CS40001: Computer Networks

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General Information

- Textbooks:
  - *Data & Computer Communications* by William Stallings
  - *Internetworking with TCP/IP Volume 1* by Douglas Comer

Other than textbooks, materials from other books and sources will also be given by me sometimes

- Course website:

  http://www.facweb.iitkgp.ernet.in/~agupta/networks

What is a Network?

- A collection of machines/devices that communicate with each other over some communication medium
- Two machines may be directly connected, or can communicate through other machines
- Some machines are sources and destinations of data
- Some devices do not generate data, but facilitate in the transfer (ex. a router)

Protocols

- Rules for communications between two communicating entities
- Entities can be
  - Applications – e-mail, telnet, ftp, web browser…
  - Systems – terminals, computers…
- Must speak the same language to understand each other
- Specifies syntax, semantics, and timing of communication

Overall Organization of the Course

1. How do two directly connected machines communicate reliably?
2. How can a link be shared between more than two machines?
3. Building networks
    1. LAN and interconnecting LANs – communication over small geographical area
    2. WANs –reliable communication over wide geographical area, when no direct link exists between all machines
4. Other miscellaneous topics (to be decided based on time available)

Part 1

- Reliable communication between two devices directly connected by a link
  - Transmission Basics
  - Types of transmission media
  - Encoding techniques
  - Error detection techniques
  - Error control
  - Flow control

Part 2

- Communication between more than two devices sharing a common direct link
  - Multiplexing techniques
  - Techniques for resolving contention for media – Medium Access Control (MAC)

Part 3

- Building Networks
  - Protocol Architecture – Layering
    - OSI and TCP/IP protocol architectures
  - Local Area Networks (LAN)
    - Basic concepts
    - Ethernet
    - Interconnecting LANs
    - Introduction to wireless LANs

Part 3 (contd.)

- Wide Area Networks
  - Switching techniques to communicate between machines that are not directly connected
  - Routing
  - Congestion control
  - Reliable communication between end applications
  - Case study of TCP/IP

Part 1

Reliable communication between two devices directly connected by a link

Transmission Basics

Assuming that you know…

- Analog / digital signals
- Periodic / aperiodic signals
- Amplitude, frequency, phase of a signal
- Time domain and frequency domain representations of signals
- Spectrum and bandwidth of a signal
- DC component of a signal

Signal Transmission Basics

- Transmitter – sender of signal
- Receiver – receiver of signal
- Transmission happens through some medium – physical path between transmitter and receiver

Transmission Types

- Simplex – only in 1 direction
- Half-Duplex – both directions, but only 1 at a time
- Full Duplex – both directions, simultaneous

Data and Signal

- Data
  - Entities that has some meaning (carry “information”)
  - We consider only digital data, i.e., the entities consist of sequence of 0’s and 1’s
  - For ex., 01 may mean the number ‘1’, or the letter ‘a’, or anything else depending on the application
- Signals
  - Electric or electromagnetic representations of data
  - Different signals can be used to represent the same data
  - Signal can be digital or analog (ex., modem)

- Encoding
  - representing data with signals
- Transmission
  - Communication of data by propagation and processing of signals

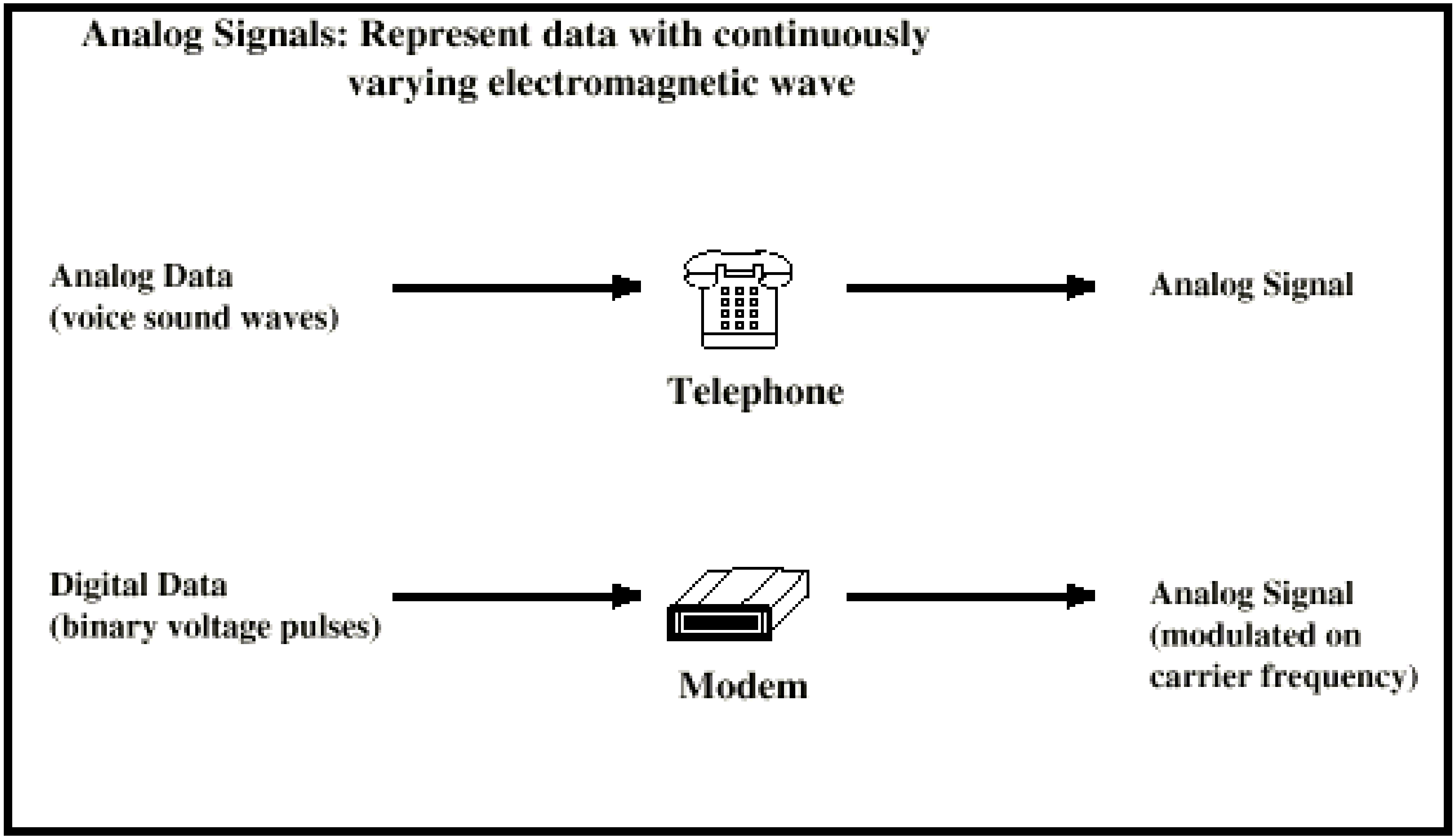
Thus, we will deal with

Analog signals carrying digital data

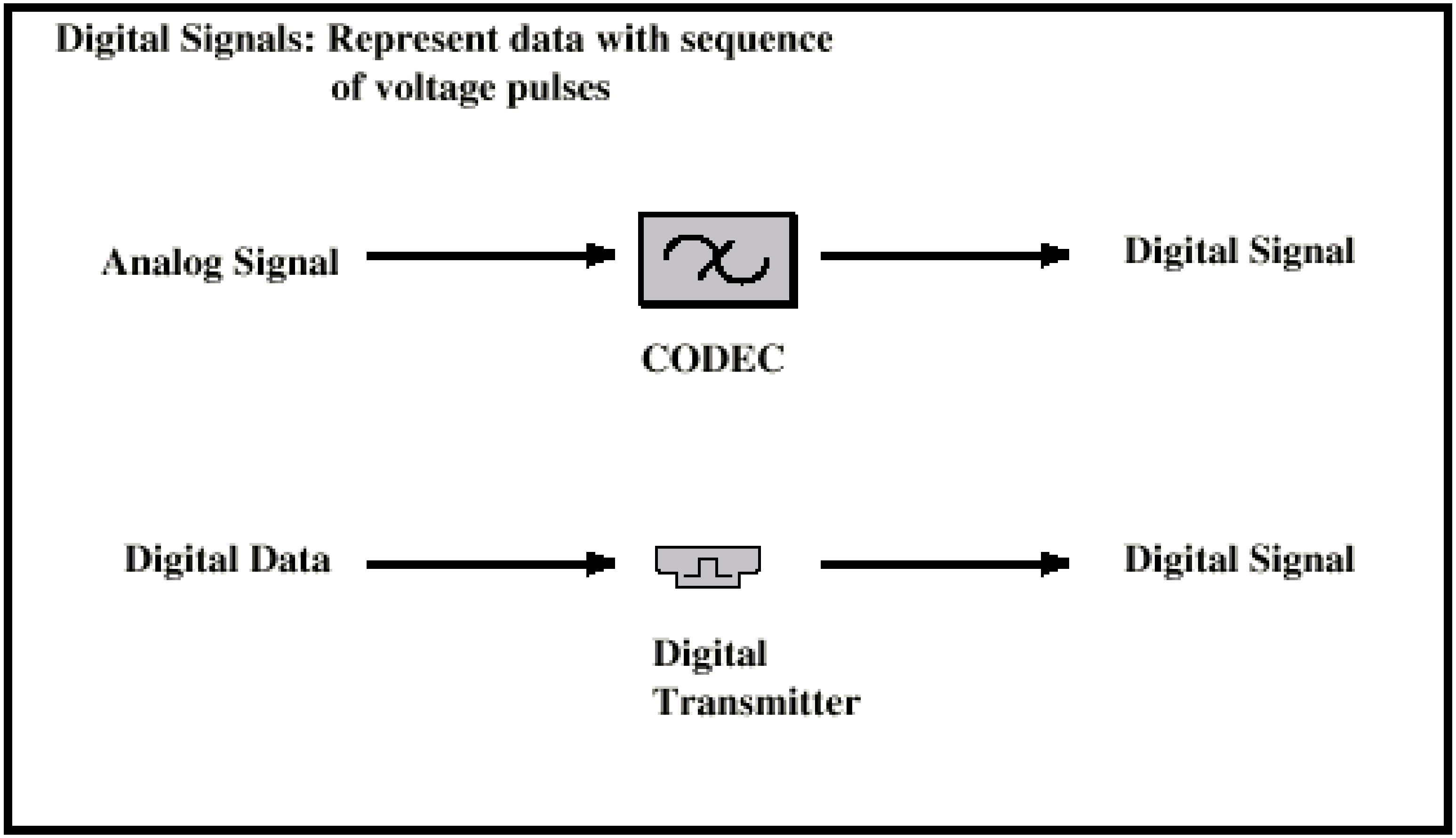
and

Digital signals carrying digital data

Analog Signals Carrying Analog and Digital Data



Digital Signals Carrying Analog and Digital Data



Analog Transmission

- Analog signal transmitted
- May be carrying analog or digital data
- Signal attenuated over distance
- Use amplifiers to boost signal
- Also amplifies noise

