EP1100

Data Communication and Computer Networks

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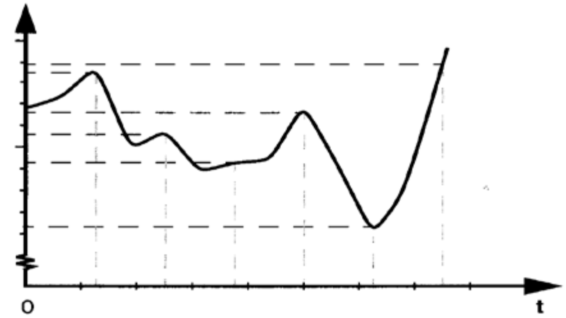
Illustrations in this material are collected from

Behrouz A Forouzan, *Data Communications and Networking*, McGraw-Hill.

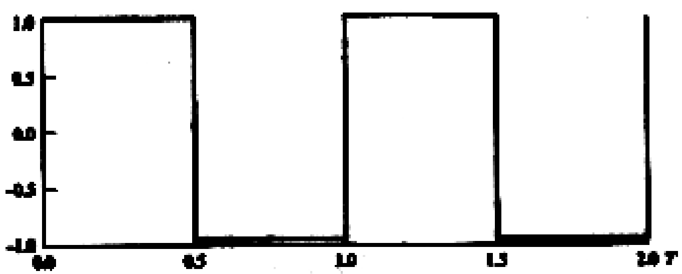
Analog and digital signals

Signals

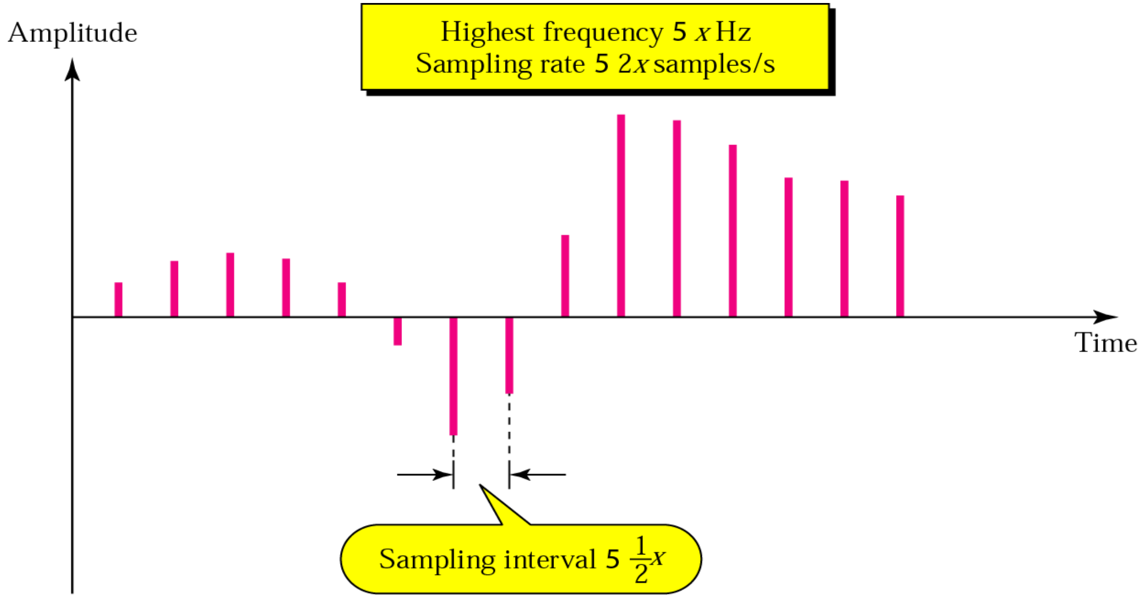
- Analog signals
  - Infinitely many amplitude levels
    - Continuously varying
  - Continuous in time



- Digital signals
  - Limited number of amplitude levels
    - Discrete
  - Discrete in time

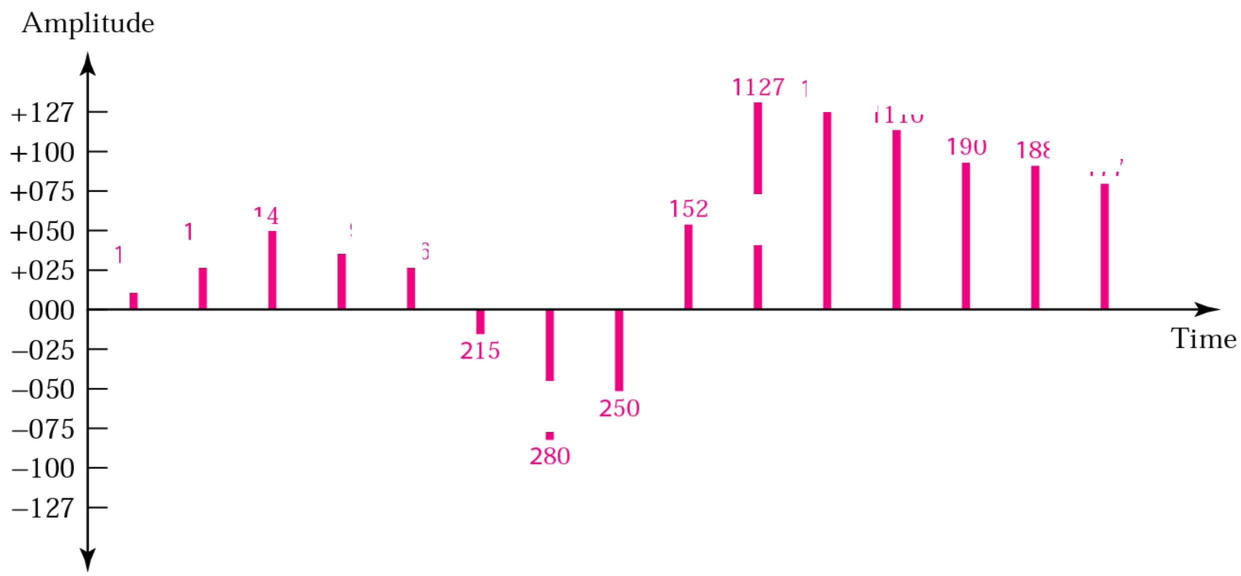


Sampling



- Sampling rate: the Nyquist theorem
  - A bandlimited signal may be sampled into a time discrete signal
    - No information loss – the analog signal can be *perfectly recovered!*
  - The sampling rate must be *at least twice the highest frequency* of the analog signal, $f_s \geq 2f_{max}$
    - This frequency is often called the Nyquist frequency, or Nyquist rate
    - No information is gained by sampling at a higher rate
- Named after Harry Nyquist (1889 – 1976) from Värmland!

Amplitude Quantization



- From continues to *discrete* sample values
  - rounds off the amplitude to closest quantization level
  - gives information loss, *not reversible*
- Binary encoding of quantization levels
  - represent each amplitude with a codeword of bits
  - examples: 0 → 0000, +25 → 0001, +50 → 0010, ... -25 → 1001, -50 → 1010, ...

Pulse code modulation (PCM)

- Sampling and quantization
  - digitalization of continuous signals
- Sampling of signal
  - A given sampling frequency and signal bandwidth
    - Analog signal is filtered to stay within specified frequency band
  - Signal levels represented by a fixed number of bits
    - Mapping of sample value to and from quantization level
      - From electric signal level in volts to a numbered level (no unit)
    - Representation of quantization level in bits
      - for example: 8 bit sample values: -127 to 127 quantization levels
- Bit rate of digital signal [b/s]
  - sampling frequency [1/s] × bits per sample [b]
  - Larger units
    - kilo (k) 10^3, mega (M) 10^6, giga (G) 10^9, tera (T) 10^{12}, peta (P) 10^{15}, exa (E) 10^{18}, zetta (Z) 10^{21}, yotta (Y) 10^{24}, ...

PCM Examples

	Sample rate (kHz)	*Sample size (bits)*	*Bit rate (kb/s)*
Telephony	8	8	64
CD	44.1	16	706*
DVD Audio	44.1, 48, 88.2, 96, 176.4, 192	16, 20, 24	4608* (max)

* Per channel

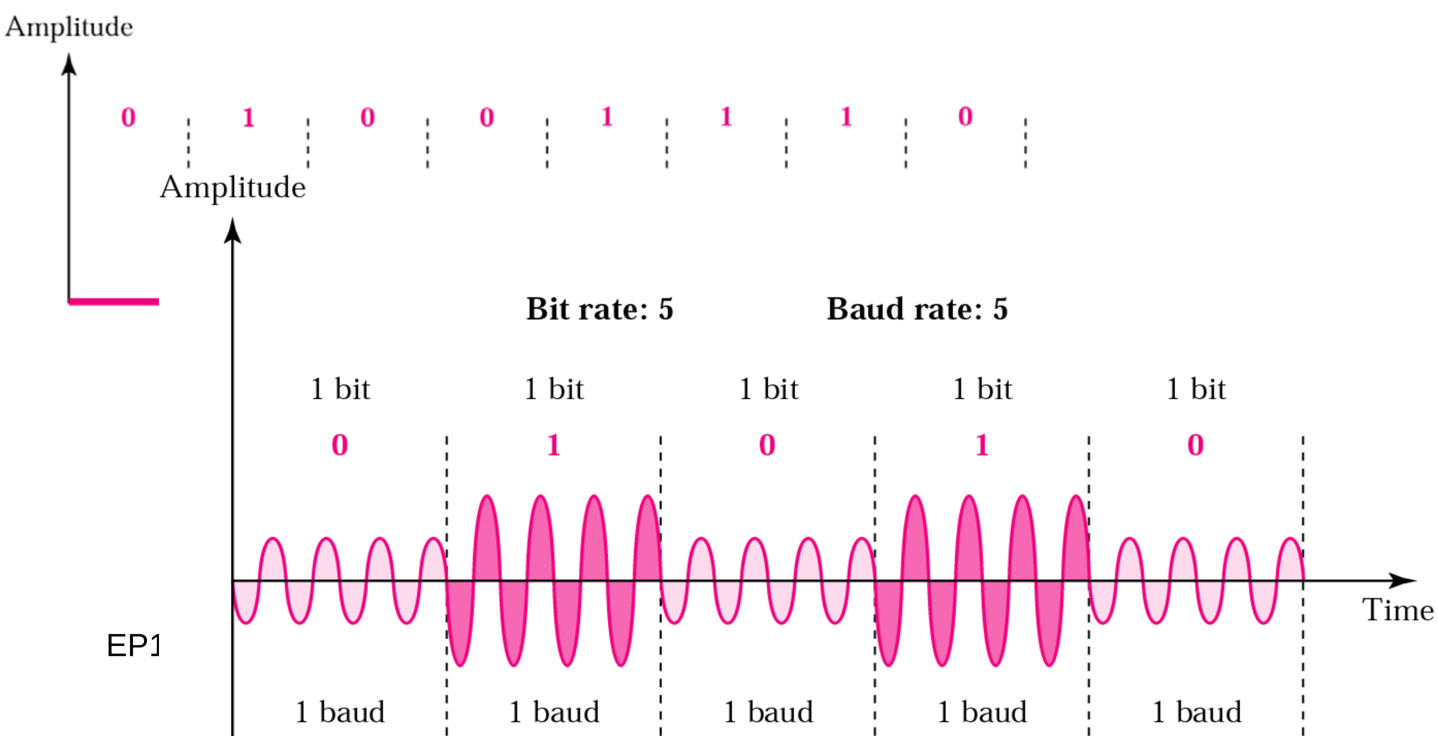
Transmission and data communication

Transmission

- Basis of data communication
- Transmission media
  - Attenuation and link budget
  - Signal distortion
  - Capacity limitations
- Modulation and line coding
- Synchronization and framing
- Multiplexing
- Capacity requirements
- Examples—TDM, ADSL

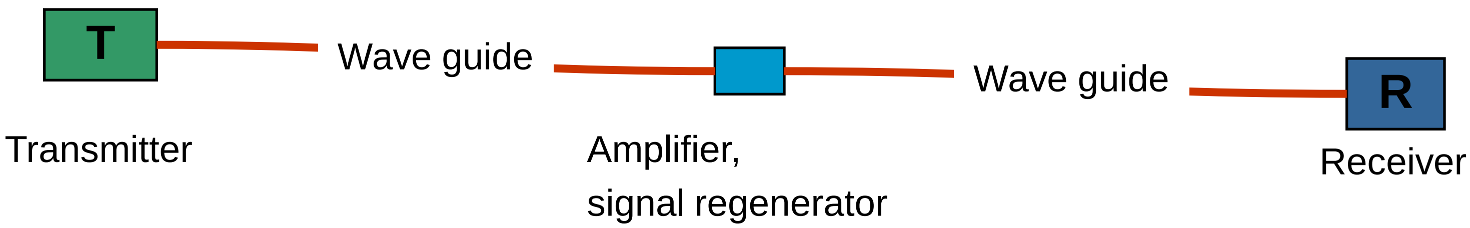
Basis of data communication

- Communication based on propagation of electromagnetic signals
  - Forming the signal into well—defined waveforms
  - Assigning bit values to each waveform
  - Sending data by the signal with waveforms selected by the data
- Signal propagated through a medium (or vacuum)
- Receiving the signal and detecting the waveforms
  - Mapping the waveform back to data bits
  - Handling errors that might occur



Transmission media

Transmission Media



- Guided media
  - For electrical and electromagnetic signals
    - Twisted pair cable
    - Coaxial cable
  - For optical signals
    - Single-mode and multimode fiber
- Unguided media
  - Electromagnetic waves in air
    - Radio
    - Microwaves (terrestrial and satellite)
    - Infrared

