Network Software: The Protocol Hierarchy

• In reality, no data is transferred from layer $n$ on any two machines. Data and control information is passed to the layer below.

• Additional information including protocol control information may be appended by each layer to data as it travels from higher to lower layers in the form of layer headers.

• Below layer 1 is the physical medium where the actual communication occur over communication channels (copper wires, optical fibers, wireless channel etc.)

• Between adjacent layers an interface defines which primitive operations and services the lower layer offers to the upper layer.

• The set of layers and associated protocols is called a network architecture.
A Generic Network Hierarchy

Host 1

Layer 5

Layer 4/5 interface

Layer 4

Layer 3/4 interface

Layer 3

Layer 2/3 interface

Layer 2

Layer 1/2 interface

Layer 1

Layer 5 protocol

Layer 4 protocol

Layer 3 protocol

Layer 2 protocol

Layer 1 protocol

Physical medium

Host 2

Layer 5

Layer 4

Layer 3

Layer 2

Layer 1
An Example of Information Flow In Layer 5

Layer 5 protocol

Layer 4 protocol

Layer 3 protocol

Layer 2 protocol

Source machine

Destination machine

M = Message  H = Header
Relationship Between Layers at An Interface

Layer N+1

Layer N

SAP = Service Access Point
IDU = Interface Data Unit
SDU = Service Data Unit
PDU = Protocol Data Unit
ICI = Interface Control Information

Layer N entities exchange N-PDUs in their layer N protocol
Layer headers are appended by each network layer to the original user data as it travels from higher to lower layers.
The layers of The OSI Reference Model were never fully adopted by a real network architecture.

OSI = Open Systems Interconnection, 1983
OSI Reference Model Layers

1 The Physical Layer:
   – Concerned with transmitting raw bits over a communication channel (bit timing, voltage ..)

2 The Data Link Layer:
   – Transform raw transmissions into error-free data.
   – Data grouped in frames with error detection and/or correction bits added.
   – Frames are sent and acknowledged by this layer.

3 The Network Layer:
   – Controls the operation of the subnet.
   – Concerned with routing of data packets from source to destination.
   – Handles protocol incompatibilities between different networks.
OSI Reference Model Layers

4 The Transport Layer:
   - Accepts data from the session layer and may split it into smaller units.
   - Ensures that message units arrive correctly at the destination.
   - Determines what type of service is provided to the session layer.

5 The Session Layer:
   - Allows users on different machines to establish sessions (login, file transfer, etc.)

6 The Presentation Layer:
   - Concerned with syntax and semantics of the information transmitted.

7 The Application Layer:
   - Handles common needed high level network protocols (e.g. email, FTP, HTTP, TELNET, etc.)
Data Transmission in The OSI Model

Some headers may be empty
Data Transmission Channel Characteristics

- Channel Noise: A small amount of background interference or stray energy present on the channel (usually electro-magnetic) that carries no data or information.
  - Main cause of transmission errors.
  - Given as the signal to noise ratio S/N and measured in decibels (dB).

- Channel Bandwidth: The size of the range of frequencies that can be transmitted through a channel. Measured in Hertz (Hz). Affected by:
  - Type and physical characteristics of media used.
  - Amount of noise present in transmission channel
  - Data encoding method used.

- Channel Data Transmission Rate (or Bit Rate): The maximum number of bits that can be transmitted per unit time through the physical medium. Measured in bits per second (bps).

- Channel Utilization: The fraction of the channel’s data rate actually used to transmit data.
Data Transmission Channel Characteristics

- **Channel Latency, or Propagation Delay:** The amount of time needed for information to propagate from source to destination through the channel. It is the distance divided by the signal propagation speed (usually the speed of light). Depends on:
  - Media characteristics
  - Signal propagation speed
  - Transmission distance

- **Transmission Delay:** The time it takes to transmit a message through the channel. It is the size of the message in bits divided by the data rate (in bps) of the channel over which the transmission takes place.