Digital Transmission

- Digital bit pattern transmitted
- Integrity of a bit depends on noise, attenuation etc.
- Repeaters used
- Repeater receives signal
- Extracts bit pattern
- Retransmits bit pattern
- Attenuation is overcome
- ***Noise is not amplified***

Advantages of Digital Transmission

- Longer distances possible over lower quality lines
- Lower cost
- High degree of multiplexing easier with digital techniques
- Security & Privacy - Encryption

Impairments/Corruption

- Impairments or corruptions exist in all forms of data transmission
- Analog signal impairments result in random modifications that impair signal quality
- Digital signal impairments result in bit errors (1s and 0s transposed)

Transmission Impairments

- Signal received may differ from signal transmitted
- Analog - degradation of signal quality
- Digital - bit errors
- Primary causes
  - Attenuation and attenuation distortion
  - Delay distortion
  - Noise

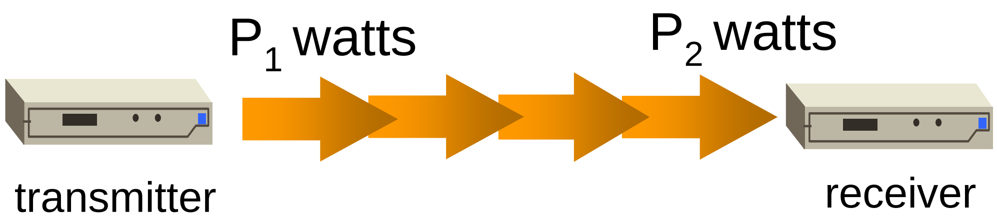
Transmission Impairments

- Attenuation
  - loss of signal strength over distance
- Attenuation Distortion
  - different losses at different frequencies
- Delay Distortion
  - different speeds for different frequencies
- Noise

Attenuation

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

Attenuation



Attenuation $10 \log_{10} (P_1/P_2)$ dB

Delay Distortion

- Only in guided media
- Propagation velocity varies with frequency
- Different frequency components of a signal can arrive at different time

Noise

- Additional signals inserted between transmitter and receiver
- Types of Noise
  - Thermal
    - Due to thermal excitement of electrons
    - Uniformly distributed, cannot be eliminated
    - White noise
  - Intermodulation
    - Signals that are the sum and difference of original frequencies sharing a medium

Noise (contd.)

- Crosstalk
  - A signal from one line is picked up by another
- Impulse
  - Irregular pulses or spikes
  - Short duration
  - High amplitude
  - Less predictable
  - Ex. external electromagnetic interferences such as from lightning etc.

Measure of Noise

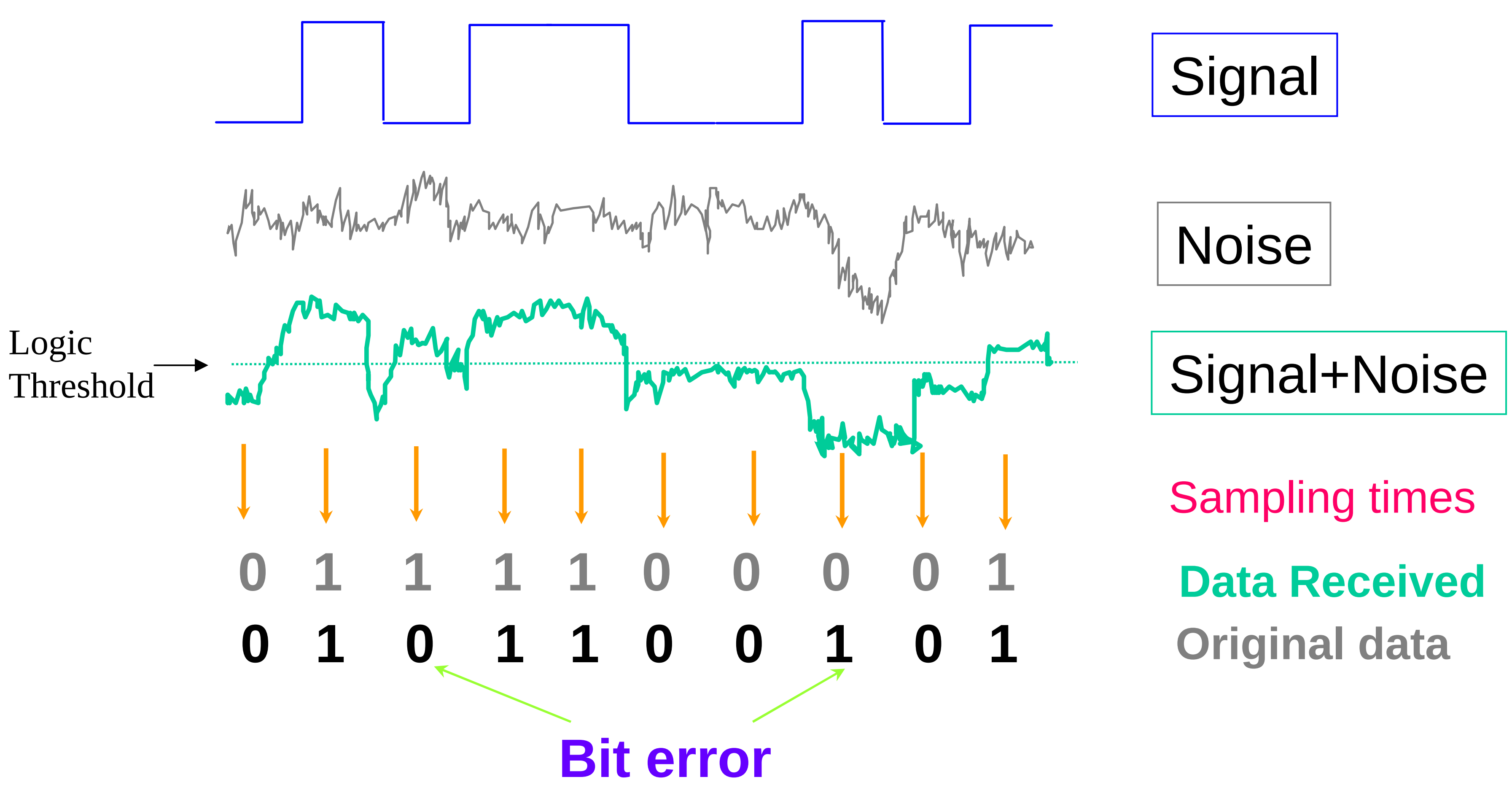
signal-to-noise ratio to quantify noise

$$\text{SNR (in dB)} = 10 \log \frac{S}{N} \quad \text{decibels}$$

S = average signal power

N= noise power

Effect of Noise



Channel Capacity

- Data rate
  - In bits per second
  - Rate at which data can be communicated
- Bandwidth
  - In cycles per second or Hertz (Hz)
  - Constrained by transmitter and medium

Data Rate and Baud Rate

- Data rate – measured in bps (bits per second)
- Baud rate – no. of signal components per second

("Baud" itself means symbols/unit time, so it is already a rate, so "baud rate" is a misnomer, but used informally)

- *Each signal component can represent more than one bit, so data rate can be greater than baud rate*

Nyquist theorem

*“ In a perfectly noiseless channel, if f is the maximum frequency the medium can transmit, the receiver can completely reconstruct a signal by sampling it 2*f times per second”*

Nyquist, 1920

Nyquist Formula for Maximum Data Rate (Capacity) of a Channel

$$C = 2B \log_2 M \text{ bits/sec}$$

B = bandwidth
M = number of discrete signal levels

Theoretical capacity for Noiseless channel

Example: Channel capacity calculation for voice bandwidth (~3100 Hz):

M	Max data rate (C)
2	6200 bps
4	12400 bps
8	18600 bps
16	24800 bps

Shannon's Law

- In the '40s Shannon extended the equation to a channel subject to thermodynamic (thermal) noise

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

S/N = Signal-to-noise ratio (just ratio of powers, not in dB)