Transmission Quality—Attenuation

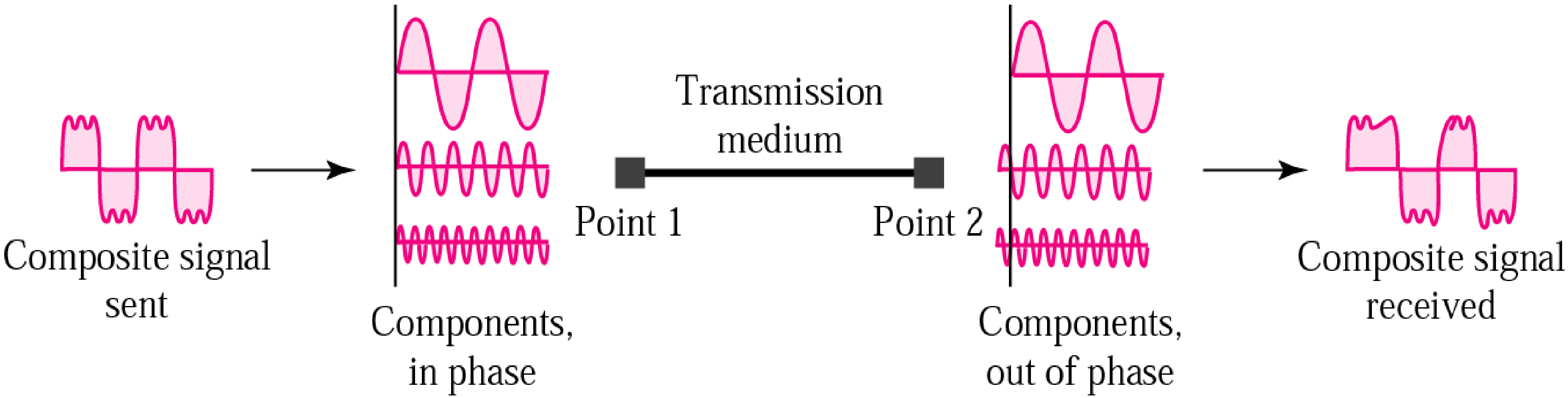
$$10 \log_{10} P_{in}/P_{out}$$

- No link is perfect
  - Power loss between sender and receiver
  - *Relationship* between incoming and outgoing power
  - Measured in decibel [dB] (from deci-Bell)
    - Example:
    - P_{in} = 120 mW
    - P_{out} = 30 mW
    - Attenuation = 10 $\log_{10}$ 4 ≈ 6 dB

Power and Sensitivity

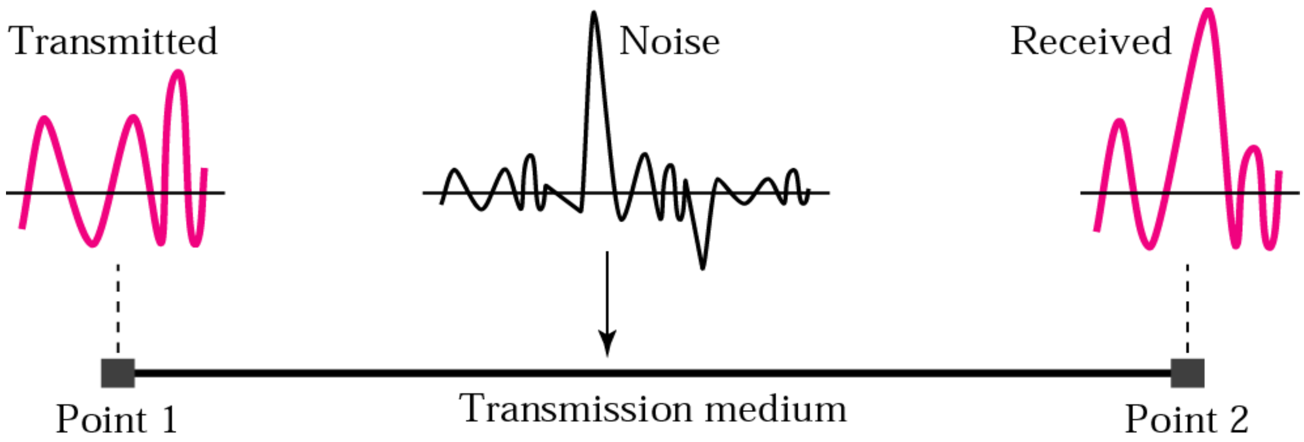
- Convenient to count in dB
  - For instance, halving power is equivalent to -3 dB
  - Represent power levels in relation to a reference power level
    - 0 dB means power is same as the reference level
  - Used for transmitter output power and receiver input *sensitivity*
    - input power needed for reception
- Measured in ”decibel watt” dBW or ”decibel milliwatt” dBm
  - $P_{dbW} = 10 \log_{10} P$
  - $P_{dBm} = 10 \log_{10} P/1\times 10^{-3}$
- Note: these are *absolute* power measures!

Transmission Quality—Distortion



- Each frequency component has its own *speed* through the medium
  - Adds up differently at the receiver
  - Signal changes form or shape
- Frequency dependent attenuation
  - *Low pass* attenuates higher frequencies more than lower ones
  - *High pass* attenuates lower frequencies more than lower ones
  - *Band pass* attenuates frequencies at both ends of spectrum

Transmission Quality— Added Noise



- Undesired signal *added* to the transmitted signal
- Thermal noise
  - Random motions of electrons
  - Independent of signal frequency and amplitude
  - White noise contains all frequencies at equal power
- Signal-to-noise ratio, SNR
  - S/N, where S is signal power, N is noise power
  - Measured in decibel

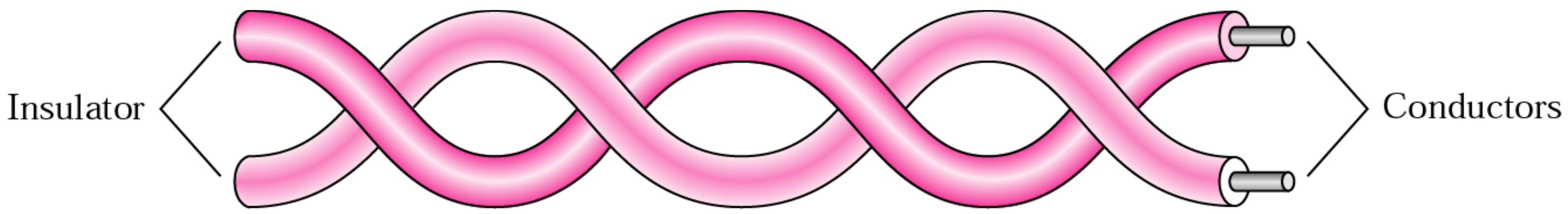
Transmission Quality—Counter Measures

- Amplification
  - Compensates for attenuation
  - Amplifies added noise as well as signal; adds its own noise
- Regeneration (for digital signals)
  - Recreates the shape of the signal
    - Cleans off noise, makes occasional errors
  - Composed of a signal receiver followed by a transmitter
- Noise filters
  - Filter out unused parts of channel bandwidth
- Protection against distortion
  - Equalizers
  - Dispersion compensation
  - Can attenuate the signal along with the noise
- Protection against disturbances and crosstalk (”överhöring”)
  - Crosstalk: signals from adjacent cables leak into one another
  - Protection by reducing leakage
    - For example shielding against electromagnetic fields

Guided Media

- Wires, cables
- Twisted pair cables
- Coaxial cables
- Optical fibers

Twisted Pair Cable



- Separately insulated
- Pair of cables twisted together
  - Reduce external disturbances
  - Receiver operates on signal differences

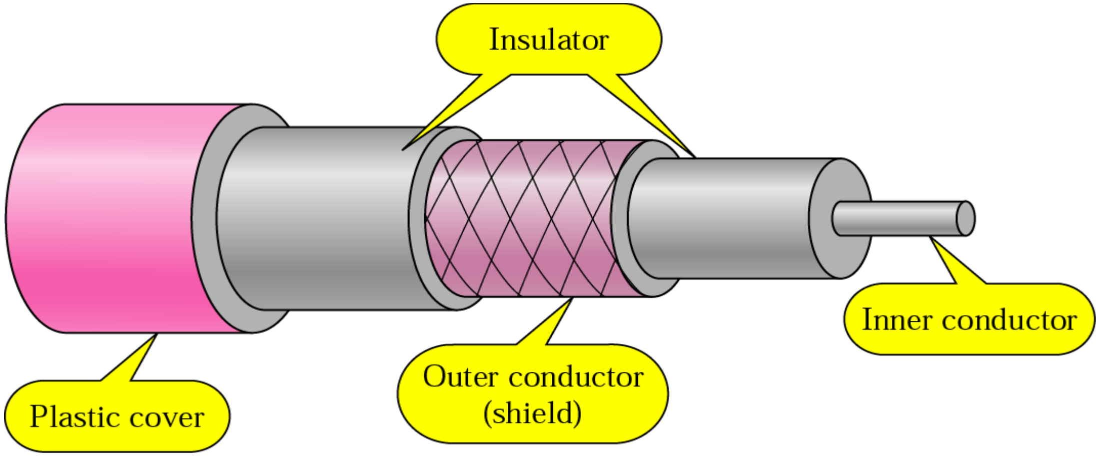
Twisted Pair Cable

- Several pairs bundled together
- Often with 8P8C connector (akin to RJ-45)
- Often installed in building when built
- Shielded (STP) and unshielded (UTP)
  - Shielding protects from external noise and crosstalk
    - Bulkier and more expensive

Cathegories of Unshielded Twisted Pair

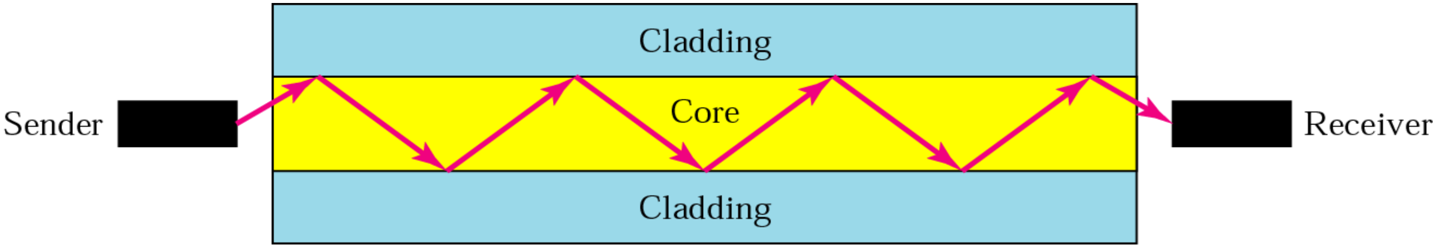
	Bandwidth [MHz]	*Bit rate [Mb/s]*	*Use*
CAT 1	Very low	< 0.1	Telephone, doorbell
CAT 2	<2	4	E-1 and T-1, token Ring
CAT 3	16	16	10Base-T, 100 Base-T4, 100 Base-T2
CAT 4	20	20	16 Mb/s Token Ring
CAT 5	100	100	100Base-T
CAT 5e	100	350	100Base-T
CAT 6	250	550-1000	1000Base-T
CAT 7	600	700-1000	1000Base-T

Coaxial Cable



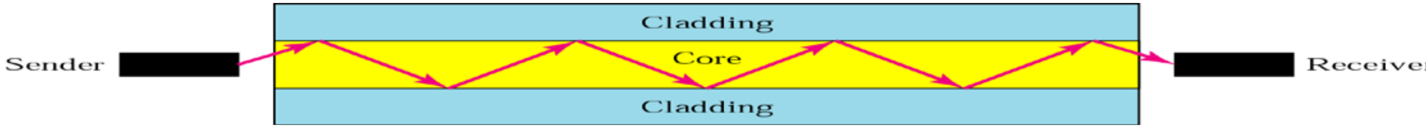
- Solid inner connector
- Outer connector is braid or metal foil
- Separated by insulating material
- Higher bandwidth than twisted pair
- Low crosstalk

Optical Fiber

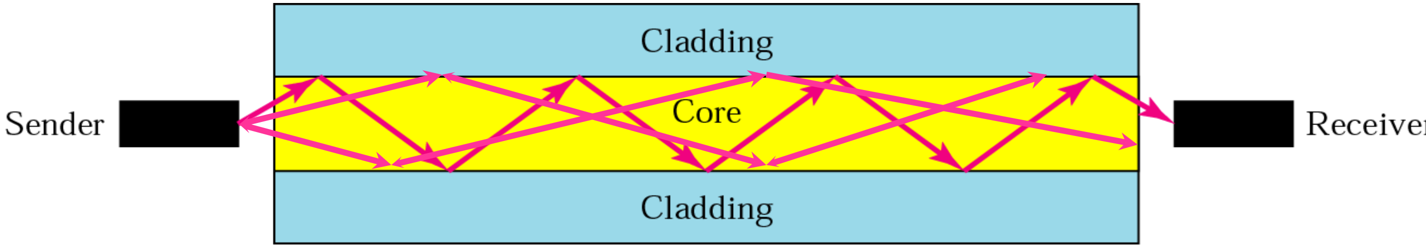


- Core of silica glass or plastic
- Cladding with lower index of refraction
  - Mirrors the light signal in the core
  - Reflection depends on angle of incidence
- Light emitting diode (LED) or laser diode as light source

