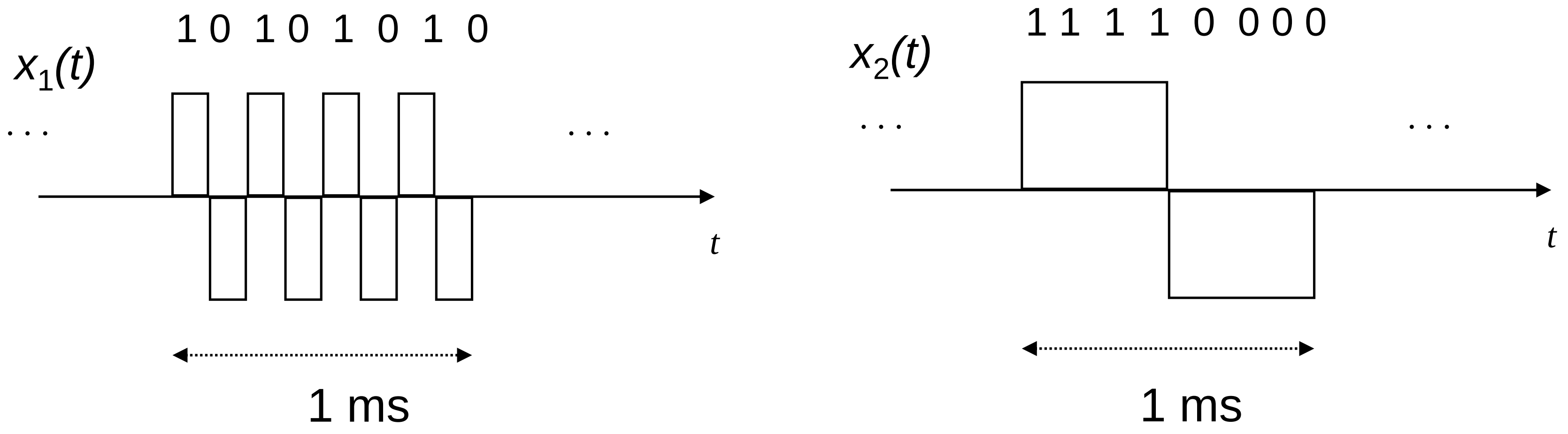

- Regenerator recovers original data sequence and retransmits on next segment
- Each regeneration is like the first time!
- Can design a transmission system with very low bit error rate
- Analogy: copy an MP3 file
- Communication is possible over very long distances
- Digital systems vs. analog systems
  - Less power, longer distances, lower system cost
  - Monitoring, multiplexing, coding, encryption, protocols…

# Digitization of analog signals

1. Sampling: obtain samples of *x(t)* at uniformly spaced time intervals
2. Quantization: map each sample into an approximation value of finite precision
    - Pulse Code Modulation (PCM): telephone speech
    - CD audio
3. Compression: to lower bit rate further, apply additional compression method
    - Differential coding: cellular telephone speech
    - Subband coding: MP3 audio

# Sampling rate and bandwidth

- A signal that varies faster needs to be sampled more frequently
- *Bandwidth* measures how fast a signal varies




- What is the bandwidth of a signal?
- How is bandwidth related to sampling rate?

# Periodic signals

- A periodic signal with period $T$ can be represented as sum of sinusoids using Fourier Series:

$$x(t) = a_0 + a_1\cos(2\pi f_0 t + \phi_1) \quad + \quad a_2\cos(2\pi 2 f_0 t + \phi_2) \quad + \ldots$$
$$+ \, a_k\cos(2\pi k f_0 t + \phi_k) + \ldots$$

"DC"
long-term
average

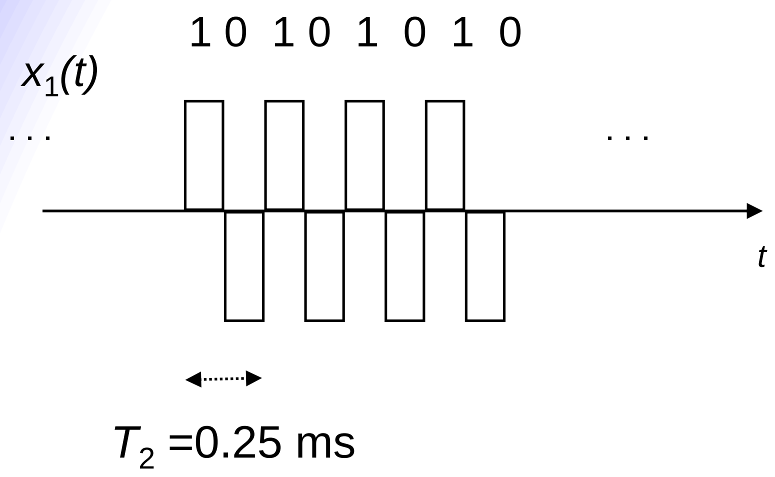
fundamental
frequency $f_0=1/T$
first harmonic

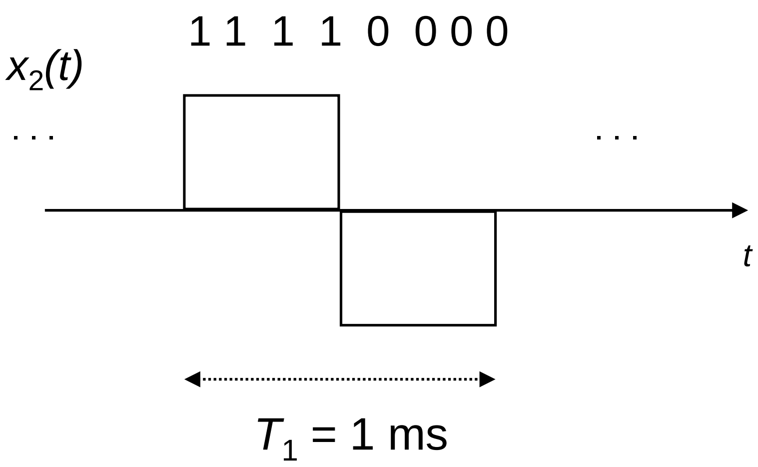
$k$th harmonic

- $|a_k|$ determines amount of power in $k$th harmonic

- Amplitude spectrum $|a_0|, |a_1|, |a_2|, \ldots$

# Example - Fourier series




$$x_1(t) = 0 + \frac{4}{\pi}\cos(2\pi 4000t) + \frac{4}{3\pi}\cos(2\pi 3(4000)t) + \frac{4}{5\pi}\cos(2\pi 5(4000)t) + \ldots$$

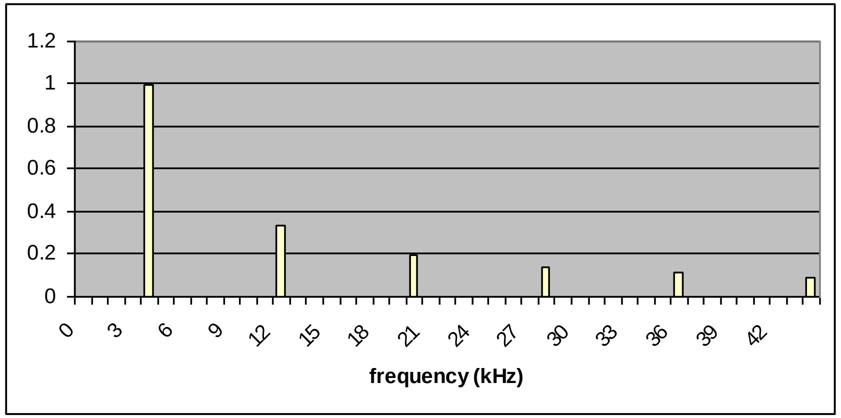
$$x_2(t) = 0 + \frac{4}{\pi}\cos(2\pi 1000t) + \frac{4}{3\pi}\cos(2\pi 3(1000)t) + \frac{4}{5\pi}\cos(2\pi 5(1000)t) + \ldots$$

Only odd harmonics have power

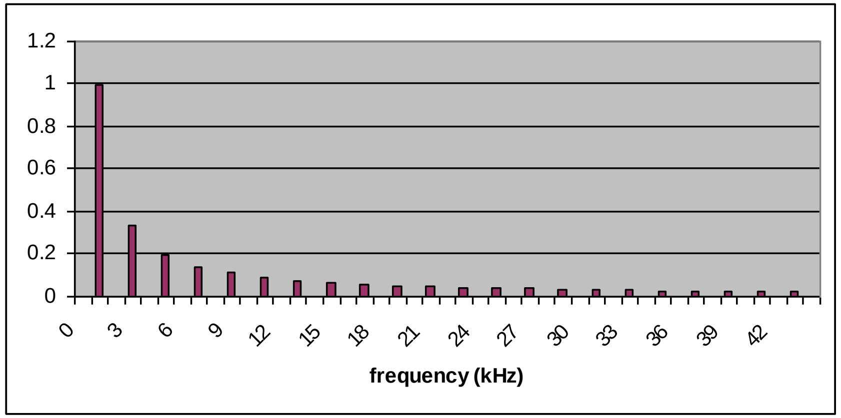
# Spectrum and bandwidth

- Spectrum of a signal: magnitude of amplitudes as a function of frequency
- $x_1(t)$ varies faster in time and has more high frequency content than $x_2(t)$
- Bandwidth $W_s$ is defined as range of frequencies where a signal has non-negligible power, e.g. range of band that contains 99% of total signal power

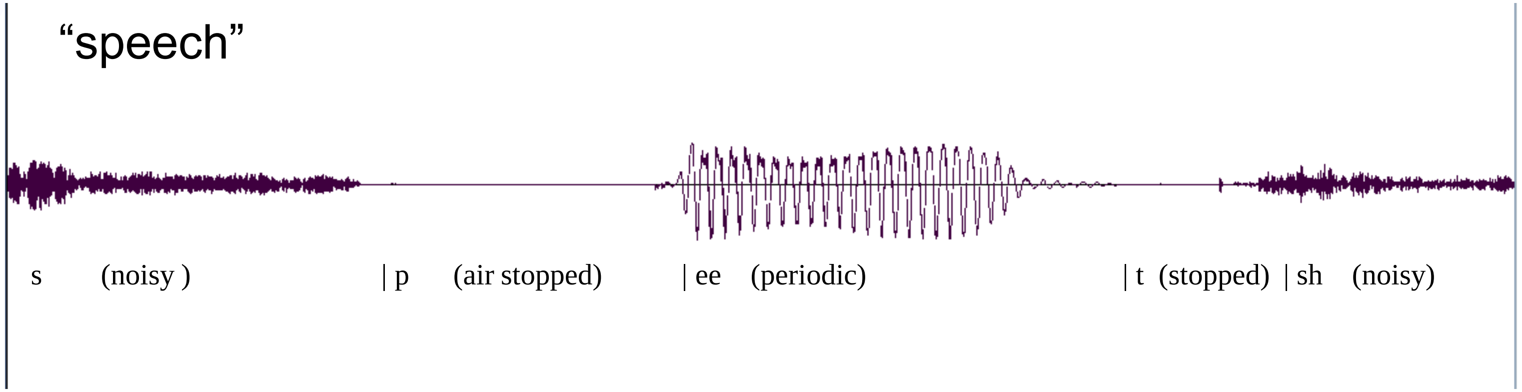
Spectrum of $x_1(t)$



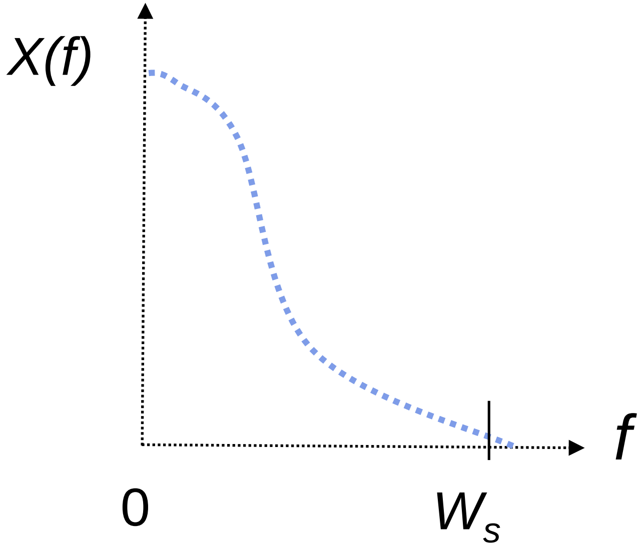

Spectrum of $x_2(t)$



# Bandwidth of general signals




- Not all signals are periodic
  - e.g. voice signal varies according to sound
  - vowels are periodic, “s” is noise-like
- Spectrum of long-term signal
  - averages over many sounds, many speakers
  - involves Fourier transform
- Telephone speech: 4 KHz
- CD Audio: 22 KHz