C = Theoretical maximum capacity with noise

Transmission Medium

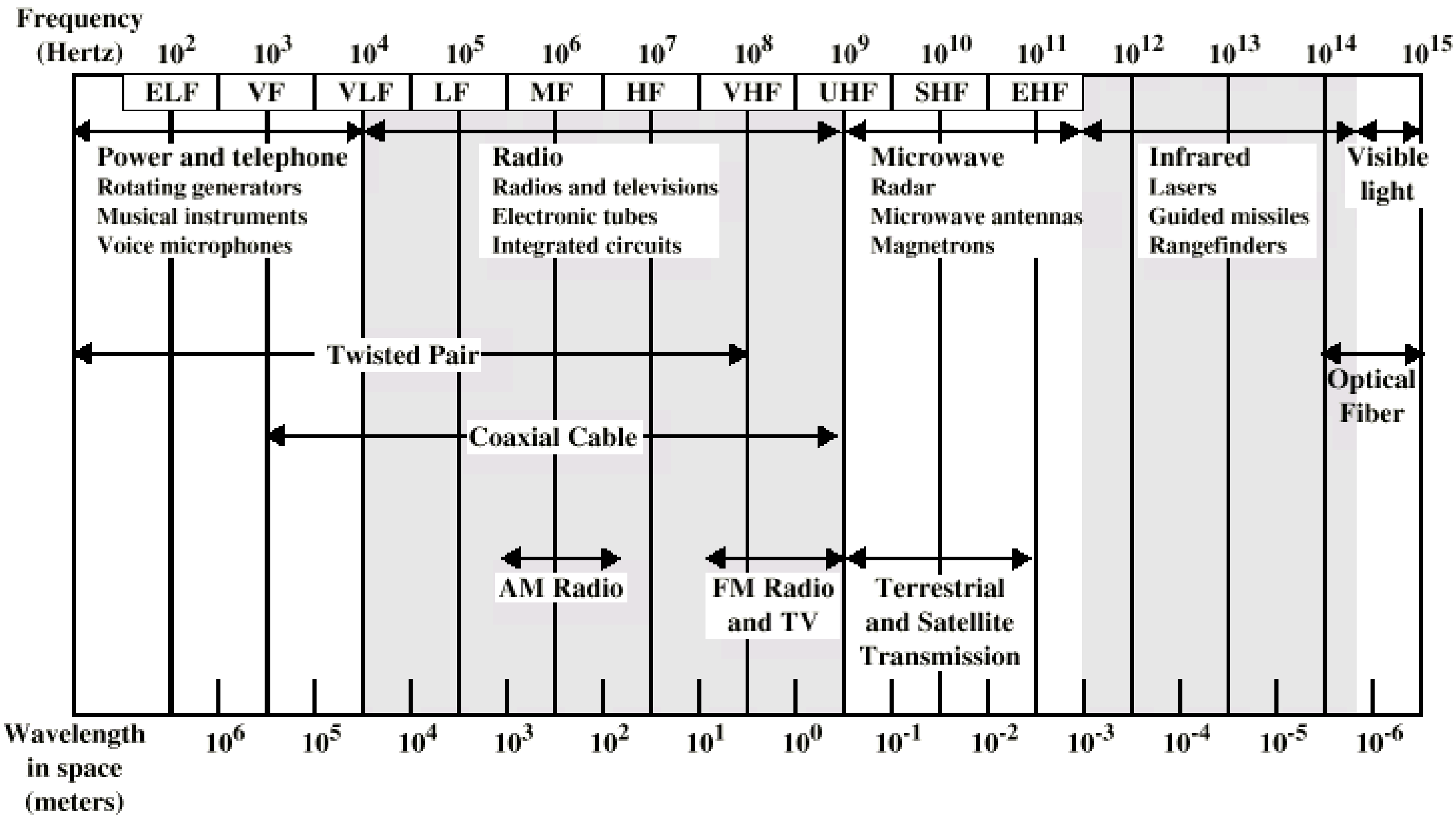
Transmission Medium

- Guided
  - Twisted pair, coaxial etc. (conducting metal)
  - Fibre optic (glass or plastic)
- Unguided
  - Microwave, satellite (wireless)
- Bandwidth, attenuation depends on medium
- Key concerns are data rate and distance

Design Factors

- Bandwidth
  - Higher bandwidth gives higher data rate
- Transmission impairments
  - Attenuation (measured in dB/Km)
- Interference

Electromagnetic Spectrum



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

Guided Transmission Media

- Transmission capacity depends on the distance and on whether the medium is point-to-point or multipoint
- Examples
  - Twisted Pair
  - Coaxial cable (hardly used now)
  - Optical fiber

Twisted Pair

- consists of two insulated copper wires arranged in a regular spiral pattern to minimize the electromagnetic interference between adjacent pairs
- low frequency transmission medium

—Separately insulated
—Twisted together
—Often "bundled" into cables
—Usually installed in building during construction

(a) Twisted pair

Twisted Pair - Applications

- Telephone network
  - Between house and local exchange (subscriber loop)
- For local area networks (LAN)
  - 10Mbps or 100Mbps

Twisted Pair - Pros and Cons

- Pros
  - Cheap
  - lightweight
  - Easy to work with
- Con
  - Relatively low bandwidth/data rate
  - Shorter range
  - susceptibility to interference and noise
  - attenuation problem

Unshielded and Shielded TP

- Unshielded Twisted Pair (UTP)
  – Ordinary telephone wire
  – Cheapest
  – Easiest to install
  – Suffers from external electromagnetic interference (EM)
- Shielded Twisted Pair (STP)
  – the pair is wrapped with metallic foil or braid to insulate the pair from electromagnetic interference
  – More expensive
  – Harder to handle (thick, heavy)

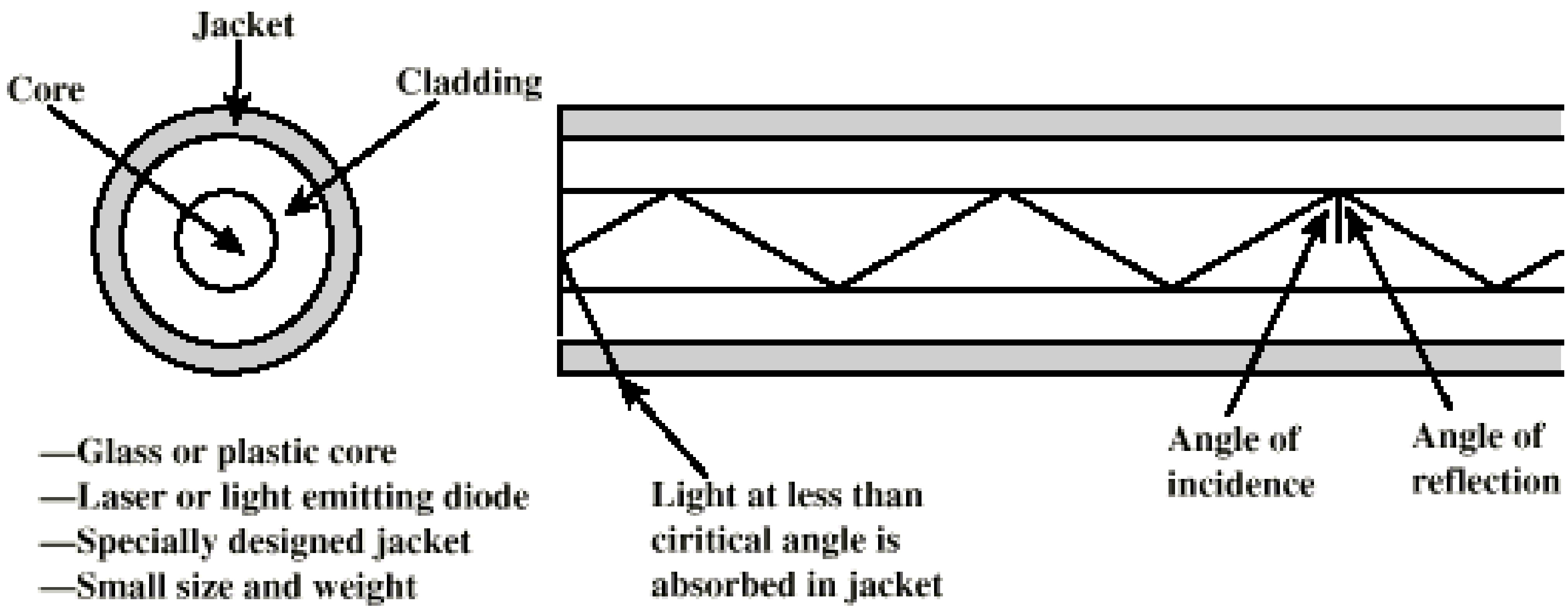
Important UTP Categories

- Cat 3
  - up to 16MHz
  - Voice grade found in many offices
  - Twist length of 7.5 cm to 10 cm
- Cat 5
  - up to 100MHz
  - Twist length 0.6 cm to 0.85 cm
  - Smaller twist length gives less crosstalk interference
- Cat 5e, Cat 6 (more common nowadays)

Optical Fiber

- Thin (2-125 micrometer), flexible medium capable of conducting an optical ray
  - Made of ultrapure fused silica, glass fiber or plastic
- Cylindrical shape with three concentric sections: the ***core***, the ***cladding***, and the ***jacket***
  - Core consists of one or more very thin strands, or fibers, made of glass or plastic
  - Cladding is a glass or plastic coating that has optical properties different from that of the core
  - Jacket surrounds one or a bundle of cladded fibers

Optical Fiber



—Glass or plastic core
—Laser or light emitting diode
—Specially designed jacket
—Small size and weight

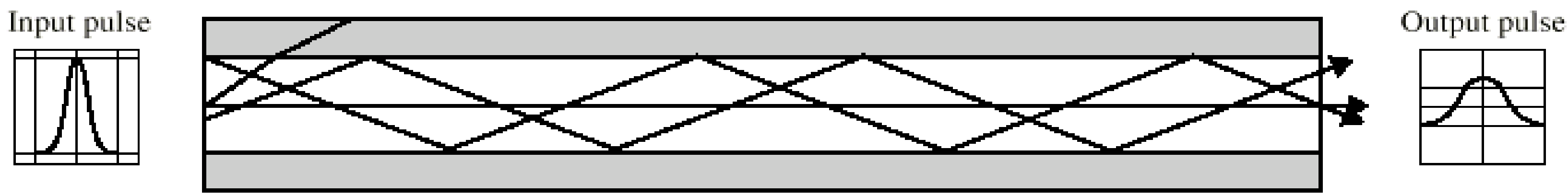
Optical Fiber - Benefits

- Greater capacity
  - Data rates of hundreds of Gbps
- Smaller size & weight
- Lower attenuation
- Electromagnetic isolation
- Greater repeater spacing
  - 10s of km at least
- Highly secure due to tap difficulty and lack of signal radiation
- Becoming omnipresent for most long distance communication needs, including telephone

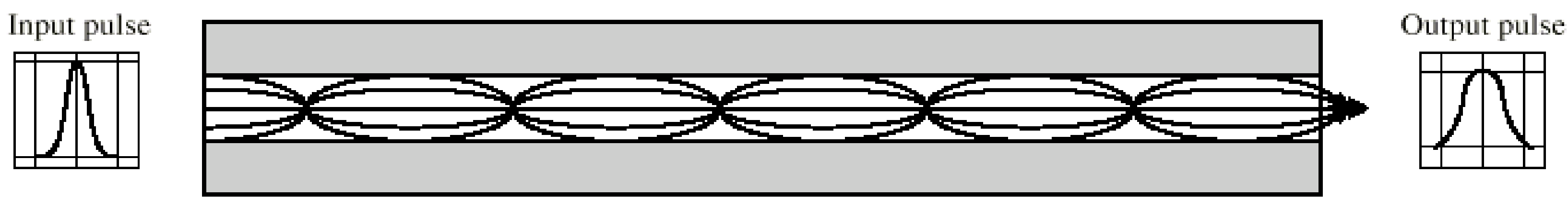
Optical Fiber Types

- Single mode fiber
  - the light is guided down the center of an extremely narrow core (only one angle of reflection)
- Multimode fiber
  - Multiple angles of reflection, hence multiple paths
  - Signal elements diffuse over time, causing interference, hence reduced data rate
- Multimode graded-index fiber
  - acts to refract the light toward the center of the fiber by variations in the density

