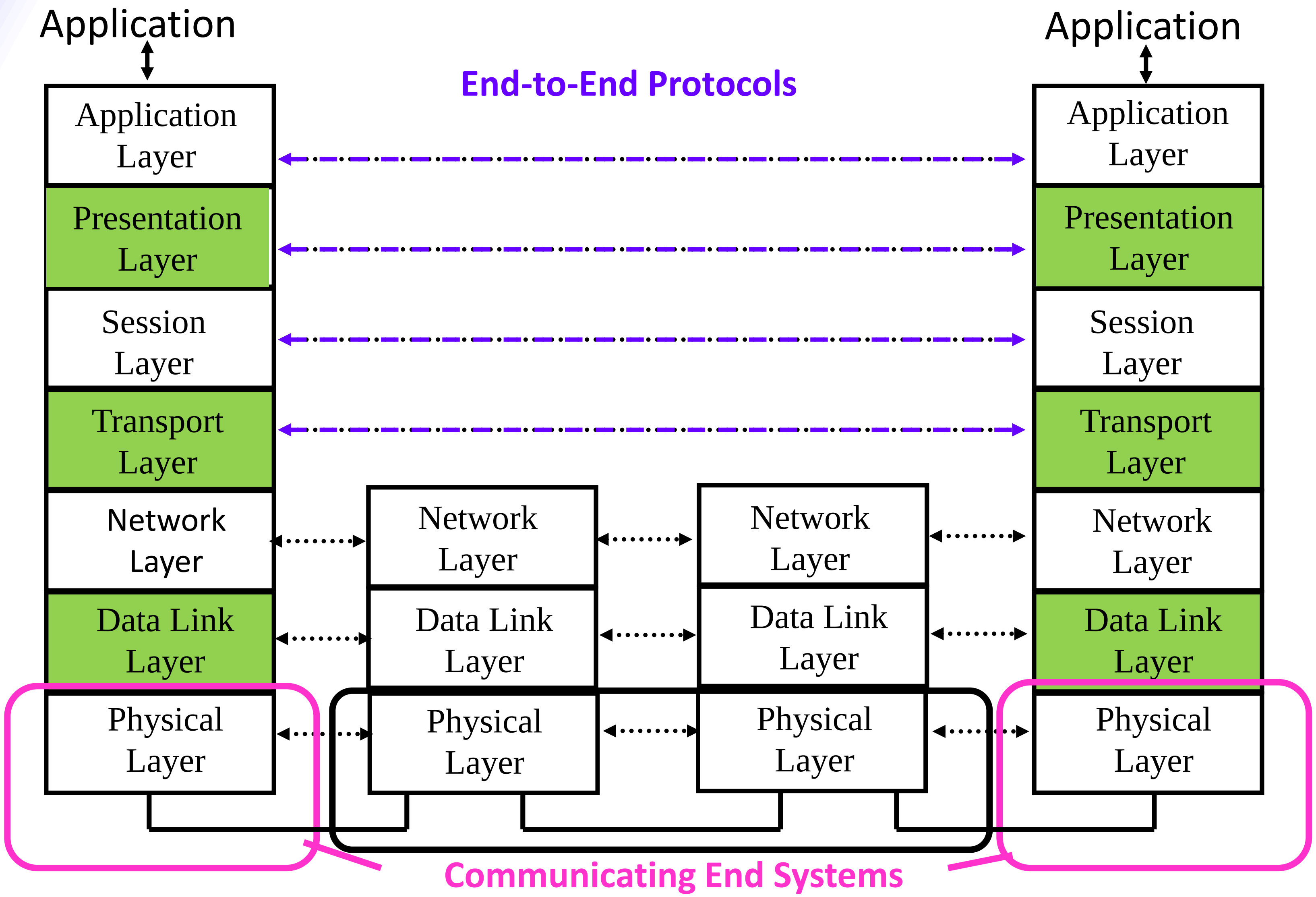
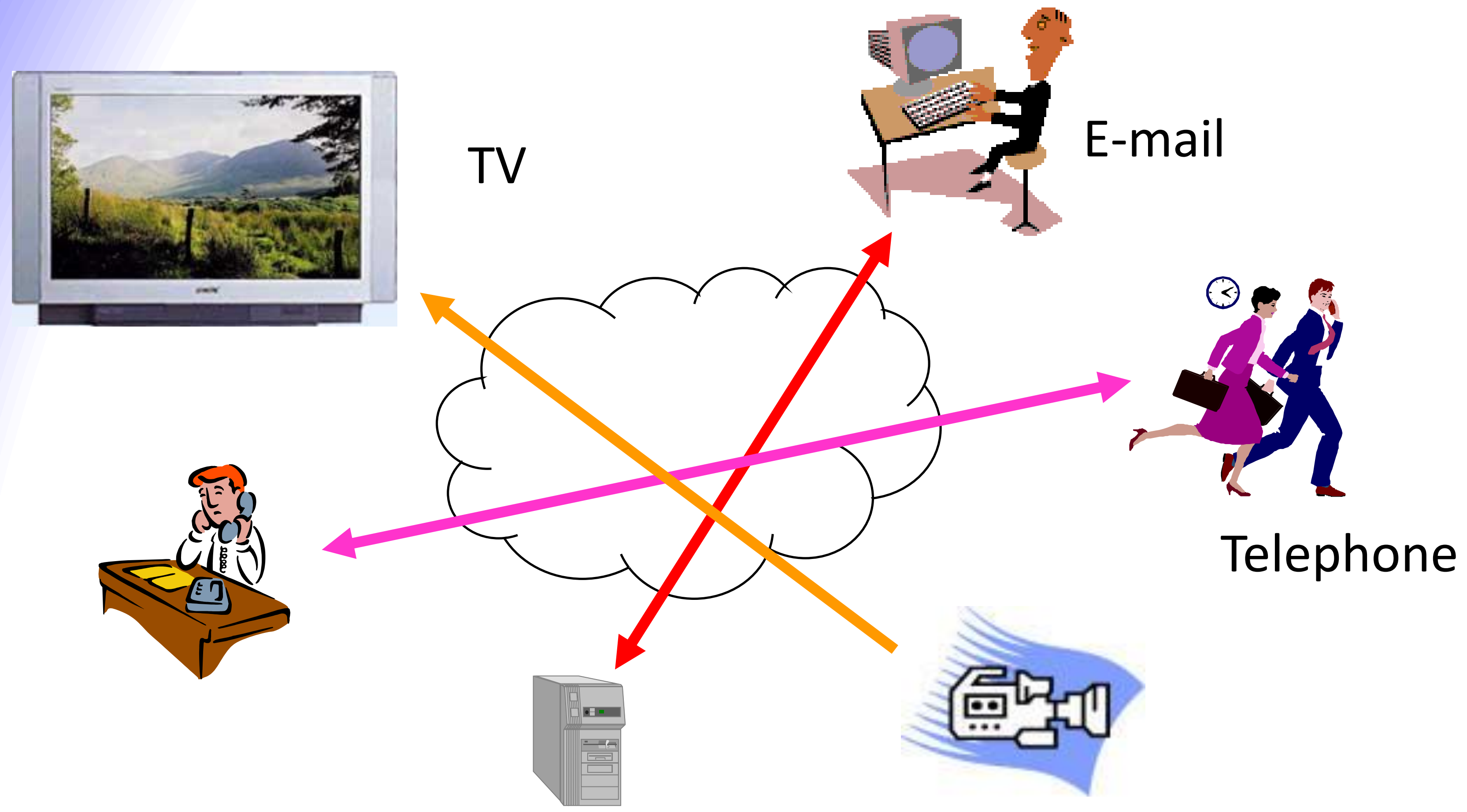
6. Data transmission

* 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

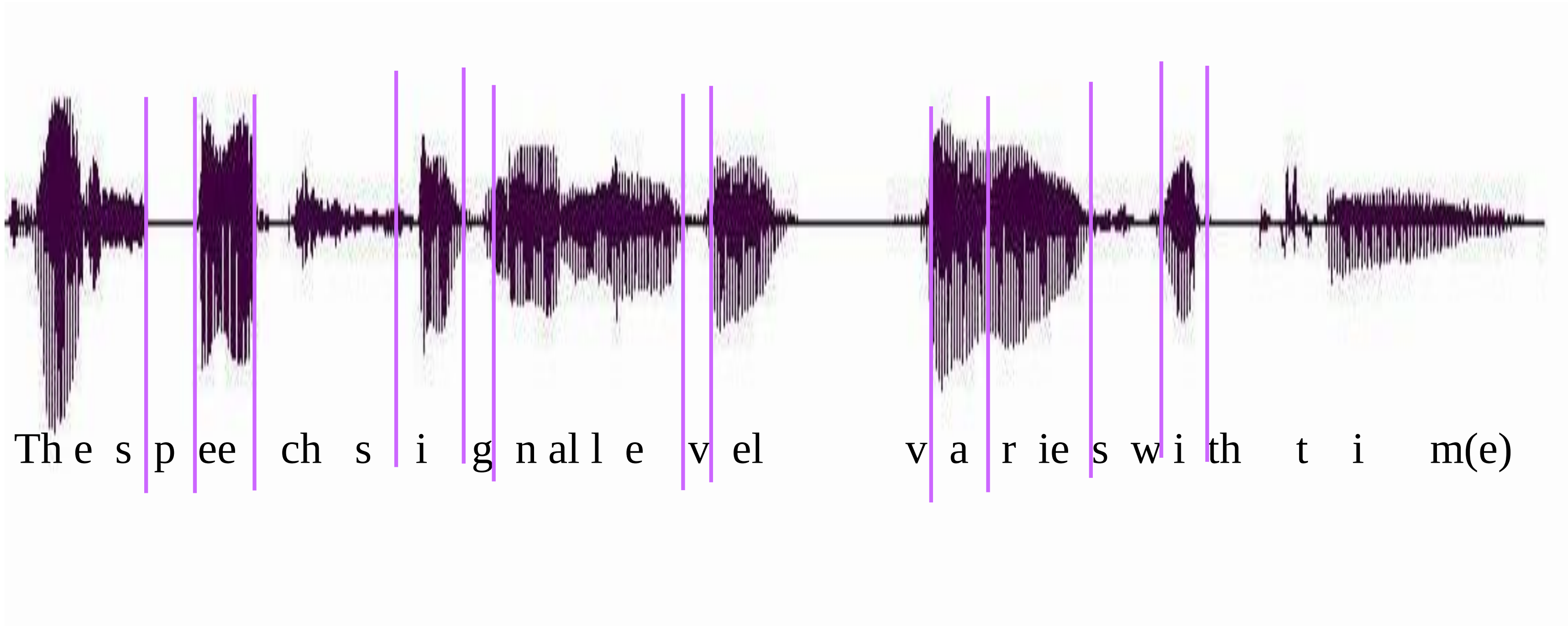
  or bytes/block
  - 1 Kbyte = 2^{10} bytes
  - 1 Mbyte = 2^{20} bytes
  - 1 Gbyte = 2^{30} bytes

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

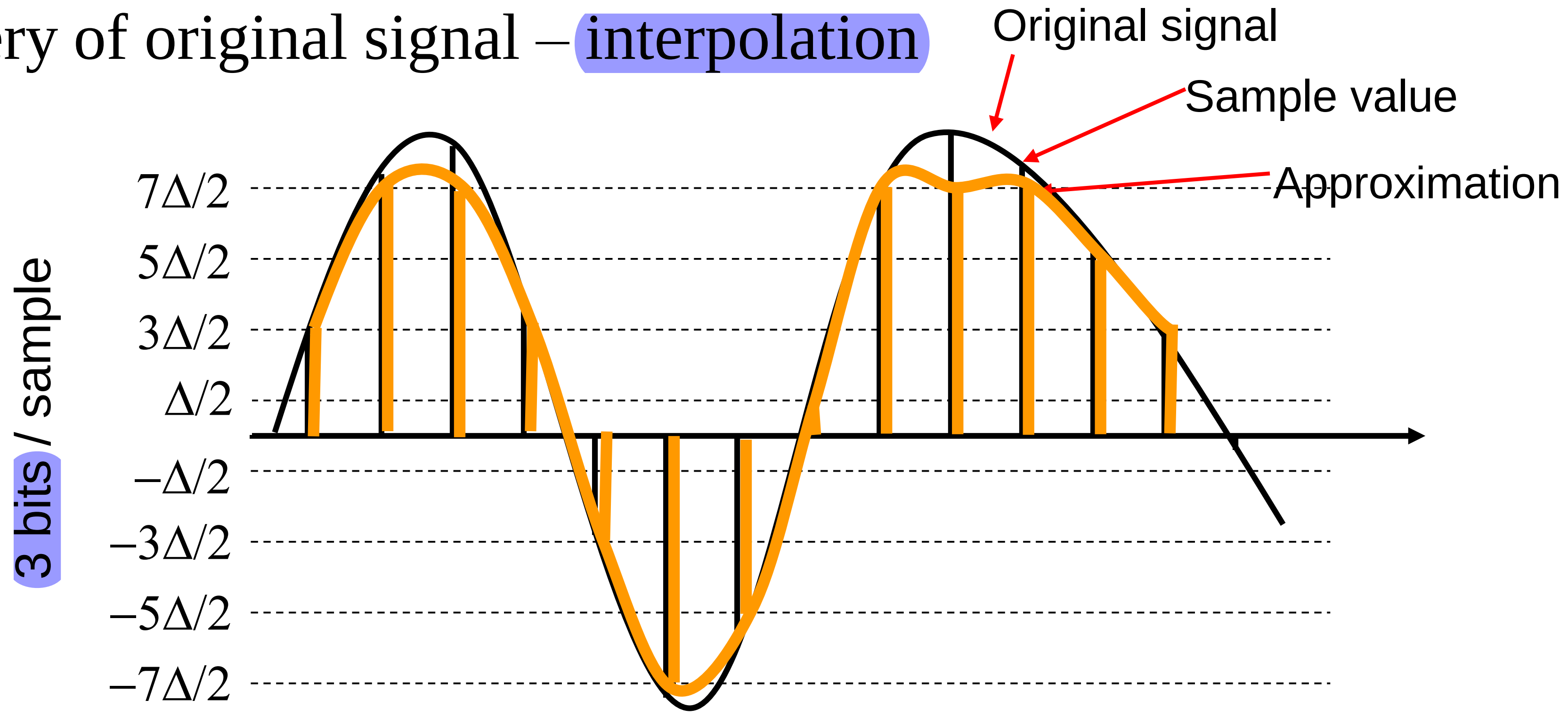
Stream information

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



Digitization of analog signal

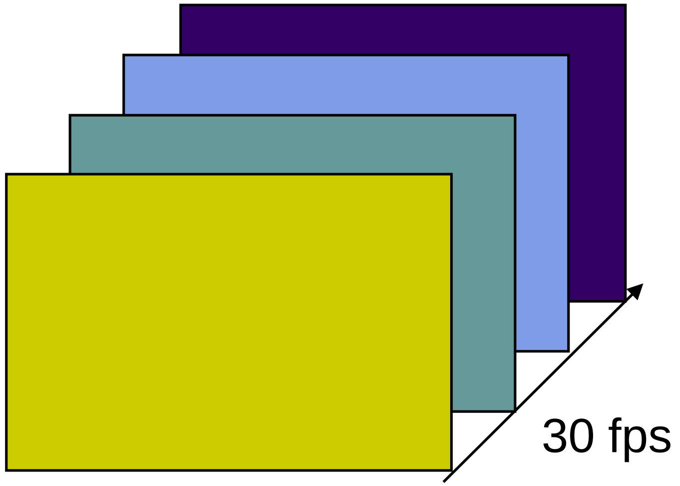
- sample analog signal in time
- find closest approximation – quantization
- recovery of original signal – interpolation