- **Bit Length:** The length of a one-bit signal being transmitted
  \[ \text{Bit Length} = \frac{\text{signal propagation speed}}{\text{data transmission rate}} \]

Example: Channel data-rate is 10Mbps. One bit is transmitted in \(10^{-7}\) seconds. Since signals propagate in a medium at about 200,000 km/s, i.e. \(2*10^8\) m/s, bit-length is: \(10^{-7} \times 2 \times 10^8 = 20\) meters.
The Physical Layer: Basic Information Encoding Theory

- Any well behaved periodic function $g(t)$ with a period $T = 1/f$ can be decomposed into a summation of a series of sine and cosine terms (Fourier Series):
  $$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2nf\pi) + \sum_{n=1}^{\infty} b_n \cos(2nf\pi)$$

- Any physical transmission channel can transmit frequencies undiminished from 0 to some frequency $f_c$
  - e.g. voice grade phone lines have a cutoff frequency of $f_c = 3000$ hz

- Channel baud rate = number of changes/sec
- Channel bit rate = (baud rate $\times$ number of bits/change) bits/sec
The Maximum Data Rate of A Channel: Nyquist’s Theorem

- The maximum data rate of a finite bandwidth noiseless transmission channel with bandwidth $H$ is given by Nyquist’s theorem:
  
  \[
  \text{Maximum data rate} = 2H \log_2 V \text{ bits/sec}
  \]
  
  where $V$ is the number of discrete levels.

- For binary transmission:
  
  \[
  \text{Maximum data rate} = 2H \log_2 2 = 2H
  \]

- Given a channel with bandwidth $H$ Hz, a signal $S$ to noise $N$ ratio of $(10 \log_{10} S/N)$ dB (decibels), the maximum data rate of the channel (or channel bandwidth) is given by Shannon as:
  
  \[
  \text{Maximum number of bits/sec} = H \log_2 (1 + S/N)
  \]

  - e.g. phone lines have $S/N$ ratio of 30 dB and $H = 3000$, according to Shannon:

    \[
    30 \text{ dB} = 10 \log_{10} S/N \\
    \text{Signal to noise ratio} = \frac{S}{N} = 10^{30/10} = 10^3 = 1000 \\
    \text{Maximum transmission rate} = 3000 \log_2 (1 + 1000) \approx 30000 \text{ bps}
    \]
Data Multiplexing

- Transmission links (channels) present in a single network usually have a wide range of available bandwidths.

- To maximize the utilization of higher bandwidth links:
  - Data from several lower-bandwidth transmission links is usually multiplexed onto a single high-bandwidth link.

- Several data multiplexing methods are used:
  - Frequency Division Multiplexing (FDM)
    - Used in voice channels
    - Uses analog circuits
  - Wavelength Division Multiplexing (WDM):
    - Used in fiber optic transmission lines.
  - Time Division Multiplexing (TDM):
    - Several digital channels are combined from local subnets.
Time Division Multiplexing (TDM)

- Digital data from a number of low-bandwidth channels is combined into a single high-bandwidth channel.
- Data from different channels is multiplexed over time to occupy alternating time slots.
- Example: T1 digital channels (1.554 Mbps) usually combine data from 24, 56000 bps channels.
Circuit Vs. Packet Switching
Virtual Circuits

- When a virtual circuit is established:
  - The route is chosen from beginning to end (circuit setup needed)
  - Routers or switches along the circuit create table entries used to route data transmitted on the virtual circuit.
  - Permanent virtual circuits   - Switched virtual circuits
Synchronous Vs. Asynchronous Transmission

Channel 1 gets exactly 1 byte at the start of each frame.

There is no requirement about cell ordering.
Data Link Layer: Virtual Vs. Actual Communication

Virtual Communication

Actual Communication
Data Link Layer: Framing

- The character count method:
  - The frame header includes the count of characters in the frame
  - A transmission error can cause an incorrect count causing the source and destination to get out of synchronization
  - Rarely used in actual data link protocols

- A character stream with no errors

- A character stream with one error
Data Link Layer: Framing

Using Starting and ending characters, with character stuffing

- Each frame starts with the ASCII character sequence DLE (Data Link Escape) and STX (Start of Text) and ends with DLE ETX (End of Text).
- When binary data is transmitted where (DLE STX or DLE ETX) can occur in data, character stuffing is used (additional DLE is inserted in the data).
- Limited to 8-bit characters and ASCII.

Network Layer Data at the sender

Data after character stuffing by the Data Link Layer at the sender

Network Layer Data at the Receiver
Data Link Layer: Framing

- Bit-Oriented Using Start/End Flags:
  - Each frame begins and ends with 0111110
  - Bit stuffing: After each five consecutive ones in a data a zero is stuffed
  - Stuffed zero bits are removed by the data link layer at receiving end.