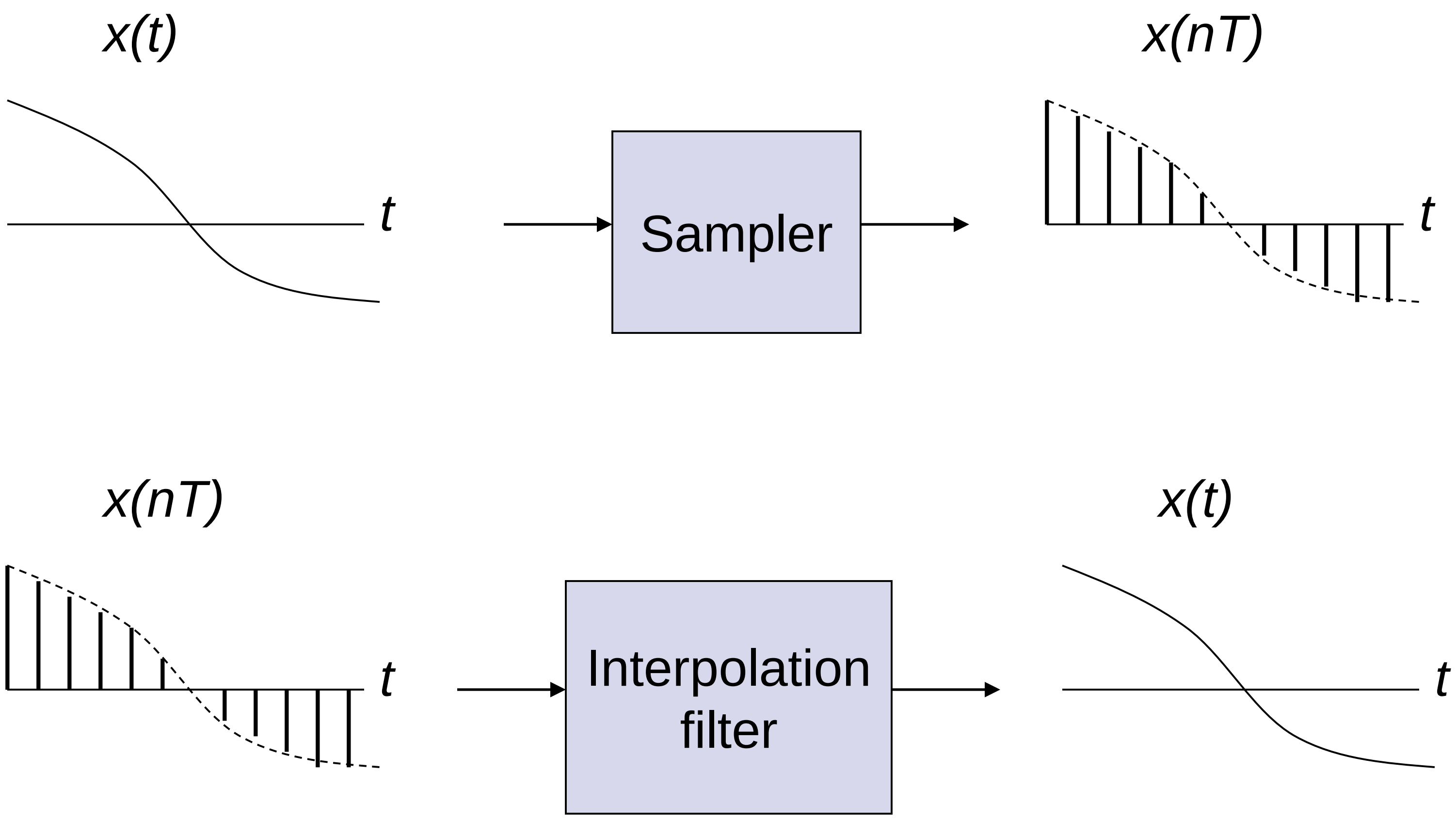


# Sampling theorem

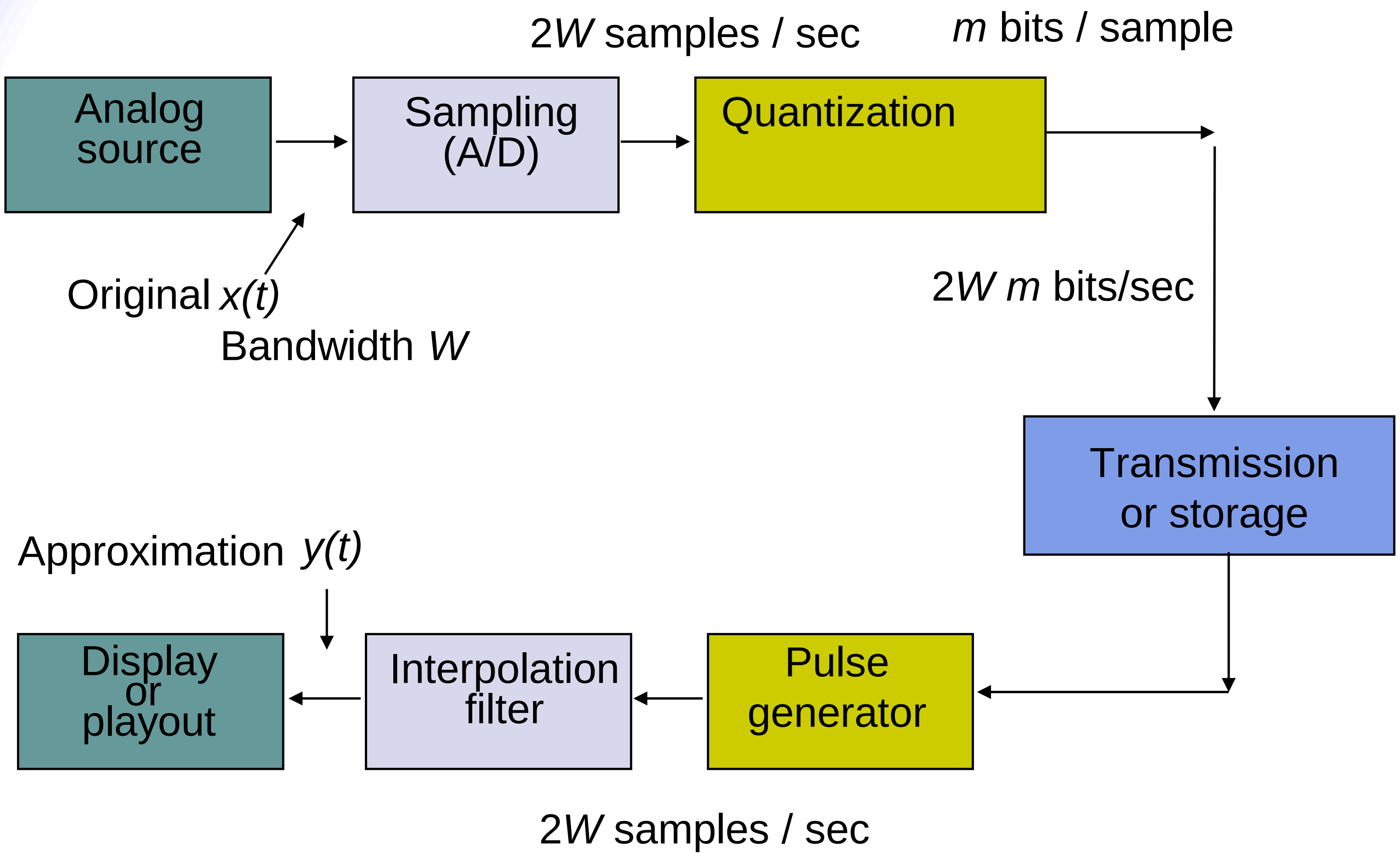
Nyquist:  Perfect reconstruction if sampling rate $1/T > 2W_s$

(a)

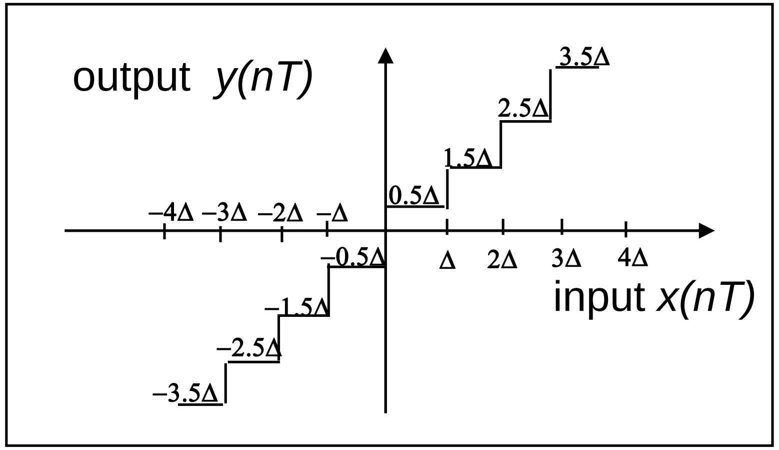
(b)



# Digital transmission of analog information

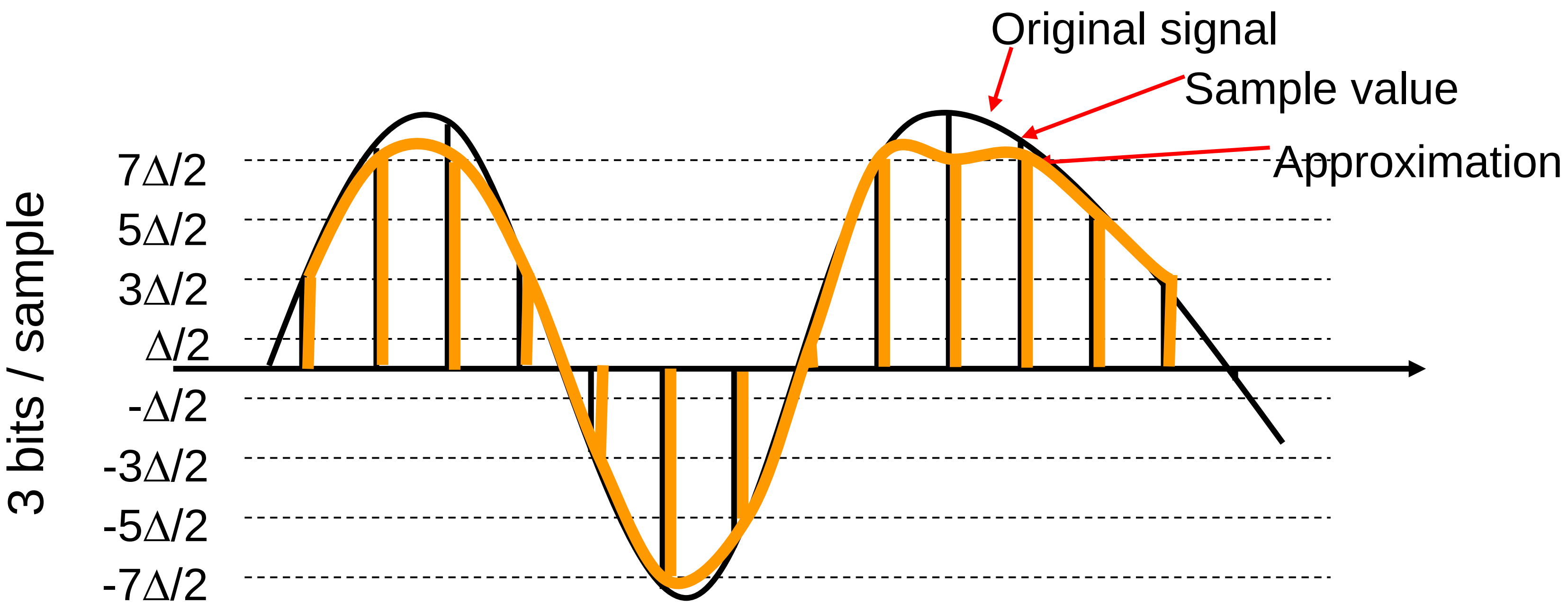


# Quantization of analog samples




Quantizer maps input
into closest of $2^m$
representation values

Quantization error:
“noise” = $x(nT) - y(nT)$



# Example:  voice and audio

**Telephone voice**

- $W_s$ = 4 KHz $\longrightarrow$ 8000 samples/sec
- 8 bits/sample
- $R_s$ = 8 x 8000 = 64 Kbps

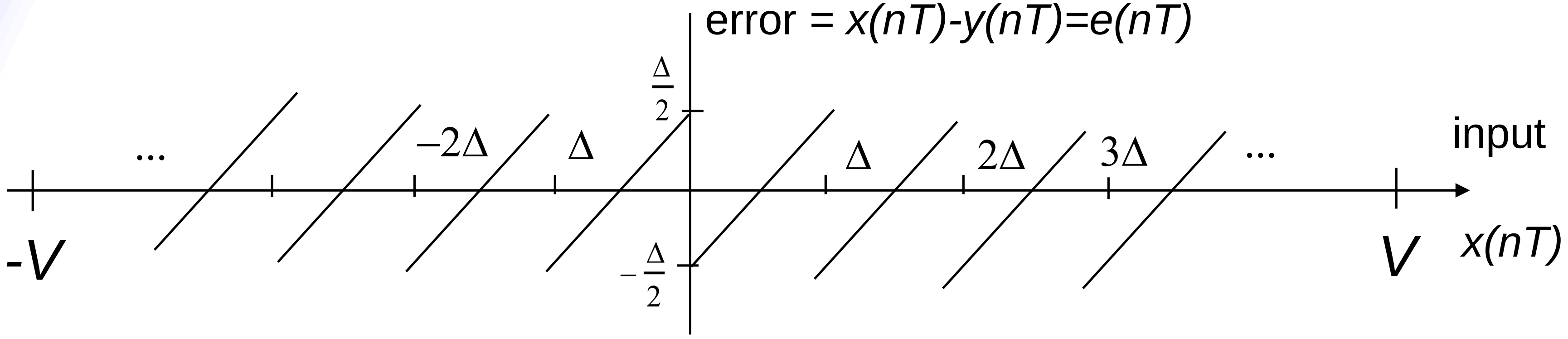
- Cellular phones use more powerful compression algorithms:  8-12 Kbps

**CD Audio**

- $W_s$ = 22 KHz $\longrightarrow$ 44,000 samples/sec
- 16 bits/sample
- $R_s$ =16 x 44000= 704 Kbps per audio channel
- MP3 uses more powerful compression algorithms: 50 Kbps per audio channel

# Quantizer performance

$M = 2^m$ levels,    Dynamic range ( $-V$, $V$) $\Delta = 2V/M$




If the number of levels $M$ is large, then the error is approximately uniformly distributed between (-Δ/2, Δ2)

Average Noise Power = Mean Square Error:

$$\sigma_e^2 = \int_{-\frac{\Delta}{2}}^{\frac{\Delta}{2}} x^2 \frac{1}{\Delta}\, dx = \frac{\Delta^2}{12}$$

Figure of merit:

Signal-to-Noise Ratio (SNR) = average signal power / average noise power

Let $\sigma_x^2$ be the signal power, then

$$SNR = \frac{\sigma_x^2}{\Delta^2/12} = \frac{12\sigma_x^2}{4V^2/M^2} = 3\left(\frac{\sigma_x}{V}\right)^2 M^2 = 3\left(\frac{\sigma_x}{V}\right)^2 2^{2m}$$

The ratio $V/\sigma_x \approx 4$

The SNR is usually stated in decibels:

$$SNR\ dB = 10 \log_{10} \sigma_x^2/\sigma_e^2 = 6m + 10 \log_{10} 3\sigma_x^2/V^2$$

$$SNR\ dB = 6m - 7.27\ dB \qquad \text{for } V/\sigma_x = 4$$

# Example: telephone speech

$W$ = 4 KHz, so Nyquist sampling theorem

$\Rightarrow$ $2W$ = 8000 samples/second

Suppose error requirement $=$ 1% error

SNR = 10 log$(1/.01)^2$ = 40 dB

Assume $V/\sigma_x = 4$, then

40 dB = 6$m$ – 7

$\Rightarrow$ $m$ = 8 bits/sample

PCM telephone speech:

Bit rate= 8000 x 8 bits/sec= 64 Kbps

# Communication channel

- A *physical medium* is an inherent part of a communications system
  - copper wires, radio medium, or optical fiber
- Communications system includes electronic or optical devices that are part of the path followed by a signal
  - equalizers, amplifiers, signal conditioners
- By *communication channel* we refer to the combined end-to-end physical medium and attached devices
- Sometimes we use the term *filter* to refer to a channel especially in the context of a specific mathematical model for the channel


**Signal Bandwidth**

- In order to transfer data faster, a signal has to vary more quickly.

**Channel Bandwidth**

- A channel or medium has an inherent limit on how fast the signals it passes can vary
- *Limits how tightly input pulses can be packed*

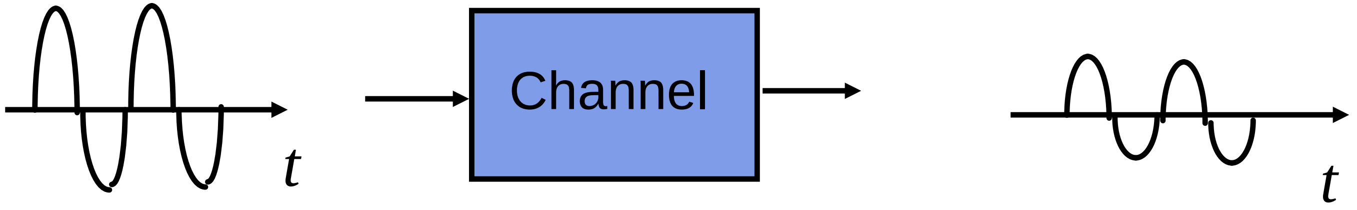
**Transmission Impairments**

- Signal attenuation
- Signal distortion
- Spurious noise
- Interference from other signals
- *Limits accuracy of measurements on received signal*

# Frequency domain channel characterization

$x(t) = A_{in} \cos 2\pi f t$

$y(t) = A_{out} \cos (2\pi f t + \varphi(f))$




$$A(f) = \frac{A_{out}}{A_{in}}$$

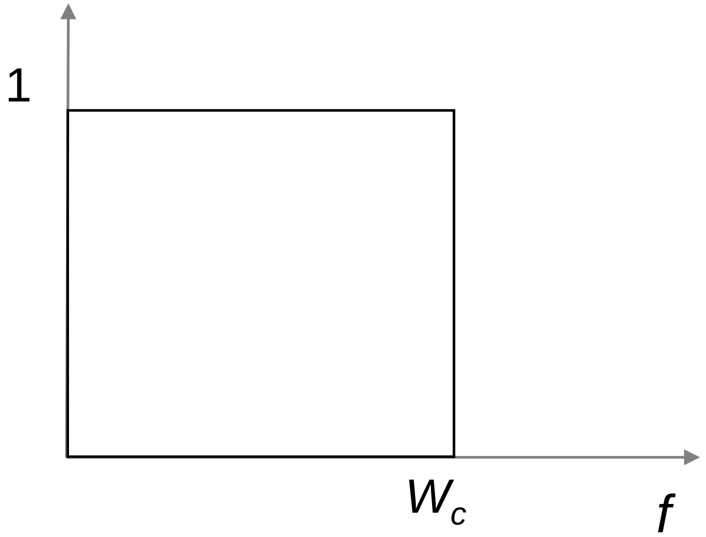
- Apply sinusoidal input at frequency *f*
  - Output is sinusoid at same frequency, but attenuated & phase-shifted
  - Measure amplitude of output sinusoid (of same frequency *f*)
  - Calculate amplitude response
    - $A(f)$ = ratio of output amplitude to input amplitude
  - If $A(f) \approx 1$, then input signal passes readily
  - If $A(f) \approx 0$, then input signal is blocked
- Bandwidth $W_c$ is range of frequencies passed by channel