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

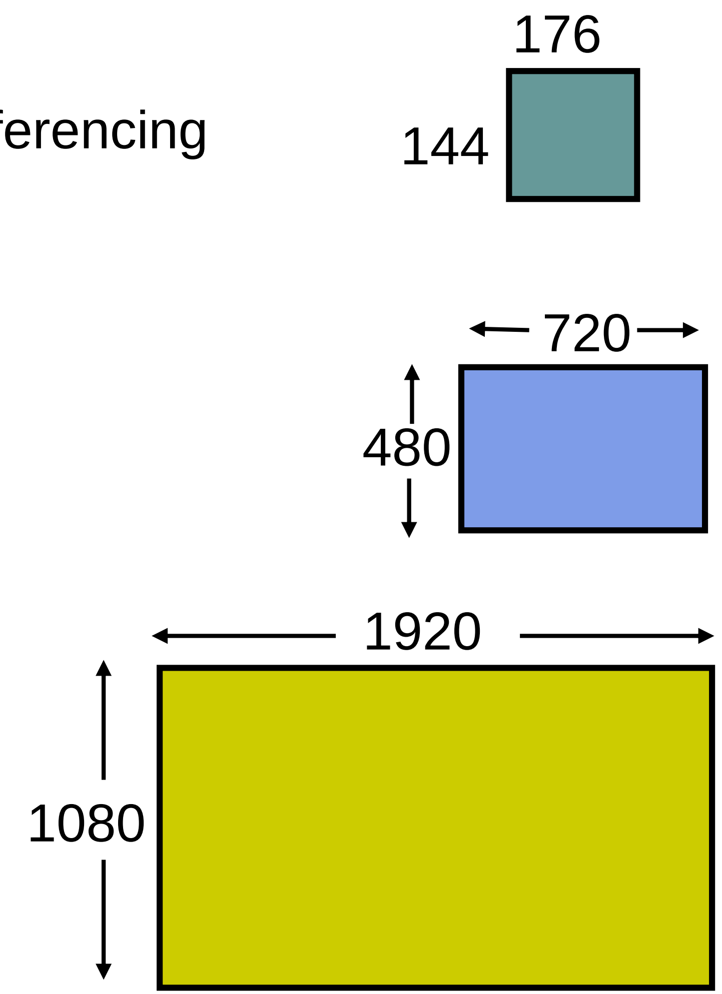
at 30 frames/sec =

10.4×10^6 pixels/sec

HDTV

at 30 frames/sec =

62×10^6 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

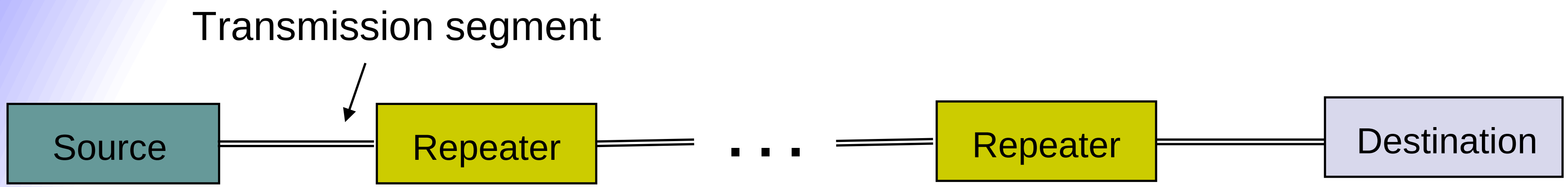
Communication Channel

- 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

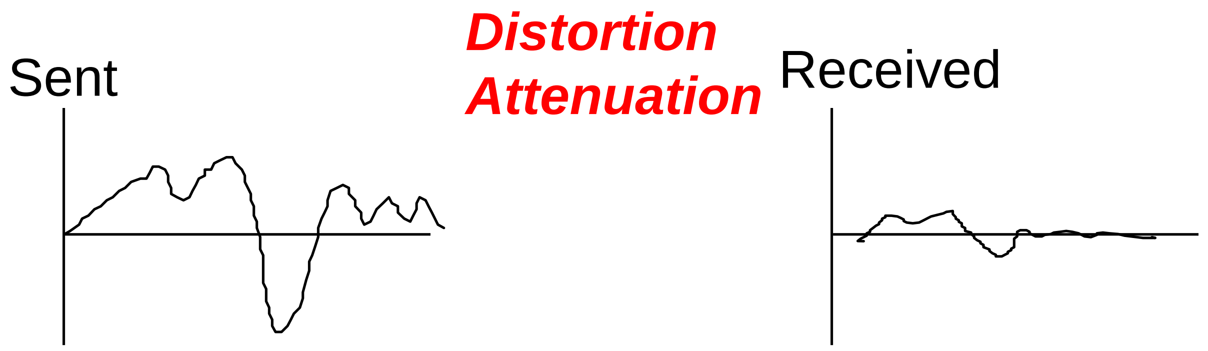
Analog long-distance communication



- 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

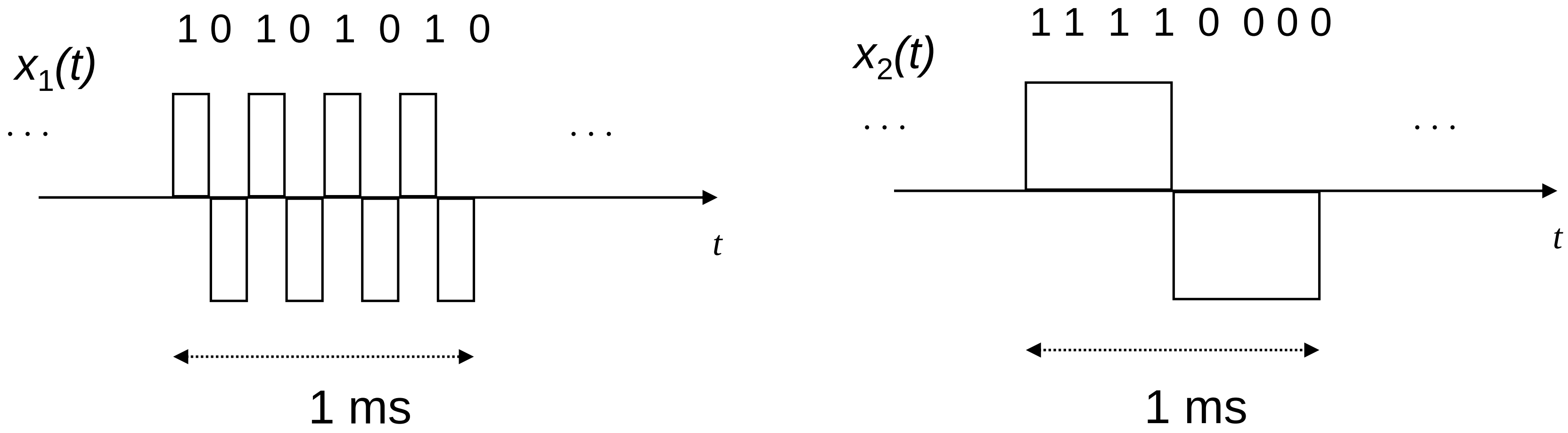
- Regenerator recovers original data sequence and retransmits on next segment
- Each regeneration is like the first time!
- Can design a transmission system with very low bit error rate
- Analogy: copy an MP3 file
- Communication is possible over very long distances
- Digital systems vs. analog systems
  - 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

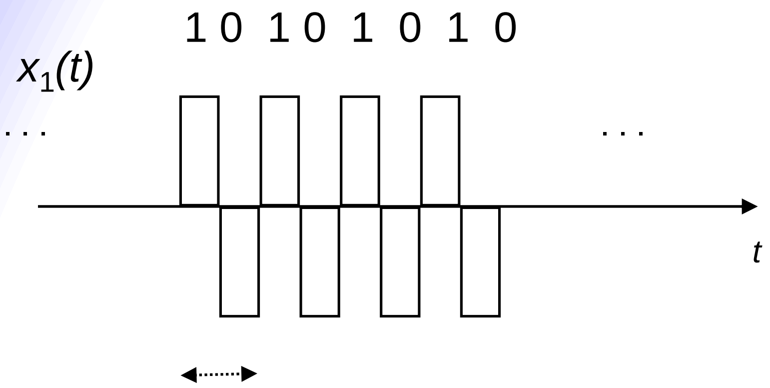
fundamental
frequency $f_0=1/T$
first harmonic

kth harmonic

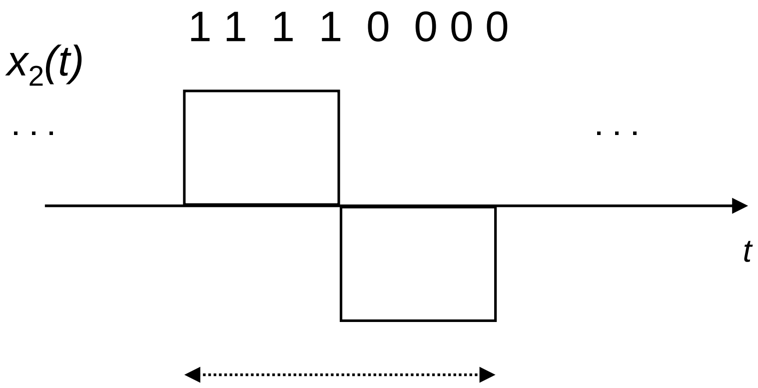
- $|a_k|$ determines amount of power in kth harmonic

- Amplitude spectrum $|a_0|$, $|a_1|$, $|a_2|$, …

Example - Fourier series



T_2 =0.25 ms



T_1 = 1 ms

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

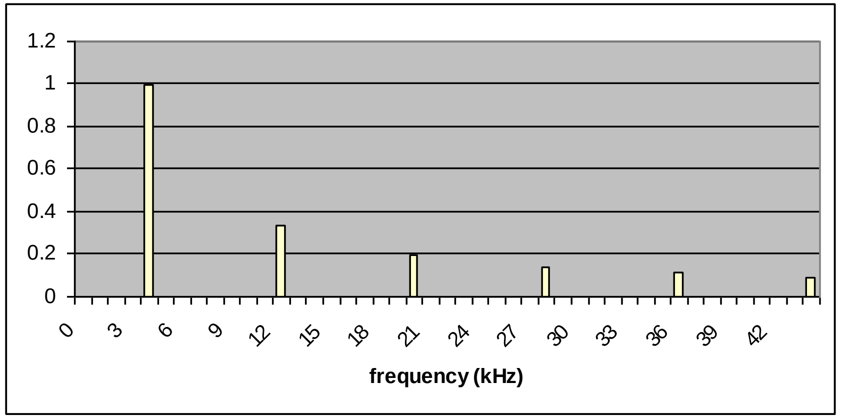
$$x_2(t) = 0 + \frac{4}{\pi}\cos(2\pi 1000t) + \frac{4}{3\pi}\cos(2\pi 3(1000)t) + \frac{4}{5\pi}\cos(2\pi 5(1000)t) + \ldots$$

Only odd harmonics have power

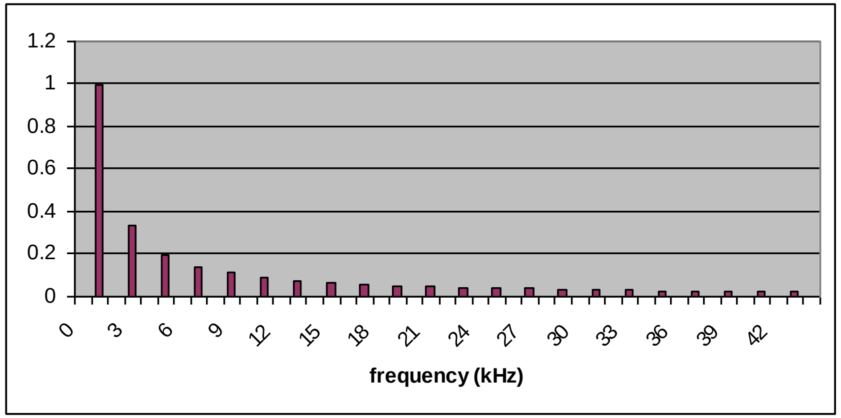
Spectrum and bandwidth

- 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

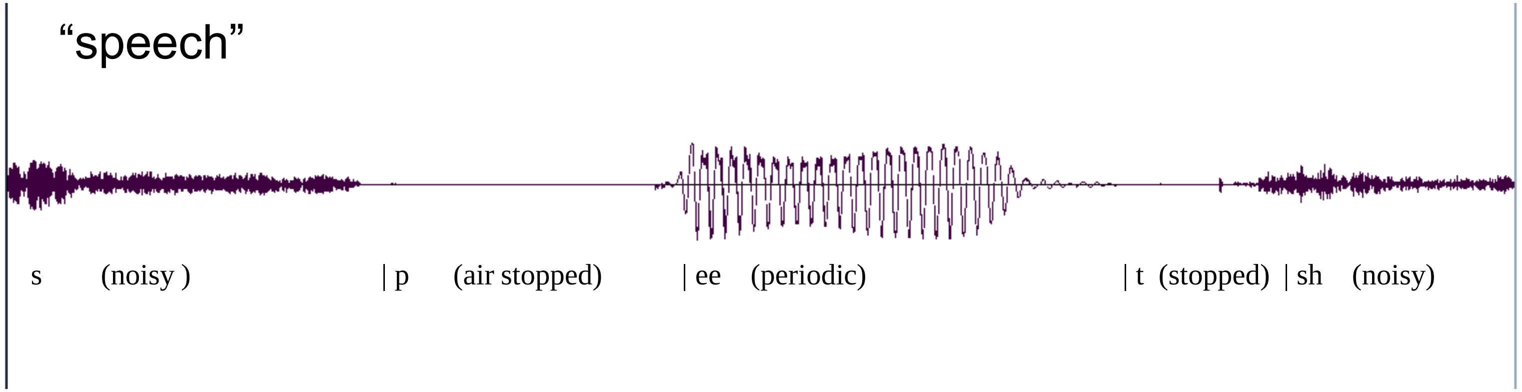
Spectrum of $x_1(t)$



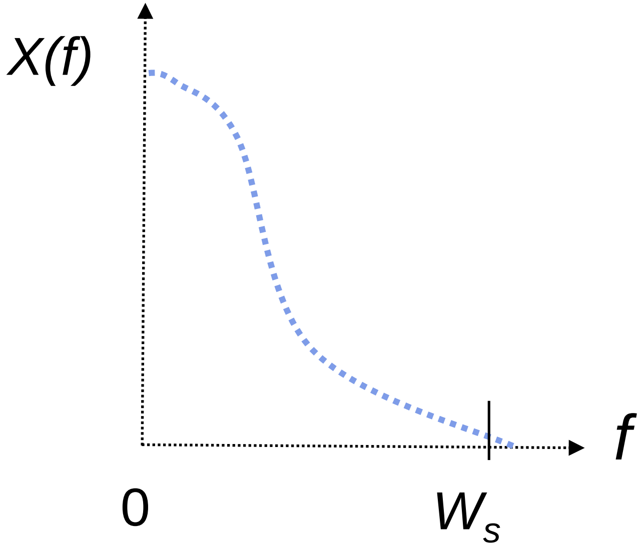
Spectrum of $x_2(t)$



Bandwidth of general signals

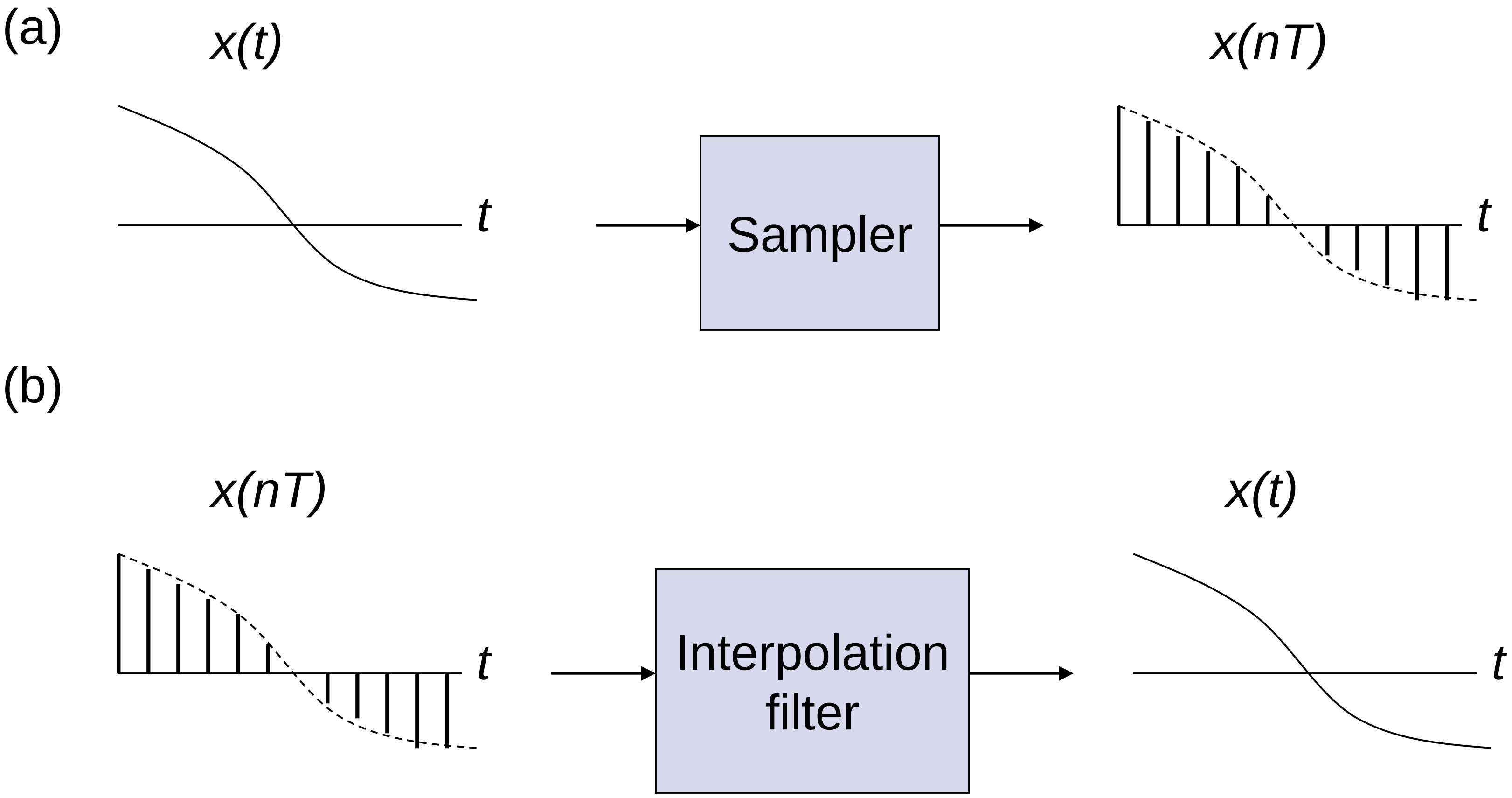


- Not all signals are periodic
  - e.g. voice signal varies according to sound
  - vowels are periodic, “s” is noise-like
- Spectrum of long-term signal
  - averages over many sounds, many speakers
  - involves Fourier transform
- Telephone speech: 4 KHz
- CD Audio: 22 KHz