The Original Data

```
0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0
```

Data appearing on the line after bit stuffing

```
0 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0
```

Data received after destuffing

```
0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0
```
Data Link Layer: Error Detection/Correction

• Simplest error detection: Parity bits and checksum (sum of 1’s in data).

• Error-detecting and -correcting codes:
  – \( m \) data bits + \( r \) redundant bits added
  – \( n = m + r \) transmitted in frame.
  – Only \( 2^m \) code words out of possible \( 2^{m+r} \) words are legal.
  – The Hamming distance --minimum number of positions any two legal code words differ-- of a code defines its error detection/correction ability.
    – To detect \( d \) errors code Hamming distance = \( d + 1 \)
    – To correct \( d \) errors code Hamming distance = \( 2d + 1 \)
    – Some codes are more suitable to correct burst errors rather than isolated errors.
    – Polynomial codes (Cyclic Redundancy Codes or CRC) are characterized by a generating polynomial \( G(X) \).
Calculation of Polynomial Code (CRC) Checksum

1. For degree of generating polynomial \( G(x) = r \), append \( r \) zero bits to low-order of frame. The frame now has \( m+r \) bits.

2. Divide the bit string corresponding to \( G(X) \) into the bit string \( x^r M(x) \mod(2) \).

3. Subtract the remainder from the bit string \( x^r M(x) \mod(2) \).

Frame: 1 1 0 1 0 1 1 0 1 1
Generator: 1 0 0 1 1
\( G(X) = X^4 + X + 1 \)

Message after appending four 0’s:
1 1 0 1 0 1 1 0 1 1 0 0 0 0

Transmitted Frame:
1 1 0 1 0 1 1 0 1 1 1 1 1 0
Hardware Computation of CRC

For $G(x) = x^{16} + x^{12} + x^5 + 1$

An Example Frame Format with CRC bits
Data Link Layer: Flow Control
Stop-and-Wait Data Link Protocols

• Such elementary protocols are also called PAR (Positive Acknowledgment with Retransmission) or ARQ (Automatic Repeat reQuest).

• Data frames are transmitted in one direction (simplex protocols) where each frame is individually acknowledged by the receiver by a separate acknowledgment frame.

• The sender transmits one frame, starts a timer and waits for an acknowledgment frame from the receiver before sending further frames.

• A time-out period is used where frames not acknowledged by the receiver are retransmitted automatically by the sender.

• Frames received damaged by the receiver are not acknowledged and are retransmitted by the sender when the expected acknowledgment is not received and timed out.

• A one bit sequence number (0 or 1) is used to distinguish between original data frames and duplicate retransmitted frames to be discarded.

• Such protocols result in a substantial percentage of wasted bandwidth and may fail under early time-out situations.
Protocol 1: An Unrestricted Simplex Protocol

- Transmission in one direction
- The receiver is always ready to receive the next frame (has infinite buffer storage).
- Error-free communication channel.
- No acknowledgments or retransmissions used.
- If frame has \( d \) data bits and \( h \) overhead bits, channel bandwidth \( b \) bits/second:
  
  \[
  \text{maximum channel utilization} = \frac{d}{d+h} \\
  \text{maximum data throughput} = \frac{d}{d+h} \times \text{channel bandwidth} = \frac{d}{d+h} \times b
  \]

Data Frame 1  
Data Frame 2  
Data Frame 3  
Data Frame 4  
Data Frame 5  
Data Frame 6

Frame transmission time = \( \frac{d+h}{b} \) 
\( b = \text{channel bandwidth} \)
Protocol #2: A Simplex Stop-and-Wait Protocol

- **Simplex**: Data transmission in one direction
- The receiver may not be always ready to receive the next frame (finite buffer storage).
- Receiver sends a positive acknowledgment frame to sender to transmit the next data frame.
- Error-free communication channel assumed. No retransmissions used.
- **Maximum channel utilization** \( \approx \frac{\text{time to transmit frame}}{\text{round trip time}} \times \frac{d}{d + h} \)
  \[ \approx \frac{d}{b \times R} \]
- **Maximum data throughput** \( \approx \) channel utilization \( \times \) channel bandwidth
  \[ \approx \frac{d}{(b \times R)} \times b = \frac{d}{R} \]
Protocol 3: A Simplex Positive Acknowledgment with Retransmission (PAR) Protocol

- The receiver may not be always ready to receive the next frame (finite buffer storage).
- Noisy communication channel; frames may be damaged or lost.
  - Frame not received correctly with probability $p$
- Receiver sends a positive acknowledgment frame to sender to transmit the next data frame. Any frame has a sequence number, either 0 or 1
- Maximum utilization and throughput similar to protocol 2 when the effect of errors is ignored.