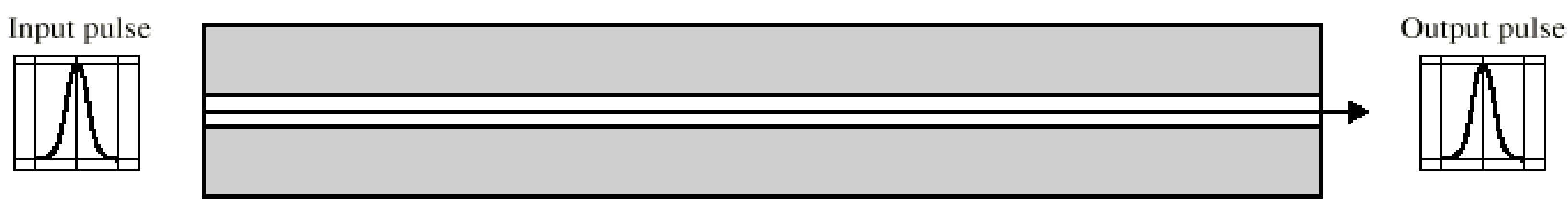
Optical Fiber Types (contd.)



(a) Step-index multimode



(b) Graded-index multimode



(c) Single mode

Wireless Transmission

- Unguided media
- Transmission and reception via antenna
- Two techniques are used:
  - Directional Antenna
    - Focused beam, longer range
    - Careful alignment required
  - Omnidirectional Antenna
    - Signal spreads in all directions
    - Can be received by many antennas

Frequencies

- 1GHz to 40GHz
  - Microwave
  - Highly directional
  - Point to point
  - Terrestrial microwave, Satellite, wireless LANs (2.4 – 5 GHz)
- 30MHz to 1GHz
  - Omnidirectional
  - Broadcast radio
- 3×10^{11} to 2×10^{14}
  - Infrared

Wireless Examples

- Terrestrial microwave transmission
- Satellite transmission
- Broadcast radio
- Wireless LANs

Encoding Techniques

Data Encoding Techniques

- Data is transmitted by propagation and processing of signals
- Encoding – specifying how data is represented by signals
  - Digital data over digital signal
  - Digital data over analog signal

Encoding Digital Data with Digital Signals

- Digital signal
  - Uses discrete, discontinuous, voltage pulses
  - Each pulse is a signal element
  - Binary data is encoded into signal elements
- Data
  - Bit string of 0's and 1's
  - Each bit is present for a duration T (*bit interval*)
  - Data rate = 1 / T bps

Some Terminology

- Unipolar
  - All signal elements have same sign
- Polar
  - Two logic states represented by +ve/-ve voltage
- Duration or length of a bit
  - Time taken for transmitter to emit the bit
- Modulation rate
  - Rate at which the signal level changes
- Mark and Space
  - Binary 1 and Binary 0 respectively

Issues in Encoding

- Signal Spectrum
  - Lack of high frequencies reduces required bandwidth
  - Lack of dc component allows ac coupling via transformer, providing isolation
- Clocking issues
  - Synchronizing transmitter and receiver is essential
  - External clock is one way used for synchronization
  - Synchronizing mechanism based on signal is also used & preferred (over using an external clock)

- Error detection
  - Can be built into signal encoding
- Signal interference and noise immunity
  - Some codes are better than others
- Cost and complexity
  - Higher signal rate (& thus data rate) lead to higher costs
  - Some codes require signal rate greater than data rate

Some Encoding Schemes

- Nonreturn to Zero-Level (NRZ-L)
- Nonreturn to Zero Inverted (NRZI)
- Bipolar-AMI (Alternate Mark Inversion)
- Pseudoternary
- Manchester
- Differential Manchester

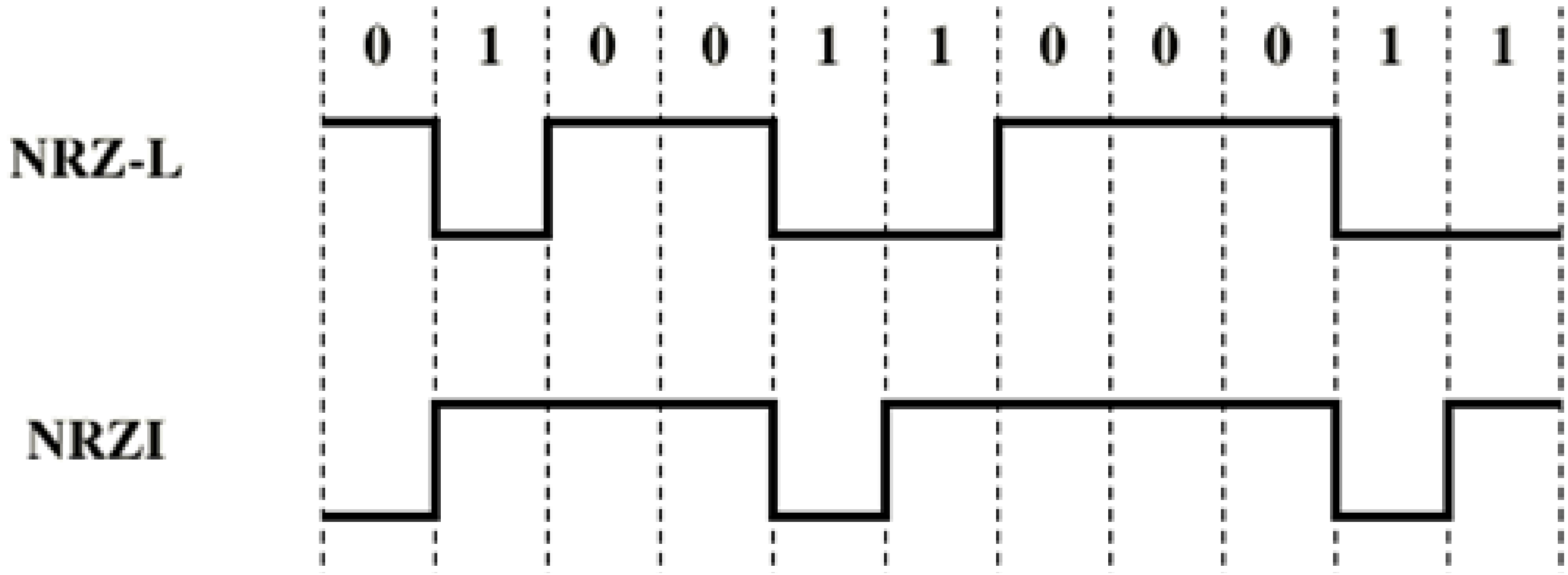
Nonreturn to Zero-Level (NRZ-L)

- Two different voltages for 0 and 1 bits
- Voltage held constant during bit interval
- Example:
  - 0 = High
  - 1 = Low

Nonreturn to Zero Inverted

- *Nonreturn to zero inverted on ones*
- Voltage held constant during bit interval
- Data encoded as presence or absence of signal transition at beginning of bit time
- Transition (low to high or high to low) denotes a binary 1
- No transition denotes binary 0
- An example of differential encoding (Data represented by changes rather than levels)

NRZ



NRZ pros and cons

- Pros
  - Easy to engineer
  - Makes good use of bandwidth
- Cons
  - DC component
  - Lack of synchronization capability
- Used for magnetic recording
- Not really used for signal transmission

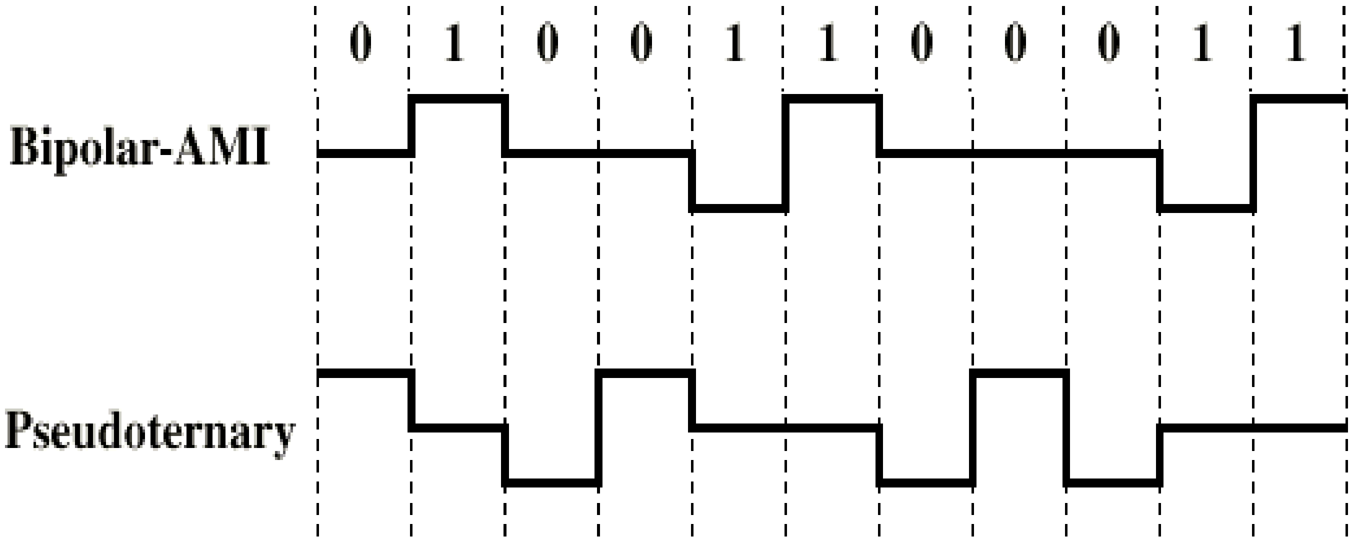
Multilevel Binary

- Use more than two levels
- Bipolar-AMI
  - Bit 0 represented by no line signal
  - Bit 1 represented by positive or negative pulse
  - Pulses for bit 1 alternate in polarity
  - No loss of sync if a long string of 1's happens (long string of 0's still a problem)
  - No net dc component
  - Lower bandwidth
  - Some error detection builtin