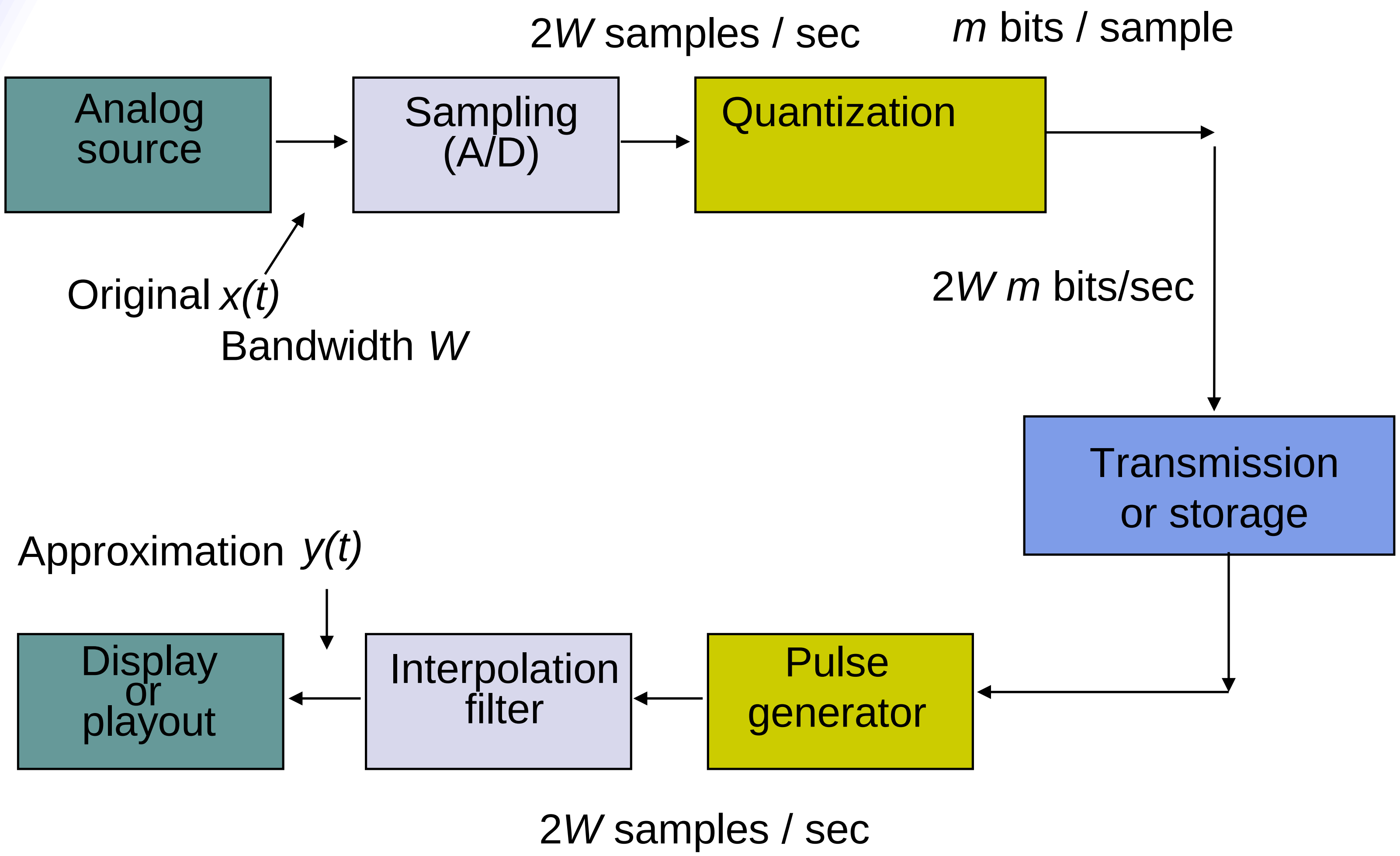


Sampling theorem

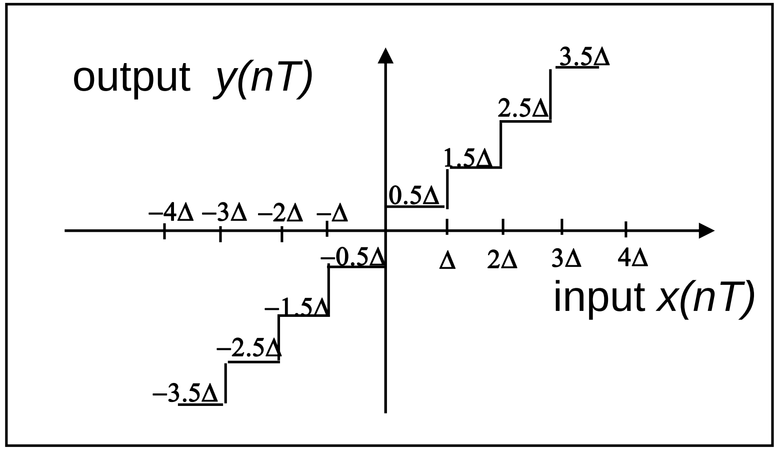
Nyquist: Perfect reconstruction if sampling rate $1/T > 2W_s$



Digital transmission of analog information

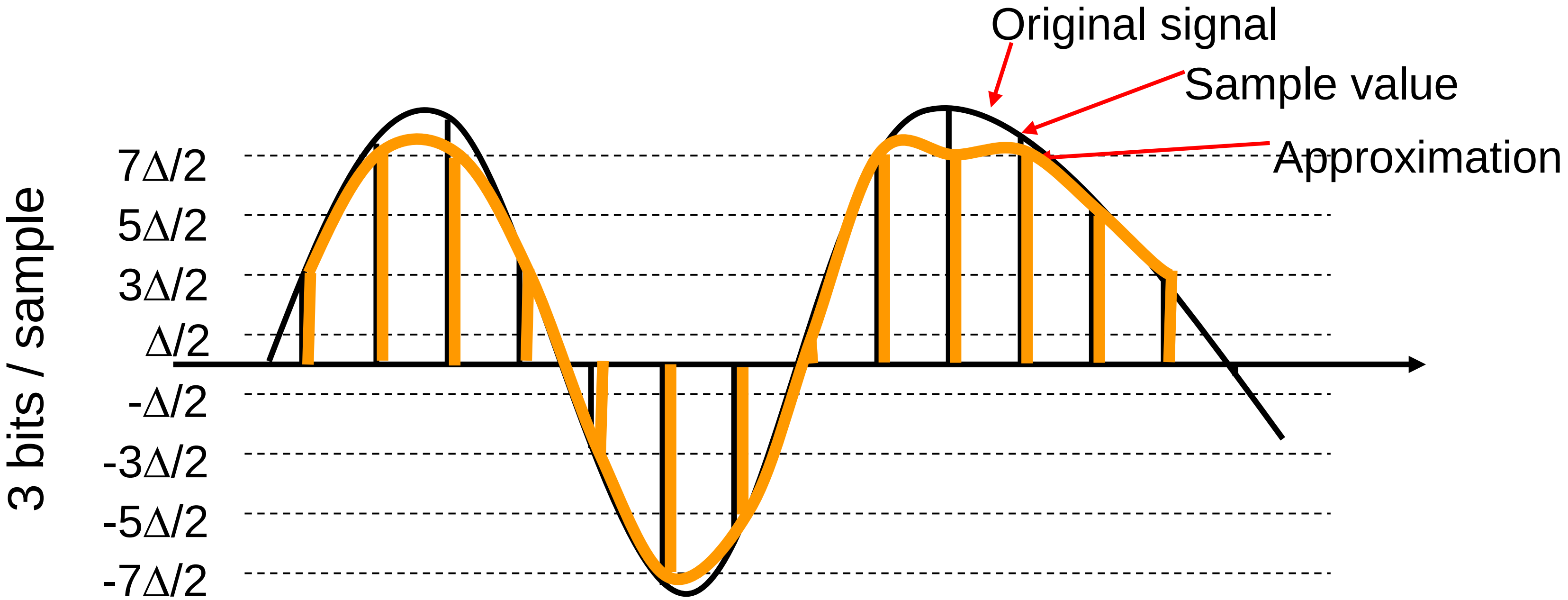


Quantization of analog samples



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 $\rightarrow$ 8000 samples/sec
- 8 bits/sample
- R_s = 8 x 8000 = 64 Kbps

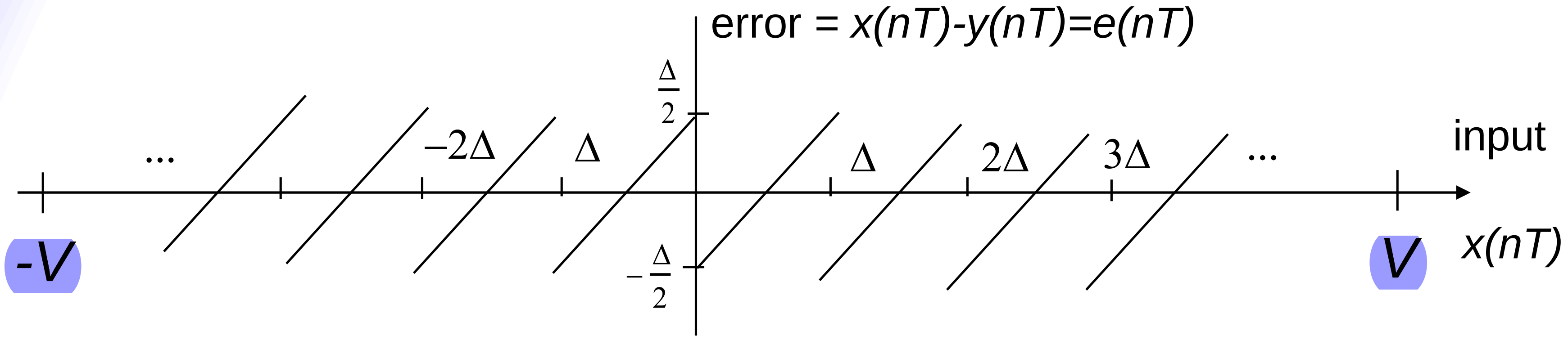
- Cellular phones use more powerful compression algorithms: 8-12 Kbps

CD Audio

- W_s = 22 KHz $\rightarrow$ 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 σ_x^2 be the signal power, then

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

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 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 = 6m – 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~~

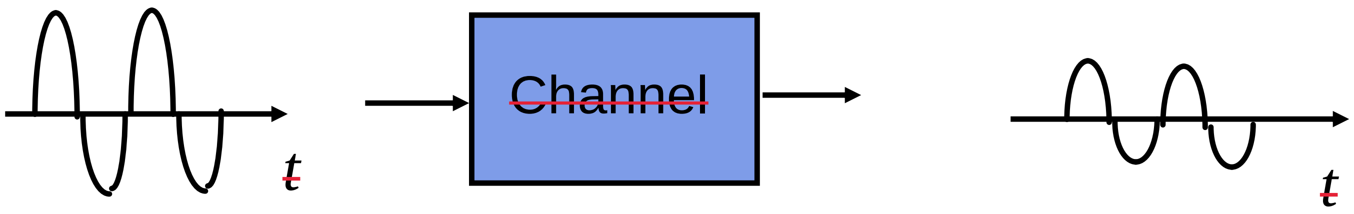
- ~~A channel or medium has an inherent limit on how fast the signals it passes can vary~~
- *~~Limits how tightly input pulses can be packed~~*

~~Transmission Impairments~~

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

Frequency domain channel characterization

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



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

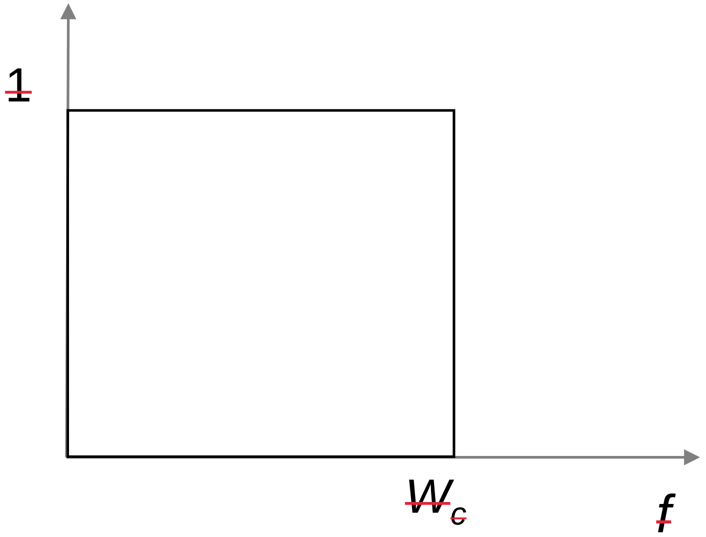
- Apply sinusoidal input at frequency *f*
  - Output is sinusoid at same frequency, but attenuated & phase-shifted
  - Measure amplitude of output sinusoid (of same frequency *f*)
  - Calculate amplitude response
    - $A(f)$ = ratio of output amplitude to input amplitude
  - If $A(f) \approx 1$, then 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

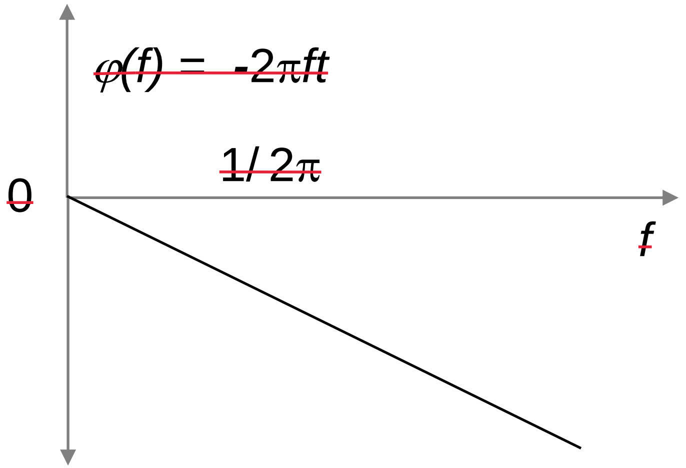
- Ideal filter: all sinusoids with frequency $f < W_c$ are passed without attenuation and delayed by τ seconds; sinusoids at other frequencies are blocked