Sender

Round trip time, $R$

Data Frame 1, sequence # 0

Ack Frame, sequence # 0

Data Frame 1, sequence # 1

Ack Frame, sequence # 1

Data Frame 1, sequence # 0

Time

Receiver
Protocol 3: A Simplex PAR Protocol (continued)

Effect of Errors

- The sender starts a timer when transmitting a data frame.
- If data frame is lost or damaged (probability $= p$):
  - Receiver does not send an acknowledgment
  - Sender times out and retransmits the data frame

![Diagram showing the effect of errors in Protocol 3]

- Start timer
- Time-out interval
- Time-out retransmit frame
- Sender

Receiver

Time

Data Frame 1, sequence # 0

Error: Frame lost or damaged, with probability $p$

Ack Frame, sequence # 0
Data Link Layer: Flow Control
Sliding Window Protocols

- These protocols allow both link nodes (A, B) to send and receive data and acknowledgments simultaneously.
- Acknowledgments are piggybacked into an acknowledgment field in the data frame header not as separate frames.
- If no new data frames are ready for transmission in a specified time, a separate acknowledgment frame is generated to avoid time-out.
- Each outbound frame contains a sequence number ranging from 0 to $2^{n-1}$ (n-bit field). $N = 1$ for stop-and-wait sliding window protocols.
- **Sending window**: A set of sequence numbers maintained by the sender and correspond to frame sequence numbers of frames sent out but not acknowledged.
- The maximum allowed size of the sending window $w$ correspond to the maximum number of frames the sender can transmit before receiving any acknowledgment without blocking (pipelining).
- All frames in the sending window may be lost or damaged and thus must be kept in memory or buffers until they are acknowledged.
Sliding Window Data Link Protocols

- **Receiving window:** A set of sequence numbers maintained by the receiver and indicate the frames sequence numbers it is allowed to receive and acknowledge.
- The size of the receiving window is fixed at a specified initial size.
- Any frame received with a sequence number outside the receiving window is discarded.
- The sending window and receiving window may not have the same upper or lower limits or have the same size.
- When pipelining is used, an error in a frame is dealt with in one of two ways:
  - **Go back n:** (Example: Protocol 5)
    - The receiver discards all subsequent frames and sends no acknowledgments.
    - The sender times out and resends all the discarded frames starting with faulty frame.
  - **Selective repeat:** (Example: Protocol 6)
    - The receiving data link stores all good frames received after a bad frame.
    - Only the bad frame is retransmitted upon time-out by the sender.
A Sliding Window Protocol of Size 1 with a 3-bit Sequence Number

(a) Initial state
(b) After the first frame has been sent
(c) After the first frame has been received
(d) After the first acknowledgment frame has been received
Difference Between PAR and Sliding Window Protocols

Positive Acknowledgment with Retransmission

Stop-and-Wait

<table>
<thead>
<tr>
<th>Sender</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Frame 1, seq # 0</td>
<td>Ack Frame, seq # 0</td>
</tr>
<tr>
<td>Data Frame 2, seq # 1</td>
<td>Ack Frame, seq # 1</td>
</tr>
<tr>
<td>Data Frame 3, seq # 0</td>
<td>Ack Frame, seq # 0</td>
</tr>
<tr>
<td>Data Frame 4, seq # 1</td>
<td>Ack Frame, seq # 1</td>
</tr>
</tbody>
</table>