Fiber transmission modes



Single-mode fiber



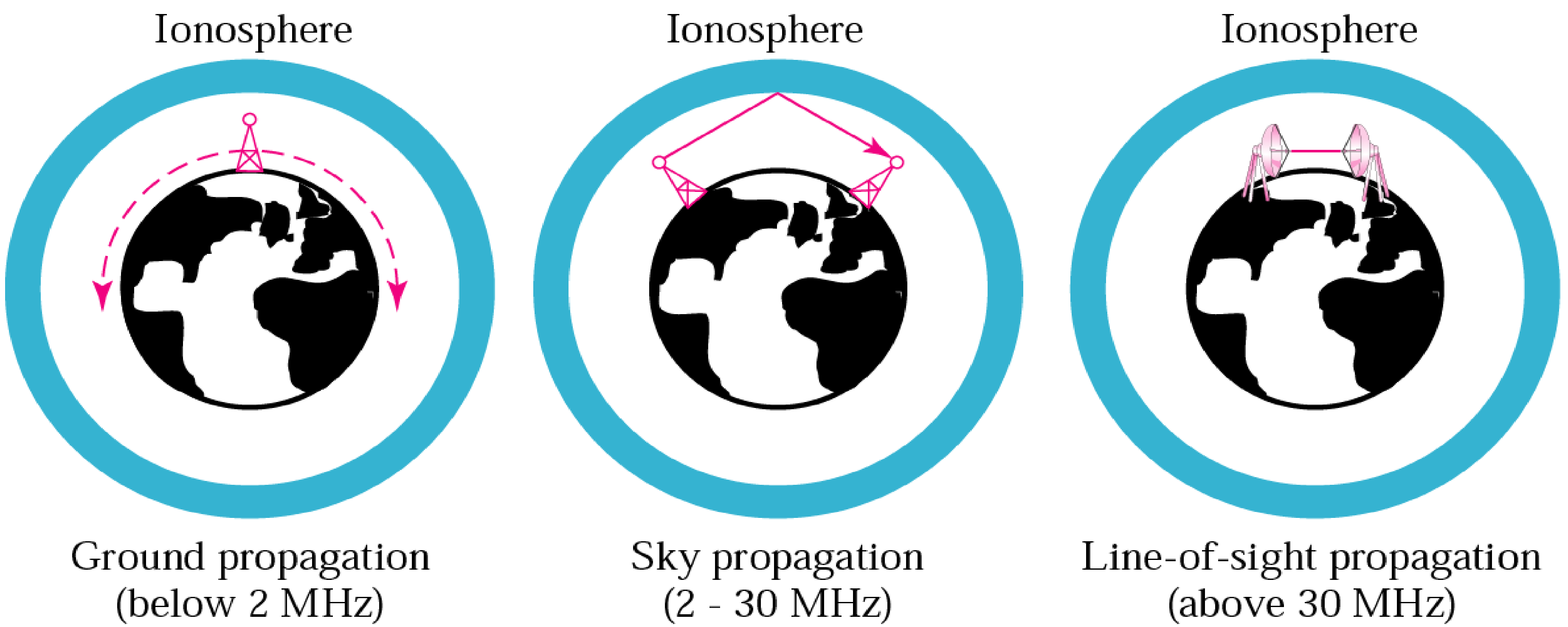
Multi-mode fiber

- Measure is loss (in dB) per kilometer of fiber
  - Typical value is 0.3 dB/km for single-mode silica glass
- Wavelength $\lambda = c/f$
  - c is propagation speed, f is frequency
  - speed of light is around 2×10^8 [m/s] in fiber

Fiber Advantages and Disadvantages

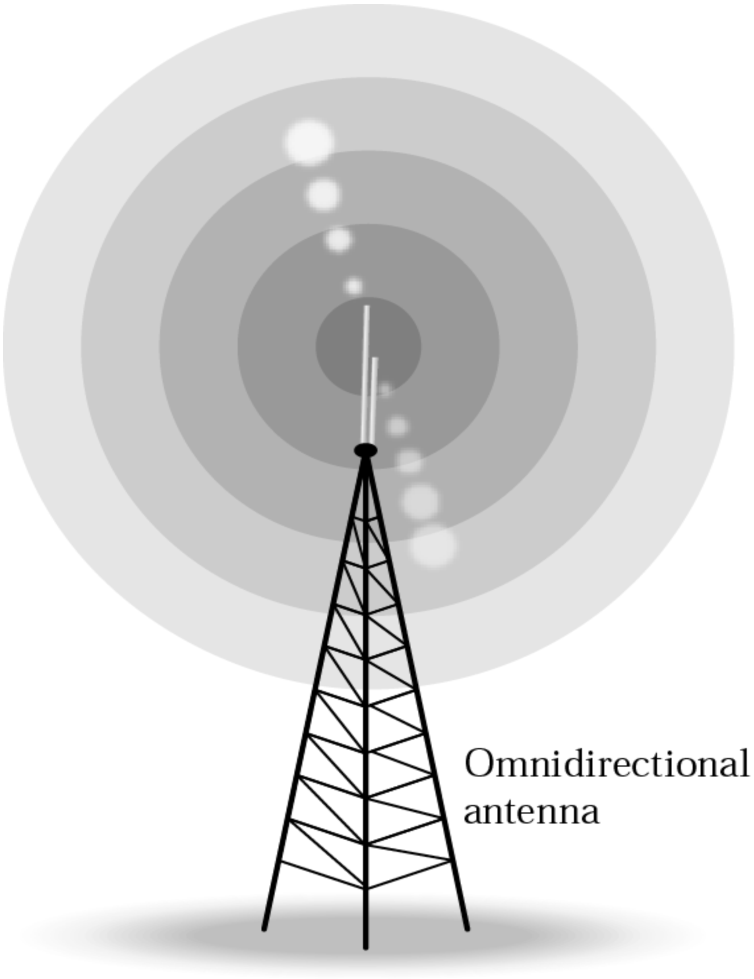
- Advantages
  - Very high bandwidth
  - Low attenuation
  - No crosstalk: *no* interference between photons
  - Not sensitive to electromagnetic noise
  - Low weight per meter of cable
- Disadvantages
  - Installation
    - To pull the cable (no sharp bends for instance)
    - Connecting cable segments together by wielding
    - Adding connectors
  - Maintenance and repair

Propagation Methods for Unguided Signals



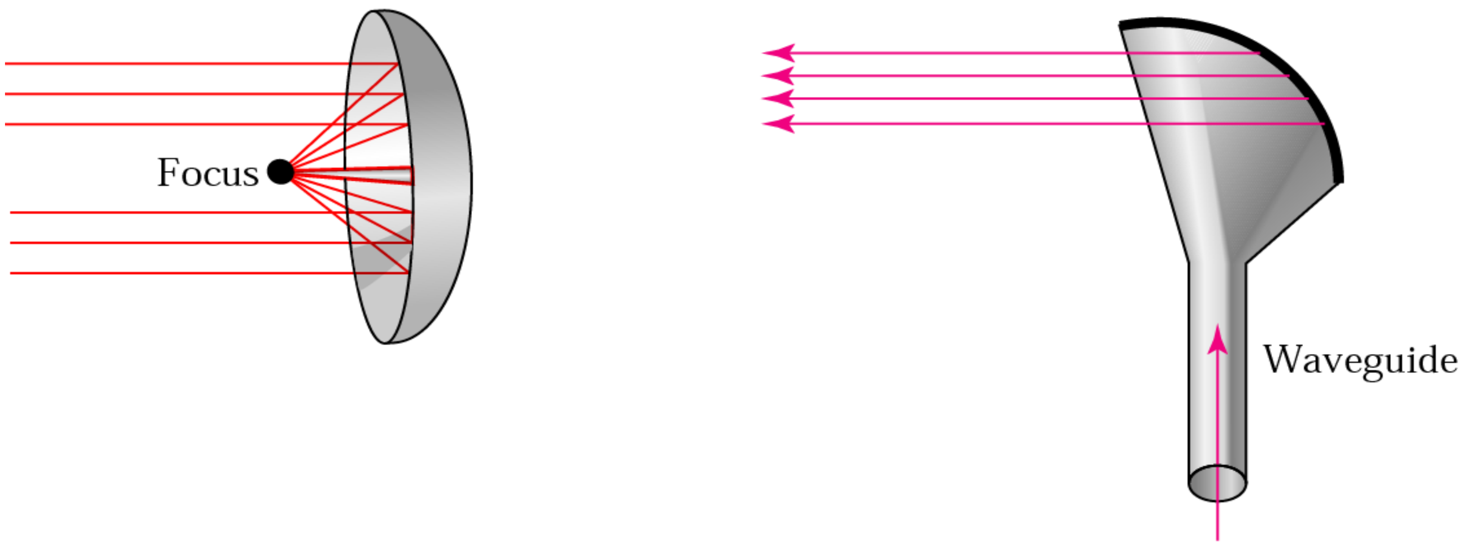
Radio Waves

- Radio, television
- Signal frequencies of up to 1 GHz
  - Signal passes through most obstacles
    - walls, vegetation
- Ground and sky propagation
- Omnidirectional antennas
  - High towers for line of sight
  - Eg, Kaknästornet, Nacka-masterna



Microwaves

- Signal frequencies of 1-300 GHz
  - Signal attenuated by obstacles, water and more
  - Signals behave more like light at higher frequencies
- Cellular phones, satellite networks, wireless LANs
- Line of sight propagation
- Unidirectional antennas for point-to-point
- Omnidirectional for mobile and broadcast communication



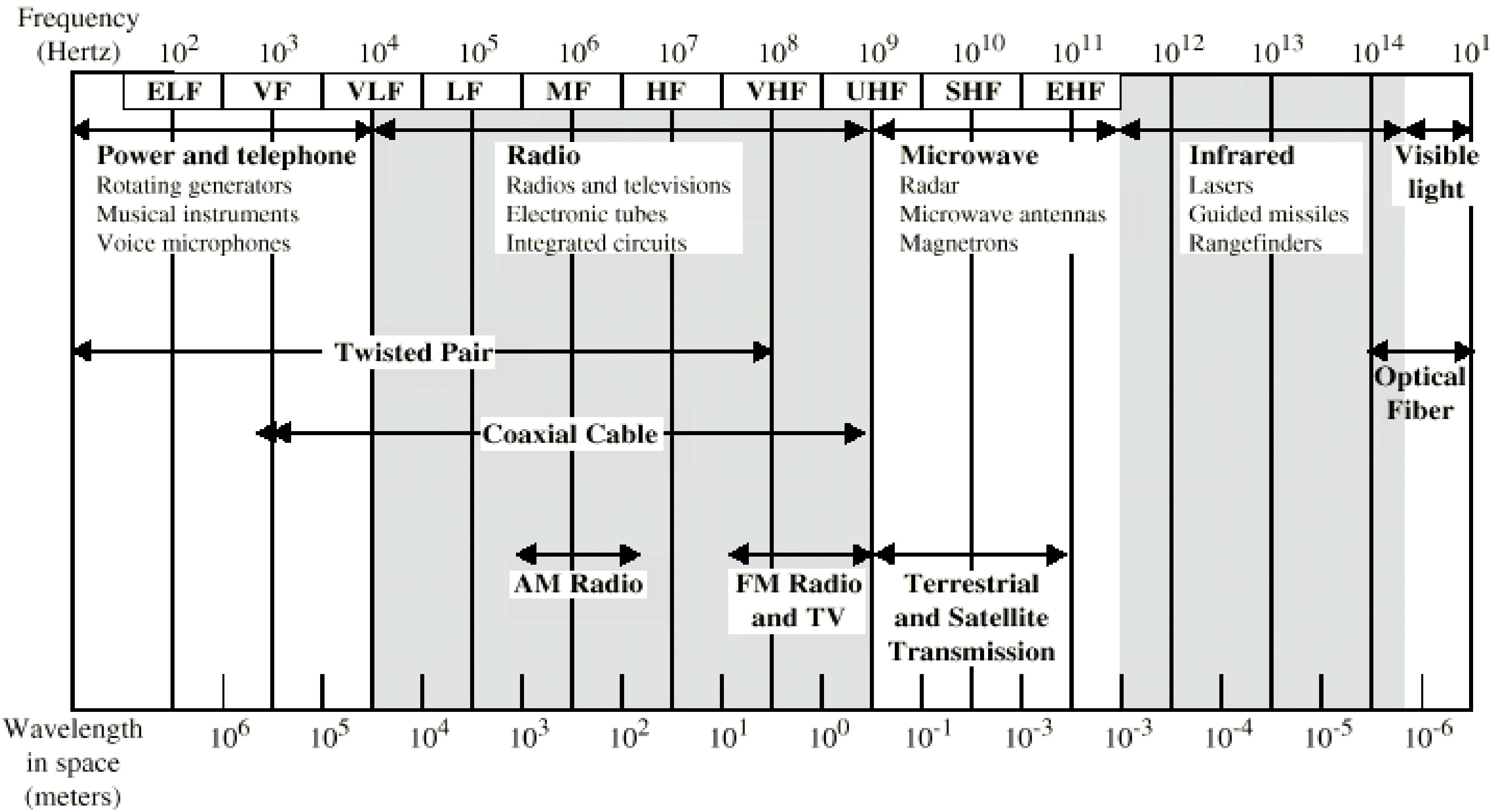
a. Dish antenna

b. Horn antenna

Infrared

- Light signals of frequencies 300 GHz – 400 THz
  - Non-visible part of light spectrum
  - Heat radiation
- Line-of-sight propagation
  - Reflections can be used to pass obstacles
- Interference from sun rays
- Short distances
  - Commonly used for remote controls

Bandwidths for different media



Transmission capacity

Capacity

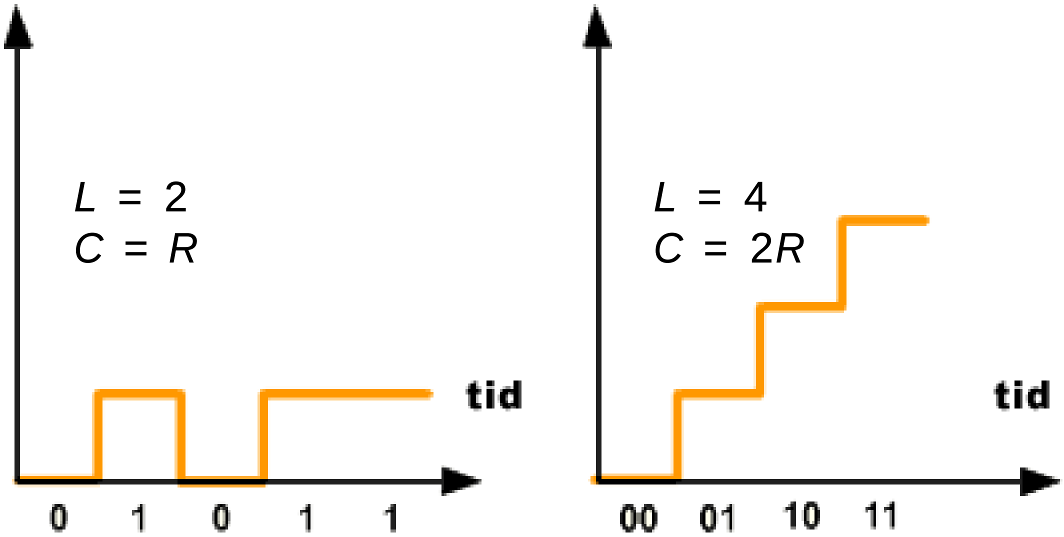
- Bandwidth of a transmission medium
  - Difference between highest and lowest frequency of signals that may be transmitted through the medium
  - Limits the channel's ability to carry data
- Transmission capacity
  - Indicates how much data can be transmitted per second
  - Measured in bits per second [b/s, bit/s, bps]
- Increased bandwidth can give higher capacity
  - A noiseless analog channel has infinite capacity
  - Noise is therefore the main limiter of the capacity