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

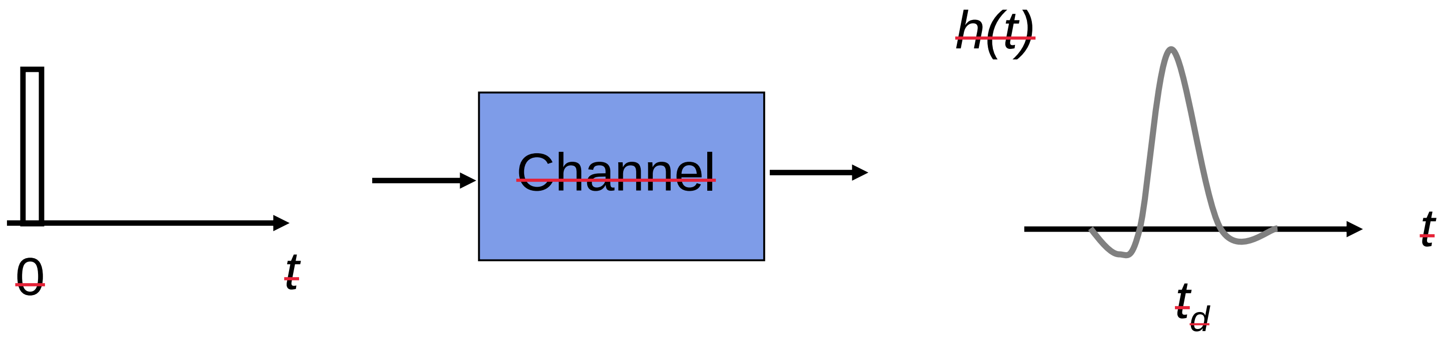
Amplitude Response



Phase Response



~~Time-domain characterization~~

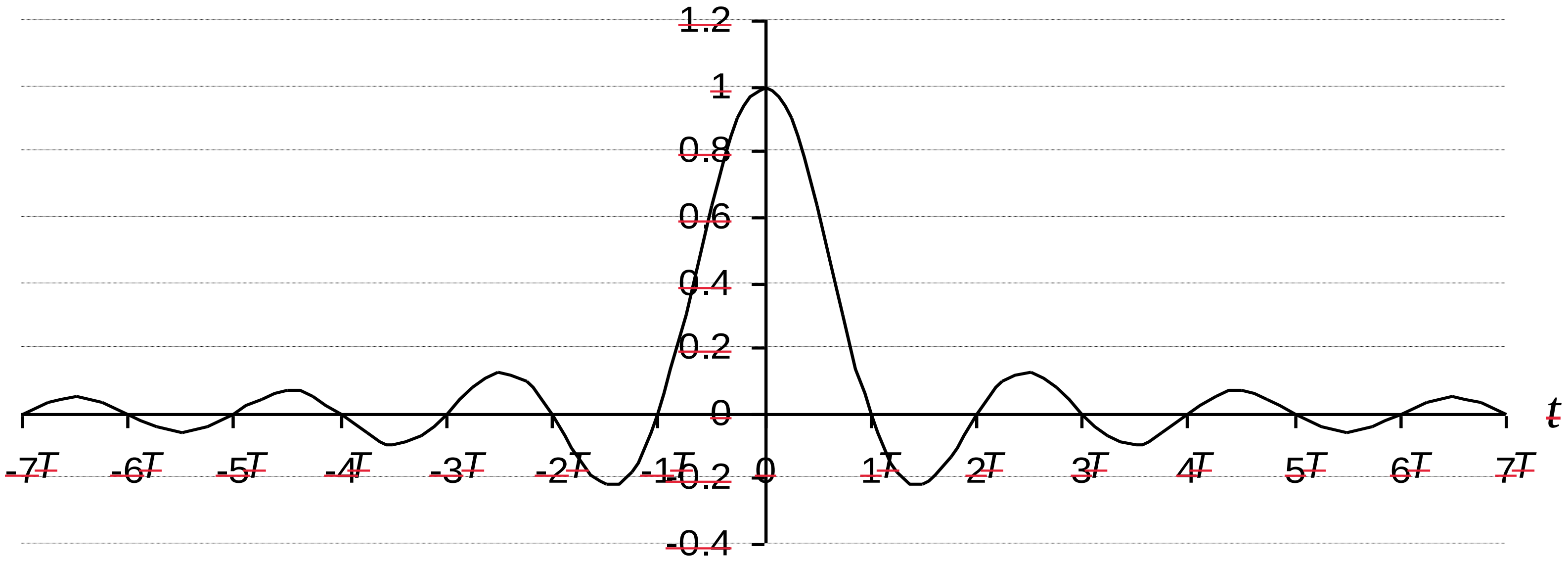


- ~~Time-domain characterization of a channel requires finding the *impulse response h(t)*~~
- ~~Apply a very narrow pulse to a channel and observe the channel output~~
  - ~~*h(t)* typically a delayed pulse with ringing~~
- ~~Interested in system designs with *h(t)* that can be packed closely without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

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

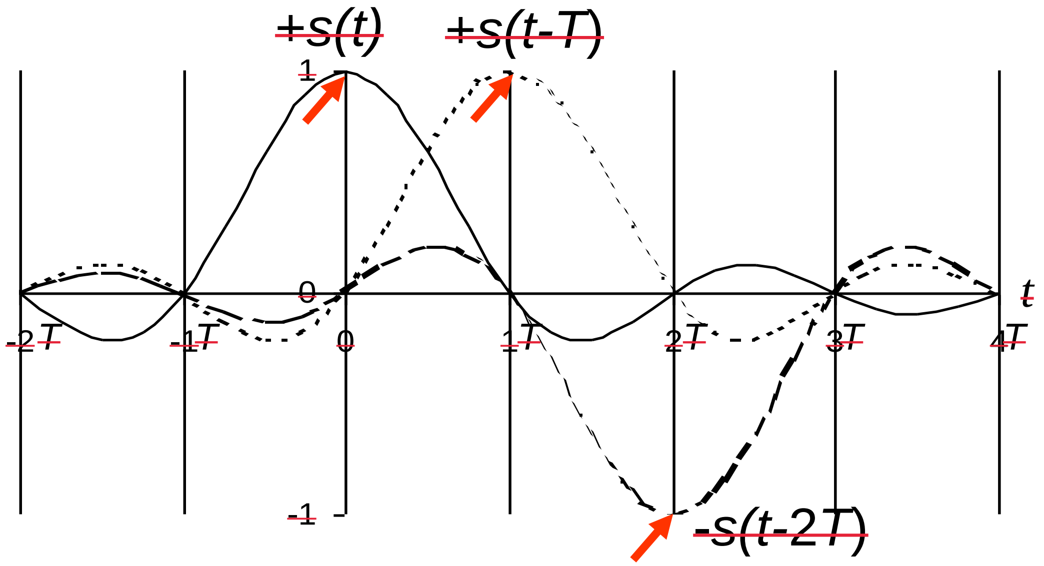
Samples at kT

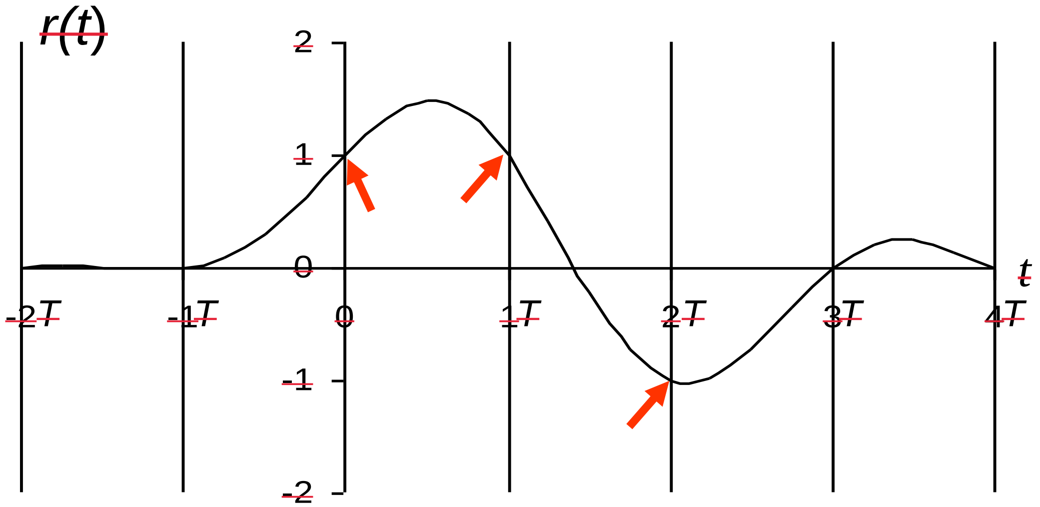
$r(0)=s(0)+s(-T)-s(-2T)=+1$

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

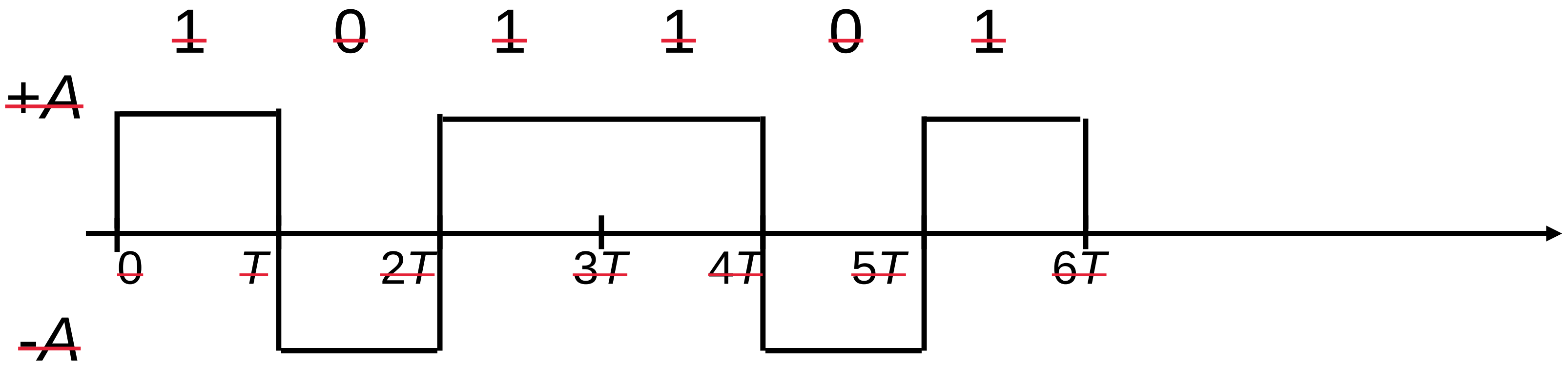
$r(2T)=s(2T)+s(T)-s(0)=-1$

Zero ISI at sampling times kT





Digital binary signal



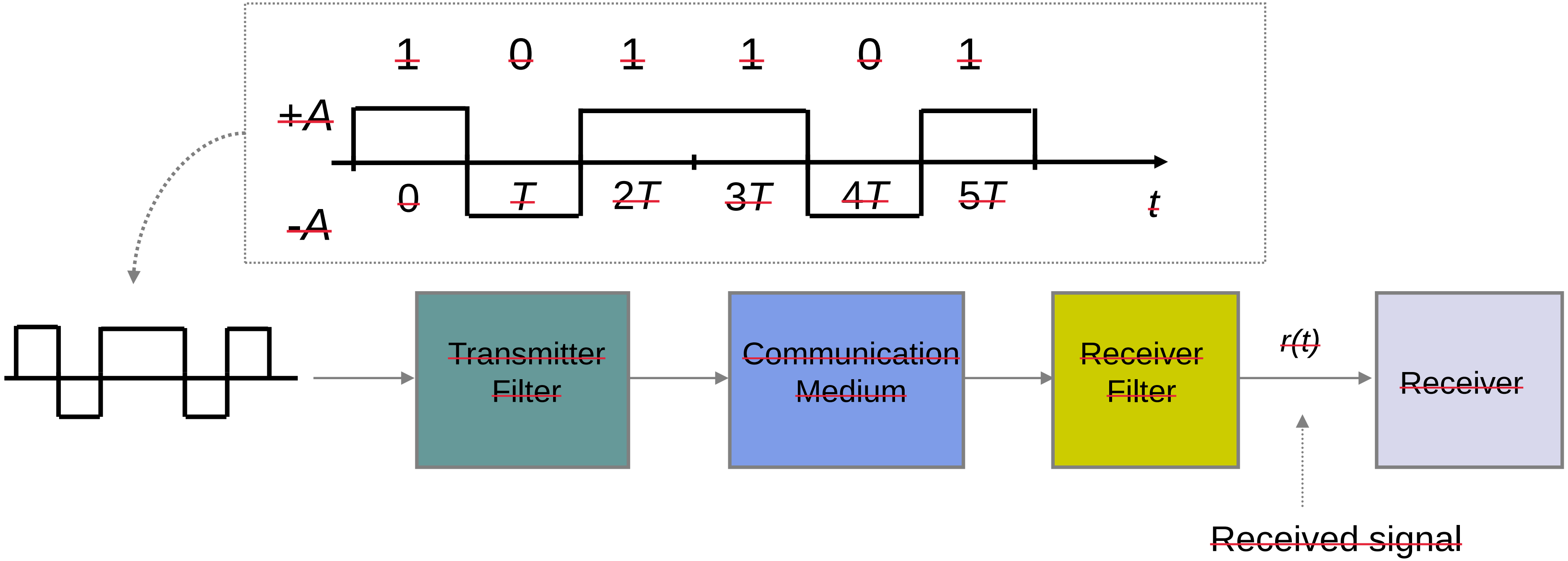
Bit rate = 1 bit / T seconds

For a given communications medium:

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

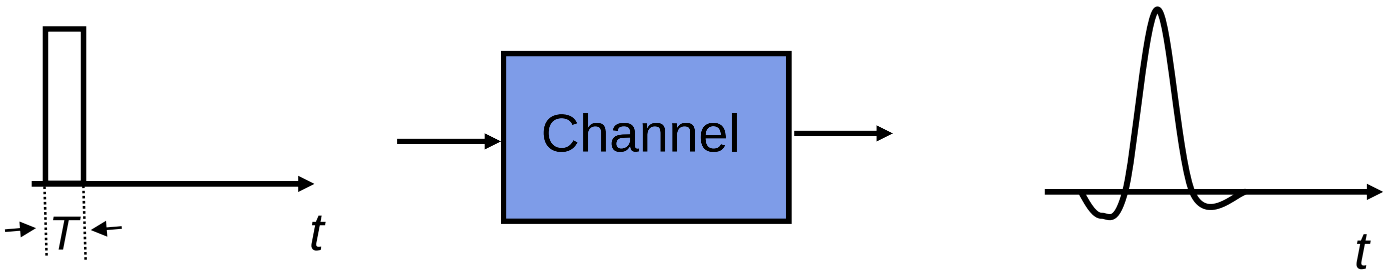
Signaling with Nyquist pulses

- *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

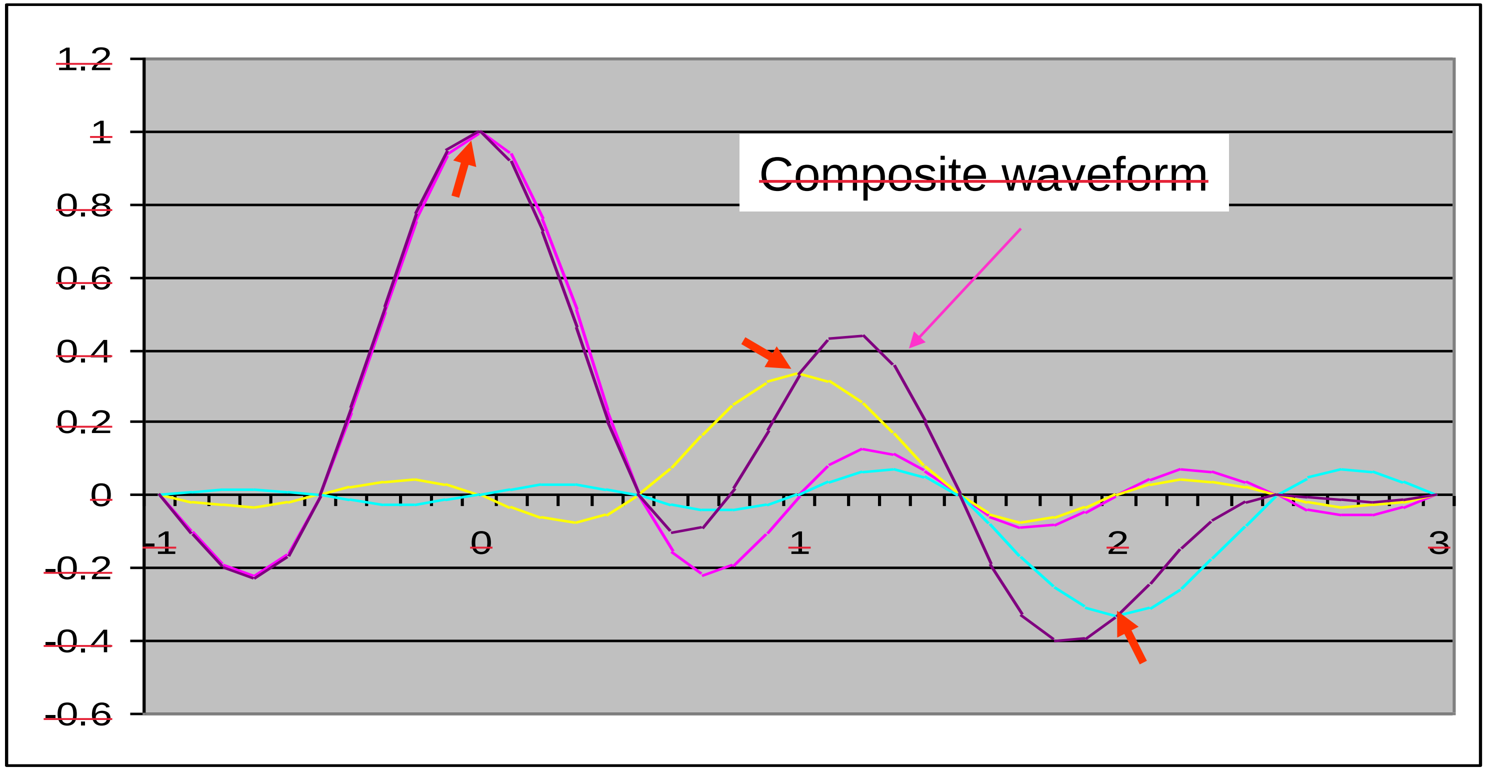
- With $M = 2^m$ signal levels, each pulse carries m bits