Pseudoternary

- Opposite of Bipolar-AMI
- Bit 1 represented by absence of line signal
- Bit 0 represented by alternating positive and negative
- No advantage or disadvantage over bipolar-AMI

Bipolar-AMI and Pseudoternary



Tradeoff for Multilevel Binary

- Not as efficient as NRZ
  - With multi-level binary coding, the line signal may take on one of 3 levels, but each signal element, which could represent $\log_2 3 = 1.58$ bits of information, bears only one bit of information
  - Receiver must distinguish between three levels (+A, -A, 0)
  - Requires approx. 3dB more signal power for same probability of bit error

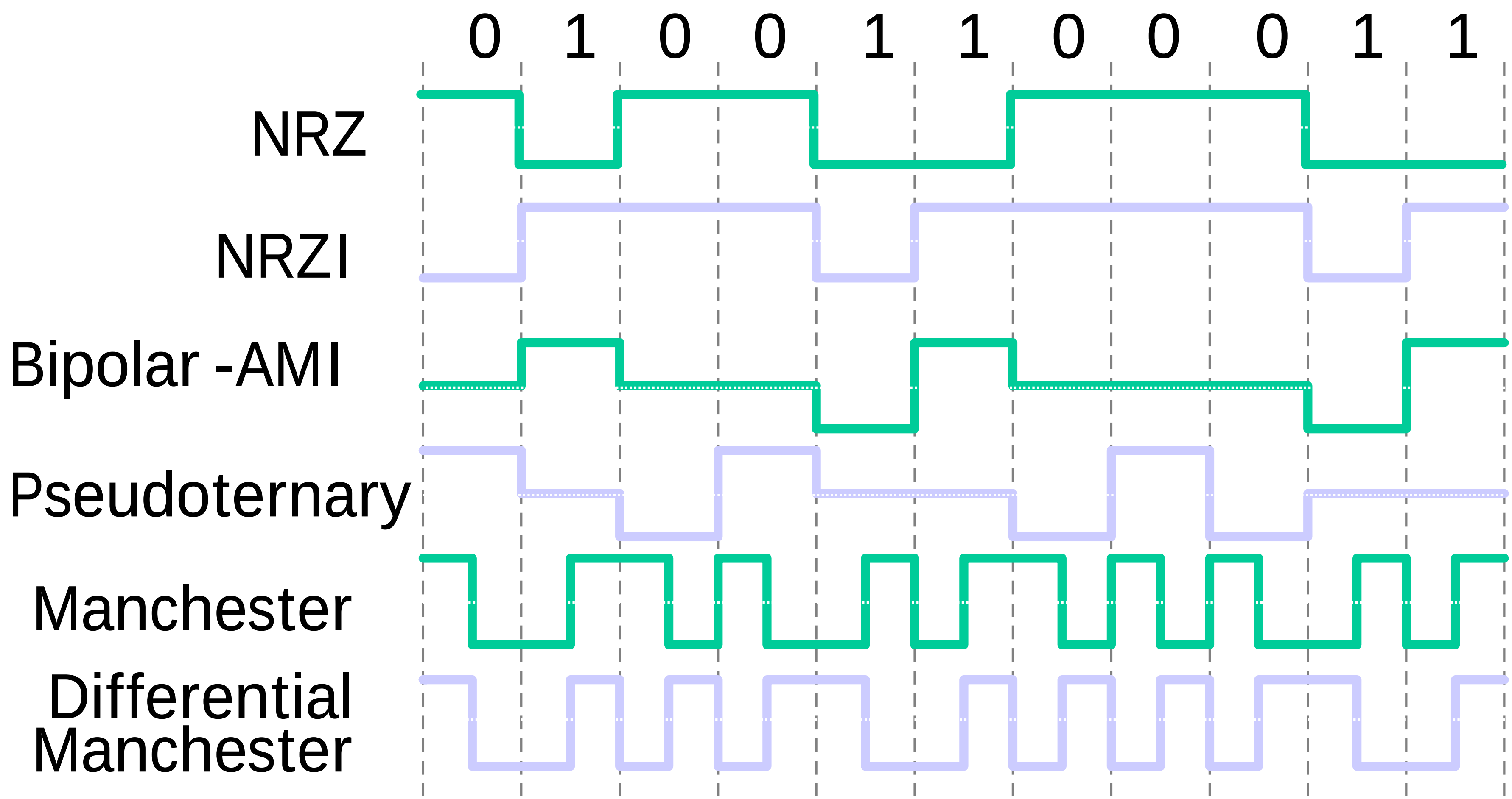
Biphase

- Manchester
  - Transition in middle of each bit period
  - Transition serves as clock and data
  - Low to high represents 1
  - High to low represents 0
  - Used by IEEE 802.3 (Ethernet)
- Differential Manchester
  - Midbit transition is for clocking only (always there_
  - Transition at start of a bit period represents 0
  - No transition at start of a bit period represents 1
  - Differential encoding scheme
  - Used by IEEE 802.5 (Token Ring)

Biphase Pros and Cons

- Con
  - At least one transition per bit time and possibly two
  - Maximum modulation rate is twice NRZ
  - Requires more bandwidth
- Pros
  - Synchronization on mid bit transition (self clocking)
  - No dc component
  - Error detection
    - Absence of expected transition points to error in transmission

Digital data, Digital signal



Modulation Rate

- Modulation rate/Signaling rate of an encoding scheme = rate of signal transitions in the channel
- Higher the modulation rate, higher is the bandwidth required
- Depends on the actual data stream
  - Should see the maximum modulation rate possible for some data stream
- Another way to characterize : No. of signal transitions per data bit (average/maximum)

No. of Signal Transitions Per Data Bit

	Minimum	**101010…**	**Maximum**
NRZ-L	0	1.0	1.0
NRZI	0	0.5	1.0
Binary-AMI	0	1.0	1.0
Pseudoternary	0	1.0	1.0
Manchester	1.0	1.0	2.0
Differential Manchester	1.0	1.5	2.0

8B/10B Encoding

- Similar idea as in 4B/5B, 5B/6B encoding earlier
- Data split into 8-bit Octets
- Each octet is replaced with a predefined 10-bit code
- Each 10-bit code has one of the following
  - 5 0’s and 5 1’s
  - 6 0’s and 4 1’s
  - 4 0’s and 6 1’s
- Ensures that in the final encoded string, not more than 5 0’s or 5 1’s can occur simultaneously
  - Ensures enough transitions for clock synchronizations

- Also ensures DC-balance
  - In a string of at least 20 bits, difference in count of 0's and 1's is at most 2
  - This requires introducing *running disparity* bits (we will not cover)
- Requires less b/w, can go over longer distances
- Reduces data rate (as more no. of bits transmitted)
- Used in many protocols, Ex: Gigabit Ethernet

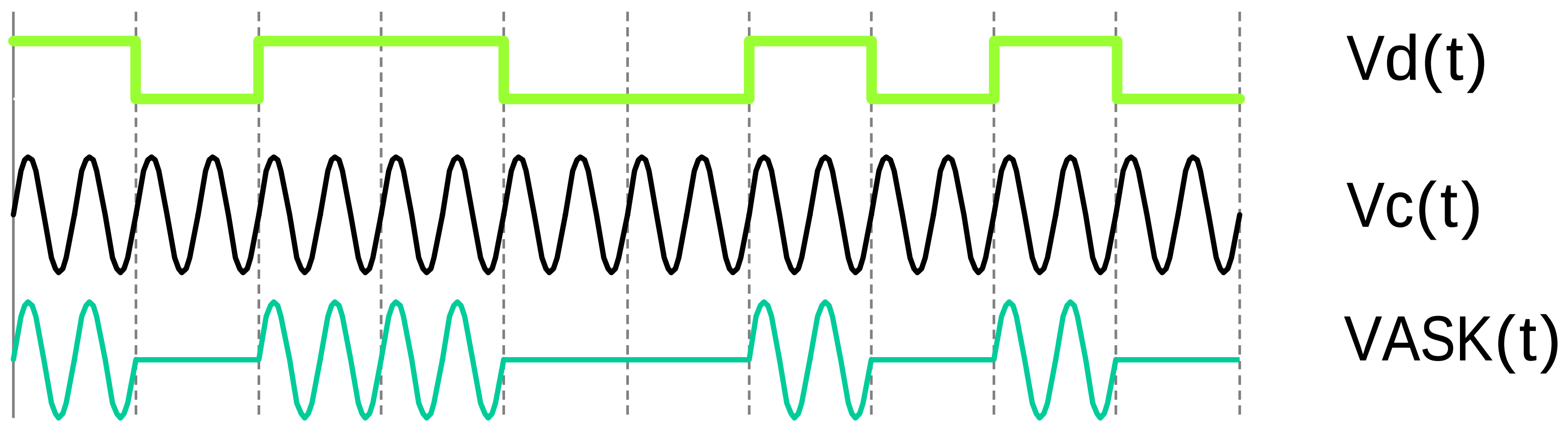
Encoding Digital Data with Analog Signals

- Transmitting digital data through PSTN (Public telephone system)
  - 300Hz to 3400Hz bandwidth
  - modem (modulator-demodulator) is used to convert digital data to analog signal and vice versa
- Three basic modulation techniques are used:
  - Amplitude shift keying (ASK)
  - Frequency shift keying (FSK)
  - Phase shift keying (PSK)

Amplitude Shift Keying

- Values represented by different amplitudes of a carrier signal
- Usually, one amplitude is zero
  - i.e. presence and absence of carrier is used
- Susceptible to noise
- Used over optical fiber (but usually with some digital encoding before ASK)