# Ideal Low-Pass Filter

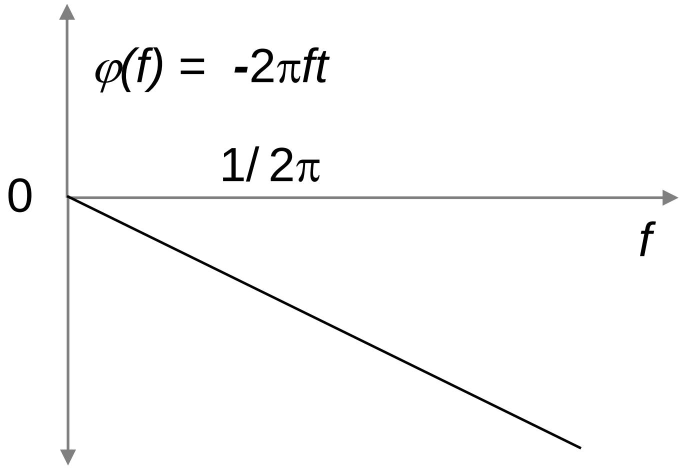
- Ideal filter: all sinusoids with frequency $f < W_c$ are passed without attenuation and delayed by $\tau$ seconds; sinusoids at other frequencies are blocked

$$y(t)=A_{in}\cos(2\pi ft - 2\pi f\tau) = A_{in}\cos(2\pi f(t - \tau)) = x(t-\tau)$$

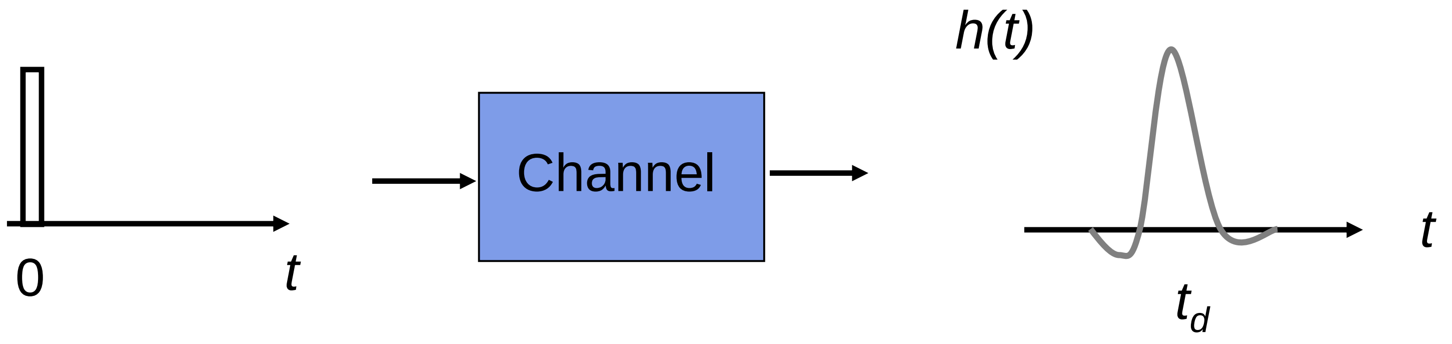
Amplitude Response




Phase Response



# Time-domain characterization

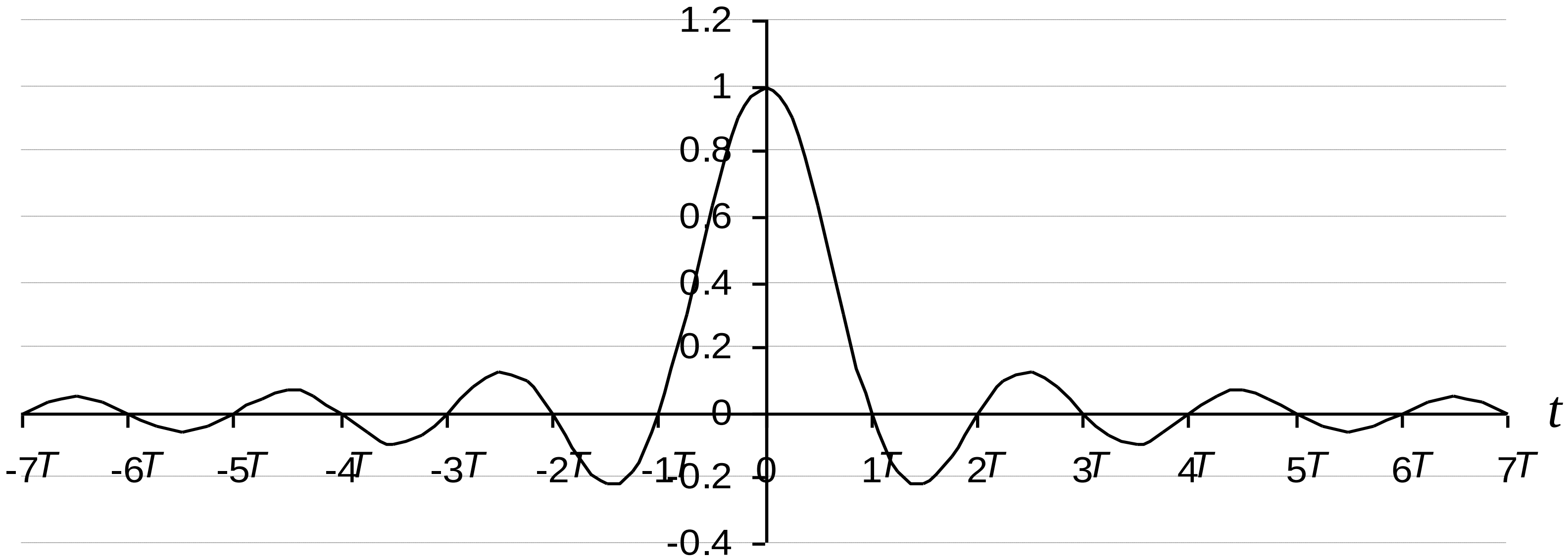



- Time-domain characterization of a channel requires finding the *impulse response h(t)*
- Apply a very narrow pulse to a channel and observe the channel output
  - *h(t)* typically a delayed pulse with ringing
- Interested in system designs with *h(t)* that can be packed closely without interfering with each other

# Nyquist pulse with zero InterSymbol Interference (ISI)

- For channel with ideal low pass amplitude response of bandwidth $W_c$, the impulse response is a Nyquist pulse $h(t)=s(t-\tau)$, where $T = 1/2W_c$, and

$$s(t) = \sin(2\pi W_c t)/ 2\pi W_c t$$




- $s(t)$ has zero crossings at $t = kT$, $k = \pm 1, \pm 2, \ldots$
- Pulses can be packed every $T$ seconds with *zero interference*

# Example - composite waveform

Three Nyquist pulses shown separately

- $+ s(t)$
- $+ s(t-T)$
- $- s(t-2T)$

**Composite waveform**

$r(t) = s(t)+s(t-T)-s(t-2T)$

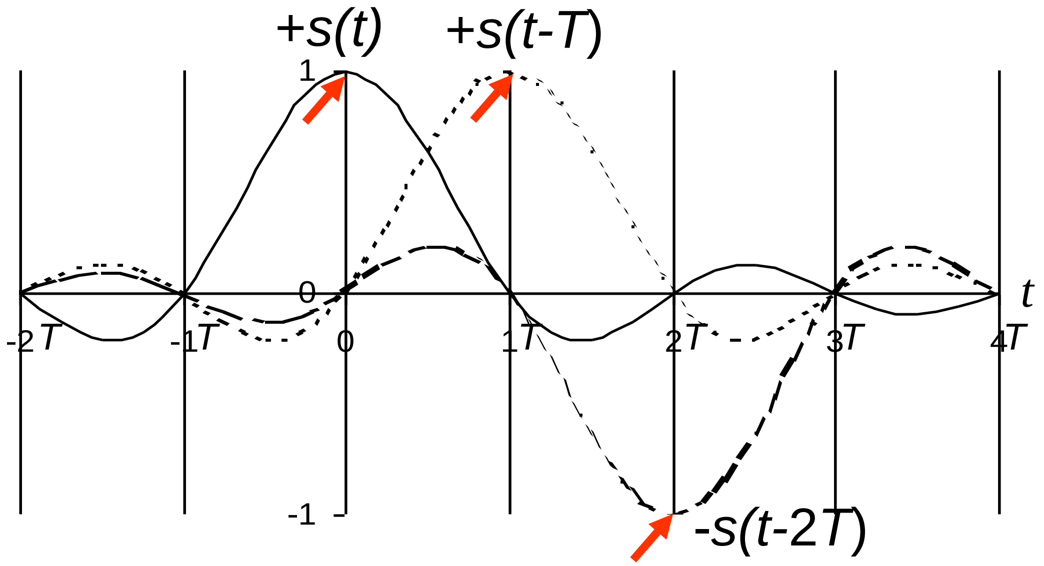
Samples at $kT$

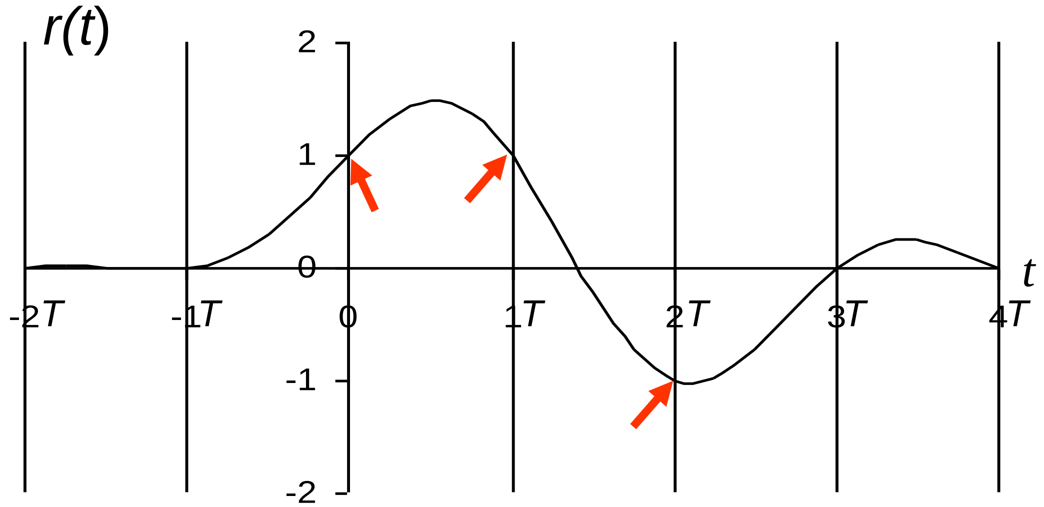
$r(0)=s(0)+s(-T)-s(-2T)=+1$

$r(T)=s(T)+s(0)-s(-T)=+1$

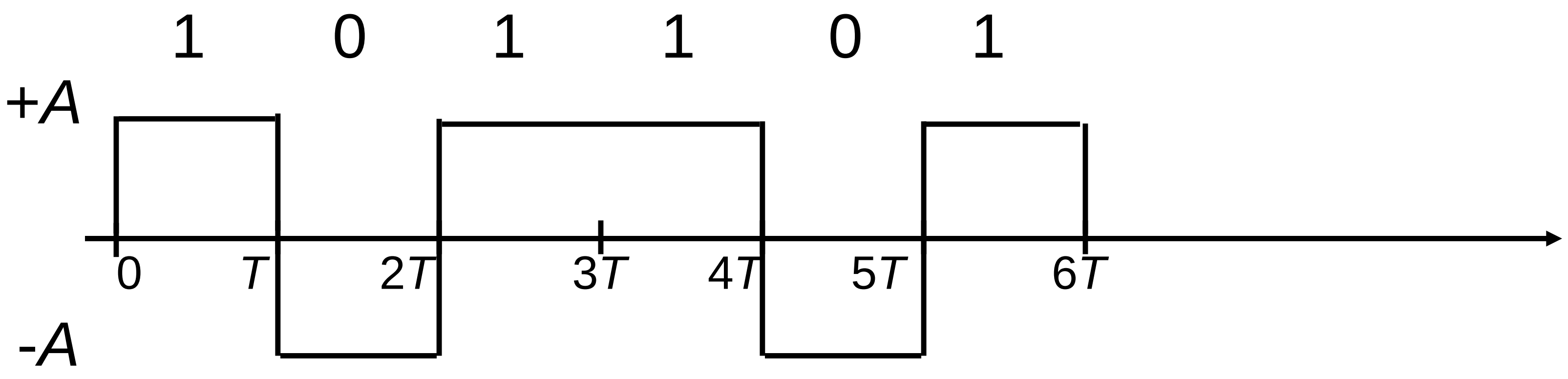
$r(2T)=s(2T)+s(T)-s(0)=-1$

**Zero ISI at sampling times *kT***



# Digital binary signal



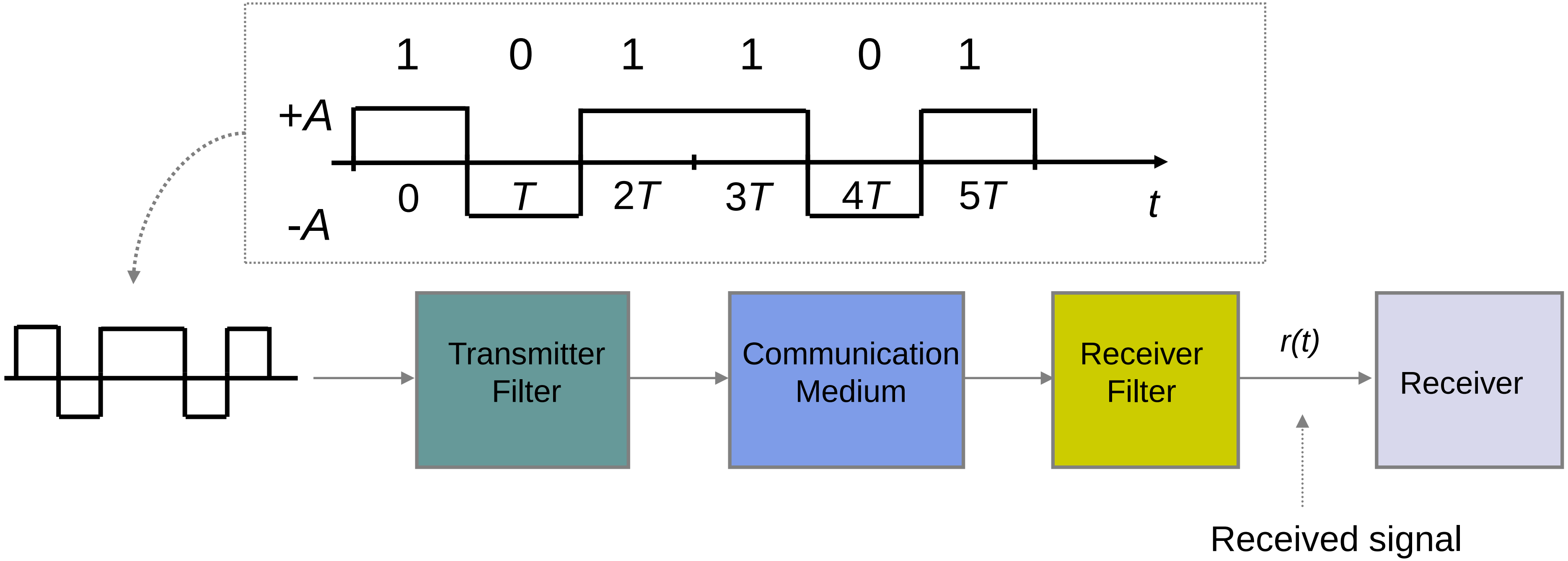

*Bit rate = 1  bit / T seconds*

For a given communications medium:

- How do we increase transmission speed?
- How do we achieve reliable communications?
- Are there limits to speed and reliability?