Bit Rate and Baud Rate

- Transmission capacity: number of bits per second (bit rate)
- Baud rate: number of signal elements per second
  - signal elements are forms used to represent data
  - the more signal elements, the less different they can be
    - easier to misinterpret signal elements at receiver

$$C = R \log_2 L$$

C: capacity
L: number of levels
R: baud rate



Nyquist Bit Rate

$$C_{max} = 2B \log_2 L$$

- Also Nyquist's/Hartley's Law
- Nyquist bit rate C_{max} is the maximum bit rate on an ideal channel
  - So maximum baud rate is $2B$
  - Capacity goes towards infinity with increasing number of signal levels

Channel capacity—Shannon's formula

$$C = B \log_2(1 + S/N)$$

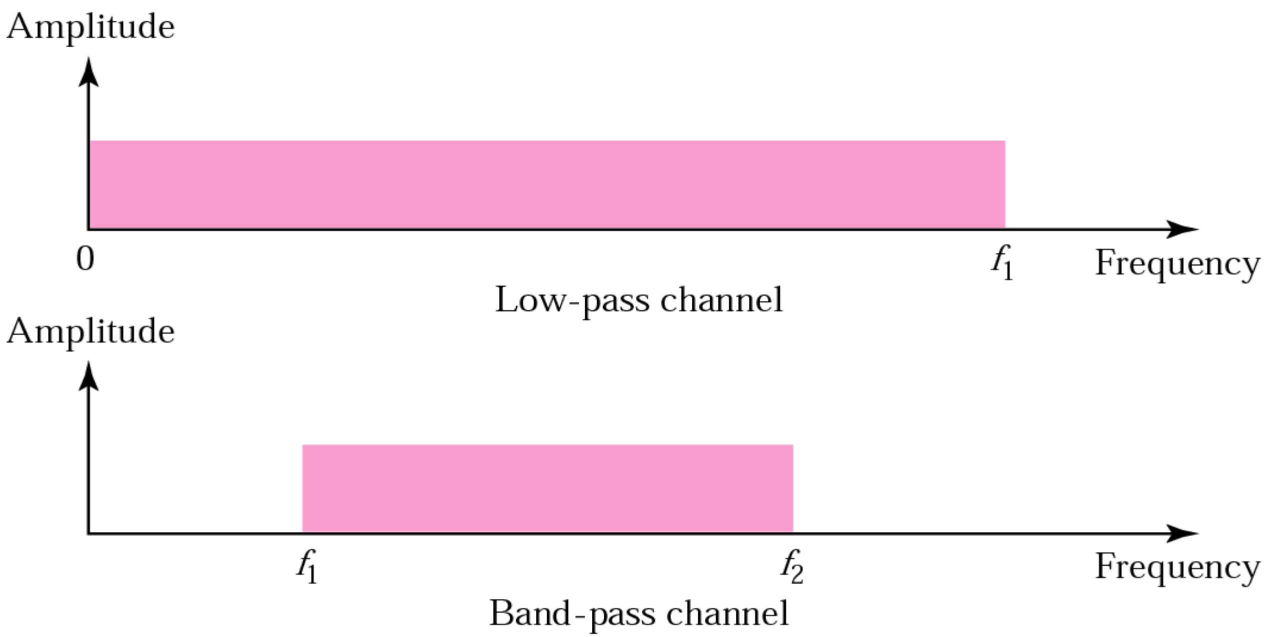
- Claude Shannon (1916 – 2001)
  - ”Father of information theory”
- Highest possible bit rate in a channel with *white* noise
  - *B* is channel bandwidth
  - *S*/*N* is signal to noise ratio (*not* in dB!)

Shannon's formula

- Example
  - B = 3400 – 300 = 3100 Hz
  - S/N = 20 dB = 100 times
  - $C = 3100 \log_2(1 + 100) = 20.6$ kb/s
  - What about ADSL modems?

Transmission of data

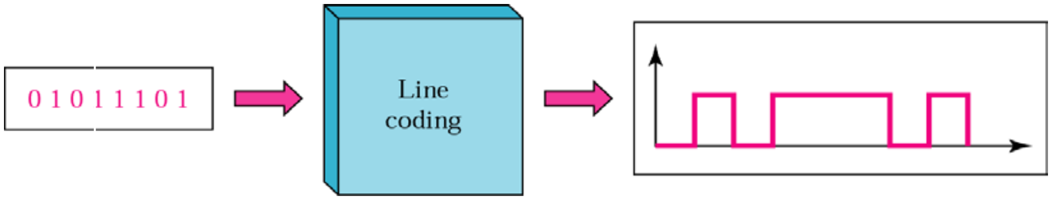
Analog and Digital Signals

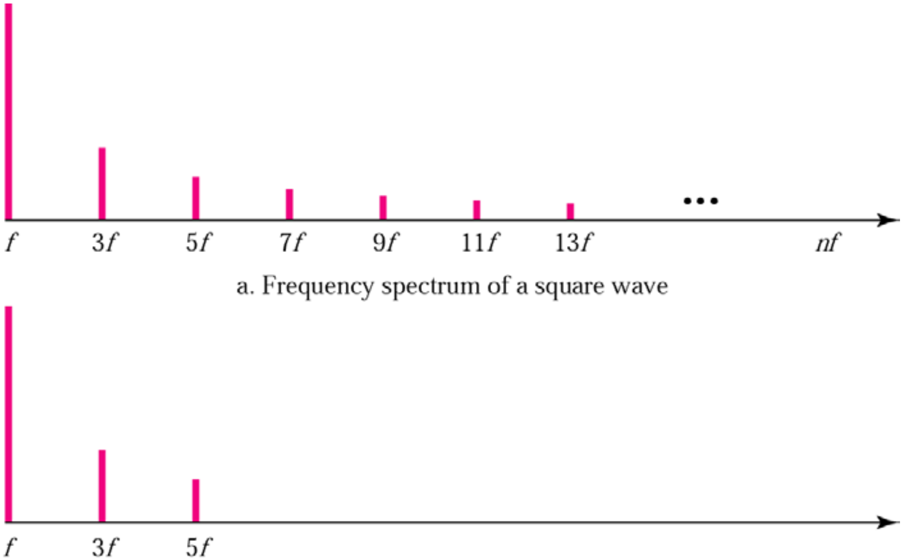


- Low-pass channel
  - Line coding
    - Baseband modulation
      - "Basbandsmodulering"
- Band-pass channel
  - Modulation of carrier
    - "Bärvågsmodulering"

Line coding (baseband modulation)

- Turn binary data into a transmission signal
  - Discrete amplitude levels
  - Transition between levels at discrete times
    - clocking
  - Signal is constant between transition times
- Transmission effect
  - Uses full bandwidth of channel
  - Spectrum of transmission signal (square wave) is infinite
  - Lowpass channel limits high frequency part of signal
  - Received signal “smoothed” at transitions

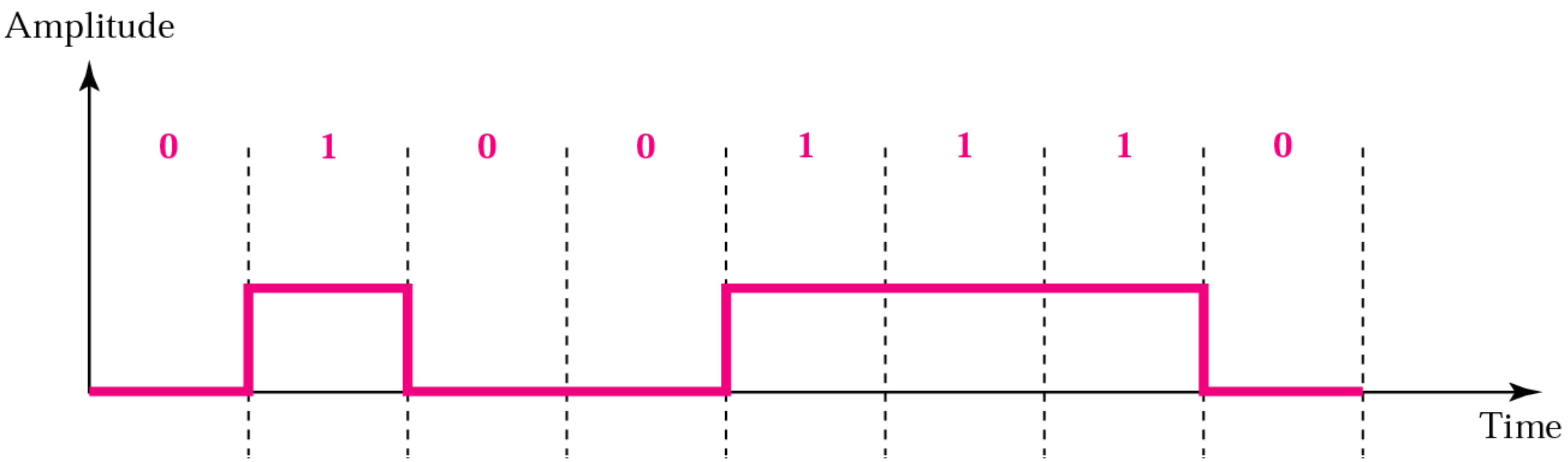




a. Frequency spectrum of a square wave

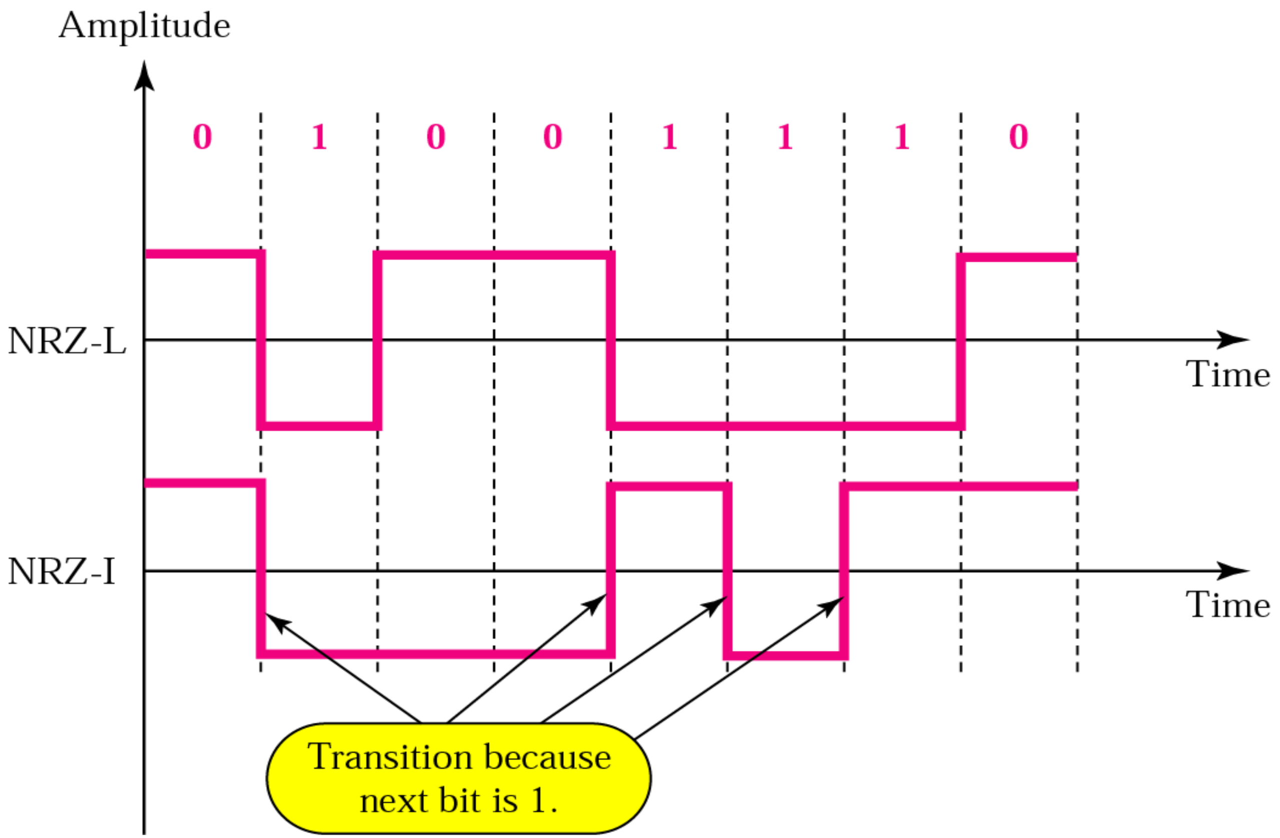
b. Frequency spectrum of an approximation with only three harmonics