Shown Here:
Four Data Frames Transmitted

Round Trip Time, $R$

ACK F, seq # 0

Sliding Window
sequence # from 0 to 3

<table>
<thead>
<tr>
<th>Sender</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF 1, seq # 0</td>
<td>Ack F, seq # 1</td>
</tr>
<tr>
<td>DF 2, seq # 1</td>
<td>Ack Frame, seq # 2</td>
</tr>
<tr>
<td>DF 3, seq # 2</td>
<td>Ack Frame, seq # 3</td>
</tr>
<tr>
<td>DF 4, seq # 3</td>
<td>: :</td>
</tr>
</tbody>
</table>

Time
A 4-Frame Sending Window

(a) Initial window

12 11 10 9 9 7 6 5 4 3 2 1

still unsent

already acknowledged

(b) After two frames have been acknowledged

6 5 4 3 2 1

Unacknowledged or Pending Frames

After nine frames have been acknowledged

12 11 10 9 9 7 6 5 4 3 2 1
Channel Utilization & Data Throughput
For Sliding Window Protocols

\[ b = \text{Channel bandwidth or transmission rate bits/sec} \]
\[ FS = \text{Frame size} = \# \text{of data bits} + \# \text{overhead bits} = d + h \]
\[ R = \text{Channel round trip time} \]
\[ N = \text{Send/receive window size} \]
\[ p = \text{Probability frame a data frame is lost or damaged} \]

- **Ignoring errors**, condition to maximize Utilization/Throughput:
  
  Time to transmit \( N \) frames \( \geq \) Round trip time
  
  \[ \frac{FS}{b} \times N = \frac{(d + h)}{b} \times N \geq R \]

Under this condition:

  Maximum channel utilization \( \approx \) data size/frame size \( = \frac{d}{d + h} \)

  Maximum data throughput \( \approx \) \( \frac{d}{FS} = \frac{d}{d + h} \times b \)

- **Including the effect of errors only on data frame; assuming selective repeat:**

  On the average \( p \) data frames have to be retransmitted

Under these condition:

  Total Data Frame overhead \( = h + p \times FS \)

  Maximum channel utilization \( \approx \) \( \frac{d}{(1 + p)FS} \)

  Maximum data throughput \( \approx \) \( \frac{d}{(1 + p)FS} \times b \)
(a) Effect of an error when the receiver size is 1

(b) Effect of an error when the receiver size is large
The protocol state machine states are represented by XYZ

- X = 0 or 1 depending on the sequence number of the frame the sender is attempting to send.
- Y = 0 or 1 depending on the sequence number of the frame the receiver expects.
- Z = 0, 1, A or empty (-) corresponding to the state (content) of the channel.
Data Link Protocol Example: HDLC - High-Level Data Link Control

- Bit-oriented protocol derived from IBM’s SNA data link protocol SDLC (Synchronous Data Link Control).
- Frame Types: Information, Supervisory, Unnumbered.
- Uses sliding window with 3-bit sequence numbers.
- Uses CRC-CCITT for error control.
- Protocol commands include:
  - DISC (DISConnect) used to disconnect a machine from the line.
  - SNRM (Set Normal Response Mode) brings a machine online and sets one machine as channel master and the other as slave (was used for dumb terminals when connected to mainframes).
  - SABM (Set Asynchronous Balanced Mode).
  - FRMR (FRaMe Reject) rejects a frame with correct checksum with impossible structure.
HDLC Bit-Oriented Frame Format

<table>
<thead>
<tr>
<th>Bits</th>
<th>8</th>
<th>8</th>
<th>8</th>
<th>≥ 0</th>
<th>16</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 1 1 1 1 1 1 0</td>
<td>Address</td>
<td>Control</td>
<td>Data</td>
<td>Checksum</td>
<td>0 1 1 1 1 1 1 0</td>
</tr>
</tbody>
</table>

Information Frame

- Frame Sequence #
- Poll/Final
- Next Frame Expected

Supervisory Frame

- Type
- Poll/Final
- Next

Unnumbered Frame

- Type
- Poll/Final
- Modifier
Serial Line IP (SLIP) RFC 1055

- Send raw IP packets with a flag byte (0xC0) at the end for framing with character stuffing (data 0xC0 replaced with 0xDB 0xDC).
- Recent versions use header compression by omitting header fields in consecutive packets and frames.
- Does not include any form of error detection or correction.
- Supports only one network protocol: IP (Internet Protocol).
- Dynamic IP address assignment not supported.
- Lacks any form of authentication.
Internet Data Link Protocols:  
Point-to-Point Protocol (PPP)