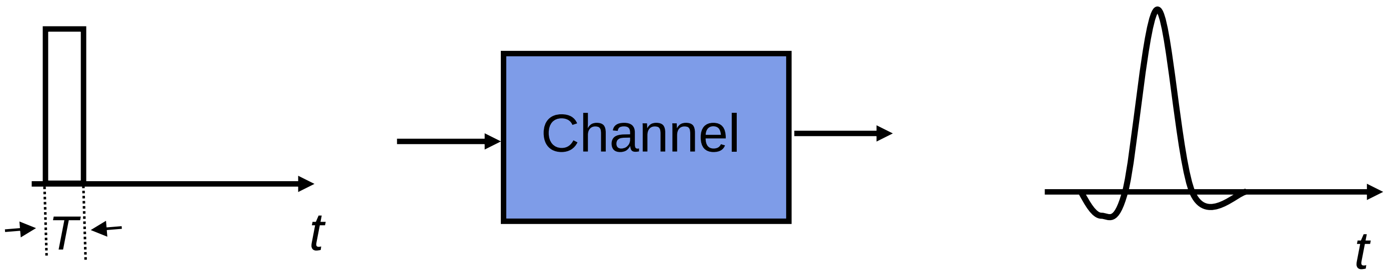
# Signaling with Nyquist pulses

- *p(t)* pulse at receiver in response to a single input pulse (takes into account pulse shape at input, transmitter and receiver filters, and communications medium)
- *r(t)* waveform that appears in response to sequence of pulses
- If *p(t)* is a Nyquist pulse, then *r(t)* has zero intersymbol interference (ISI) when sampled at multiples of *T*



# Pulse transmission rate

- Objective: maximize pulse rate through a channel, that is, make $T$ as small as possible




- If input is a narrow pulse, then typical output is a spread-out pulse with ringing
- Question: How frequently can these pulses be transmitted without interfering with each other?
- Answer: 2 x $W_c$ pulses/second

where $W_c$ is the bandwidth of the channel

# Multilevel signaling

- Nyquist pulses achieve the maximum signalling rate with zero ISI,
  $2W_c$ pulses per second or
  $2W_c$ pulses / $W_c$ Hz = 2 pulses / Hz

- With two signal levels, each pulse carries one bit of information

  Bit rate = $2W_c$ bits/second

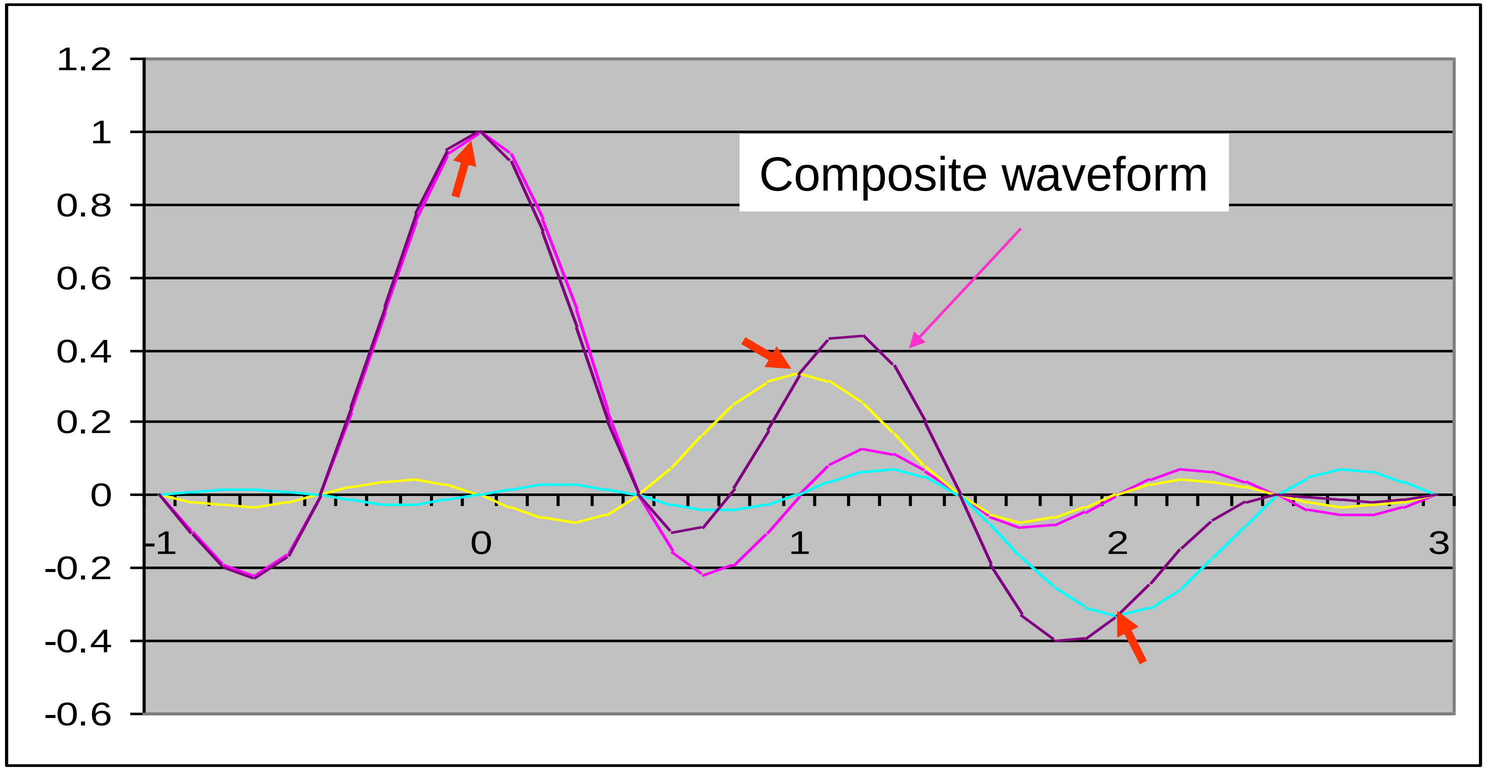
- With $M = 2^m$ signal levels, each pulse carries $m$ bits

  Bit rate = $2W_c$ pulses/sec. * $m$ bits/pulse = $2W_c\, m$ bps

- *Bit rate can be increased by increasing number of levels*
- *r(t) includes additive noise, that limits number of levels that can be used reliably.*

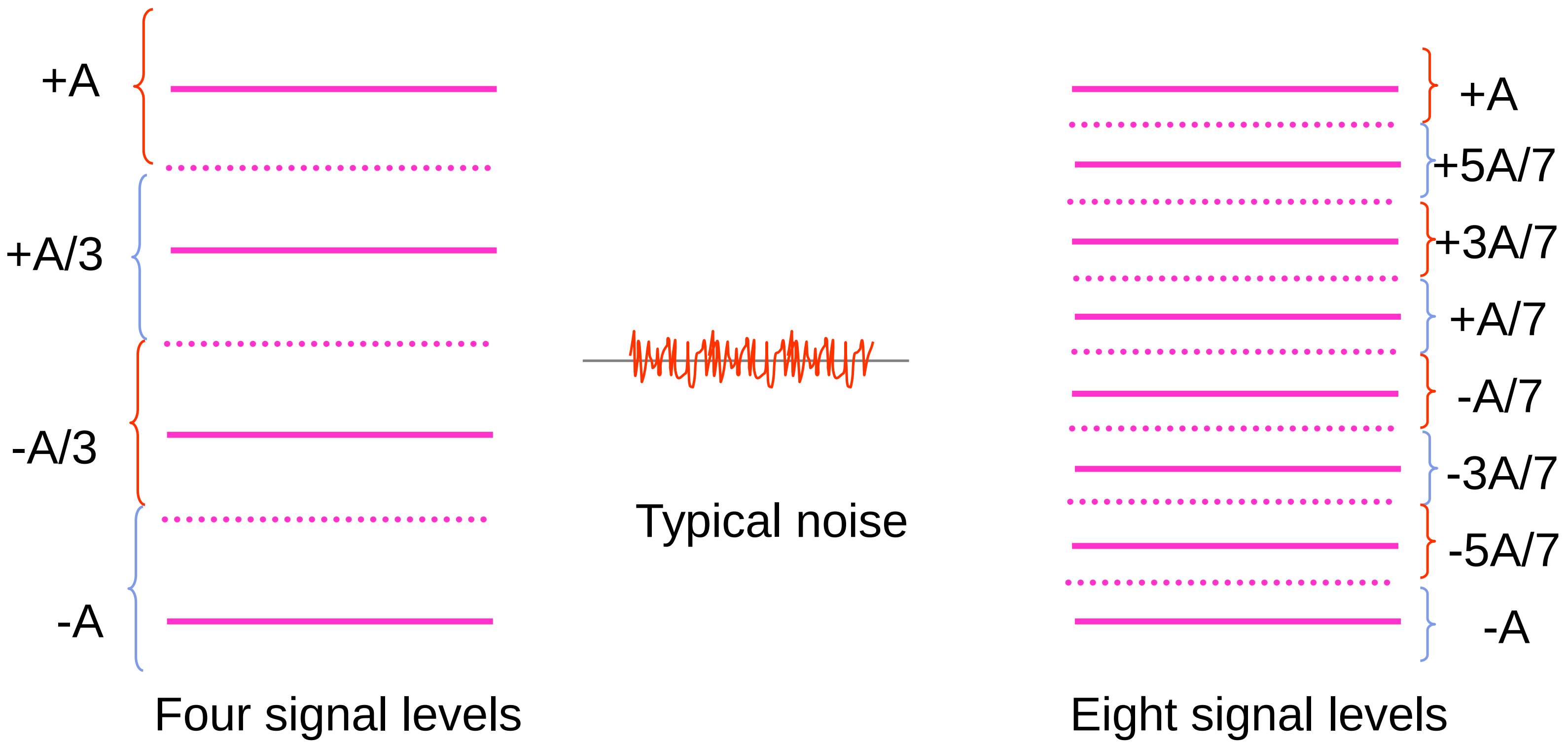
# Example

- Four levels {-1, -1/3, 1/3, +1} for {00, 01, 10, 11}
- Waveform for 11, 10, 01 sends +1, +1/3, -1/3
- Zero ISI at sampling instants



# Noise limits accuracy

- Receiver makes decision based on transmitted pulse level + noise
- Error rate depends on relative value of noise amplitude and spacing between signal levels
- Large (positive or negative) noise values can cause wrong decision
- Noise level below impacts 8-level signaling more than 4-level signaling

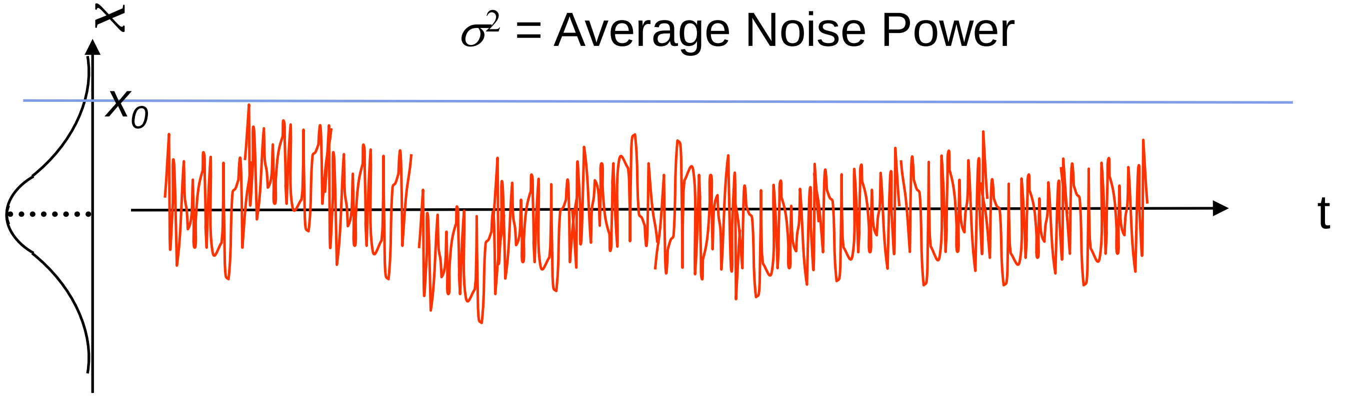


# Noise distribution

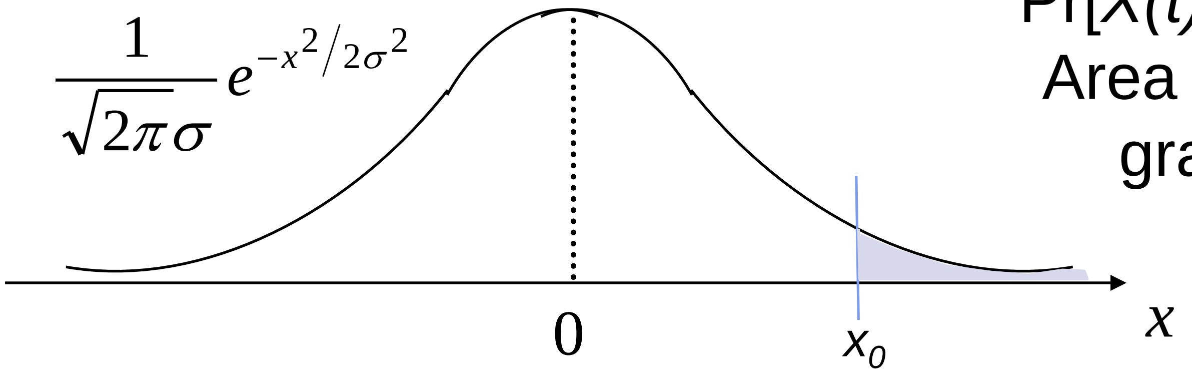
- Noise is characterized by probability density of amplitude samples
- Likelihood that certain amplitude occurs
- Thermal electronic noise is inevitable (due to vibrations of electrons)
- Noise distribution is Gaussian (bell-shaped) as below

$\sigma^2$ = Average Noise Power

$\Pr[X(t)>x_0] = ?$




$$\frac{1}{\sqrt{2\pi}\sigma} e^{-x^2/2\sigma^2}$$

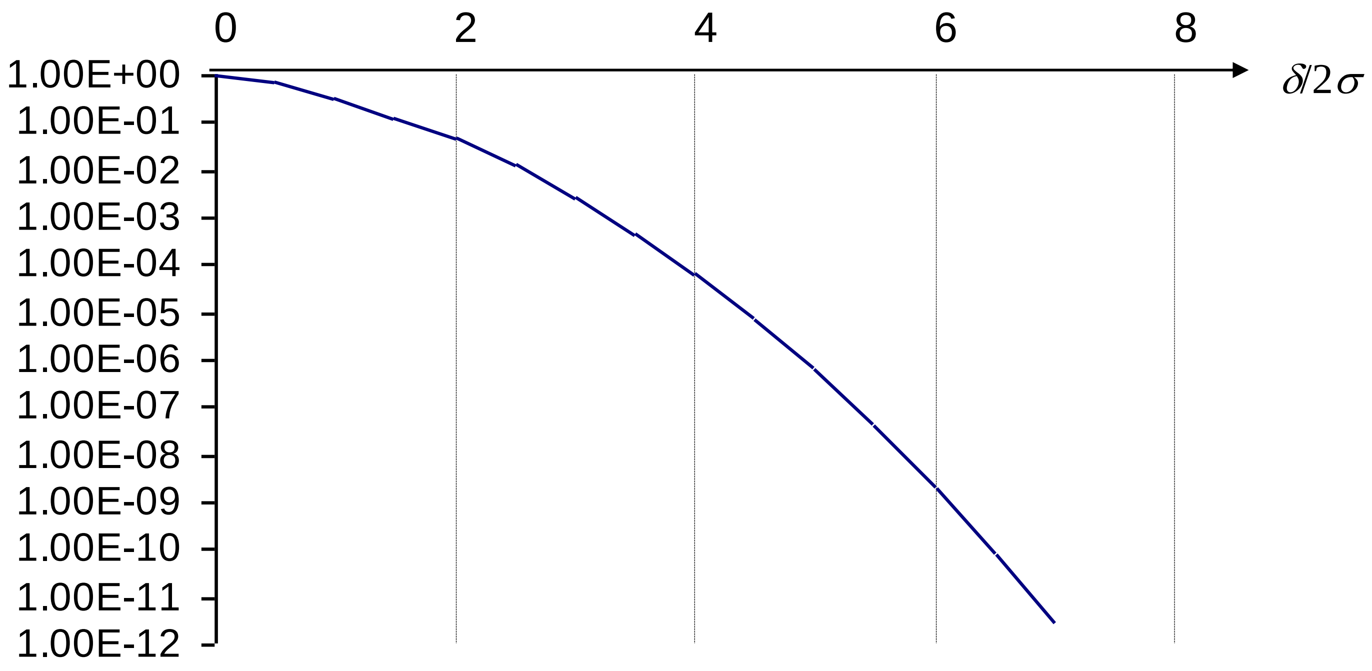



$\Pr[X(t)>x_0] =$ Area under graph

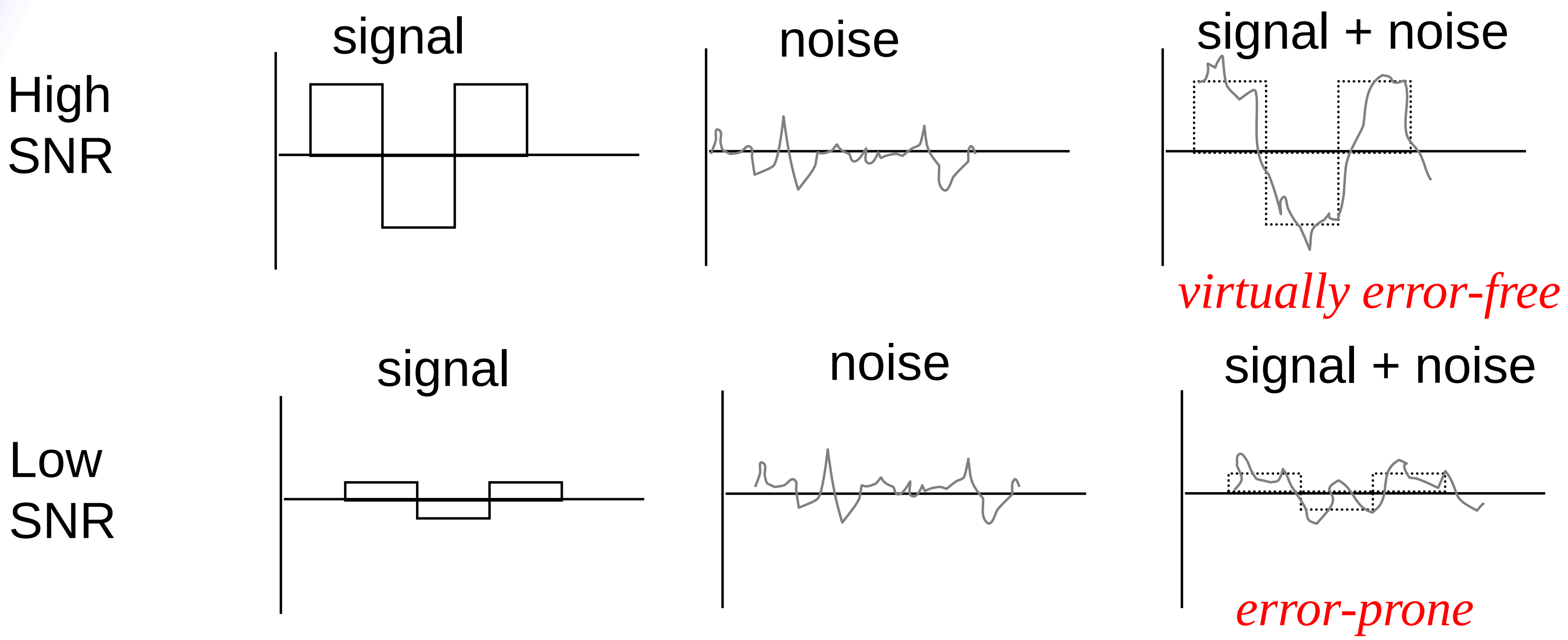
# Probability of error

- Error occurs if noise value exceeds certain magnitude
- Probability of large values drops quickly with Gaussian noise
- Target probability of error achieved by designing system so separation between signal levels is appropriate relative to average noise power