Unipolar Encoding



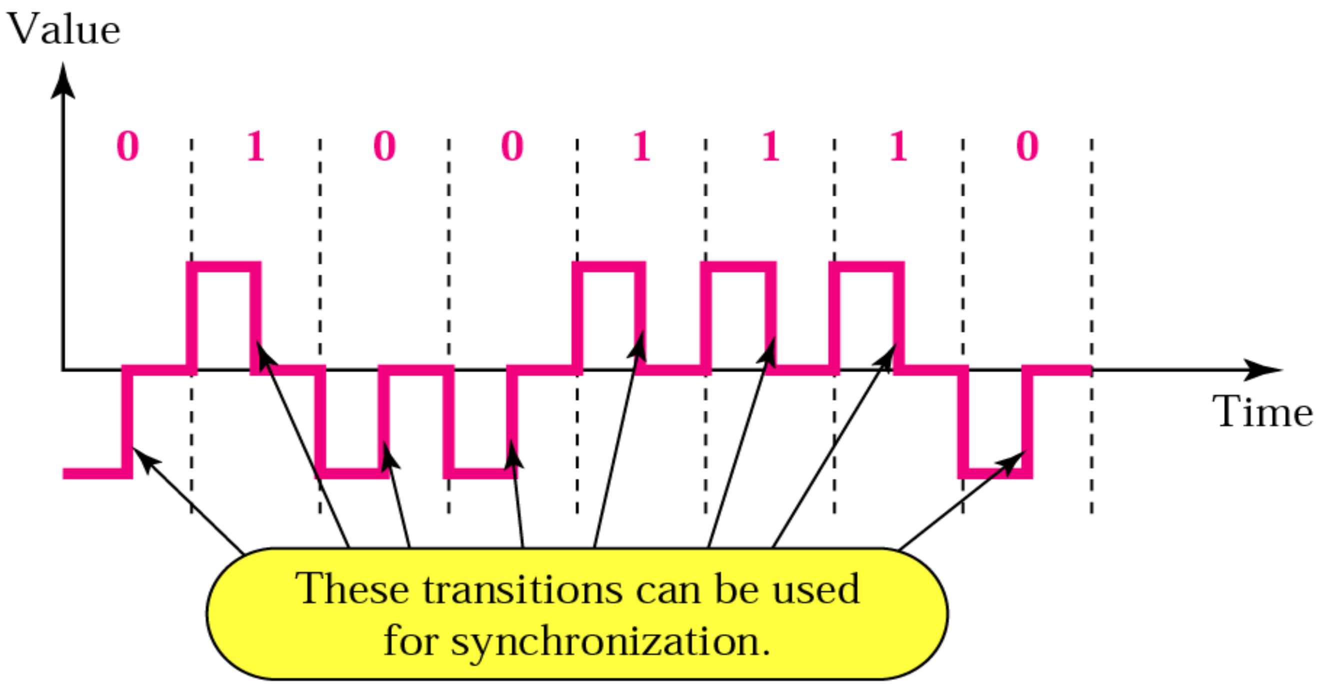
- Two signal levels
  - Zero level and positive level (or negative, but not both)
- Contains DC component (0 Hz frequency)
  - Average level of the signal (depends on rate of 1s in data)
  - Require cable with lowpass channel
- Lack of synchronization (clocking information)
  - Long sequences of all ones or all zeros may cause receiver to loose synchronization

Nonreturn to Zero (NRZ)



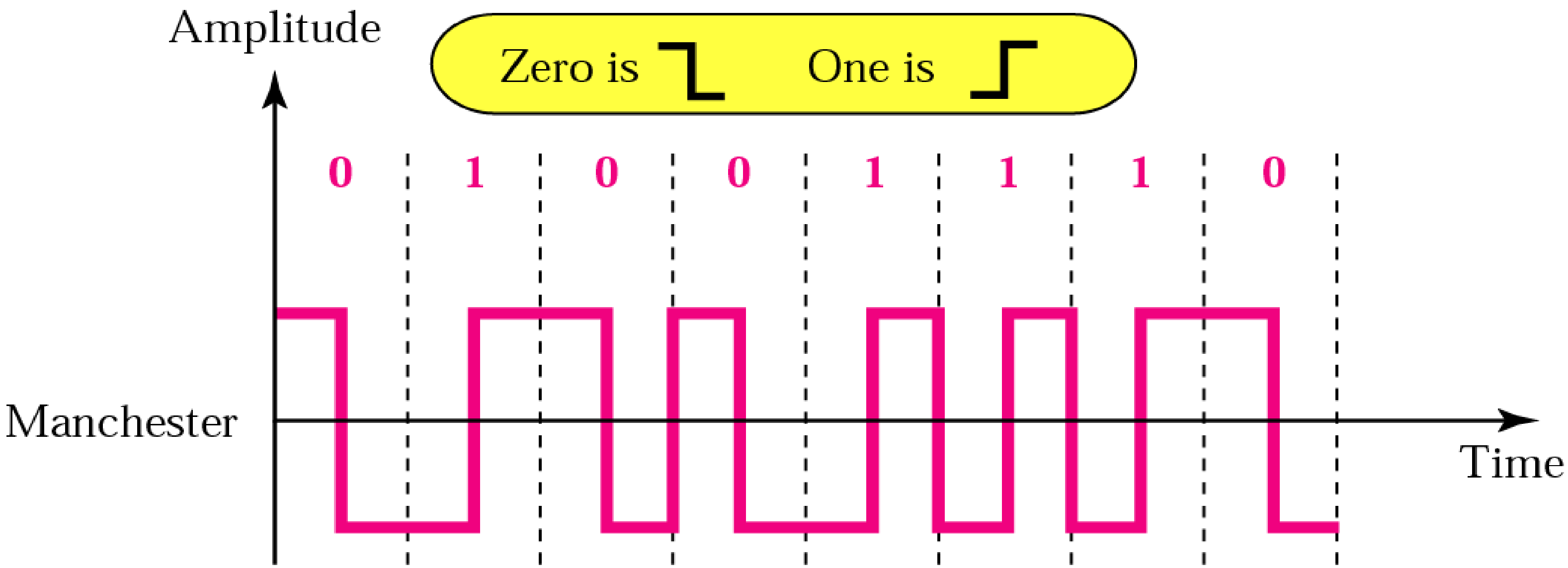
- Bi-polar signal (two levels)
  - Average signal level reduced
- Synchronization may still a problem

Return to Zero (RZ) Encoding



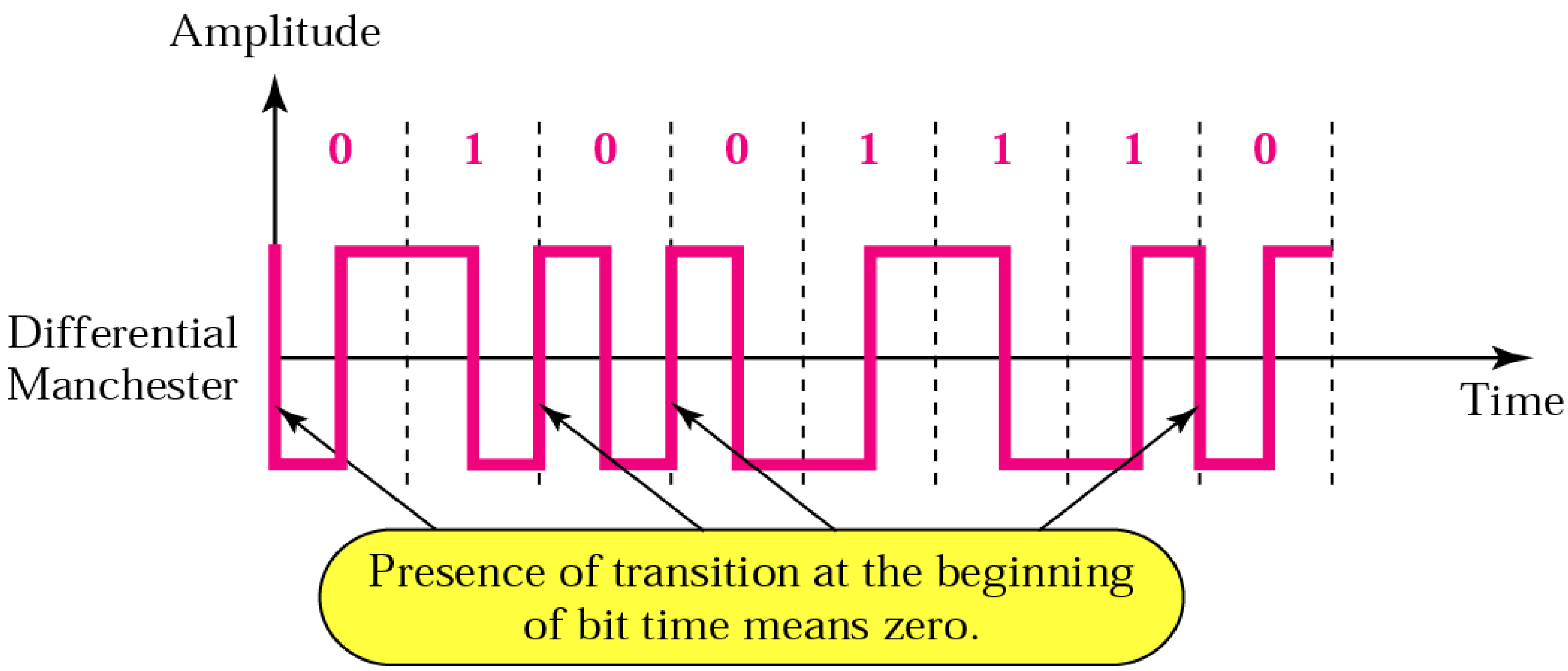
- Three levels: positive, negative and zero
  - Always return to zero before next transition up or down
- Synchronization even for long strings of 1s or 0s
- Two signal-changes per bit—more bandwidth

Manchester Encoding



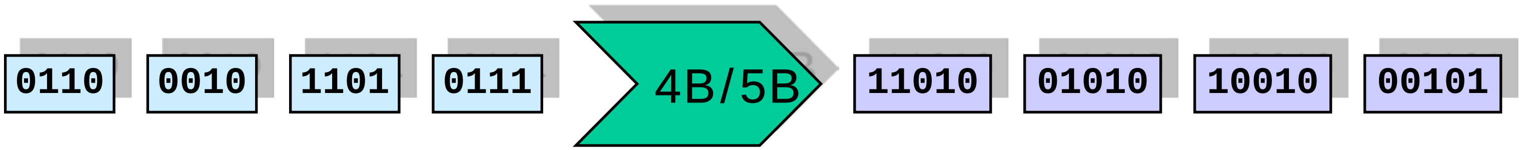
- Two signal levels
  - Always transition in middle of interval
- Higher pulse rate requires larger bandwidth

Differential Manchester Encoding



- Need only detect ”transition” or ”no transition”

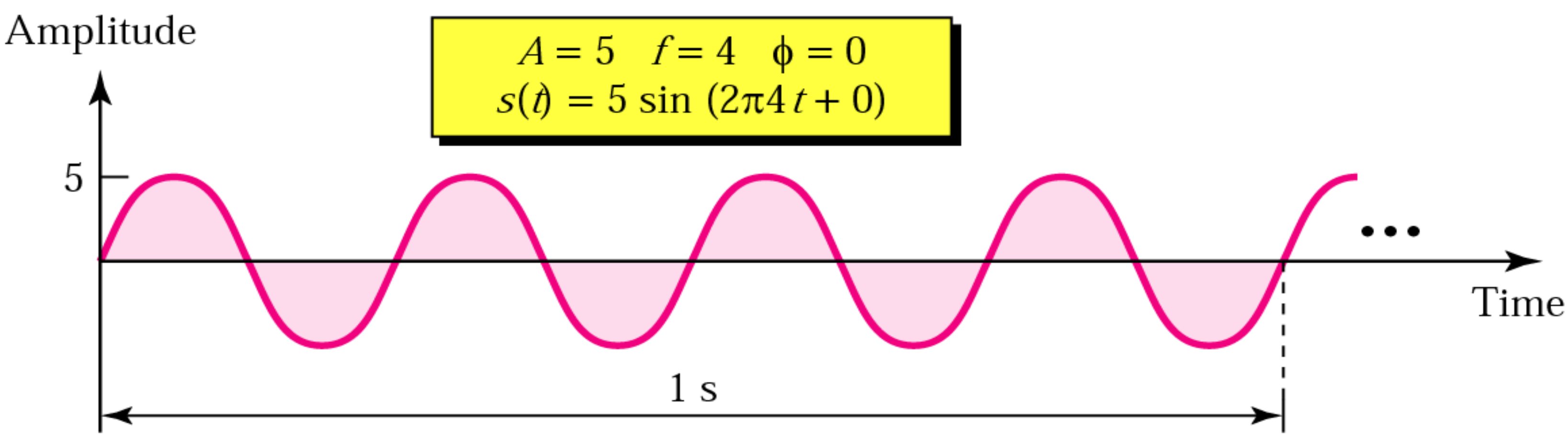
Block coding



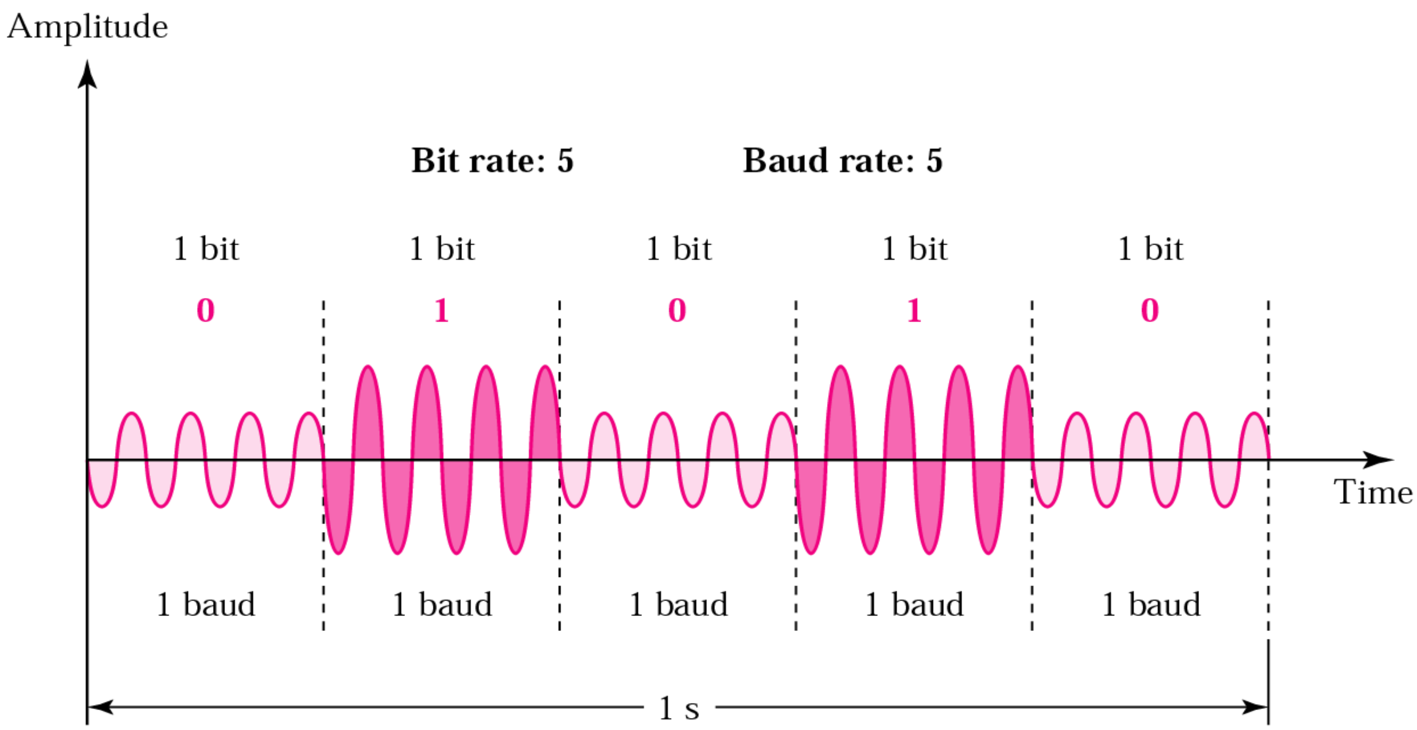
- Bit stream is divided into *m*-bit groups
- Groups are encoded as *n*-bit codes
  - 4B/5B: 5-bit codes represent 4-bit groups
  - 8B/10B: 10-bit codes represent 8-bit groups
- Select the *n*-bit codes smartly
  - Sufficient number of 1s in each codeword
  - *n*-bit codes transmitted by some line coding, eg NRZ