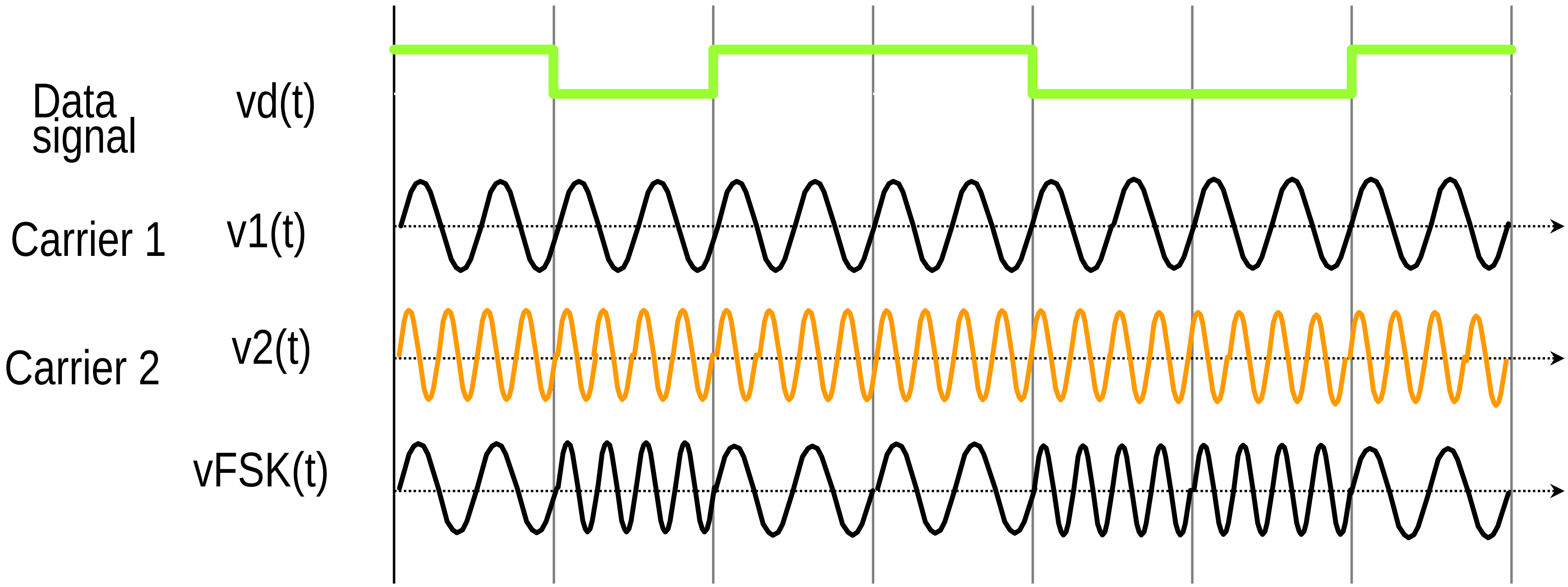
ASK



Frequency Shift Keying

- Values represented by different frequencies (near carrier)
- Less susceptible to noise than ASK
- Up to 1200bps on voice grade lines, high frequency radio (3-30 MHz)
- Constrained by bandwidth of channel

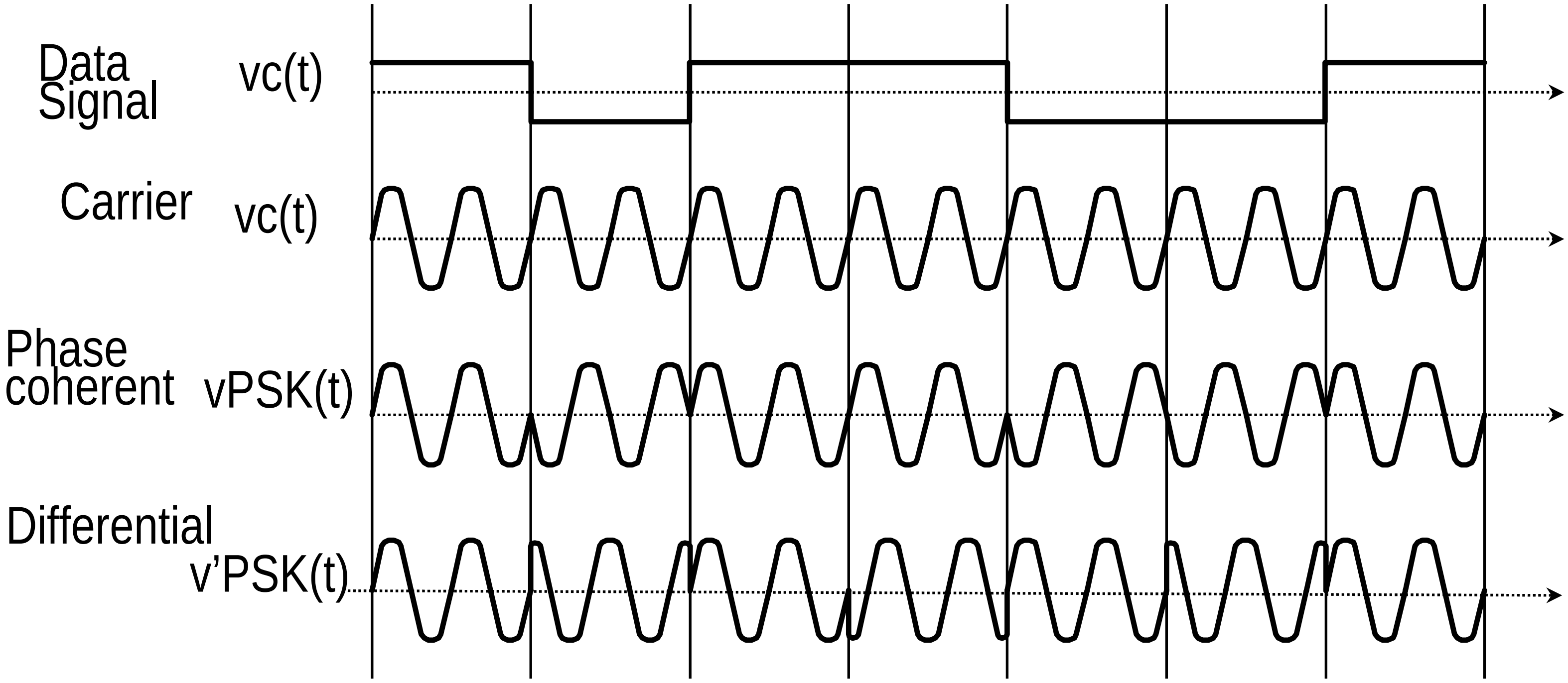
FSK



Phase Shift Keying

- Phase of carrier signal is shifted to represent data
- Differential PSK
  - Phase shifted relative to previous transmission rather than some reference signal

PSK and DPSK

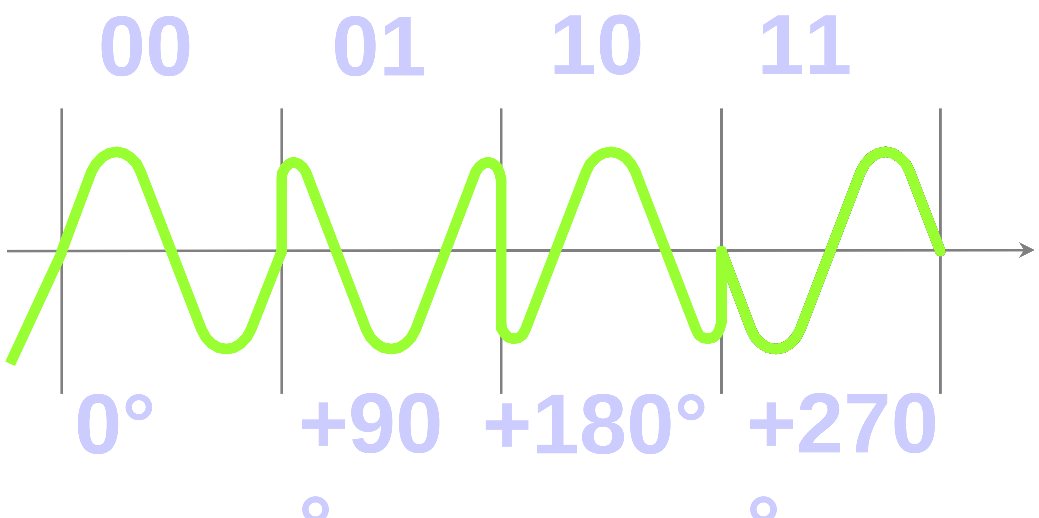


Differential example: for every logic 1, 180 degree phase shift

Quadrature PSK

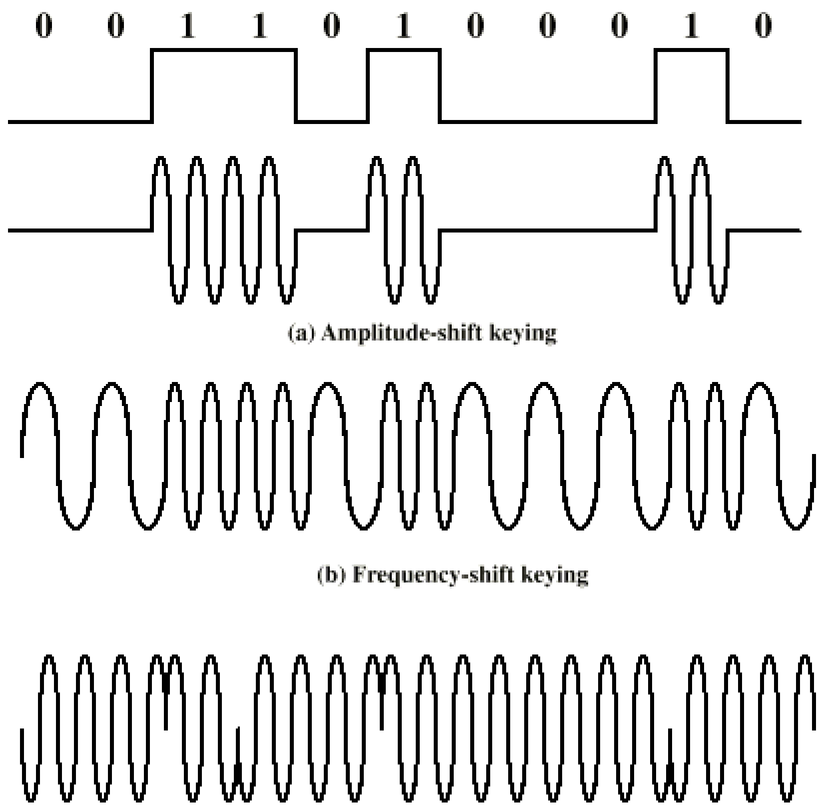
- More efficient use by each signal element representing more than one bit
  - e.g. shifts of $\pi/2$ (90^o)
  - Each element represents two bits
  - Bit rate = 2 x baud rate
  - High-speed modems use different combination of phase and amplitude (*Quadrature Amplitude Modulation or QAM*)