$\Pr[X(t)>\delta]$



# Channel noise affects reliability




$$\text{SNR} = \frac{\text{Average Signal Power}}{\text{Average Noise Power}}$$

$$\text{SNR (dB)} = 10 \log_{10} \text{SNR}$$

- If transmitted power is limited, then as $M$ increases spacing between levels decreases
- Presence of noise at receiver causes more frequent errors to occur as $M$ is increased

**Shannon channel capacity**:

The maximum reliable transmission rate over an ideal channel with bandwidth $W$ Hz, with Gaussian distributed noise, and with SNR $S/N$ is

$$C = W \log_2 ( 1 + S/N ) \text{ bps}$$

- Reliable means error rate can be made arbitrarily small by proper coding

# Example

- Consider a 3 KHz channel with 8-level signaling. Compare bit rate to channel capacity at 20 dB SNR

- 3KHz telephone channel with 8 level signaling

  Bit rate = 2*3000 pulses/sec * 3 bits/pulse = 18 Kbps

- 20 dB SNR means $10 \log_{10} S/N = 20$

  Implies $S/N = 100$

- Shannon channel capacity is then

  $C = 3000 \log ( 1 + 100) = 19{,}974$ bps

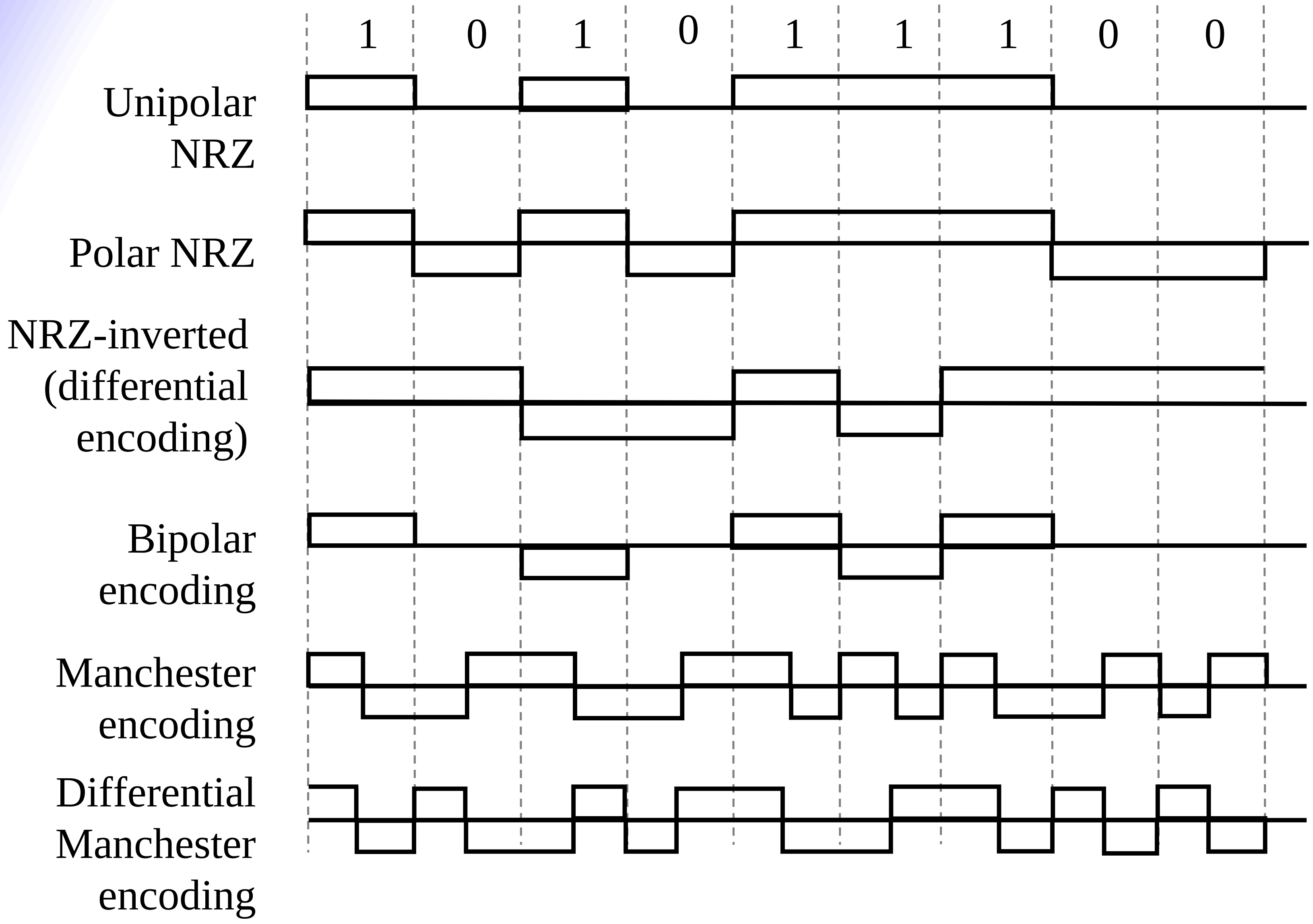
# Bit rates of digital transmission systems

| System | Bit Rate | Observations |
|---|---|---|
| Telephone twisted pair | 33.6-56 Kbps | 4 KHz telephone channel |
| Ethernet twisted pair | 10 Mbps, 100 Mbps | 100 meters of unshielded twisted copper wire pair |
| Cable modem | 500 Kbps-4 Mbps | Shared CATV return channel |
| ADSL twisted pair | 64-640 Kbps in, 1.536-6.144 Mbps out | Coexists with analog telephone signal |
| 2.4 GHz radio | 2-11 Mbps | IEEE 802.11 wireless LAN |
| 28 GHz radio | 1.5-45 Mbps | 5 Km multipoint radio |
| Optical fiber | 2.5-10 Gbps | 1 wavelength |
| Optical fiber | >1600 Gbps | Many wavelengths |

# Line coding

- Mapping of binary information sequence into the digital signal that enters the channel
  - Example - “1” maps to +A square pulse; “0” to –A pulse
- Line code selected to meet system requirements:
  - *Transmitted power*: Power consumption = $
  - *Bit timing*: Transitions in signal help timing recovery
  - *Bandwidth efficiency*: Excessive transitions wastes bandwidth
  - *Low frequency content*: Some channels block low frequencies
    - Waveform should not have low-frequency content
  - *Error detection*: Ability to detect errors helps
  - *Complexity/cost*: Is code implementable in chip at high speed?

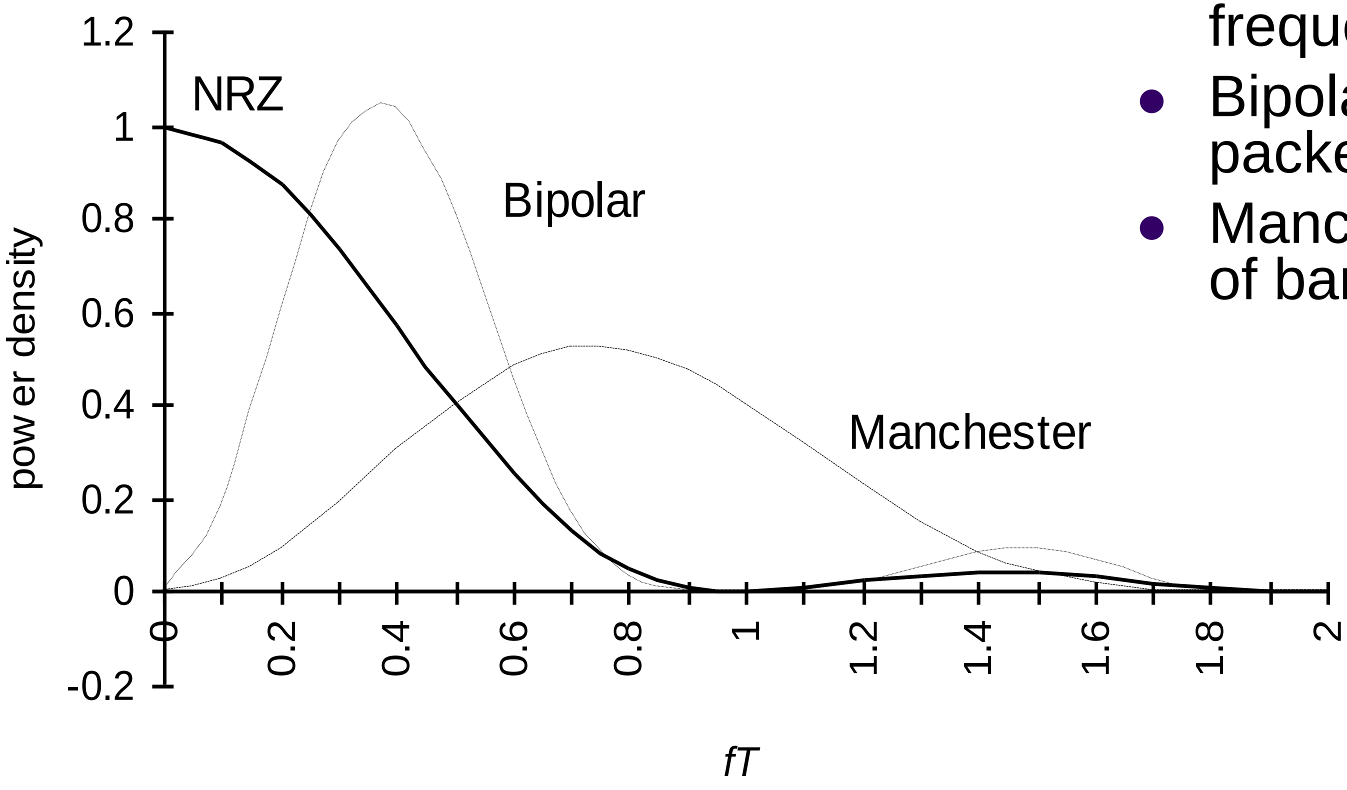
# Examples



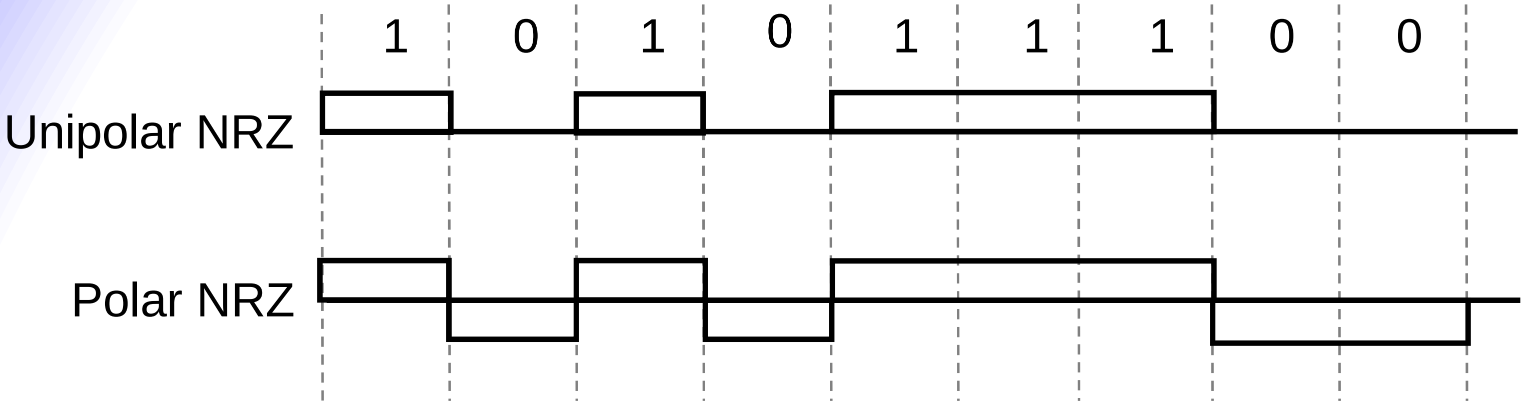
1 0 1 0 1 1 1 0 0
Unipolar NRZ
Polar NRZ
NRZ-inverted (differential encoding)
Bipolar encoding
Manchester encoding
Differential Manchester encoding

# Spectrum of line codes

- Assume 1s and 0s independent and equiprobable




- NRZ has high content at low frequencies
- Bipolar tightly packed around *T*/2
- Manchester wasteful of bandwidth

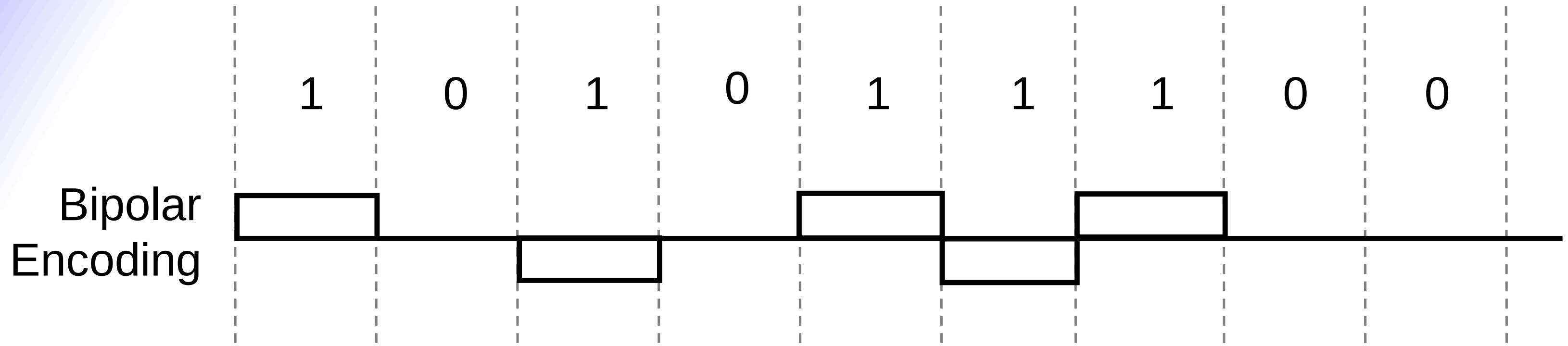



## Unipolar NRZ

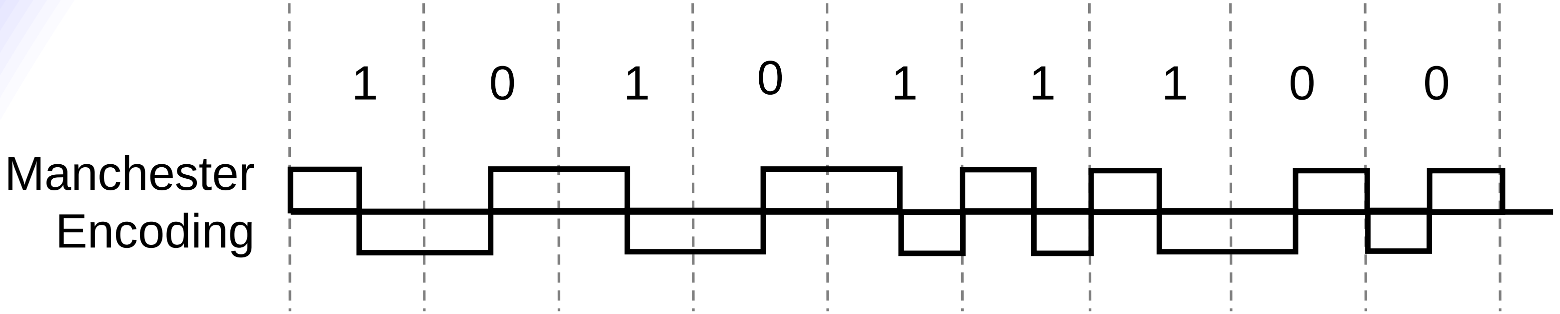
- “1” maps to +A pulse
- “0” maps to no pulse
- High Average Power
  $0.5*A^2 + 0.5*0^2 = A^2/2$
- Long strings of A or 0
  - Poor timing
  - Low-frequency content
- Simple