  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.*

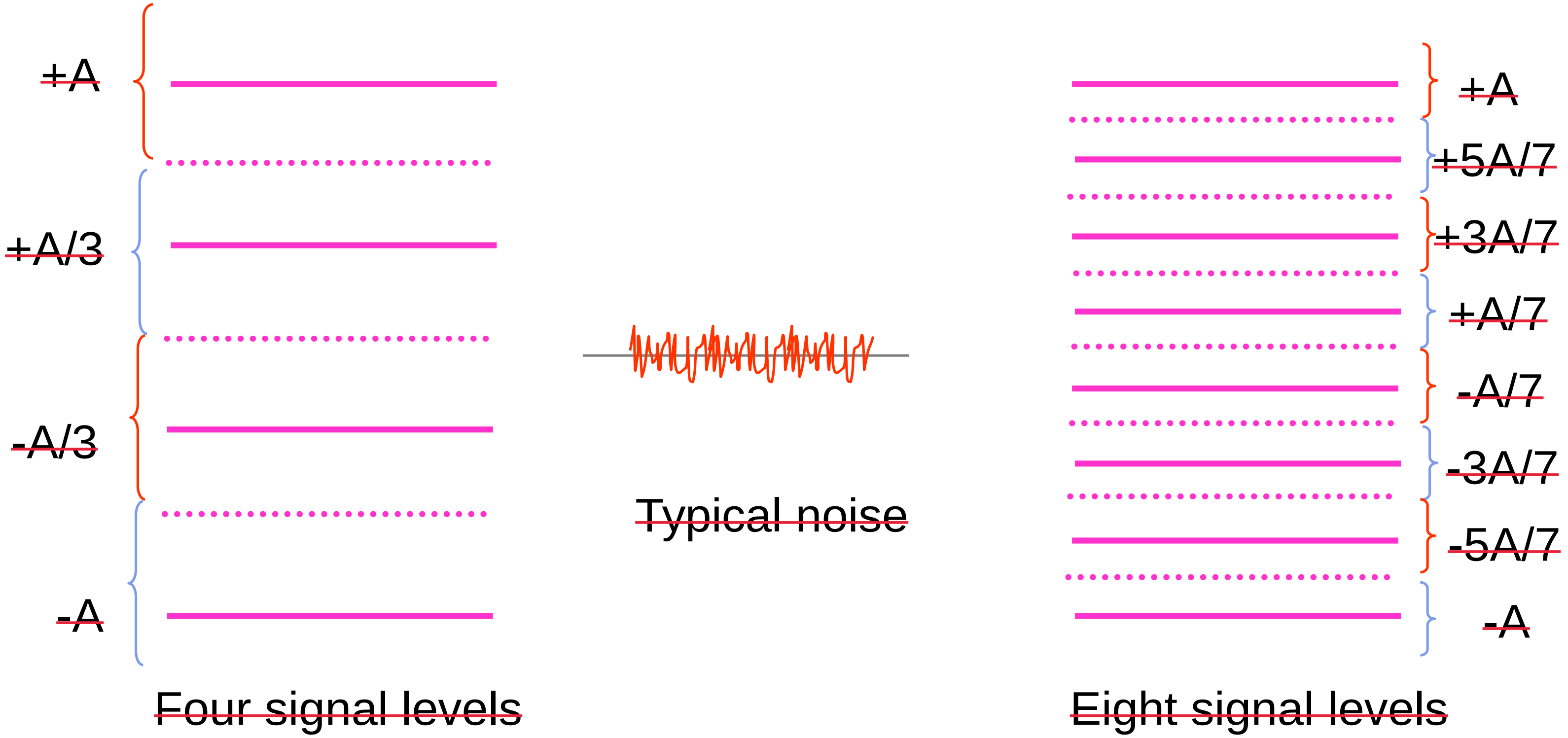
Example

- 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~~

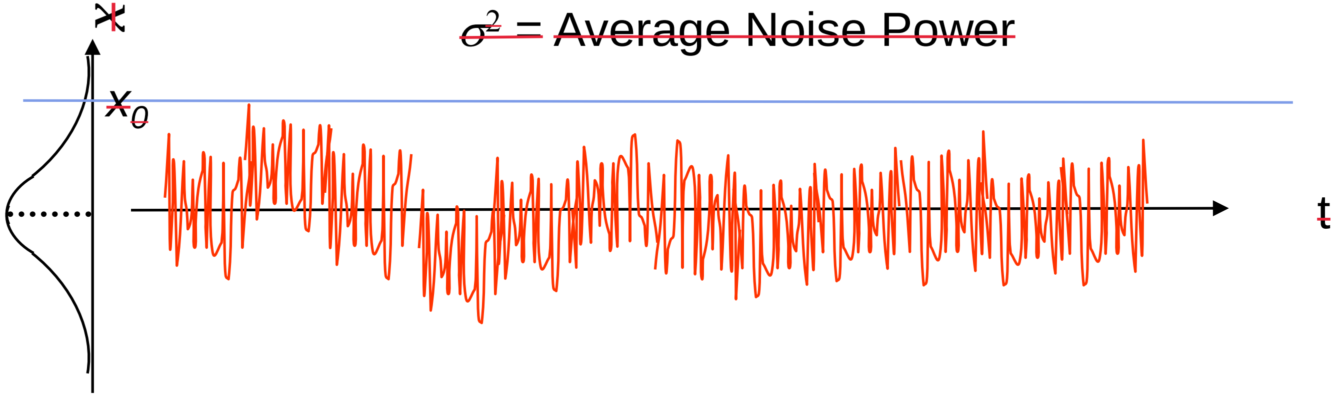


Noise distribution

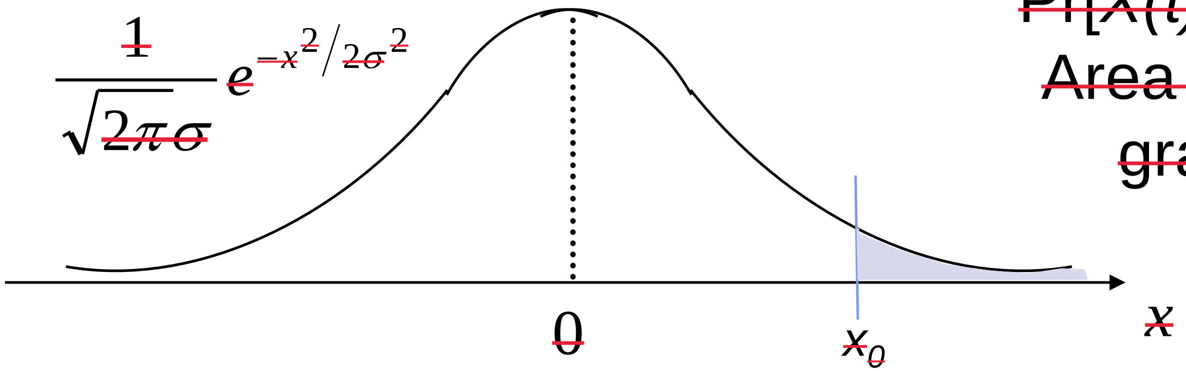
- Noise is characterized by probability density of amplitude samples
- Likelihood that certain amplitude occurs
- Thermal electronic noise is inevitable (due to vibrations of electrons)
- Noise distribution is Gaussian (bell-shaped) as below

σ^2 = Average Noise Power

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



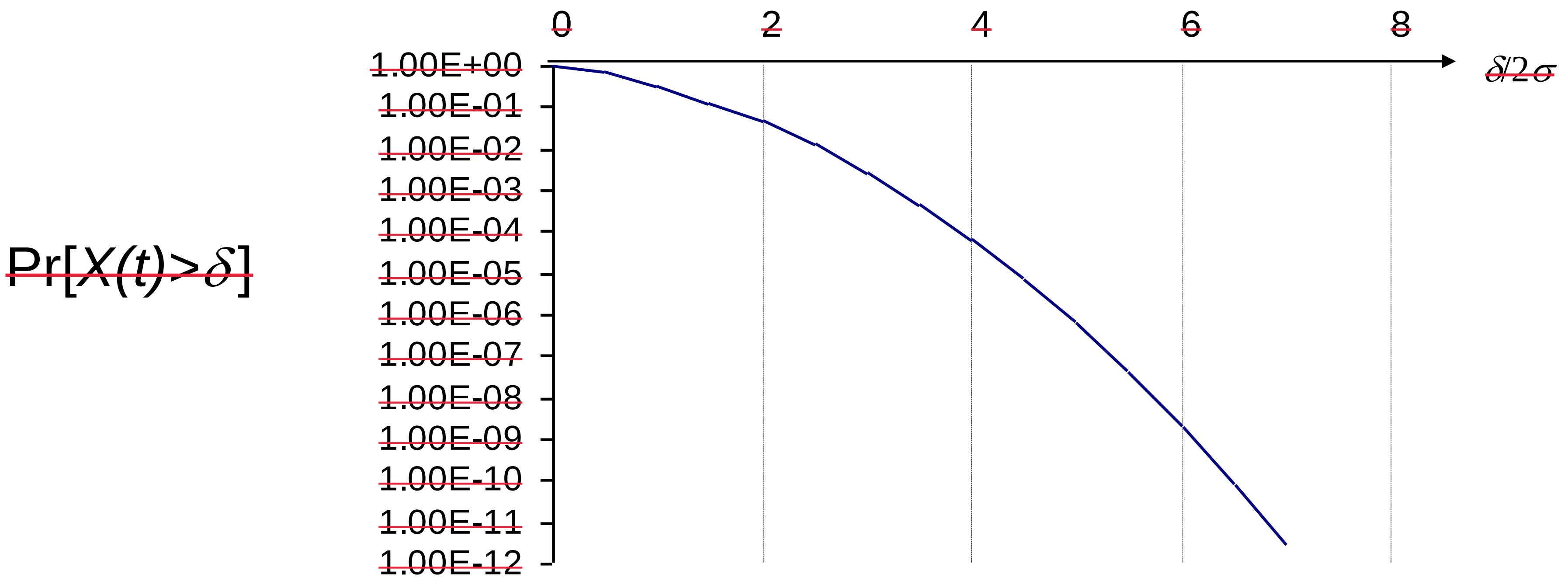
$$\frac{1}{\sqrt{2\pi}\sigma} e^{-x^2/2\sigma^2}$$



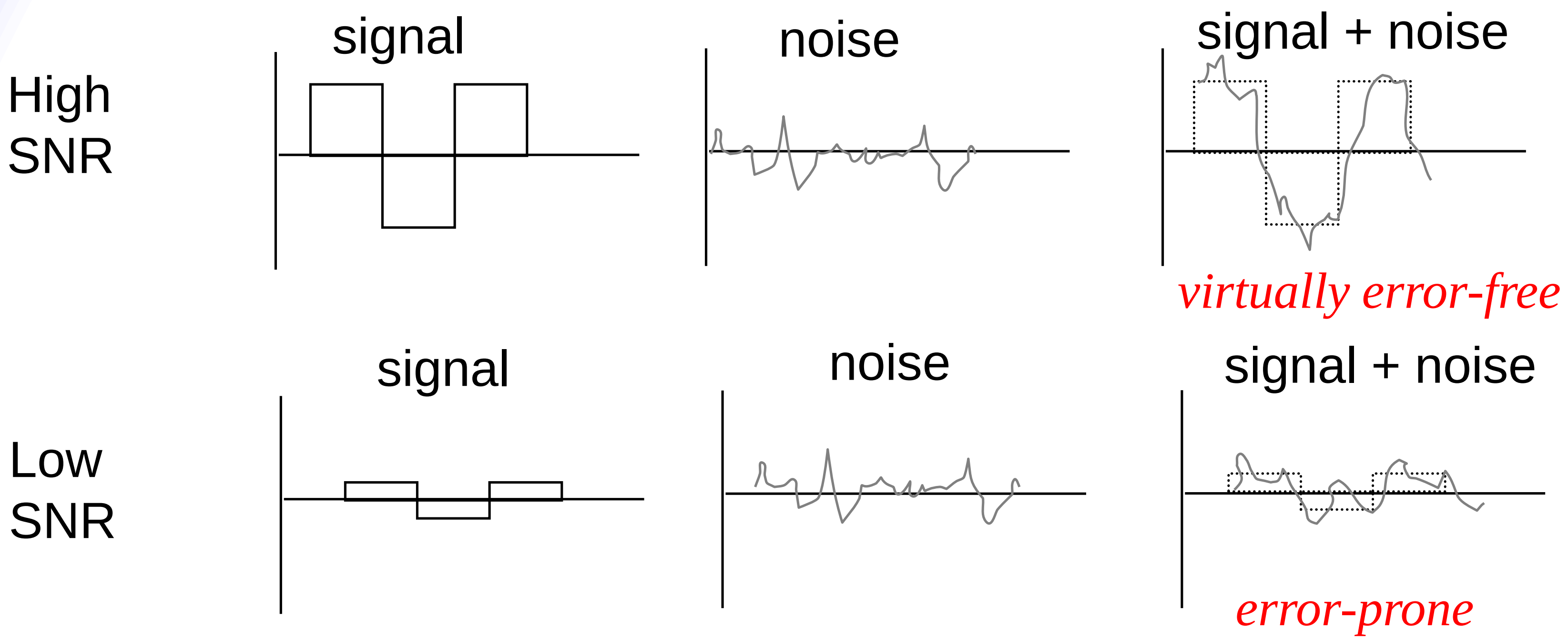
$\Pr[X(t)>x_0]$ = Area under graph

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



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

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

- 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

  $C = 3000 \log_2 (1 + 100) = 19{,}974$ bps

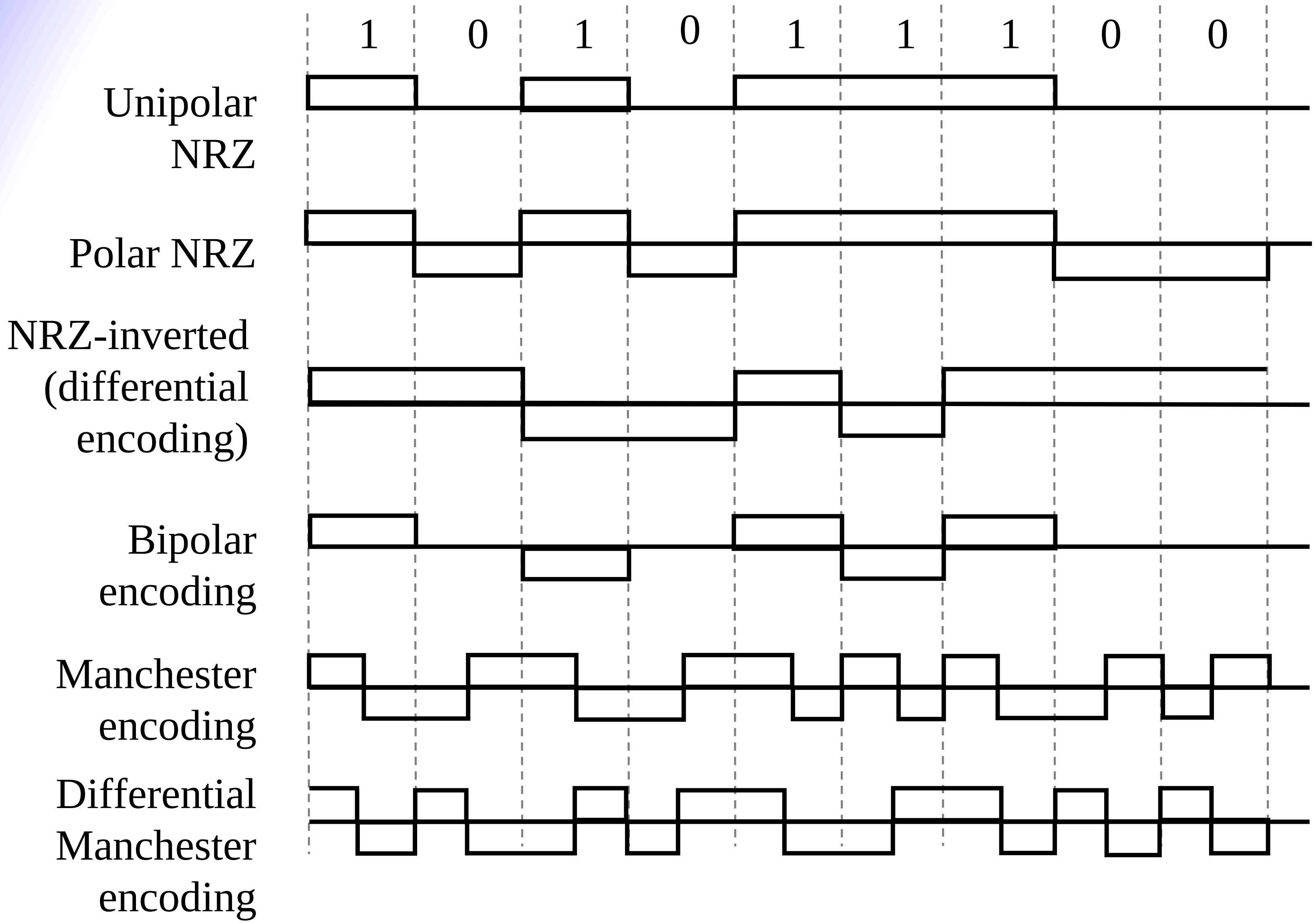
Bit rates of digital transmission systems