Modulation

- Sine wave fully described by amplitude *A*, frequency *f* and phase ϕ
  - $s(t) = A \sin(2\pi f t + \phi)$
- Vary one (or more) to represent symbols

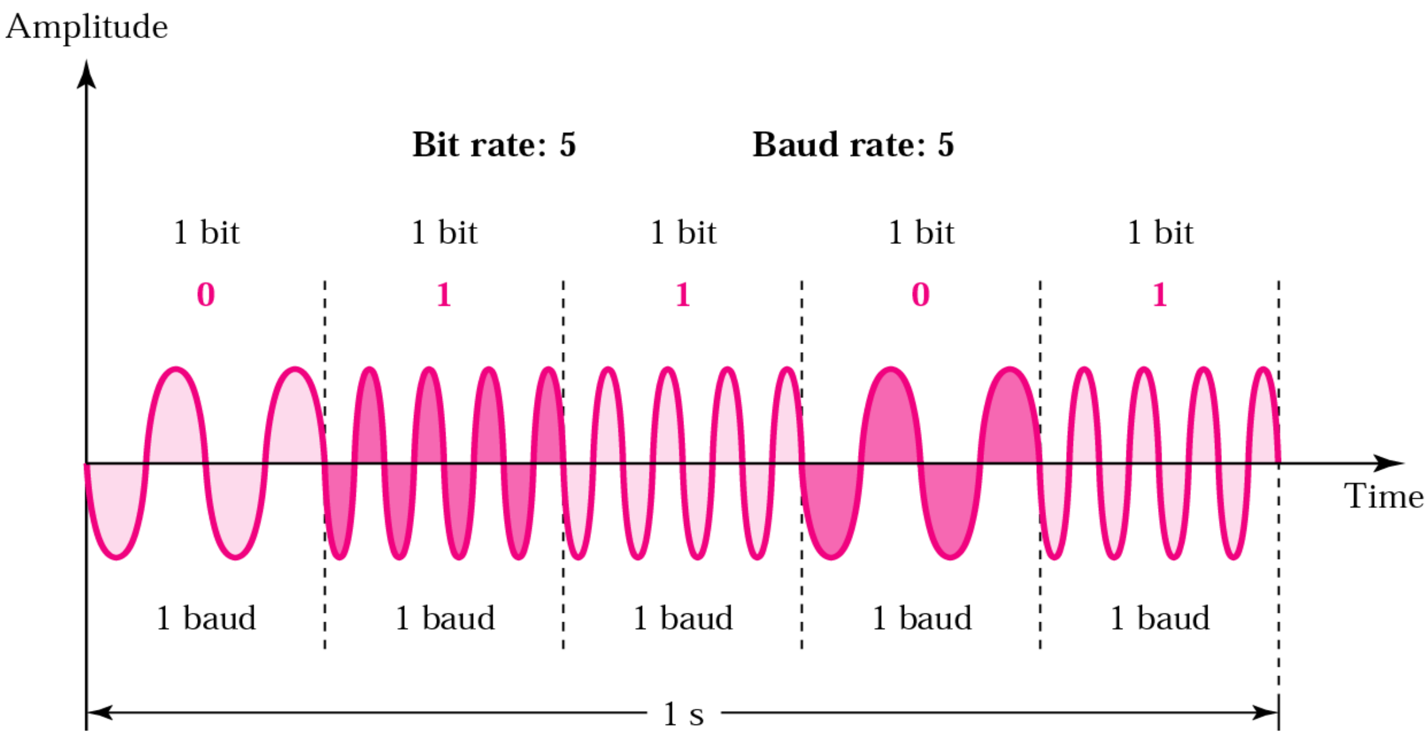


Amplitude Shift Keying (ASK)



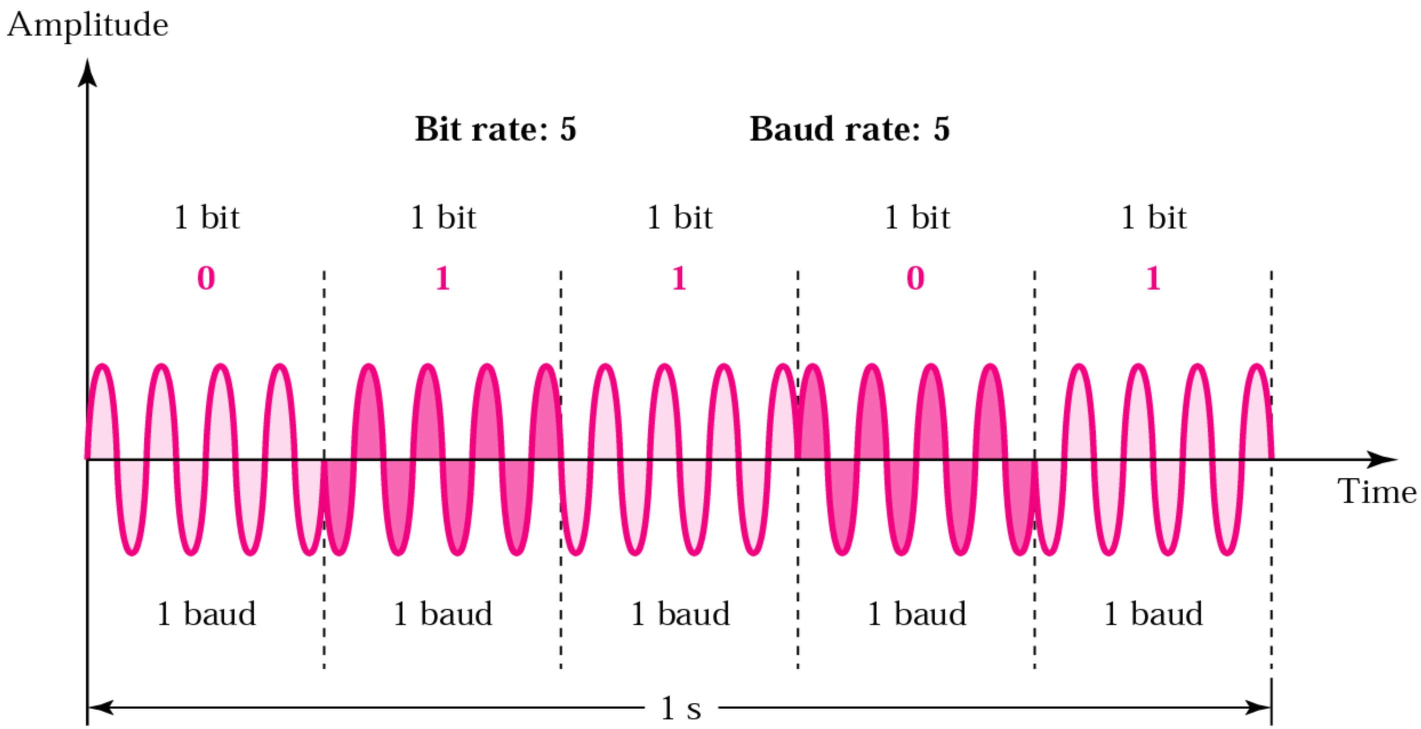
- Signal level is varied to represent symbols
- Amplitude sensitive to noise and attenuation

Frequency Shift Keying (FSK)



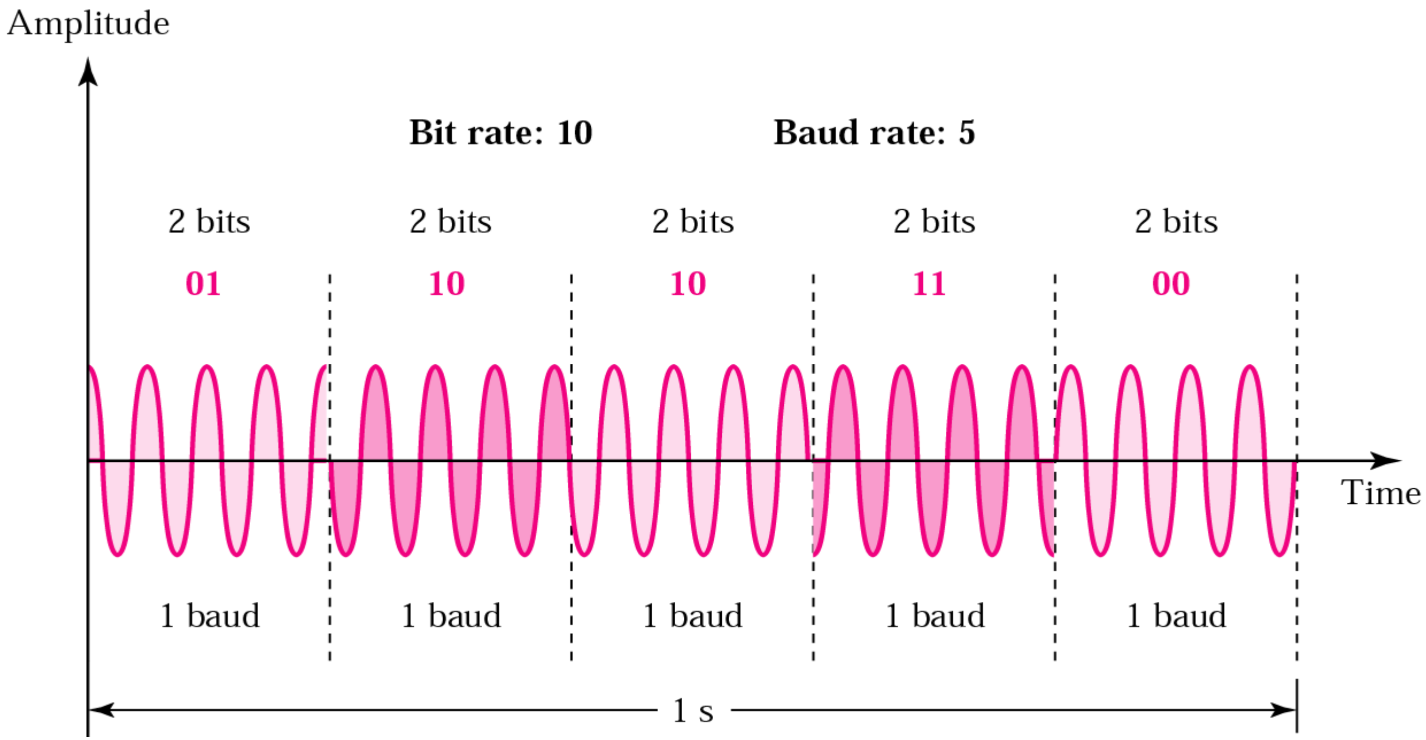
- Signal frequency is varied to represent symbols
- Bandwidth limitations

Phase Shift Keying (PSK)



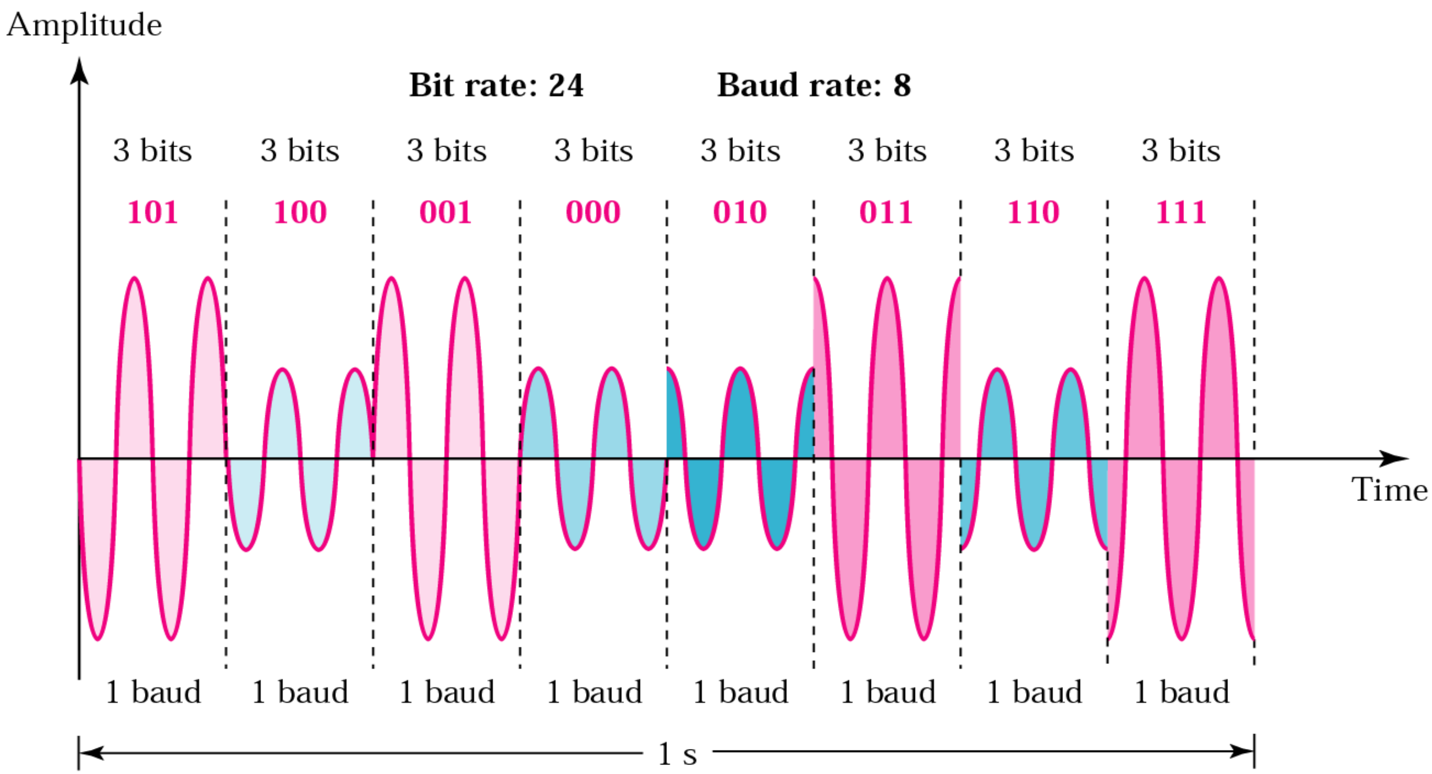
- Signal phase is varied to represent symbols
- Limited by receiver’s ability to detect phase changes