## Polar NRZ

- “1” maps to +A/2 pulse
- “0” maps to –A/2 pulse
- Better Average Power
  $0.5*(A/2)^2 + 0.5*(-A/2)^2 = A^2/4$
- Long strings of +A/2 or –A/2
  - Poor timing
  - Low-frequency content
- Simple

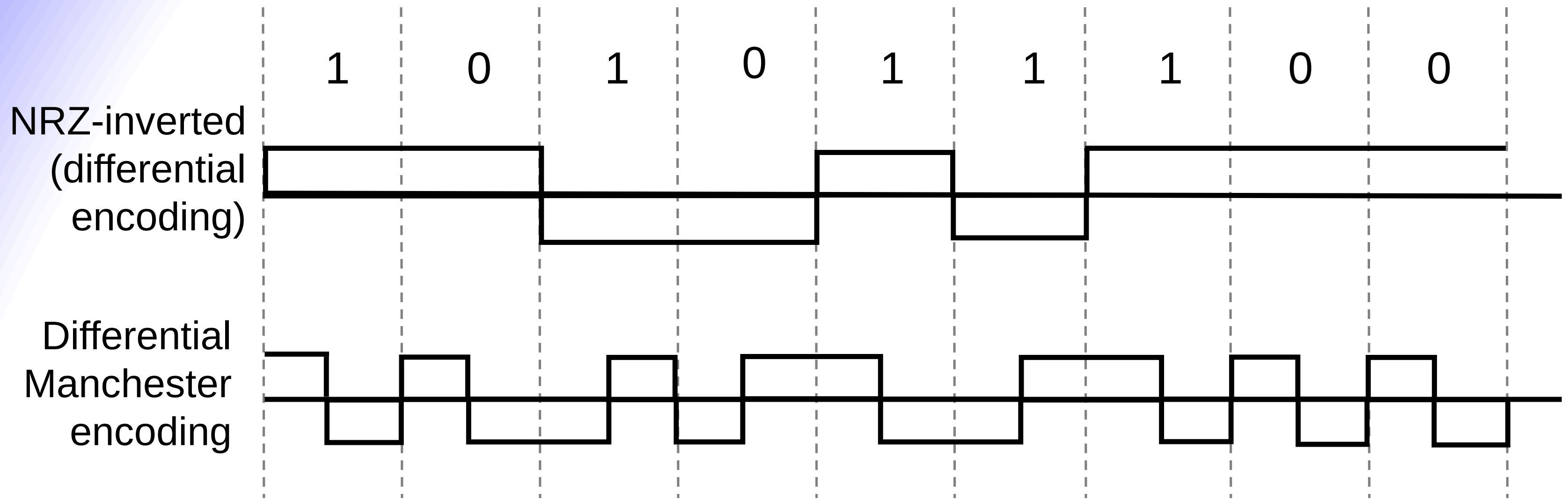



- Three signal levels: {-A, 0, +A}
- "1" maps to +A or –A in alternation
- "0" maps to no pulse
  - Every +pulse matched by –pulse so little content at low frequencies
- String of 1s produces a square wave
  - Spectrum centered at *T*/2
- Long string of 0s causes receiver to lose synchronization
- Zero-substitution codes




- “1” maps into A/2 first *T*/2, -A/2 last *T*/2
- “0” maps into -A/2 first *T*/2, A/2 last *T*/2
- Every interval has transition in middle
  - Timing recovery easy
  - Uses double the minimum bandwidth
- Simple to implement
- Used in 10-Mbps Ethernet and other LAN standards

- *m*B*n*B line code
- Maps block of *m* bits into *n* bits
- Manchester code is 1B2B code
- 4B5B code used in FDDI LAN
- 8B10B code used in Gigabit Ethernet
- 64B66B code used in 10G Ethernet

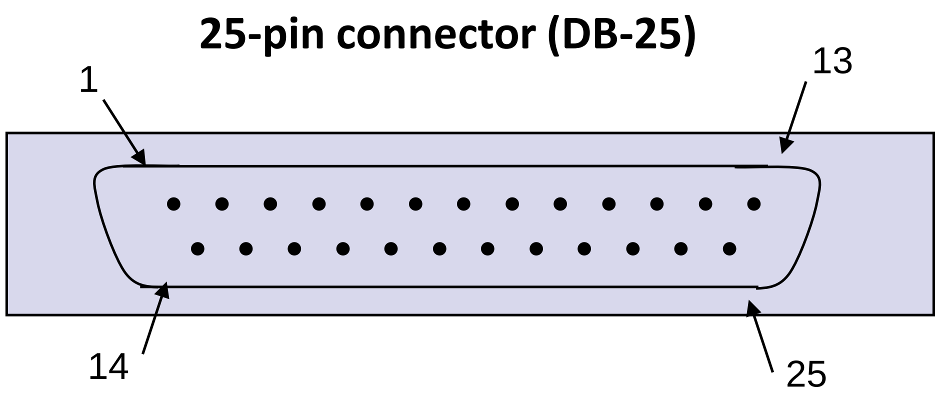



- Errors in some systems cause transposition in polarity, +A become –A and vice versa
  - All subsequent bits in Polar NRZ coding would be in error
- Differential line coding provides robustness to this type of error
- “1” mapped into transition in signal level
- “0” mapped into no transition in signal level
- Same spectrum as NRZ
- Errors occur in pairs
- Also used with Manchester coding

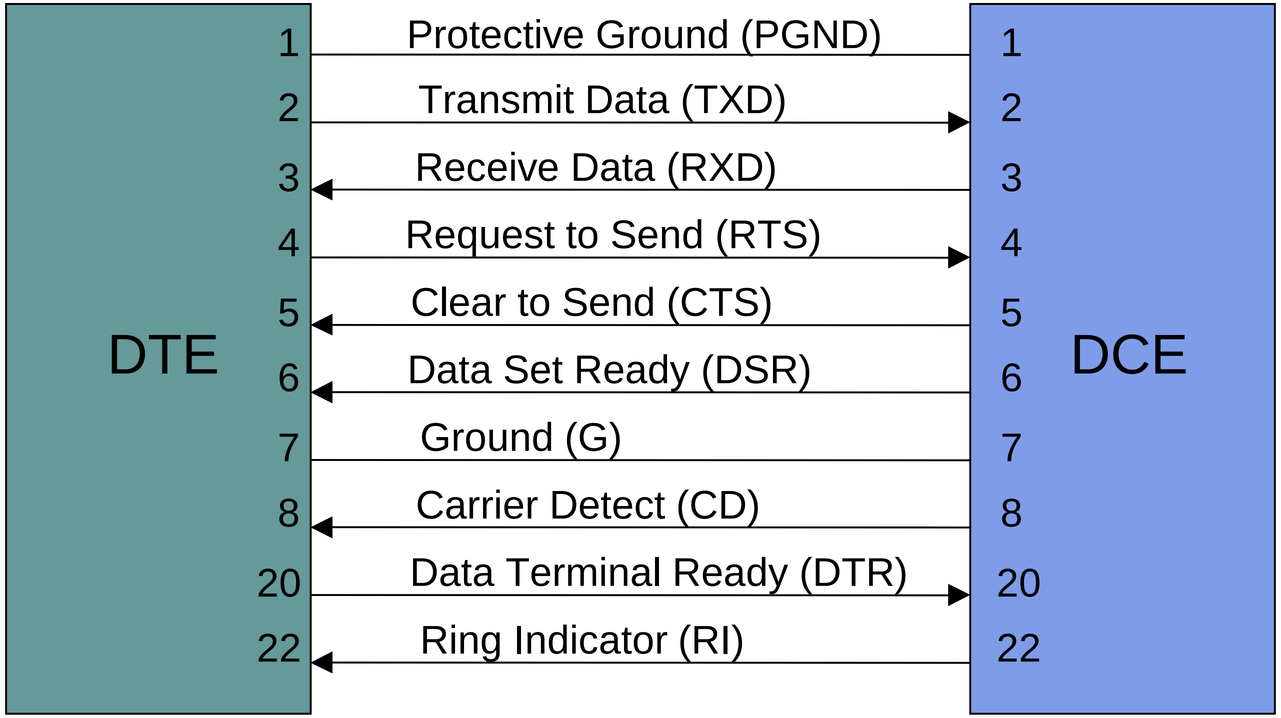
## 6.3 Asynchronous and synchronous communications

- Recommended Standard (RS) 232
- serial line interface between computer and modem or similar device
- Data Terminal Equipment (DTE): computer
- Data Communications Equipment (DCE): modem
- mechanical and electrical specification

(a)

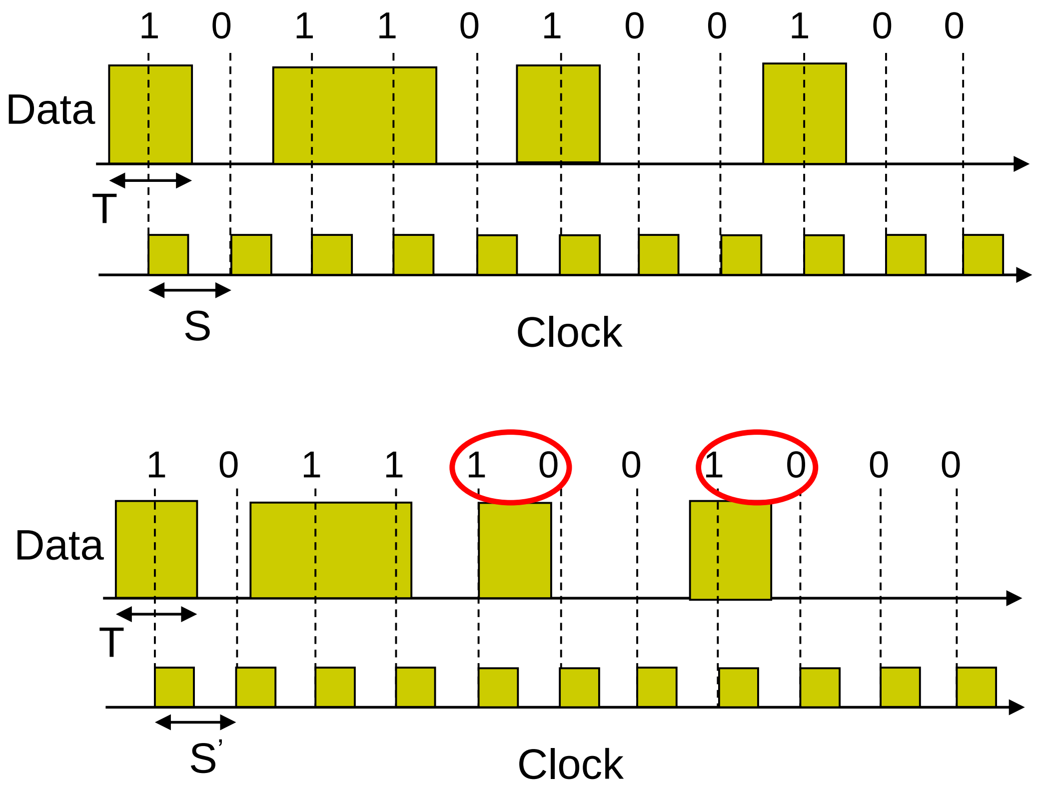

25-pin connector (DB-25)
1
13
14
25

(b)

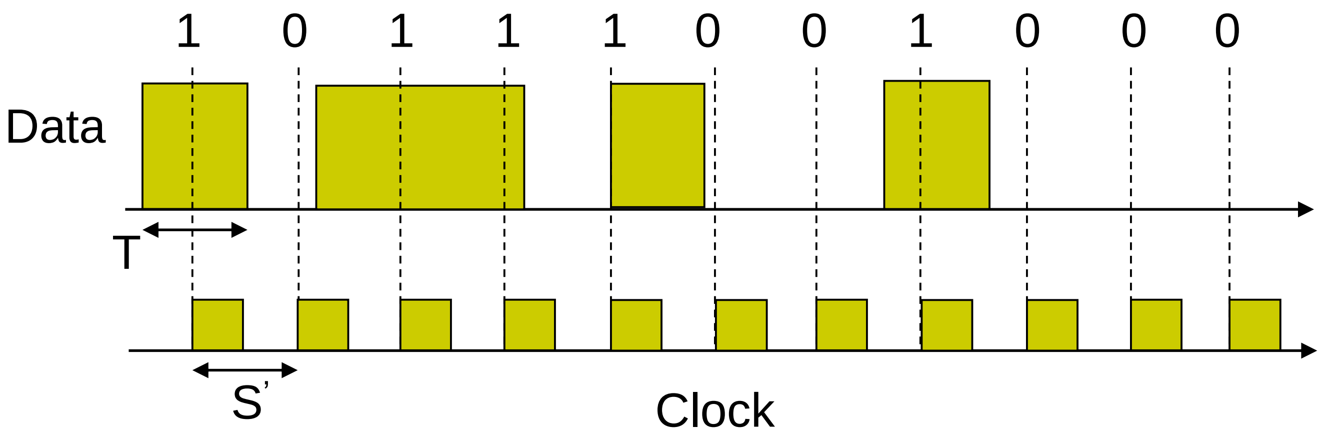

DTE
DCE
1 Protective Ground (PGND) 1
2 Transmit Data (TXD) 2
3 Receive Data (RXD) 3
4 Request to Send (RTS) 4
5 Clear to Send (CTS) 5
6 Data Set Ready (DSR) 6
7 Ground (G) 7
8 Carrier Detect (CD) 8
20 Data Terminal Ready (DTR) 20
22 Ring Indicator (RI) 22

# Synchronization

- Synchronization of clocks in transmitters and receivers.
  - clock drift causes a loss of synchronization
- Example: assume ‘1’ and ‘0’ are represented by V volts and 0 volts respectively
  - Correct reception
  - Incorrect reception due to incorrect clock (slower clock)