Multilevel modulation method



- bit rate = n x signaling rate

Modulation Techniques



(a) Amplitude-shift keying

(b) Frequency-shift keying

(c) Phase-shift keying

Error Detection

Error Detection & Correction

- Error – bit pattern sent and bit pattern received are different. Possible causes
  - Framing errors
  - Noise…
- Error detection – detects error but may or may not correct
- Error correction – detects and corrects errors
  - Usually requires larger number of extra bits with data bits, not usually done in networks, we will skip

Error Detection Techniques

- Basic Principle
  - Transmitter: For a given bit stream M, additional bits (called error-detecting code) are calculated as a function of M and appended to the end of M
  - Receiver: On receiving the bit stream, performs the same calculation and compares the two results. A detected error occurs if there is a mismatch

Common Methods

- Parity check
  - One extra “parity” bit is added to each word
    - Odd parity: bit added so as to make # of 1’s odd
    - Even parity: makes total # of 1’s even
  - Detects any odd number of bit errors (error in 1bit, 3 bits, 5 bits …), but can be fooled by any even number of errors
  - Simple and easy to implement
  - Not very robust against noise

- Cyclic Redundancy Check (CRC)
  - Powerful error detection method, easily implemented
  - Message (M) to be transmitted is appended with extra frame checksum bits (F), so that bit pattern transmitted (T) is perfectly divisible by a special “generator” pattern (P) - (divisor)
  - At destination, divide received message by the same P. If remainder is nonzero $\Rightarrow$ error

Cyclic Redundancy Checks

- Let
  - T = (k+n)-bit frame to be transmitted, n<k
  - M = k-bit message, the first k bits of T
  - F = n-bit FCS, the last n bits of T
  - P = n+1 bits, generator pattern (predetermined divisor)
- The concept uses modulo-2 arithmetic
  - no carries/borrows; add ≡ subtract ≡ XOR

Cyclic Redundancy Checks

- Method
  - Extend M with n '0's to the right ($\equiv 2^n M$)(shift left by n bits
  - Divide extended message by P to get R ($2^n M / P = Q + R/P$)
  - Add R to extended message to form T ($T = 2^n M + R$)
  - Transmit T
  - At receiver, divide T by P. Nonzero remainder means: $\Rightarrow$ error

Note: Remainder R=F=FCS in these examples

$$\frac{T}{P} = \frac{2^n M + R}{P} = Q + \frac{R}{P} + \frac{R}{P} = Q + \frac{R+R}{P} = Q$$

Note: R+R=0 in mod-2 arithmetic

$$0 \oplus 0 = 0$$

$$1 \oplus 1 = 0$$

Cyclic Redundancy Checks Examples

- M = 110011, P = 11001, R = 4 bits
- 1. Append 4 zeros to M, we get 1100110000

– 2.

```
                 100001
       _____________________
11001 ) 1100110000
       ⊕11001
        -----
         00001
        ⊕00000
         -----
          00010
         ⊕00000
          -----
           00100
          ⊕00000
           -----
            01000
           ⊕00000
            -----
             10000
            ⊕11001
             -----
              1001
```

– 3. ∴ T = 110011$\boxed{1001}$

-For each stage of division, if the number of dividend bits equals number of divisor P bits, then Q=1, otherwise Q=0

Cyclic Redundancy Checks

- Can view CRC generation in terms of polynomial arithmetic
- Any bit pattern $\equiv$ polynomial in dummy variable X with the bits as coefficients as shown in the following example:
  - e.g., $M = 110011 \equiv 1 \cdot X^5 + 1 \cdot X^4 + 0 \cdot X^3 + 0 \cdot X^2 + 1 \cdot X + 1 \cdot X^0 \therefore M(X) = X^5 + X^4 + X + 1$

Cyclic Redundancy Checks

- CRC generation in terms of polynomial
  - Append n '0's $\equiv X^n M(X)$
  - Modulo 2 division $\rightarrow$
  - Transmit $X^n M(X)+R(X)$ = $\frac{X^n M(X)}{P(X)} = Q(X) + \frac{R(X)}{P(X)}$
  - At receiver:

$$\frac{X^n M(X)+R(X)}{P(X)} = \frac{X^n M(X)}{P(X)} + \frac{R(X)}{P(X)}$$

$$= Q(X) + \boxed{\frac{R(X)+R(X)}{P(X)}}$$

If no error 0 always

Cyclic Redundancy Checks

- Commonly used polynomials, P(X)
  - CRC-16 = $X^{16} + X^{15} + X^2 + 1$
  - CRC-CCITT = $X^{16} + X^{12} + X^5 + 1$
  - CRC-32 = $X^{32} + X^{26} + X^{23} + X^{22} + X^{16} + X^{12} + X^{11} + X^{10} + X^8 + X^7 + X^{12} + X^4 + X^2 + X + 1$

Can detect

- All single-bit errors
- All double-bit errors, as long as P(X) has a factor with at least three terms (as long as p has at least three 1s)
- Any odd number of errors, as long as P(X) contains a factor (X+1)
- Any burst error for which the length of the burst is less than or equal to the length of the FCS
- Many other larger burst errors

Error Control

Error Control

- Ensures finally received bit pattern is same as sent bit pattern, though may require more than one transmission
- Two types
  - Forward error control:
    - Error recovery by correction at the receiver [Forward Error Correction (FEC)]
    - Requires extra bits to be added to data bits (Ex. Hamming code)
    - No. of bits needed large for even small number of bit errors
  - Backward error control:
    - Error recovery by retransmission [Automatic Repeat Request (ARQ)]

ARQ

- Basic idea
  - Break up bit pattern into fixed length data blocks or "frames"
  - Add error detection bits with each frame
  - Ask Tx to retransmit frames that show error or that are expected but not received within a timeout
  - Reconstruct final received bit pattern when all frames received successfully

Need to understand framing a bit before proceeding further

Framing

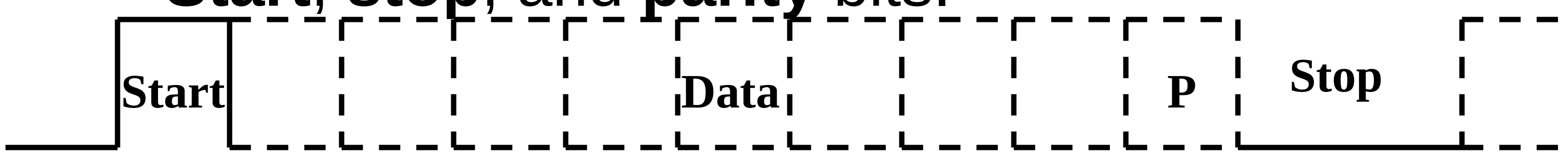
- Break up the bit pattern into multiple “frames”
- Issues
  - Needs identifier for each frame to distinguish between frames
  - Needs technique to identify where a frame ends and the next one begins
  - Frame synchronization problem

Frame Synchronization

- When data are transferred from the transmitter to the receiver, unless steps are taken to provide synchronization, the receiver may start interpreting the data erroneously
- Two common approaches:
  - ***Asynchronous Transmission***
  - ***Synchronous Transmission***

Asynchronous Transmission

- Transmitter and Receiver has separate clocks
- Data rate and frame format negotiated a-priori
- Data are transmitted one character at a time (5-8 bits)
  - Timing or synchronization must only be maintained within each character
  - Start bit and the beginning of each new character to resynchronize (start the receiver clock at the right time)
- When no character is being transmitted, the line between transmitter and receiver is in an *idle* state
  - **Start**, **stop**, and **parity** bits.



Synchronous Transmission

- Receiver clock is synchronized with transmitter clock
- A block of bits is transmitted in a steady stream without start and stop codes
  - The block may be arbitrarily long
  - To prevent timing drift between transmitter and receiver, clock signal is embedded in the data signal or separate clock signal
- There is another level of synchronization required, so as to allow the receiver to determine the beginning and end of a block of data
  - Every block begins with a *preamble* bit pattern, and generally ends with a *postamble* bit pattern

Synchronous Transmission (contd.)

- A typical synchronous frame format:
  - 8-bit flag (preamble)
  - Control fields
  - Data field
  - Control fields
  - 8-bit flag (postamble)
- Special inter-frame fill pattern is sent when no frame to send to maintain synchronization
- What if data itself contains the preamble/postamble pattern?
  - Use *bit-stuffing*

- For sizable blocks of data, synchronous transmission is far more efficient than asynchronous mode
  - Asynchronous transmission requires 20% or more overhead
  - The control information, preamble and postamble in synchronous transmission are typically less than 100 bits