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

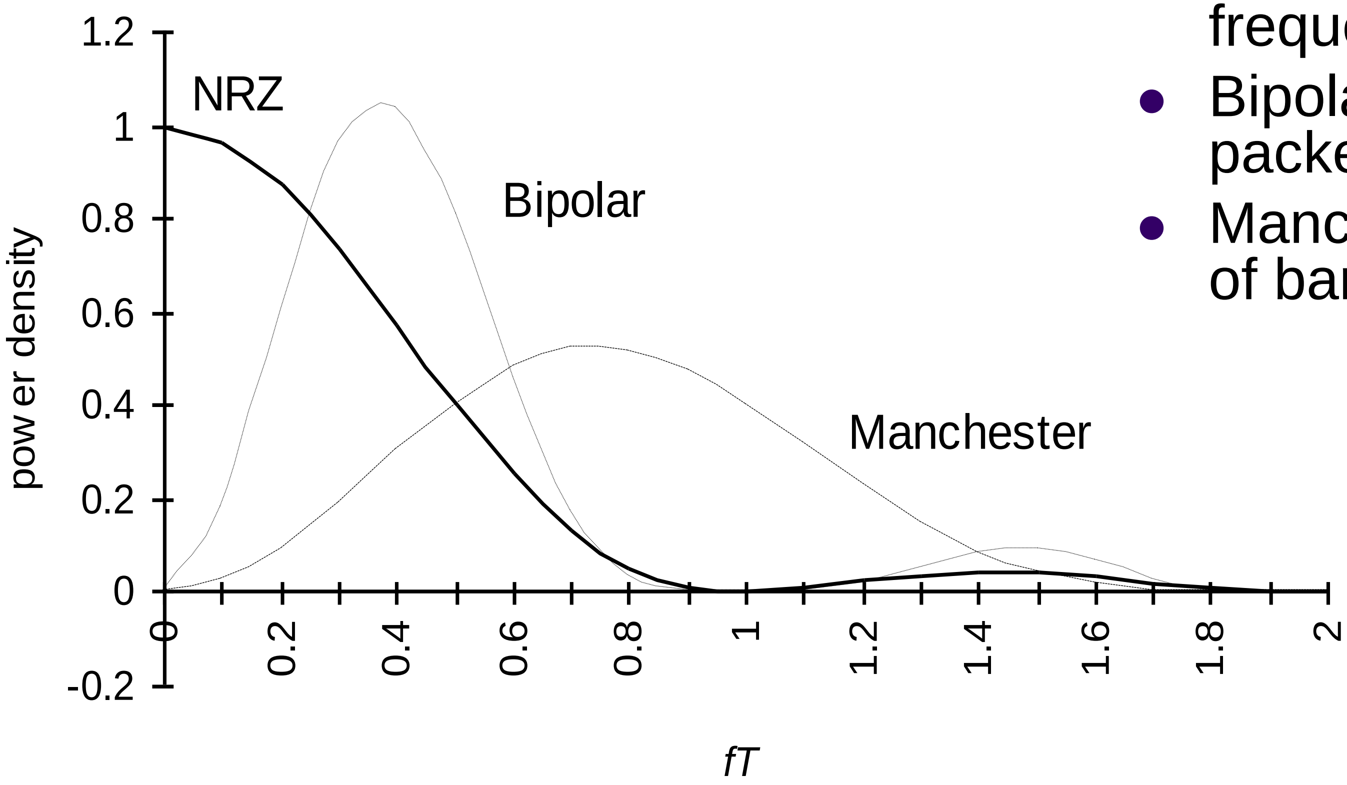
- Mapping of binary information sequence into the digital signal that enters the channel
  - Example - “1” maps to +A square pulse; “0” to –A pulse
- Line code selected to meet system requirements:
  - *Transmitted power*: Power consumption = $
  - *Bit timing*: Transitions in signal help timing recovery
  - *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

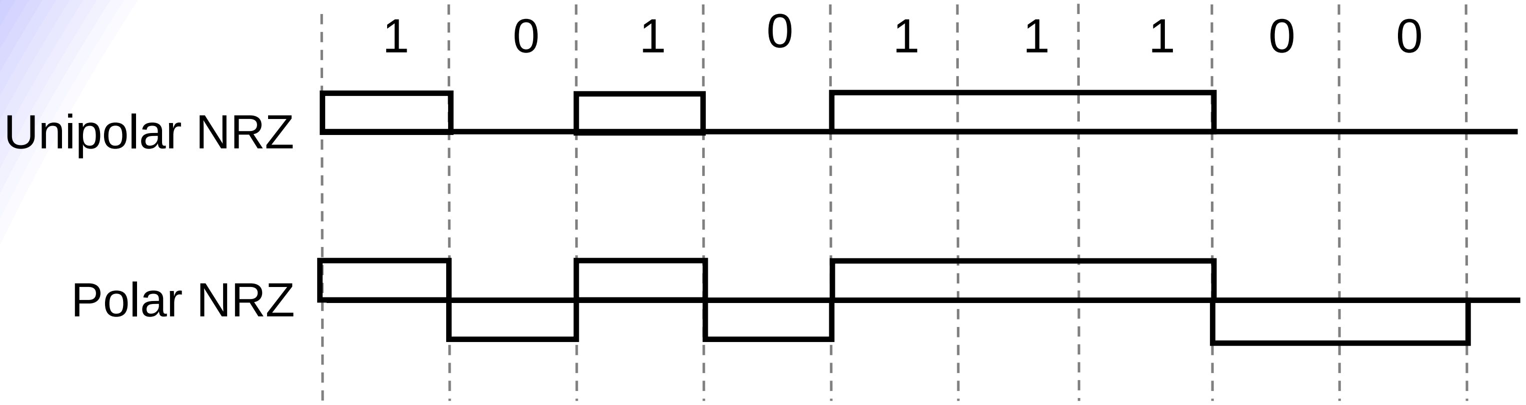

1 0 1 0 1 1 1 0 0
Unipolar NRZ
Polar NRZ
NRZ-inverted (differential encoding)
Bipolar encoding
Manchester encoding
Differential Manchester encoding

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

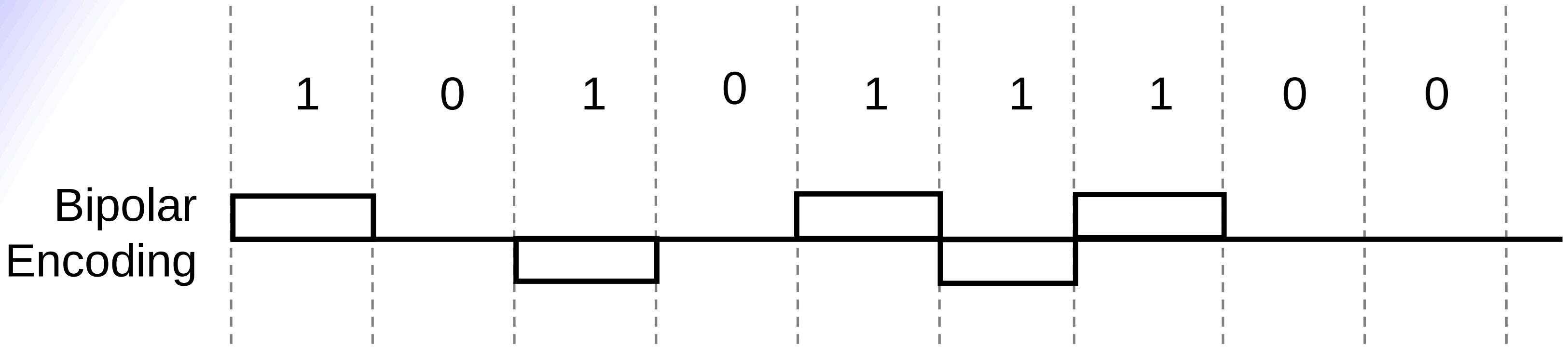


Unipolar NRZ

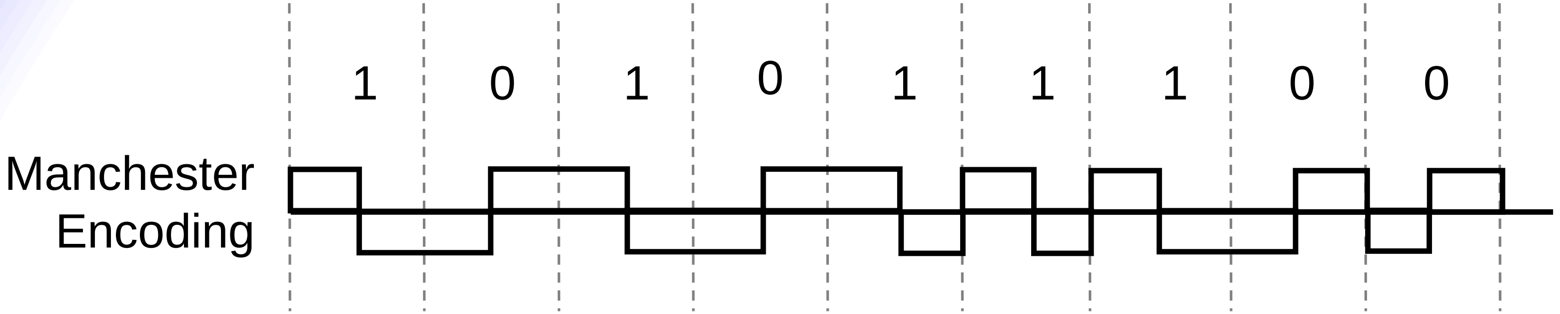
- “1” maps to +A pulse
- “0” maps to no pulse
- High Average Power
  $0.5{*}A^2 + 0.5{*}0^2 = A^2/2$
- Long strings of A or 0
  - Poor timing
  - Low-frequency content
- Simple

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

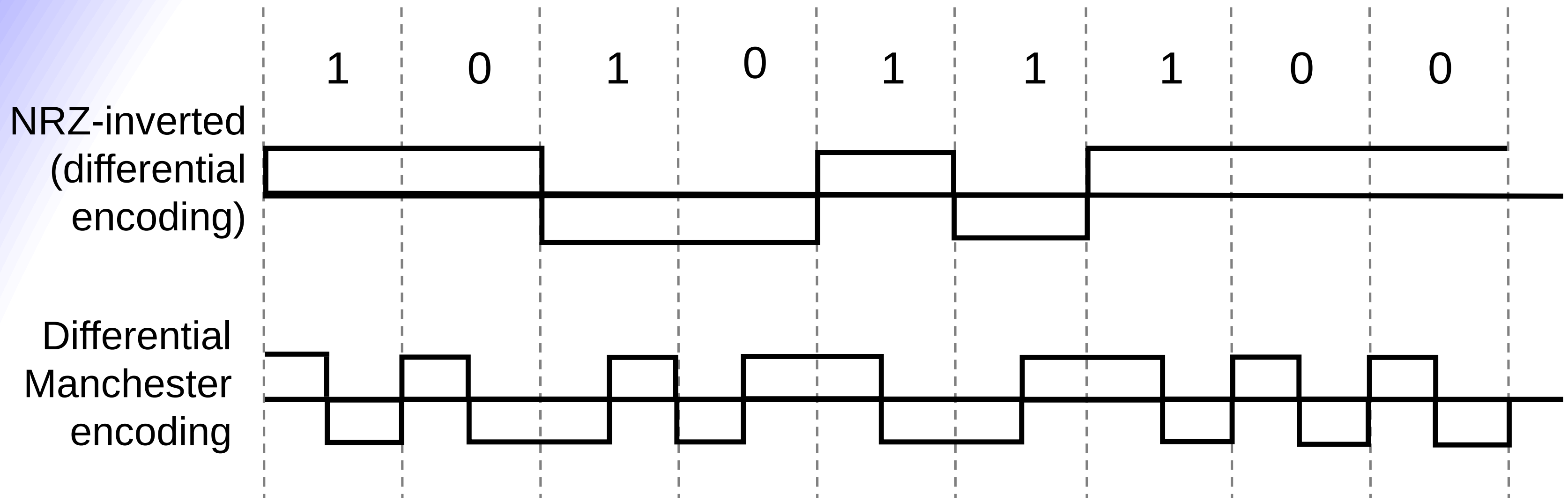


- Three signal levels: {-A, 0, +A}
- "1" maps to +A or –A in alternation
- "0" maps to no pulse
  - Every +pulse matched by –pulse so little content at low frequencies
- String of 1s produces a square wave
  - Spectrum centered at $T/2$
- Long string of 0s causes receiver to lose synchronization
- Zero-substitution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



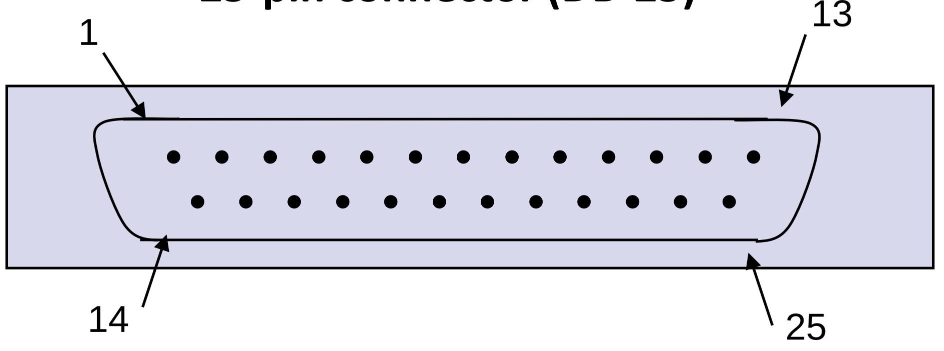
- Errors in some systems cause transposition in polarity, +A become –A and vice versa
  - All subsequent bits in Polar NRZ coding would be in error
- Differential line coding provides robustness to this type of error
- “1” mapped into transition in signal level
- “0” mapped into no transition in signal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

6.3 Asynchronous and synchronous communications

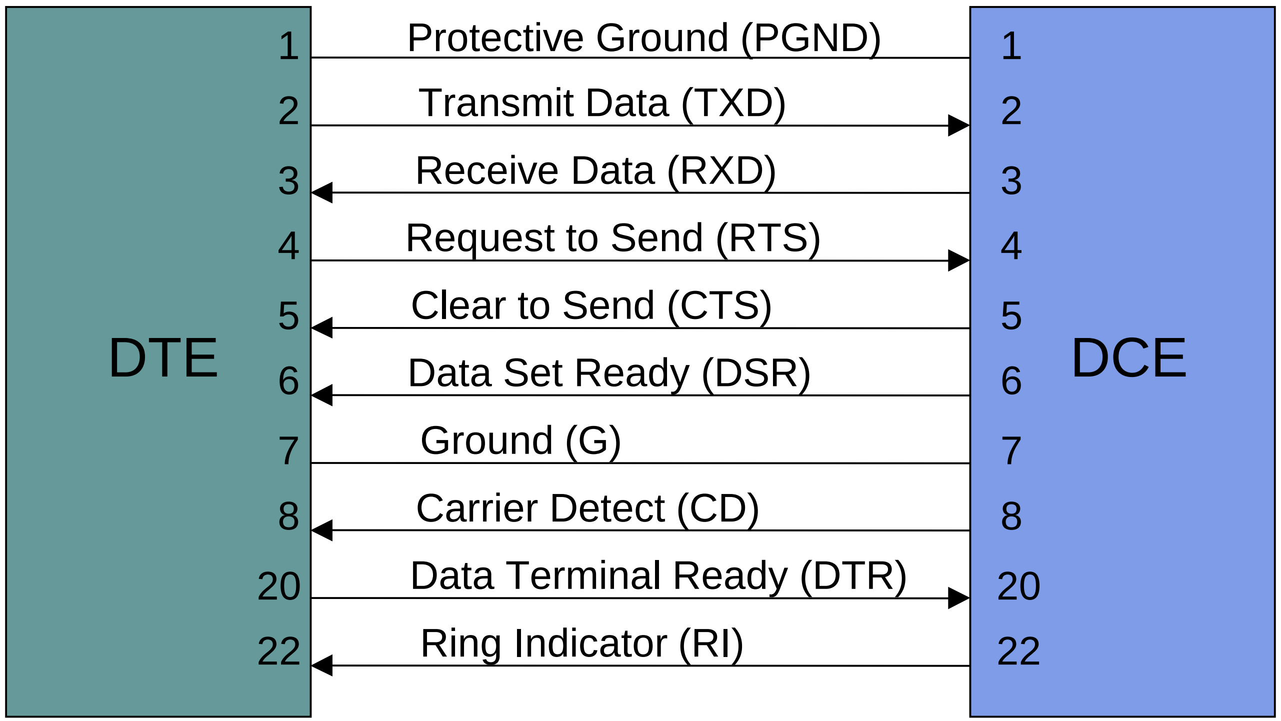
- Recommended Standard (RS) 232
- serial line interface between computer and modem or similar device
- Data Terminal Equipment (DTE): computer
- Data Communications Equipment (DCE): modem
- mechanical and electrical specification

25-pin connector (DB-25)

(a)