4-PSK (Q-PSK)



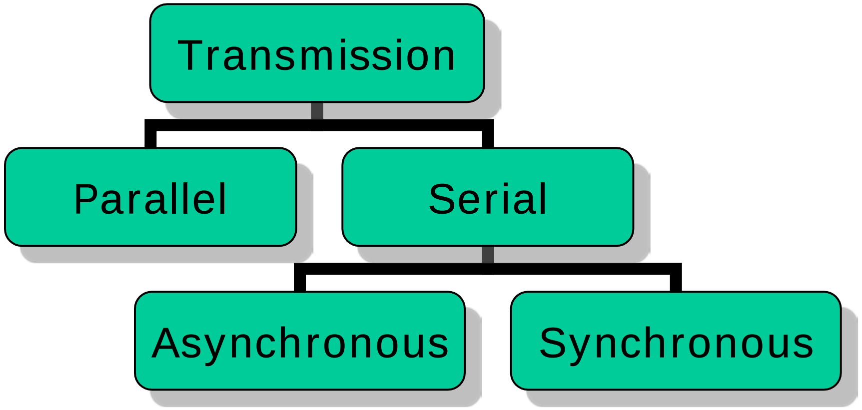
- Four different phases
- Each phase represents two bits

Qadrature Amplitude Modulation (QAM)

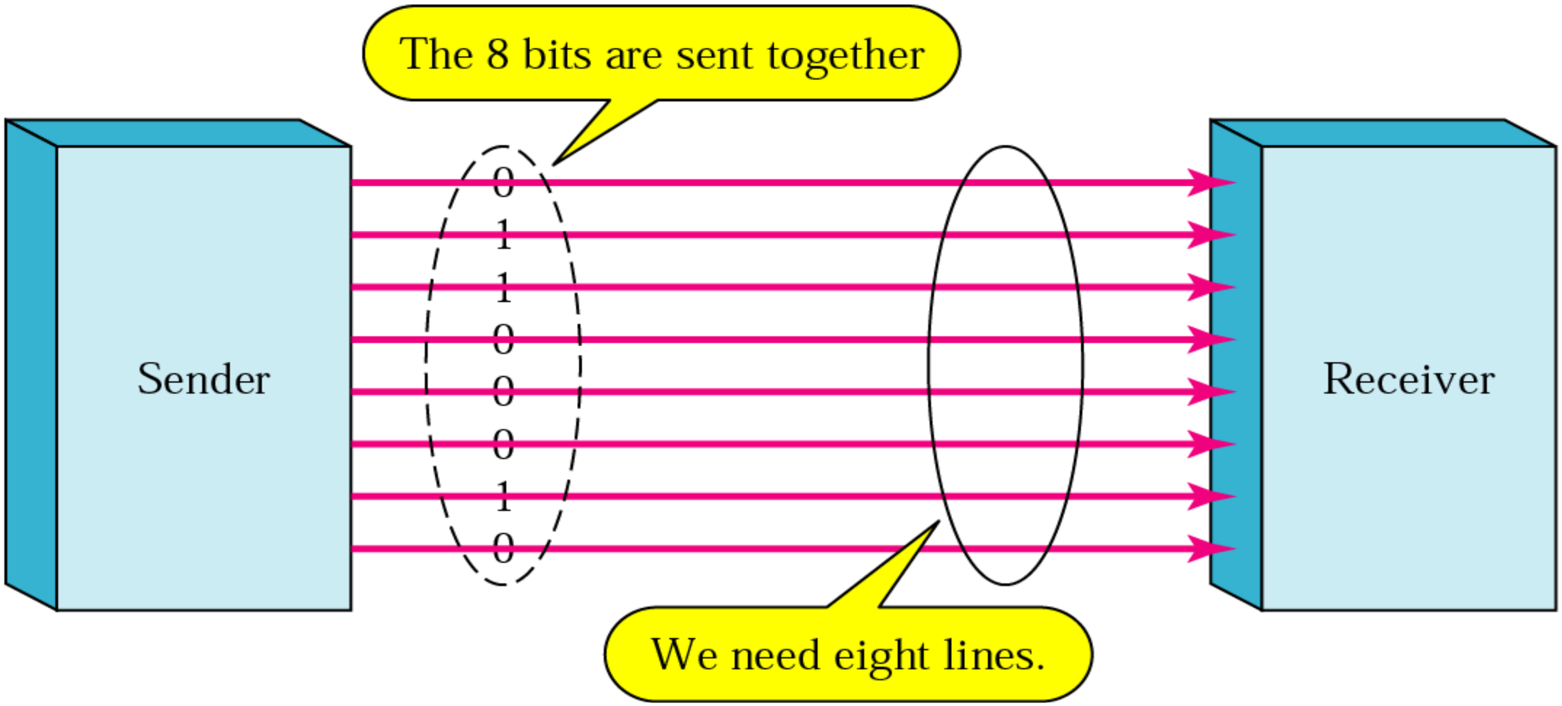


- Combination of ASK and PSK
  - Allows for more combinations—more bits per baud
- Maximum contrast between signal units

Data Transmission Modes

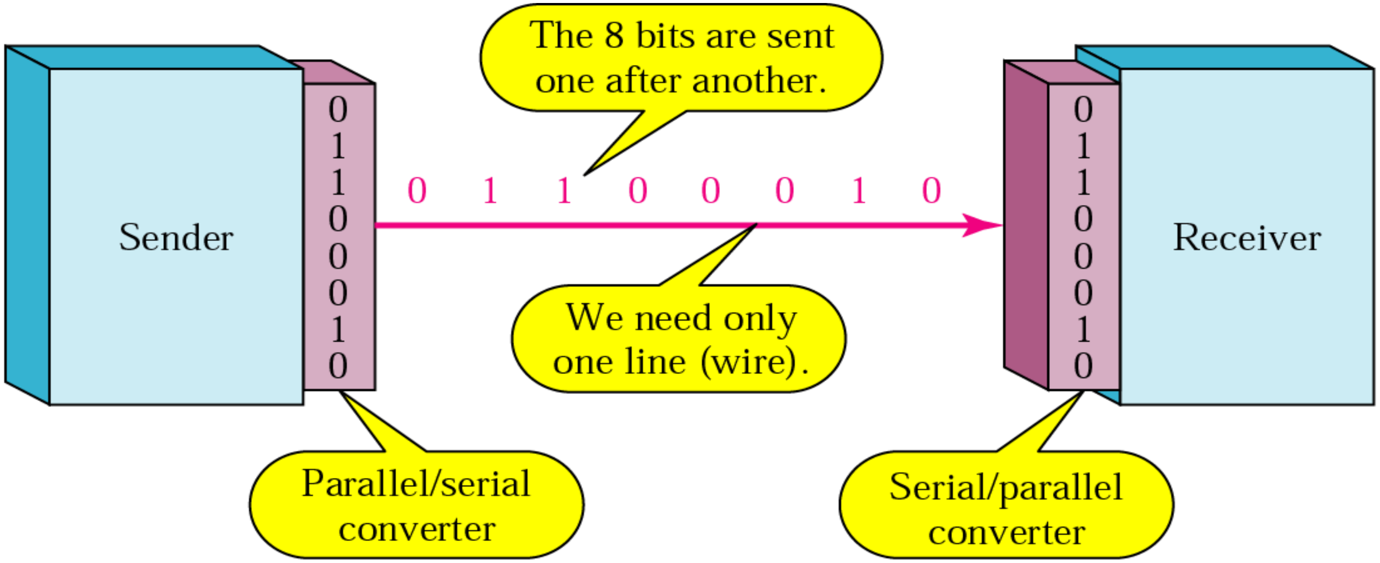


Parallel Transmission



- High capacity (or lower clock rate)
- Requires multiple cables or wider cables

Serial Transmission



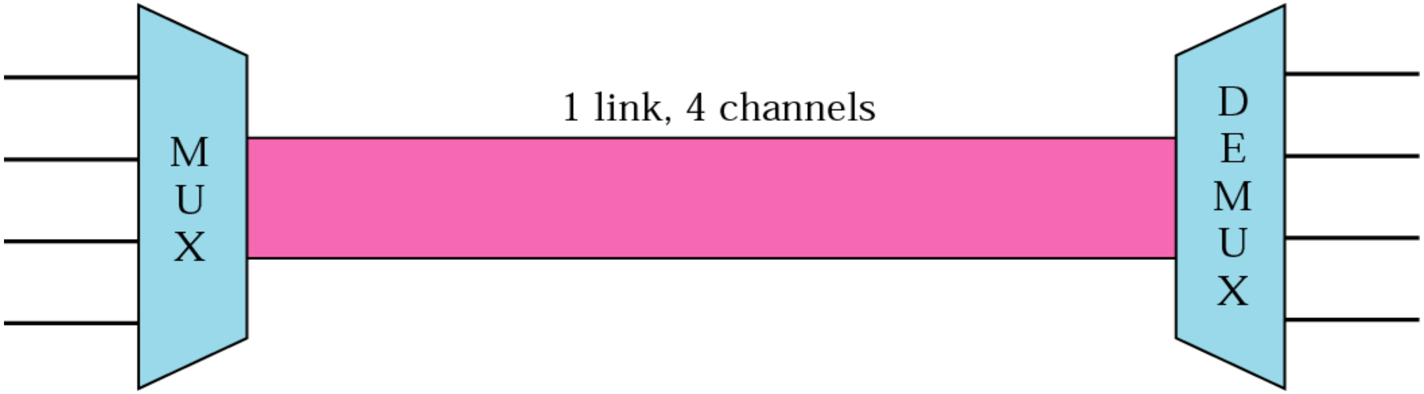
- Need for synchronization at bit level
  - External clock, such as GPS
  - Separate link for clock signal
  - Line coding with embedded clock
    - Manchester coding, for example
  - Receiver resynchronization

Framing of messages

- Sender might run out of data
  - Intermittent data source
- Receiver interprets incoming signal
  - Only noise if there is no transmission
  - Noise signal taken as data
- Solution: Framing
  - Mark start and stop of message
  - Added control (protocol) data per message
  - Allows multiplexing of messages from multiple sources
    - Separate frames from each source
    - Division of a frame for multiple sources

Multiplexing

Multiplexing

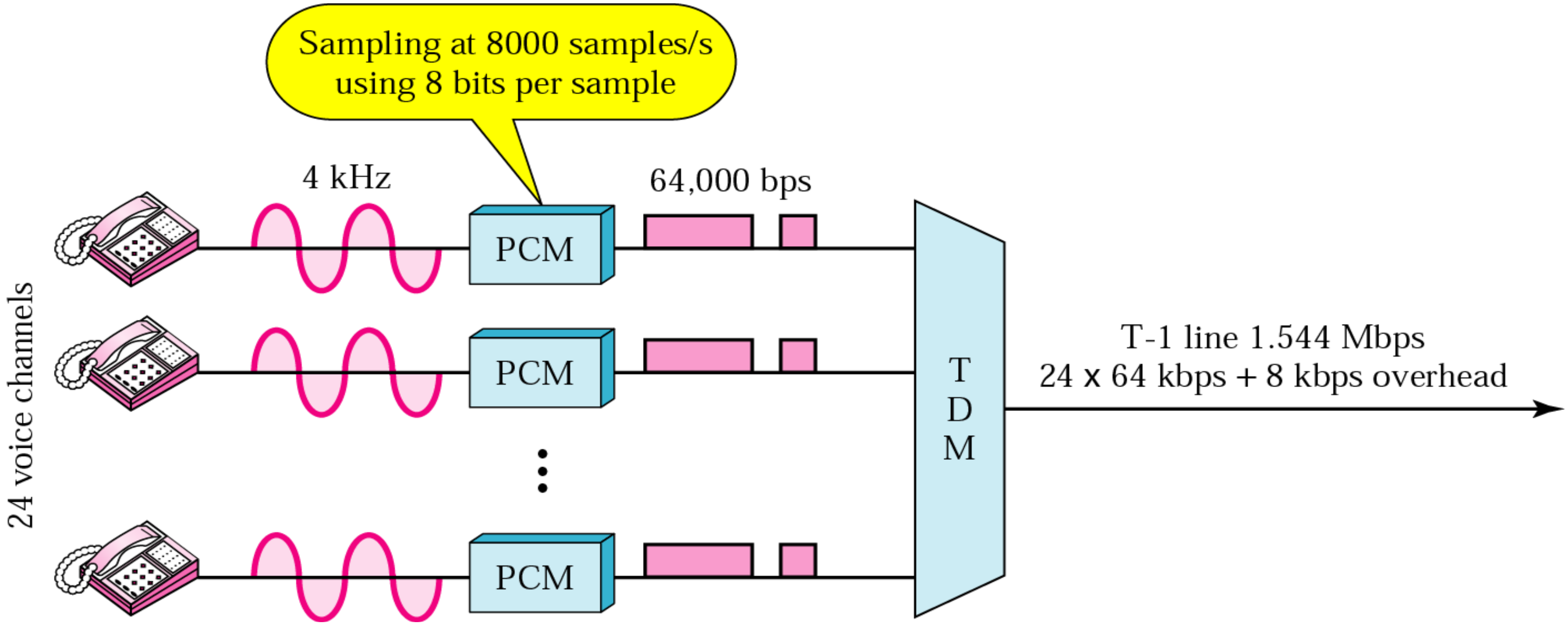


- Subdivision of a link into multiple channels
  - Multiple sender/receiver pairs can share a link
- Resource sharing
  - Bandwidth divided into frequency channels
  - Transmission time divided into time slots