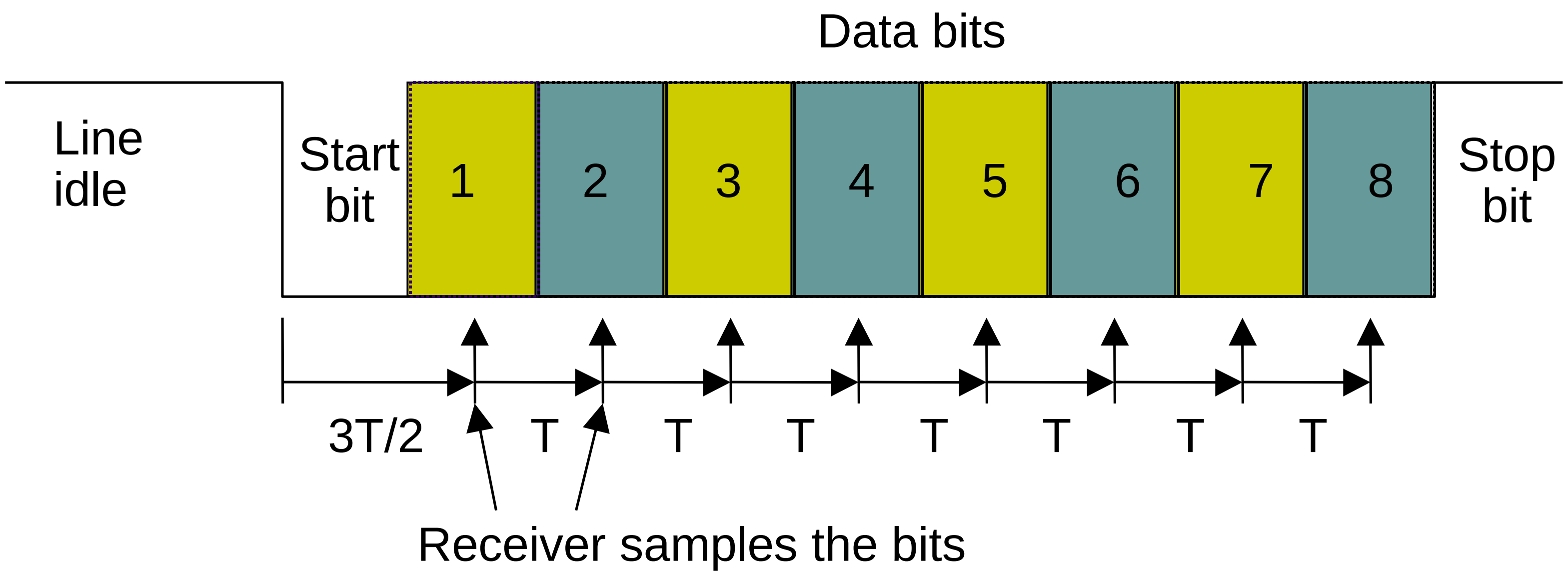


- Incorrect reception
- How  to avoid a loss of synchronization?
  - Asynchronous transmission
  - Synchronous transmission



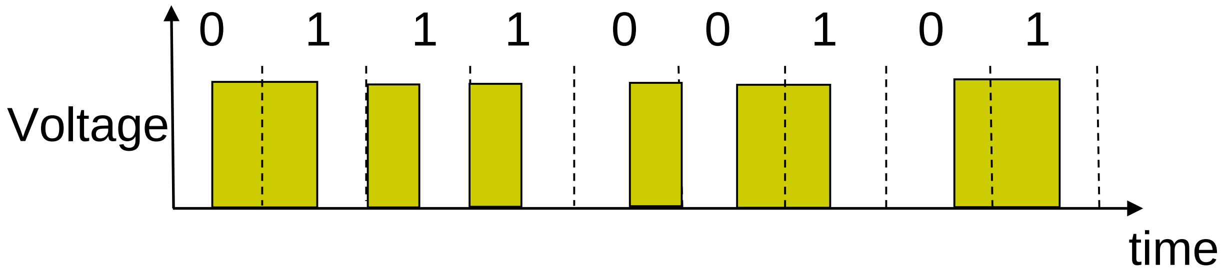
# Asynchronous transmission

- Avoids synchronization loss by specifying a short maximum length for the bit sequences and resetting the clock in the beginning of each bit sequence.

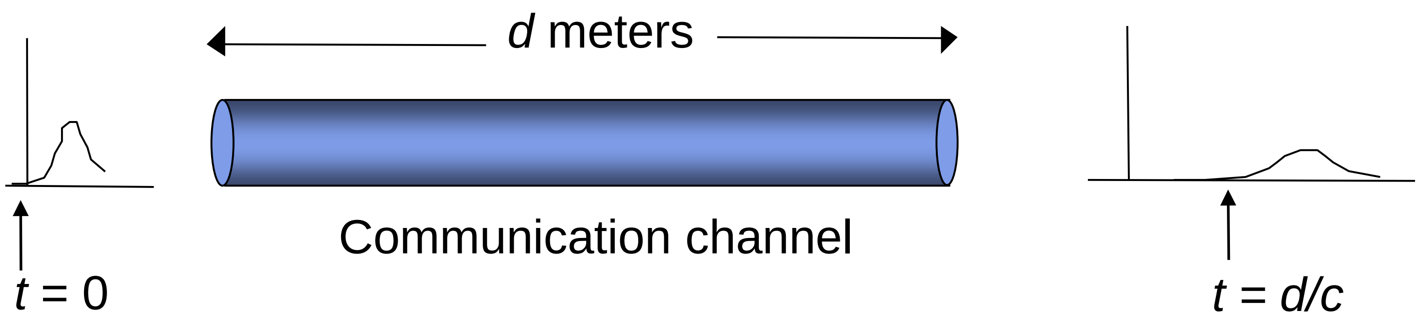


# Synchronous transmission

- Sequence contains data + clock information (line coding)
  - i.e. Manchester encoding, self-synchronizing codes, is used.
- R transition for *R* bits per second transmission

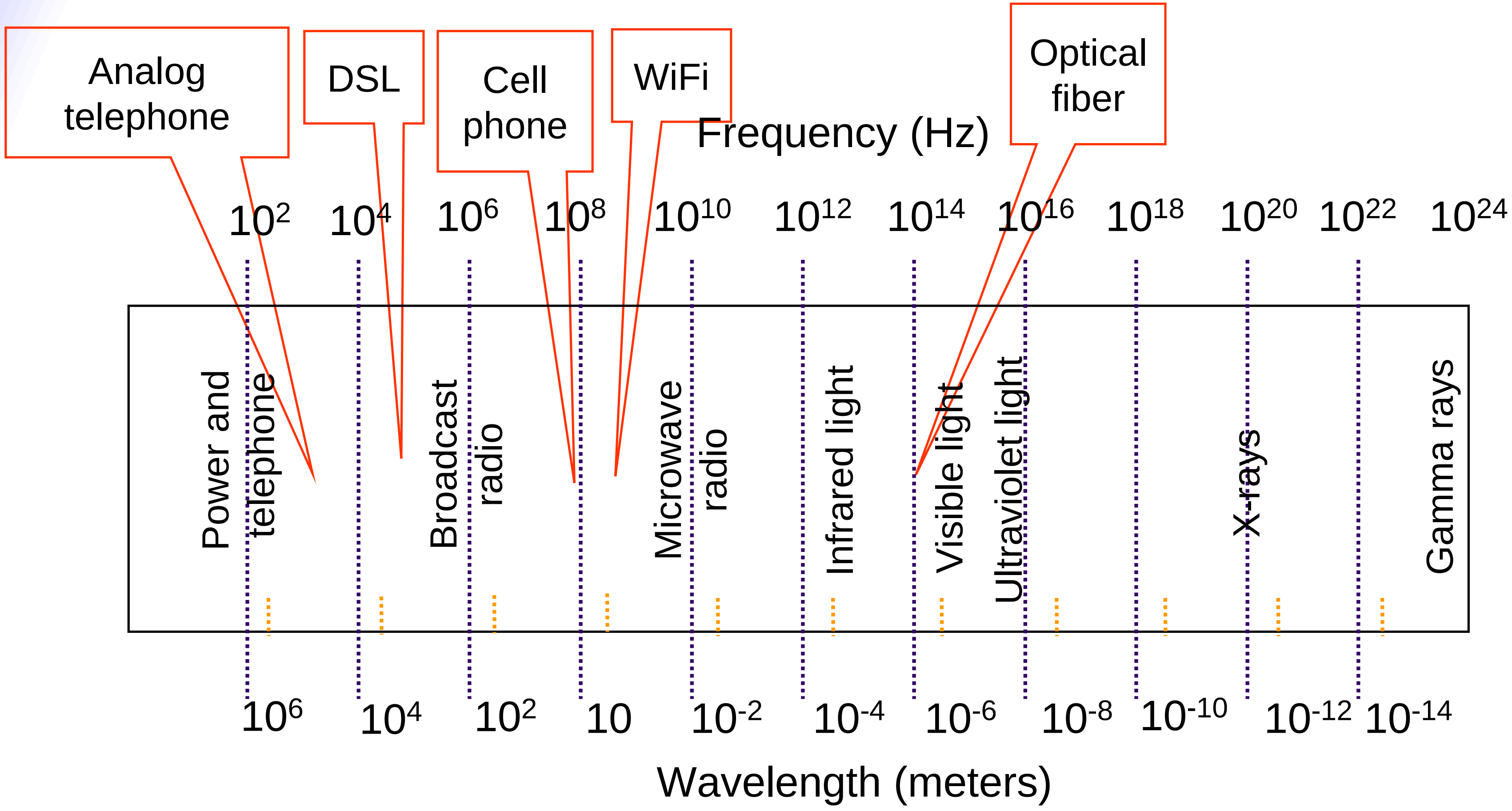


# 6.4 Transmission media




- Information bearing capacity
  - Amplitude response and bandwidth
    - depend on distance
  - Susceptibility to noise and interference
    - error rates and SNRs
- Propagation speed of signal
  - $c = 3 \times 10^8$ m/s in vacuum
  - $n = c/\sqrt{e}$ speed of light in medium where $e > 1$ is the dielectric constant of the medium
  - $n = 2.3 \times 10^8$ m/s in copper wire; $n = 2.0 \times 10^8$ m/s in optical fiber

- frequency of communication signals



Wireless Media

- Signal energy propagates in space, limited directionality
- Interference possible, so spectrum regulated
- Limited bandwidth
- Simple infrastructure: antennas & transmitters
- No physical connection between network & user
- Users can move

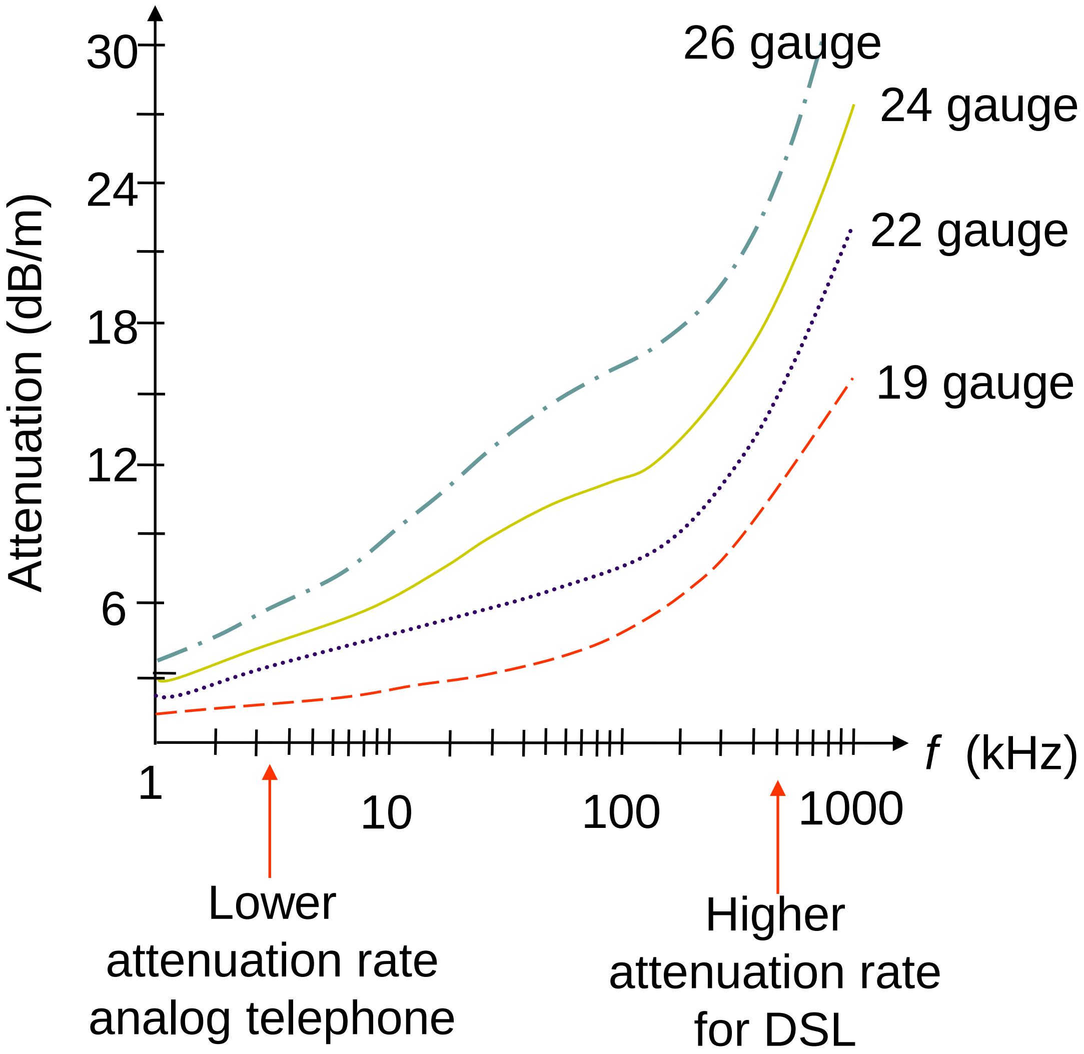
Wired Media

- Signal energy contained & guided within medium
- Spectrum can be re-used in separate media (wires or cables), more scalable
- Extremely high bandwidth
- Complex infrastructure: ducts, conduits, poles, right-of-way

- Attenuation varies with media
  - Dependence on distance of central importance
- Wired media has exponential dependence
  - Received power at $d$ meters proportional to $10^{-kd}$
  - Attenuation in dB = $k\,d$, where $k$ is dB/meter
- Wireless media has logarithmic dependence
  - Received power at $d$ meters proportional to $d^{-n}$
  - Attenuation in dB = $n \log d$, where $n$ is path loss exponent; $n=2$ in free space
  - Signal level maintained for much longer distances
  - Space communications possible

# Twisted pair

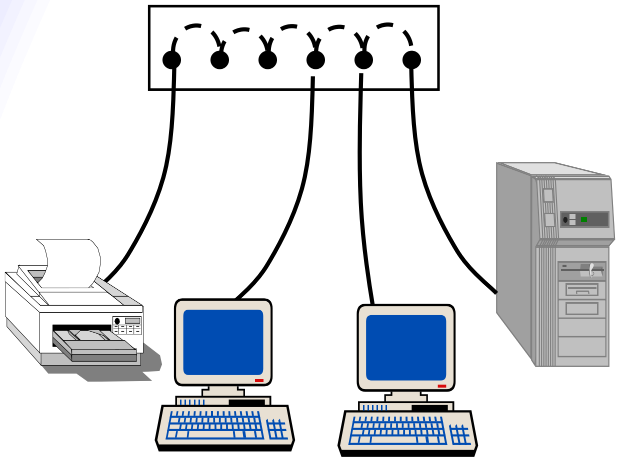
- Two insulated copper wires arranged in a regular spiral pattern to minimize interference
- Various thicknesses, e.g. 0.016 inch (24 gauge)
- Low cost
- Telephone subscriber loop from customer to CO
- Old trunk plant connecting telephone COs
- Intra-building telephone from wiring closet to desktop
- In old installations, loading coils added to improve quality in 3 KHz band, but more attenuation at higher frequencies



| Standard | Data Rate | Distance |
|---|---|---|
| T-1 | 1.544 Mbps | 18,000 feet, 5.5 Km |
| DS2 | 6.312 Mbps | 12,000 feet, 3.7 Km |
| 1/4 STS-1 | 12.960 Mbps | 4500 feet, 1.4 Km |
| 1/2 STS-1 | 25.920 Mbps | 3000 feet, 0.9 Km |
| STS-1 | 51.840 Mbps | 1000 feet, 300 m |

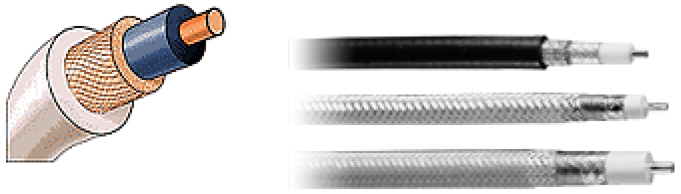
- Twisted pairs can provide high bit rates at short distances
- Asymmetric Digital Subscriber Loop (ADSL)
  - High-speed Internet Access
  - Lower 3 KHz for voice
  - Upper band for data
  - 64 Kbps inbound
  - 640 Kbps outbound
- Much higher rates possible at shorter distances
  - Strategy for telephone companies is to bring fiber close to home and then twisted pair
  - Higher-speed access + video