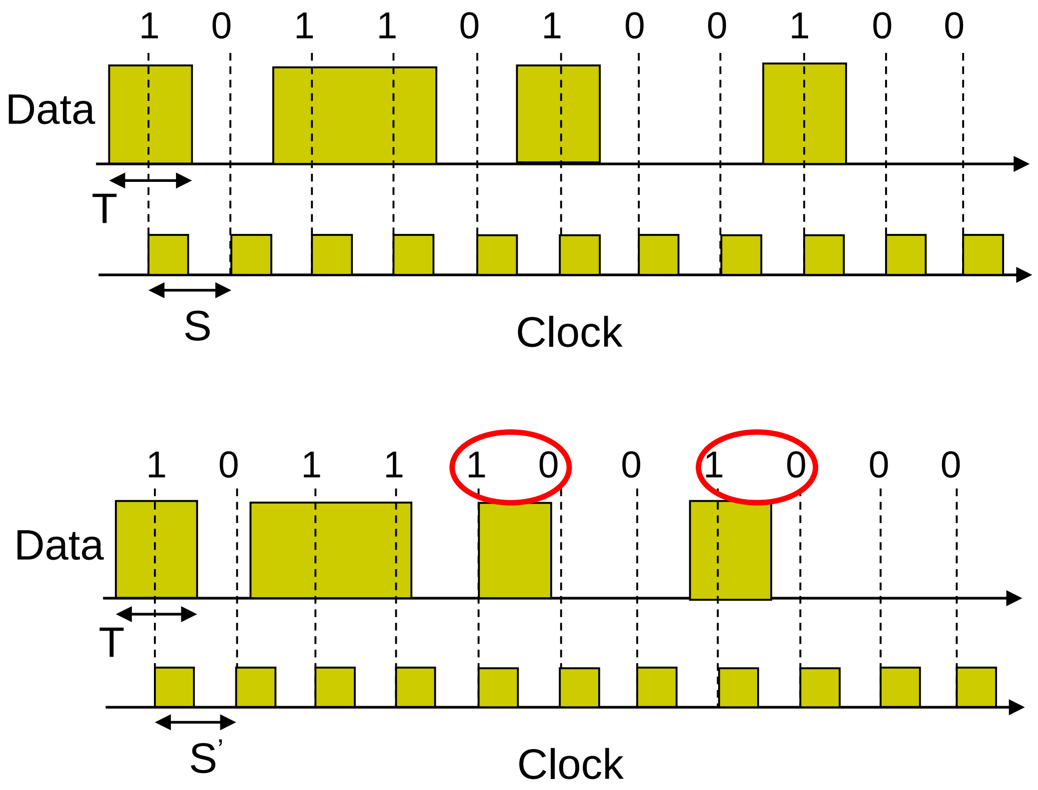


(b)

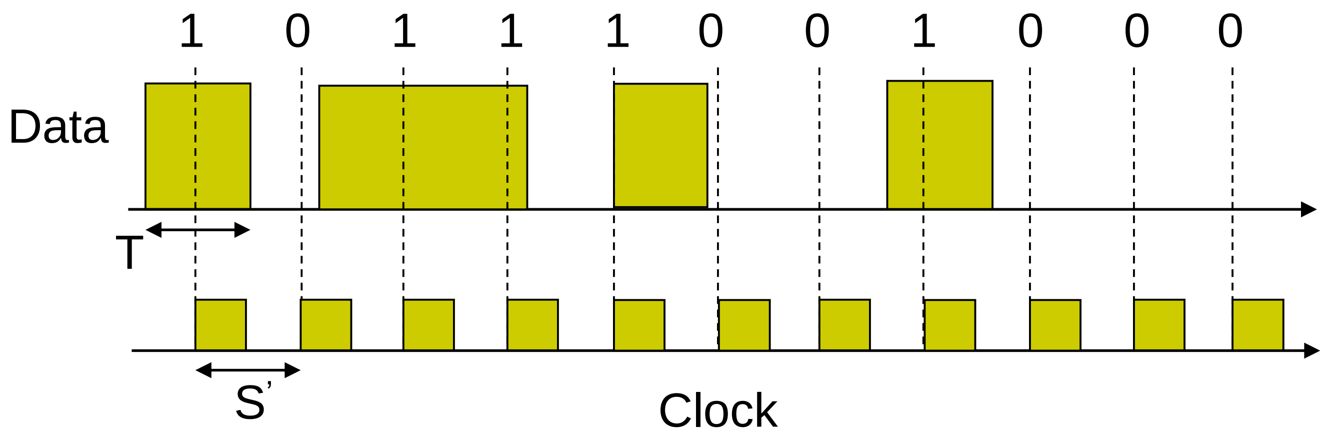


Synchronization

- 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)

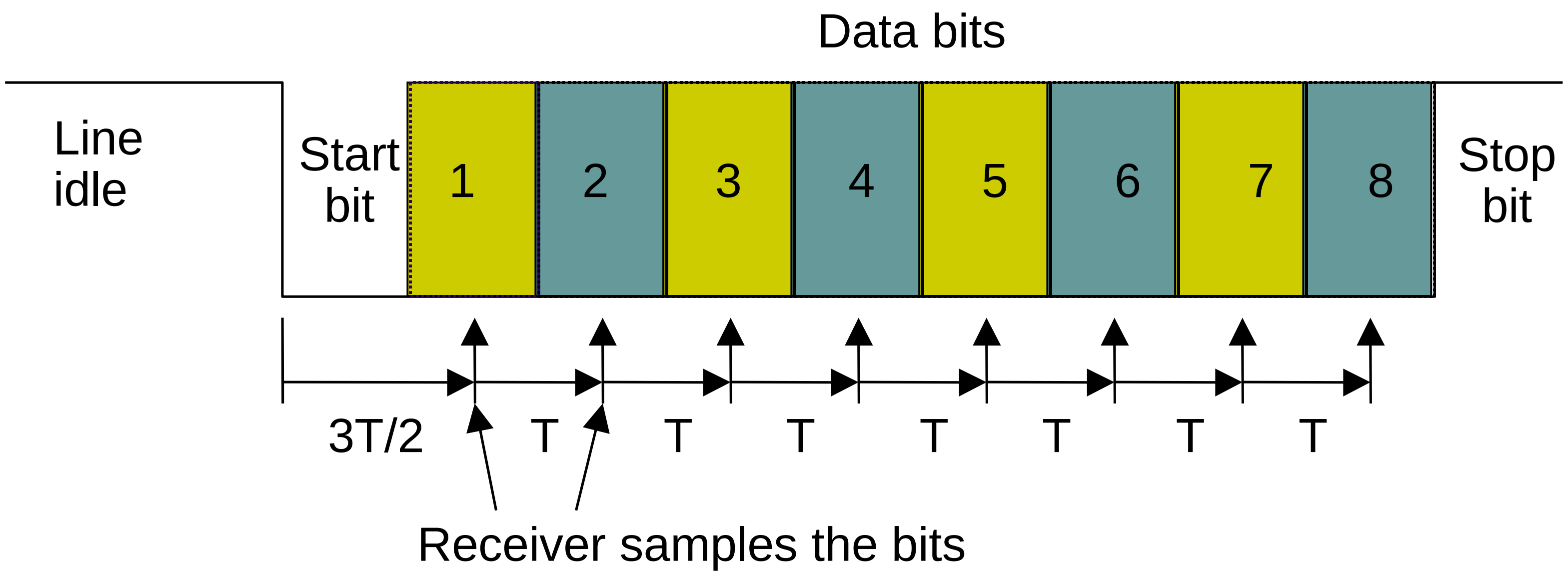


- Incorrect reception
- How to avoid a loss of synchronization?
  - Asynchronous transmission
  - Synchronous transmission



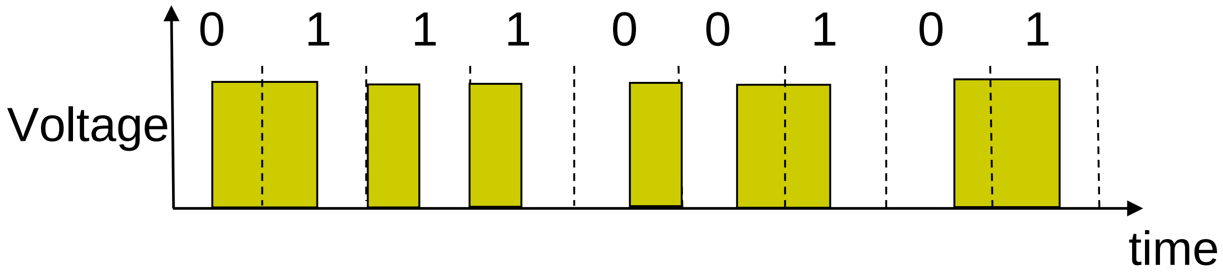
Asynchronous transmission

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

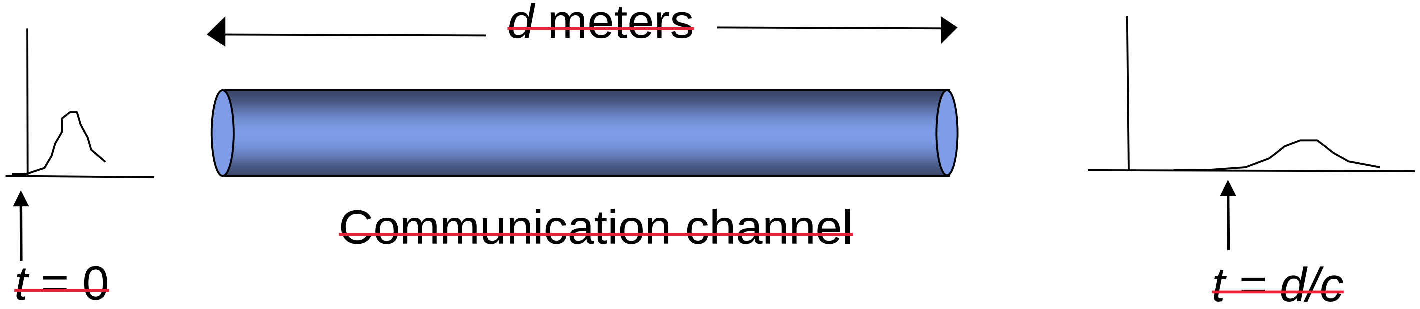


Synchronous transmission

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

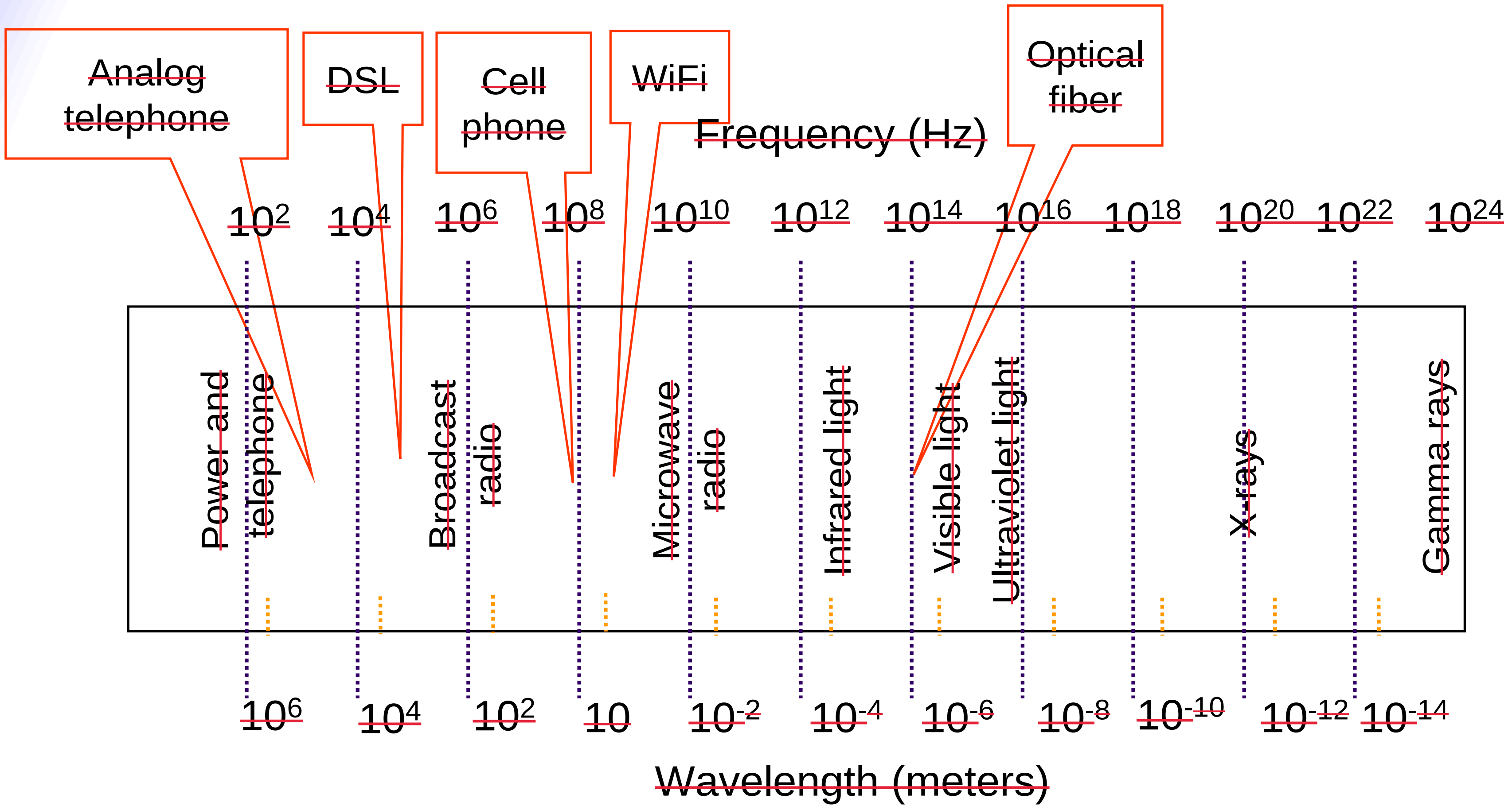


~~6.4 Transmission media~~



- ~~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~~

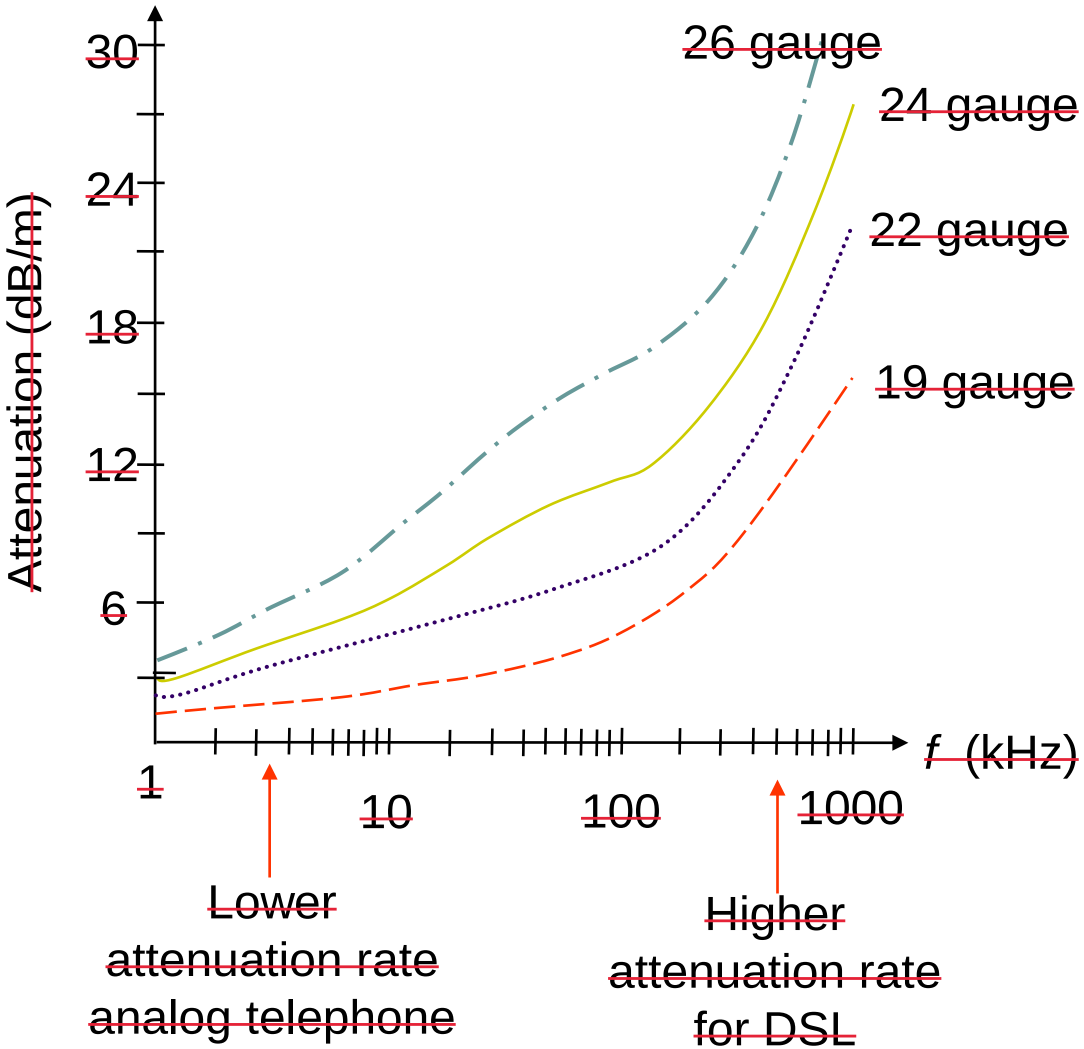
~~Wired Media~~

- ~~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

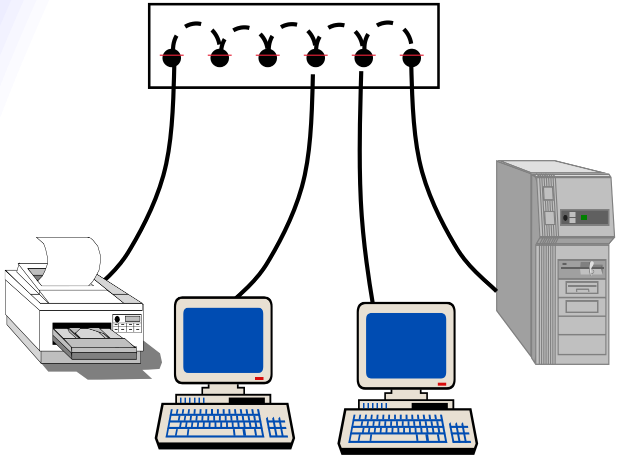
- Two insulated copper wires arranged in a regular spiral pattern to minimize interference
- Various thicknesses, e.g. 0.016 inch (24 gauge)
- Low cost
- Telephone subscriber loop from customer to CO
- Old trunk plant connecting telephone COs
- Intra-building telephone from wiring closet to desktop
- 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~~