Multiplexing

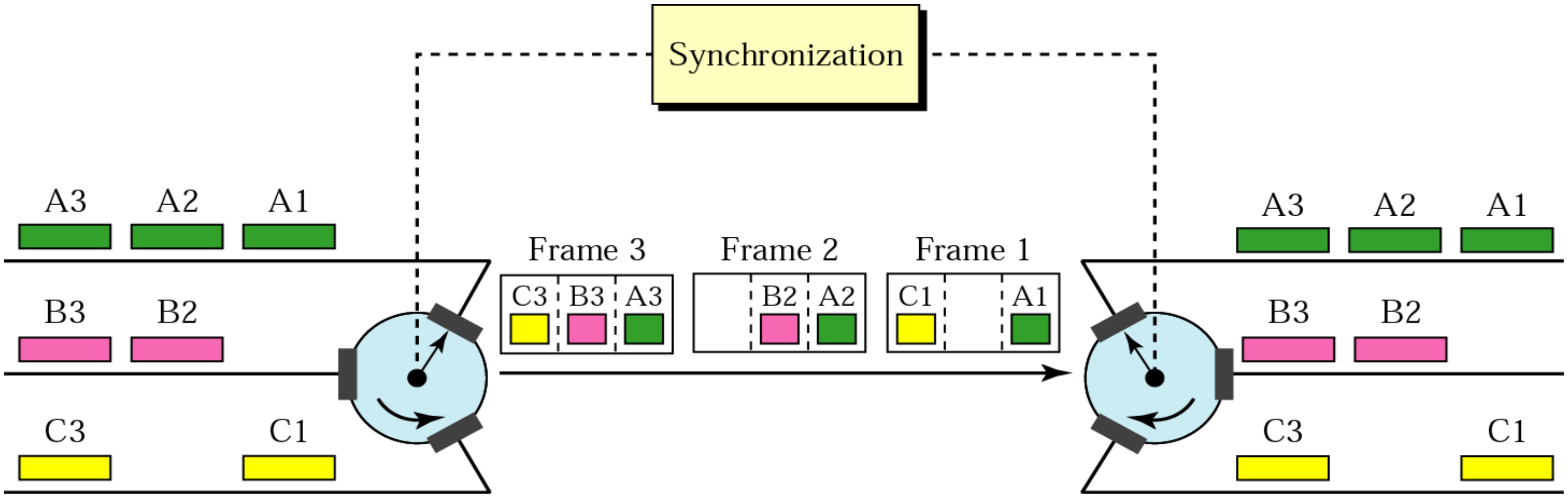
- Analog multiplexing
  - Frequency division multiplexing (FDM)
    - Multiple frequency channels
    - Bandpass modulation
    - TV and radio broadcast
  - Wavelength division multiplexing (WDM)
    - Similar to FDM for optical transmission
- Digital multiplexing
  - Time division multiplexing (TDM)
    - Access according to time slots
      - — Synchronous TDM
    - Statistical TDM
      - — Asynchronous TDM

Time division multiplexing for telephony



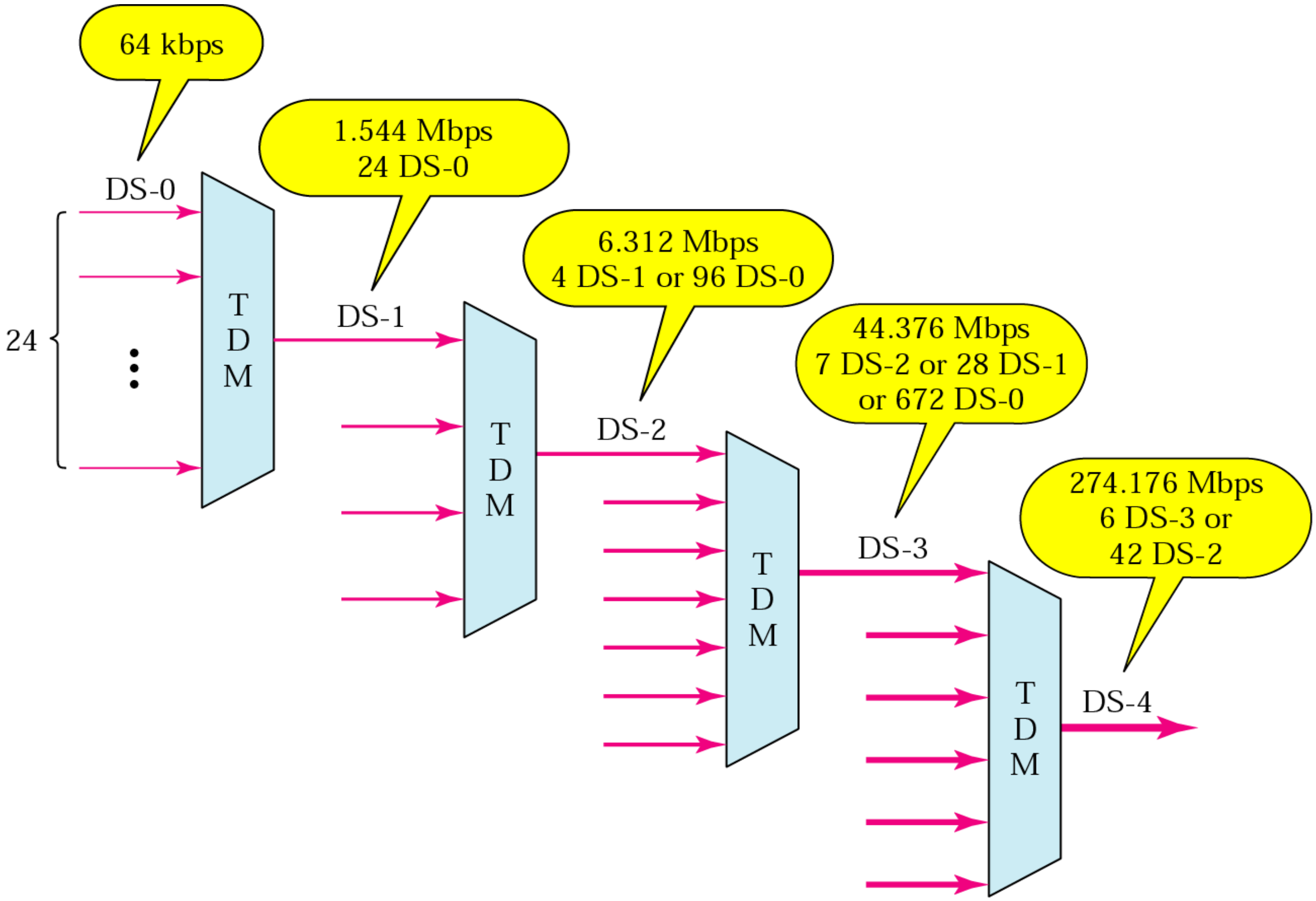
- Carries PCM voice channels
  - T1 (North America, Japan)
    - 24 channels, 1.544 Mb/s
  - E1
    - 30 channels, 2.048 Mb/s

Synchronous Time Division Multiplexing



- Access according to time slots
- Time slots grouped into frames
- If *n* is the number of inputs, the output link needs to be *n* times faster than each input link
- Frame duration is the same as the duration of a data unit on the input

Hierarchical Multiplexing



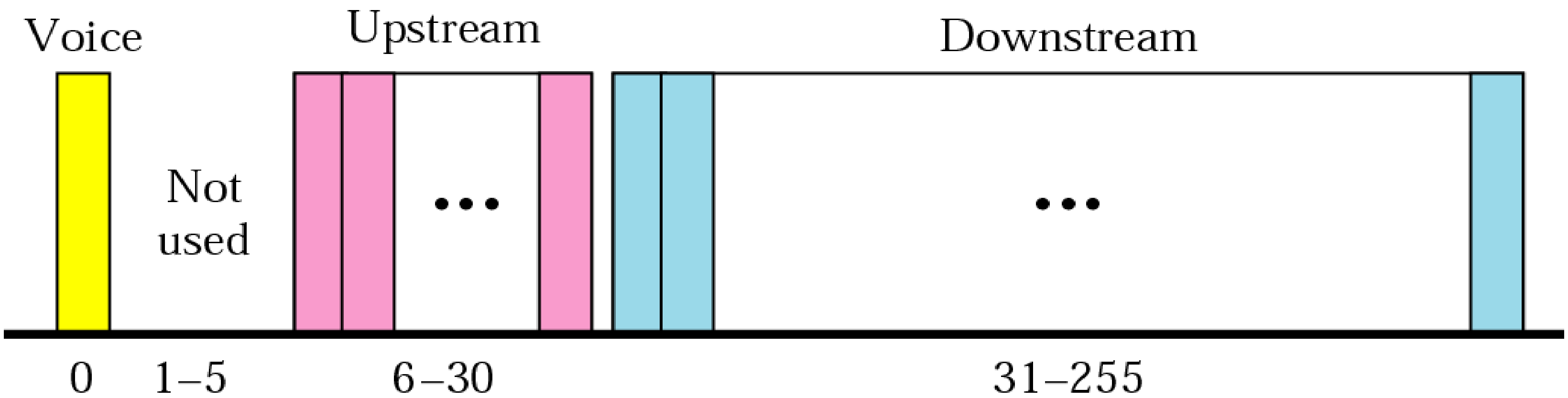
E Line Rates

E Line	Rate (Mbps)	Voice Channels
E-1	2.048	30
E-2	8.448	120
E-3	34.368	480
E-4	139.264	1920

Example: Digital Subscriber Link (DSL)

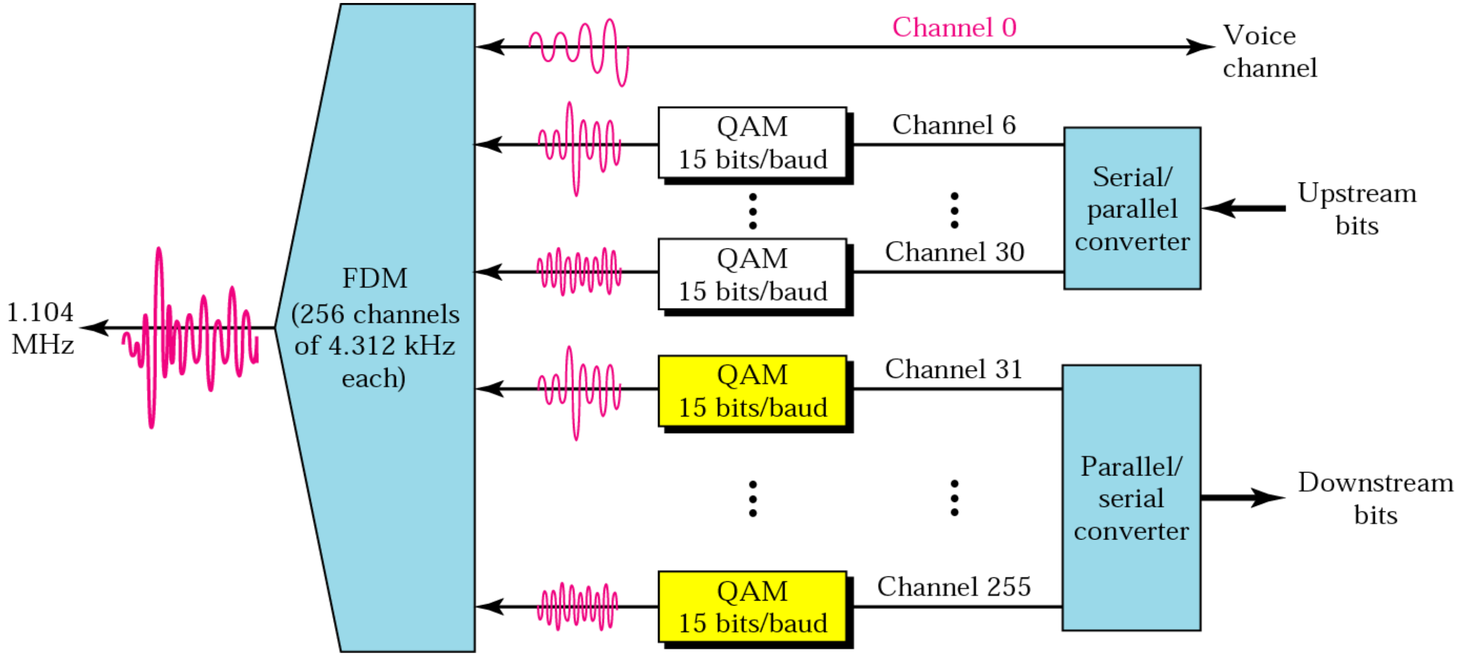
- High-speed Digital Access to Internet
- Exploit the actual bandwidth available in twisted pair cables in subscriber access lines (local loop)
  - Up to 1.1 MHz
  - Subject to strict physical limitations
    - Cable distance
    - Size of cable
    - Signaling

Asymmetrical DSL (ADSL)



- Bandwidth (typically) divided into 4 kHz channels
  - Adaptive: bandwidth and data rate depends on conditions
- Lower rate in upstream direction (from subscriber)
  - For residential access
  - Upstream 64 kb/s to 1 Mb/s, Downstream 500 kb/s to 8 Mb/s

Discrete Multitone Technique (DMT)



- Combination of QAM and FDM
- 4 kHz channels and 15 bits/baud $\Rightarrow$ 60 kb/s channels

Summary

- Transmission media
  - Link budget
  - Capacity limitations
- Transmission of digital information
  - Line coding
  - Digital modulation
- Transmission of analog information
  - Conversion to digital signals
  - Sampling
- Synchronization
- Multiplexing
- Examples
  - PCM
  - ADSL