Now lets get back to error control

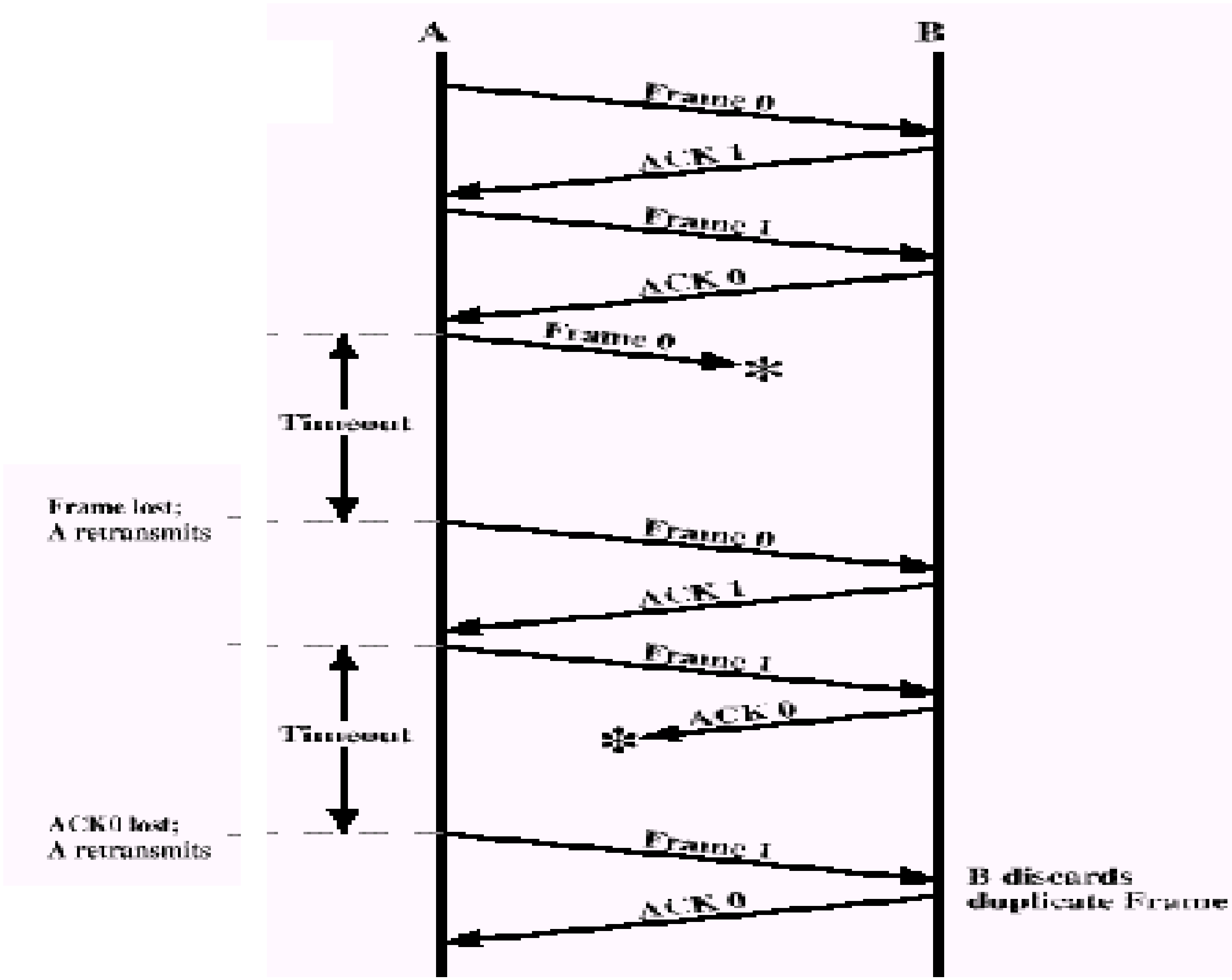
Stop & Wait ARQ

- Sender transmits message frame
- Receiver checks received frame for errors; sends ACK/NAK
- Sender waits for ACK/NAK. NAK $\Rightarrow$ retrans; ACK $\Rightarrow$ next frame
- Simple and minimum buffer requirement
- Very poor line efficiency if large number of frames

Stop & Wait ARQ (contd.)

- Frame/ACK could be lost $\Rightarrow$ Uses a timeout mechanism
- Possibility of duplication $\Rightarrow$ Number frames
- Only need a 1-bit frame number alternating 1 and 0 since they are sent one at a time

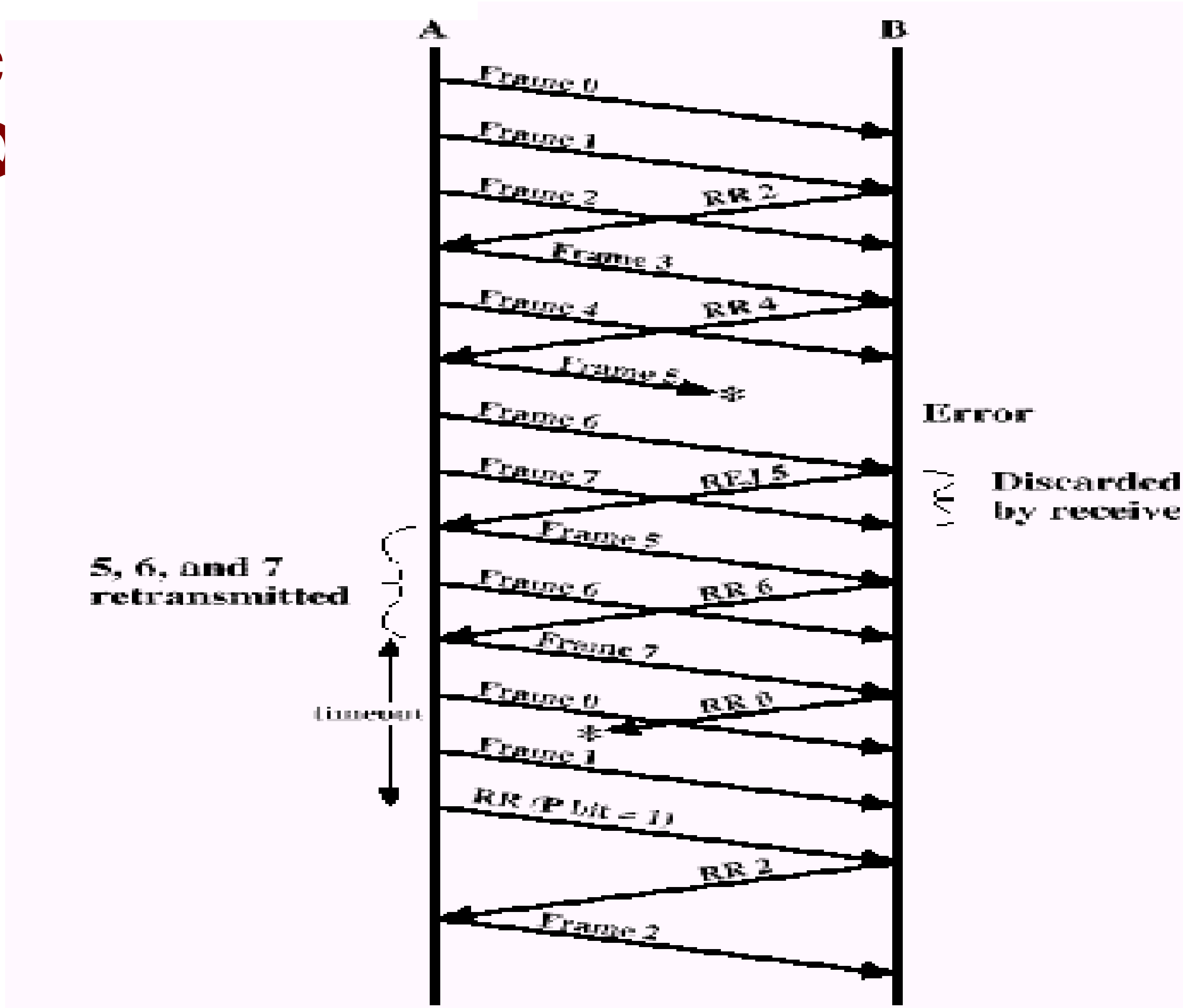
Stop & Wait ARQ (contd.)



Go-back-N ARQ

- If the receiver detects an error on a frame, it sends a NAK for that frame. The receiver will discard all future frames until the frame in error is correctly received
- The sender, when it receives a NAK or timeout, must retransmit the frame in error plus all succeeding frames. (Sender must maintain a copy of each unacknowledged frame)

Go-bac
ARQ



A
B
Frame 0
Frame 1
Frame 2
RR 2
Frame 3
Frame 4
RR 4
Frame 5
Error
Frame 6
Frame 7
REJ 5
Discarded by receiver
Frame 5
5, 6, and 7 retransmitted
Frame 6
RR 6
Frame 7
Frame 0
RR 0
timeout
Frame 1
RR (P bit = 1)
RR 2
Frame 2

Selective-Reject ARQ

- The only frames retransmitted are those that receive a NAK or which timeout
- Can save retransmissions, but requires more buffer space and complicated logic

Maximum Window Size (with n-bit sequence number)

- Go-back-N : $2^n - 1$
- Selective-reject : 2^{n-1}

Flow Control

Flow Control

- What if sender sends the bit pattern too fast? Receiver may not be able to process the data as fast as the sender is sending it
  - Receiver can buffer, but buffer has finite size. After that is filled, data is lost
- Flow control – technique to control data flow between sender and receiver so that sender is blocked if receiver cannot accept any more data

Stop & Wait Flow Control

- Sender sends a frame
- Receiver receives frame & acknowledges it
- Sender waits to receive “ack” before sending next frame (If receiver is not ready to receive another frame it holds back the ack)
- One frame at a time is sent over the transmission line
- Simple, easy to implement
- Line utilization is low

Sliding Window Flow Control

- Reduces line inefficiency problem of stop-and-wait by transmitting multiple frames without waiting for acknowledgement
- Suppose two stations A and B are connected by a full-duplex link

Sliding Window (contd.)

- Station *B* allocates buffer space for *n* frames.
  - Thus *B* can accept *n* frames, and *A* is allowed to send *n* frames without waiting for any acknowledgement
- Each frame is labeled with a sequence number
  - To keep track of the frames which have been acknowledged
  - *B* acknowledges a frame by sending an ACK that includes the sequence number of the next frame expected. This also explicitly announces that *B* is prepared to receive the next *n* frames, beginning with the number specified

Sliding Window (contd.)

- This scheme can be used to acknowledge multiple frames
  - *B* could receive frames 2,3,4 but withhold ACK until frame 4 has arrived. By returning an ACK with sequence number 5, *B* acknowledges frames 2,3,4 at one time

Sliding Window (contd.)

- Sender maintains a list of sequence numbers that it is allowed to send (***sender window***)
- Receiver also maintains a list of sequence numbers that it is prepared to receive (***receiver window***)
- Since the sequence number to be used occupies a field in the frame, it is clearly of bounded size
  - For a *k*-bit field, the range of sequence numbers is 0 through 2^k-1, and frames are numbered modulo 2^k

Sliding Window (contd.)

- The actual window size need not be the maximum possible size for a given sequence number length
  - For a 3-bit sequence number, a window size of 4 can be configured
- If two stations exchange data, each need to maintain two windows. To save communication capacity, a technique called ***piggybacking*** is used
  - Each data frame includes a field that holds the sequence number of that frame plus a field that holds the sequence number used for ACK
  - If a station has an ACK but no data to send, it sends a separate ACK frame