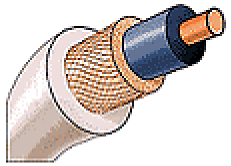
- ~~Twisted pairs can provide high bit rates at short distances~~
- ~~Asymmetric Digital Subscriber Loop (ADSL)~~
  - ~~High-speed Internet Access~~
  - ~~Lower 3 KHz for voice~~
  - ~~Upper band for data~~
  - ~~64 Kbps inbound~~
  - ~~640 Kbps outbound~~
- ~~Much higher rates possible at shorter distances~~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

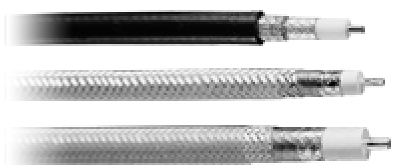
~~Ethernet LAN~~



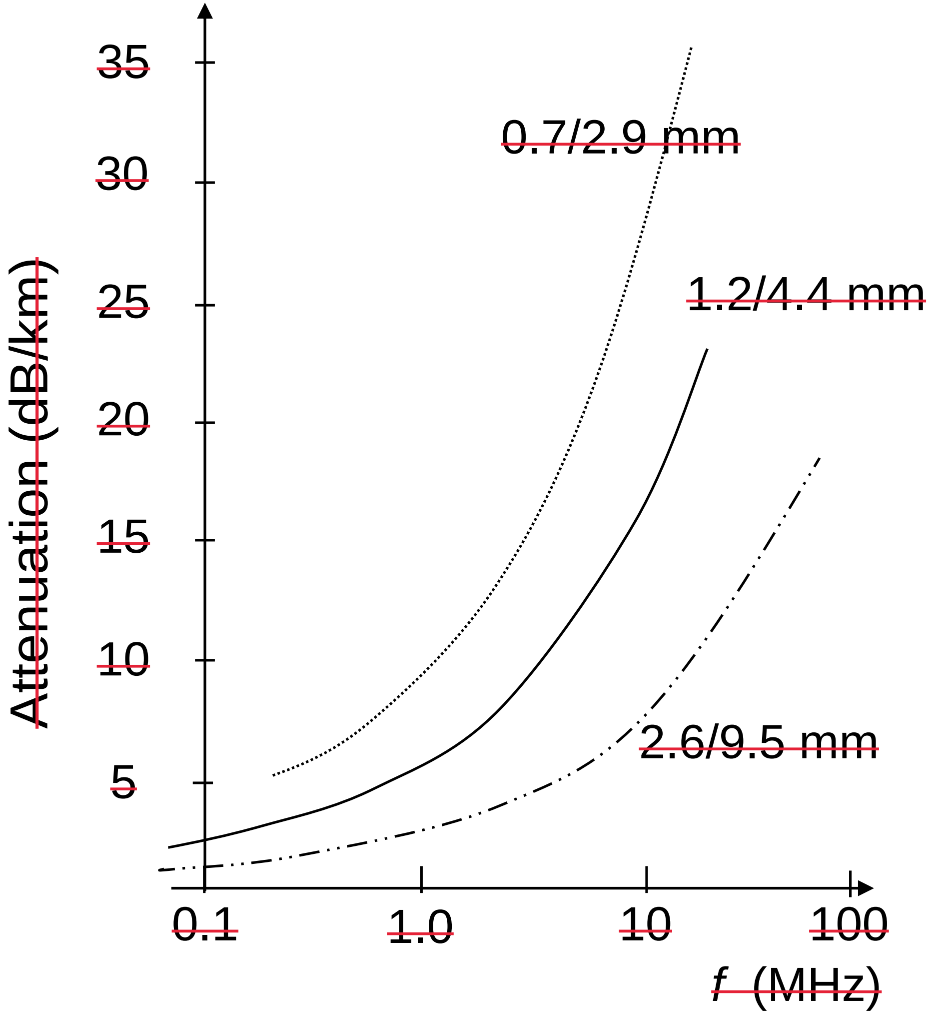
- ~~Category 3 unshielded twisted pair (UTP): ordinary telephone wires~~
- ~~Category 5 UTP: tighter twisting to improve signal quality~~
- ~~Shielded twisted pair (STP): to minimize interference; costly~~
- ~~10BASE-T Ethernet~~
  - ~~10 Mbps, Baseband, Twisted pair~~
  - ~~Two Cat3 pairs~~
  - ~~Manchester 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~~

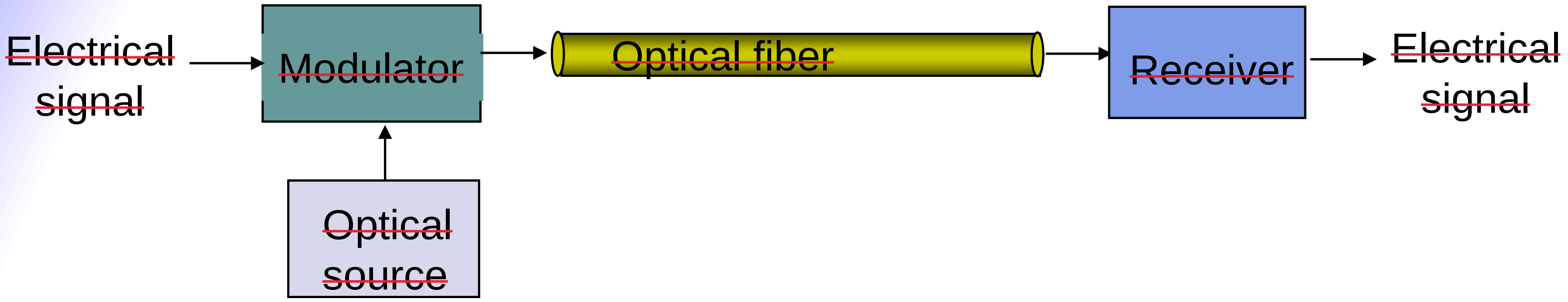




- ~~Cylindrical braided outer conductor surrounds insulated inner wire conductor~~
- ~~High interference immunity~~
- ~~Higher bandwidth than twisted pair~~
- ~~Hundreds of MHz~~
- ~~Cable TV distribution~~
- ~~Long distance telephone transmission~~
- ~~Original Ethernet LAN medium~~

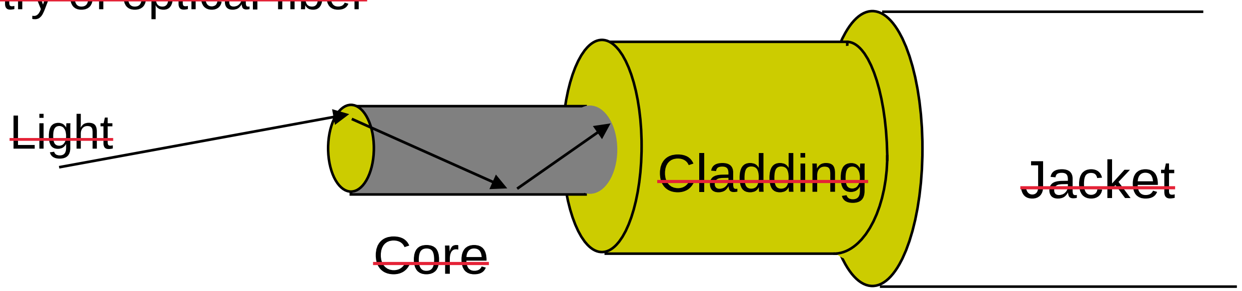


Optical fiber

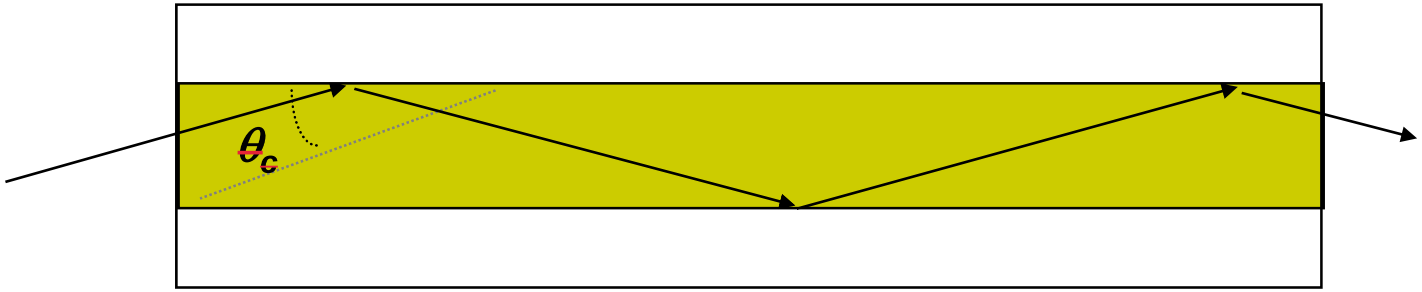


- Light sources (lasers, LEDs) generate pulses of light that are transmitted on optical fiber
  - Very long distances (>1000 Km)
  - Very high speeds (>40 Gbps/wavelength)
  - Nearly error-free (BER of 10^{-15})
- Profound influence on network architecture
  - Dominates long distance transmission
  -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

Geometry of optical fiber

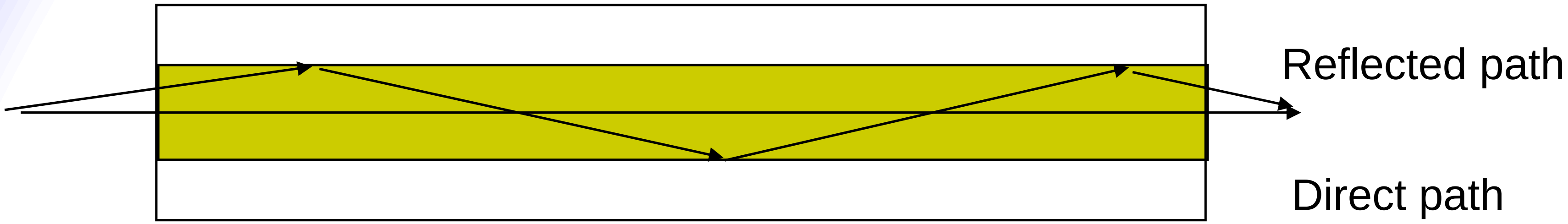


Total Internal Reflection in optical fiber

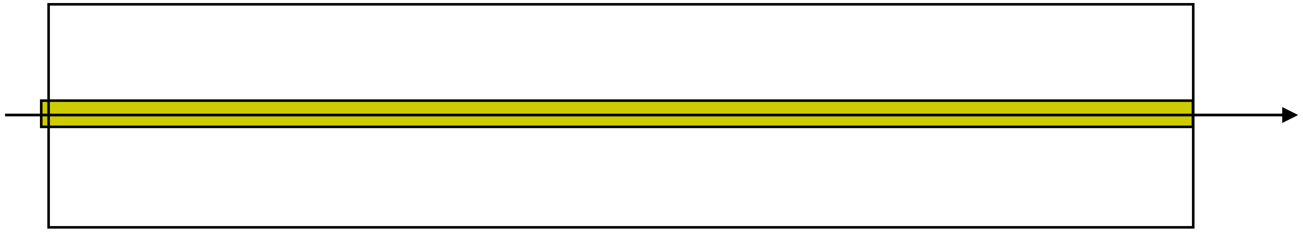


- Very fine glass cylindrical core surrounded by concentric layer of glass (cladding)
- Core has higher index of refraction than cladding
- Light rays incident at less than critical angle θ_c is completely reflected back into the core

Multimode fiber: multiple rays follow different paths



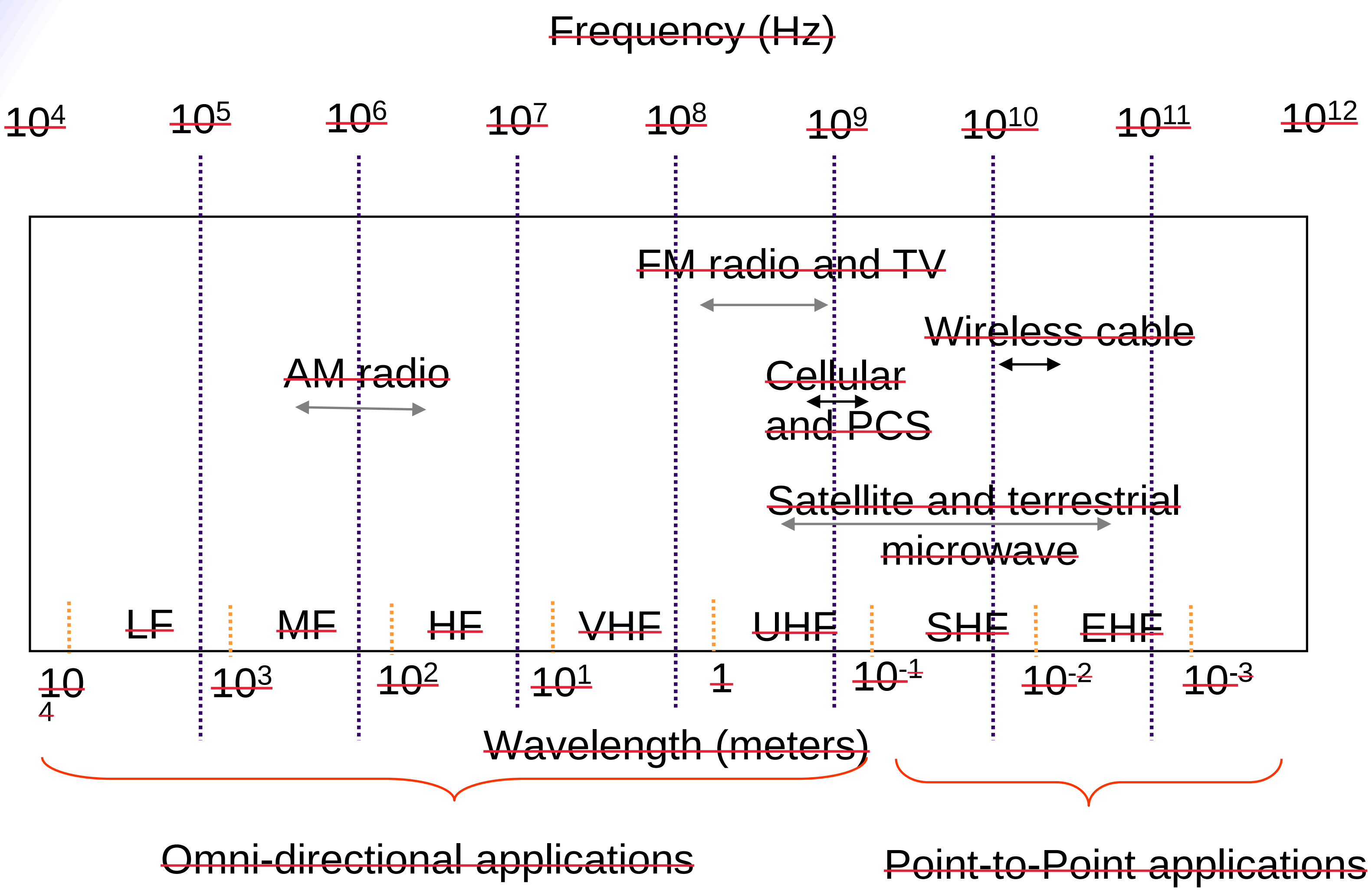
Single-mode fiber: only direct path propagates in fiber



- 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