# Ethernet LAN

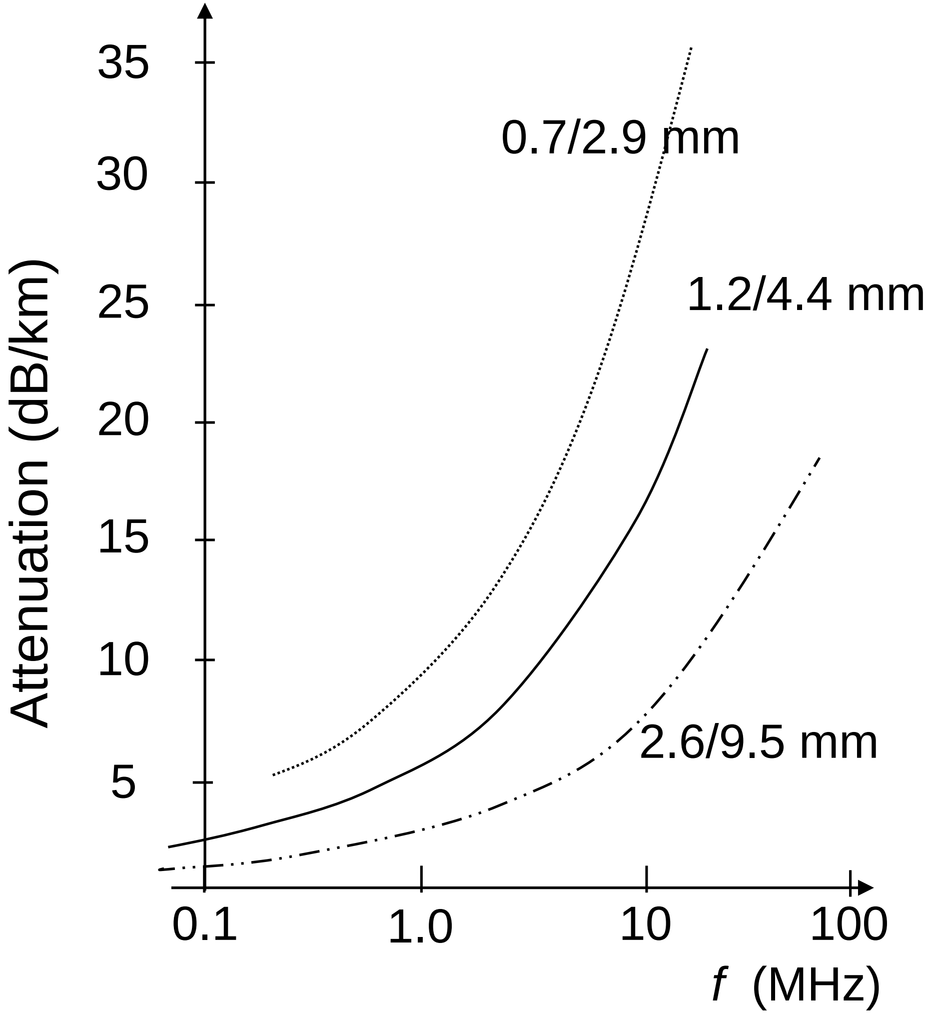


- Category 3 unshielded twisted pair (UTP): ordinary telephone wires
- Category 5 UTP: tighter twisting to improve signal quality
- Shielded twisted pair (STP): to minimize interference; costly
- 10BASE-T Ethernet
  - 10 Mbps, Baseband, Twisted pair
  - Two Cat3 pairs
  - Manchester coding, 100 meters
- 100BASE-T4 *Fast* Ethernet
  - 100 Mbps, Baseband, Twisted pair
  - Four Cat3 pairs
  - Three pairs for one direction at-a-time
  - 100/3 Mbps per pair;
  - 3B6T line code, 100 meters
- Cat5 and STP provide other options

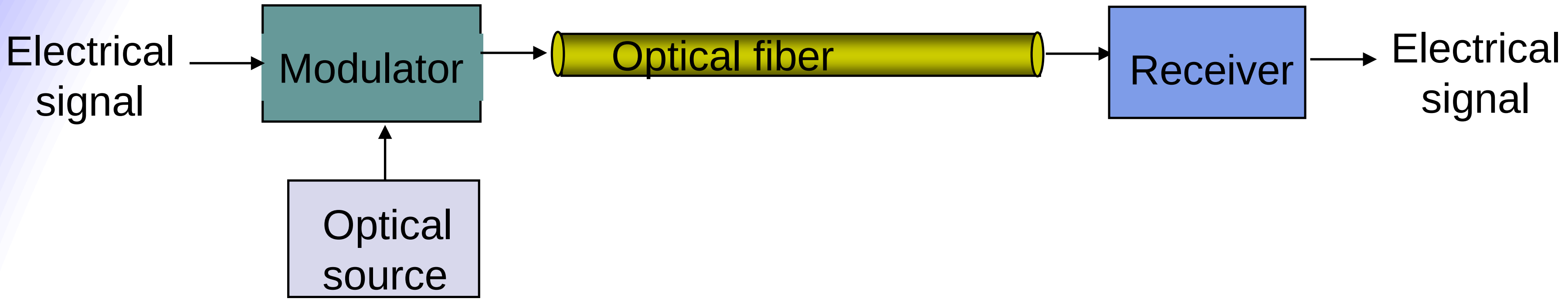
# Coaxial cable



- Cylindrical braided outer conductor surrounds insulated inner wire conductor
- High interference immunity
- Higher bandwidth than twisted pair
- Hundreds of MHz
- Cable TV distribution
- Long distance telephone transmission
- Original Ethernet LAN medium

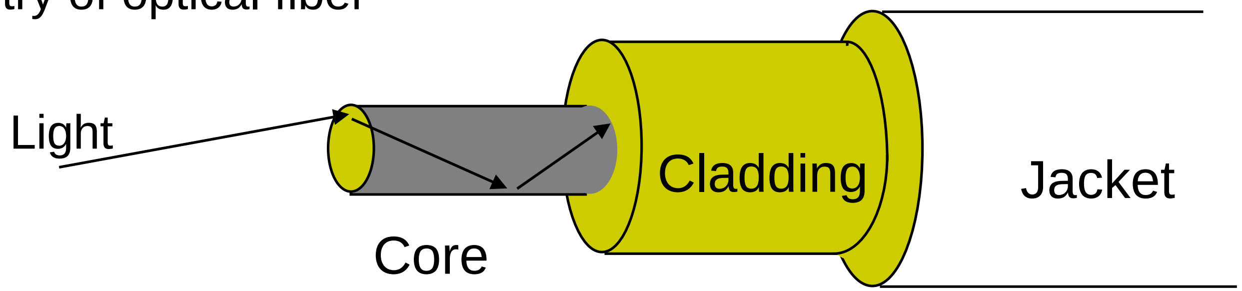


# Optical fiber

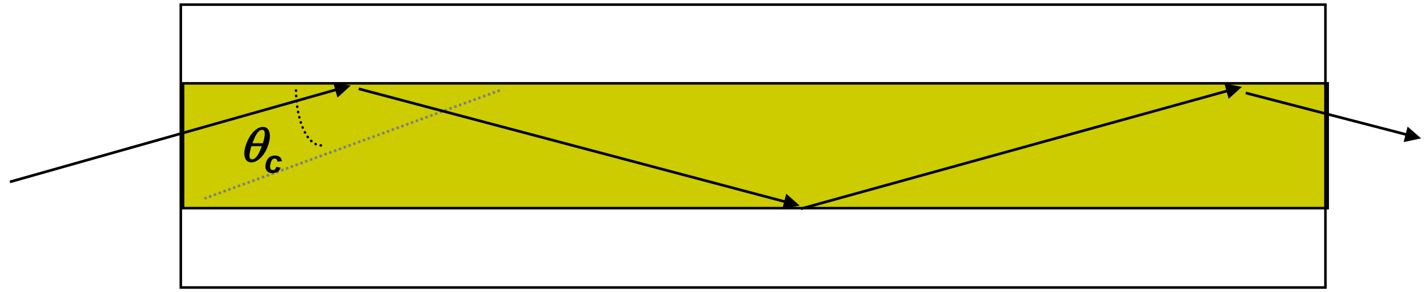



- Light sources (lasers, LEDs) generate pulses of light that are transmitted on optical fiber
  - Very long distances (>1000 Km)
  - Very high speeds (>40 Gbps/wavelength)
  - Nearly error-free (BER of $10^{-15}$)
- Profound influence on network architecture
  - Dominates long distance transmission
  - Distance less of a cost factor in communications
  - Plentiful bandwidth for new services

Geometry of optical fiber

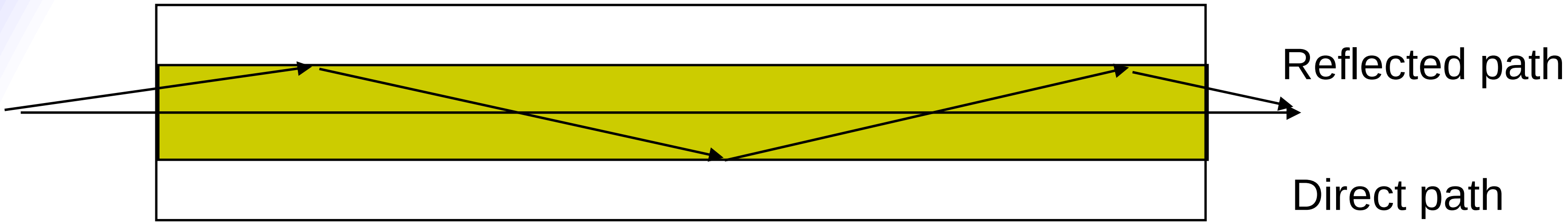



Total Internal Reflection in optical fiber

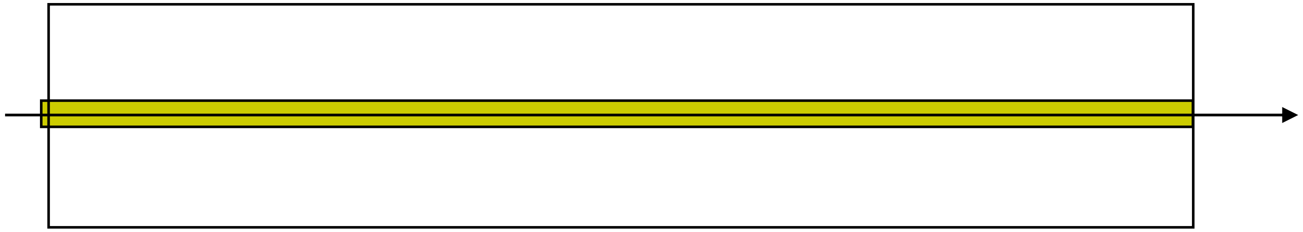



- Very fine glass cylindrical core surrounded by concentric layer of glass (cladding)
- Core has higher index of refraction than cladding
- Light rays incident at less than critical angle $\theta_c$ is completely reflected back into the core

Multimode fiber: multiple rays follow different paths



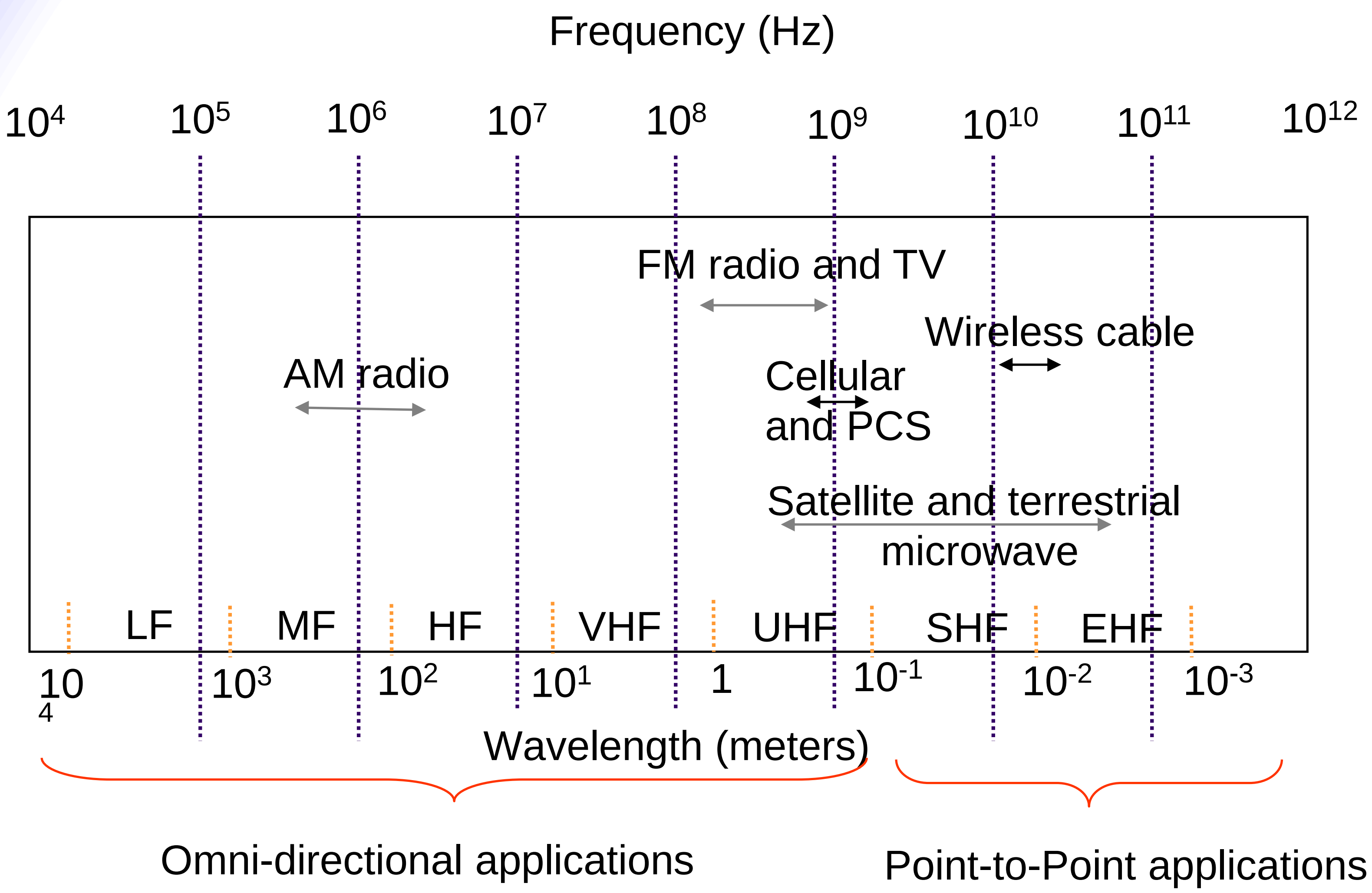

Single-mode fiber: only direct path propagates in fiber



- Multimode:  thicker core, shorter reach
  - Rays on different paths interfere causing dispersion and limiting bit rate
- Single mode:  very thin core supports only one mode (path)
  - More expensive lasers, but achieves very high speeds

# Radio transmission

- Radio signals: antenna transmits sinusoidal signal (“carrier”) that radiates in air/space
- Information embedded in carrier signal using modulation, e.g. Quadrature Amplitude Modulation (QAM)
- Communications without tethering
  - cellular phones, satellite transmissions, wireless LANs
- Multipath propagation causes fading
- Interference from other users
- Spectrum regulated by national and international regulatory organizations


Frequency (Hz)
$10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$
FM radio and TV
Wireless cable
AM radio
Cellular and PCS
Satellite and terrestrial microwave
LF MF HF VHF UHF SHF EHF
$10^4$ $10^3$ $10^2$ $10^1$ 1 $10^{-1}$ $10^{-2}$ $10^{-3}$
Wavelength (meters)
Omni-directional applications
Point-to-Point applications

# Examples

### Cellular Phone

- Allocated spectrum
- First generation:
  - 800, 900 MHz
  - Initially analog voice
- Second generation:
  - 1800-1900 MHz
  - Digital voice, messaging

### Wireless LAN

- Unlicenced ISM spectrum
  - Industrial, Scientific, Medical
  - 902-928 MHz, 2.400-2.4835 GHz, 5.725-5.850 GHz
- IEEE 802.11 LAN standard
  - 11-54 Mbps

### Satellite Communications

- Geostationary satellite @ 36,000 Km above equator
- Relays microwave signals from uplink frequency to downlink frequency
- Long distance telephone
- Satellite TV broadcast

# Chapter Summary

- digital representation of information
- digital transmission – digitization of analog signal, characterization of communication channel, limitations, line coding
- asynchronous and synchronous communications
- transmission media

# Reference

Chapter 3, Communication Networks: Fundamental Concepts and Key Architectures