- Uses standard HDLC framing byte (01111110) with error detection.
- Uses Link Control Protocol (LCP) for bringing lines up, option negotiation, and to bring lines down.
- Network layer options and configurations are negotiated independent of the network layer used by utilizing different NCPs (Network Control Protocol) packets for each supported network layer.
- Support for several packet types by using a protocol field:  
  - Network protocols (protocol field starts with 0): IP, IPX, AppleTalk etc.
  - Negotiating protocols (protocol field starts with 1): LCP, NCP.
- PPP is used for both dial-up network access and for router-to-router communication in subnets.
PPP Frame Format & Transition Diagram

PPP Frame Format for unnumbered mode operation.

Simplified PPP phase diagram for bringing a line up or down.
Data Link In Broadcast Networks: The Media Access Sublayer

• Broadcast networks with multi-access (or random access) shared channels include the majority of LANS, all wireless and satellite networks.

• **Medium Access Control** (MAC):
  Protocols to allocate a single shared broadcast channel among competing senders by determining which sender gets access to the channel next and transmit its data.

• **Static Channel Allocation**: Frequency Division Multiplexing (FDM), Time Division Multiplexing (TDM) --- too wasteful of available bandwidth.

• **Dynamic Channel Allocation**: No predetermined sender access order to the channel.
Dynamic Channel Allocation: Protocol Assumptions

- \( N \) independent stations (senders or, computers etc.)
- A station is blocked until its generated frame is transmitted.
- Probability of a frame being generated in a period of length \( \Delta t \) is \( \lambda \Delta t \) where \( \lambda \) is the arrival rate of frames.
- Only a single channel is available
- The transmission of two or more frames on the channel at the same time creates a collision and destroyed data.
- Time can be either: Continuous or slotted.
- Carrier sense: A station can sense if a channel is busy before transmission.
- No Carrier sense: Timeout used to sense loss of data.
Multiple Access Protocols: Pure ALOHA

- Stations transmit whenever data is available at arbitrary times (forming a contention system).
- Colliding frames are destroyed
- Frame destruction sensed by listening to channel:
  - Immediate collision feedback in LANs
  - 270 msec feedback delay in satellite transmission.
- When a frame is destroyed the sender waits a random period of time before retransmitting the frame
Frame Throughput of Pure ALOHA

• Infinite sender population assumed.
• New frames rate (or frames success rate):
  Poisson distribution with mean rate $S$ frames/frame time.
• Combined frame rate with retransmissions:
  $G$ frames/frame time.
• $S = GP_0$ where $P_0 =$ probability a frame is successful
• $t =$ time required to transmit a frame
• A frame is successful if no other frames are transmitted in the vulnerable period from $t_0$ to $t_0 + 2t$
• Probability $k$ frames are generated during a frame time:
  $$P_r[k] = \frac{G^k e^{-G}}{K!}$$

• Probability of zero frames in two frame periods is $P_0 = e^{-2G}$
  $$\Rightarrow \quad S = G P_0 = G e^{-2G} \quad \text{Max (S) } = \frac{1}{2e} \quad \text{at } G = .5$$
Vulnerable Period in Pure ALOHA

For successful frame transmission:
No other frame should be on the channel for vulnerable period equal to twice the time to transmit one frame $= 2t$.
Slotted ALOHA

- Time is divided into discrete frame time slots.
- A station is required to wait for the beginning of the next slot to transmit.
- Vulnerable period is halved as opposed to pure ALOHA.

\[ S = G P_0 = G e^{-G} \quad \text{Max (s)} = \frac{1}{e} \quad \text{at} \quad G = 1 \]

- Expected number of retransmissions: \( E = e^G \)
Carrier Sense Multiple Access (CSMA) Protocols

- **Medium Access Control (MAC) Protocols** for shared channels where a station listens to the channel and has the ability sense the carrier and thus can detect if the channel is idle before transmitting, and possibly detect the occurrence of a collision after attempting to transmit a frame.

- **1-persistent CSMA:**
  - A ready station first listens to the channel for other transmissions.
  - Once it detects an idle channel it transmits a frame immediately.
  - In case of a collision, the stations involved in the collision wait a random period of time before retransmission.

- **nonpersistent CSMA:**
  - If a ready station senses an idle channel it starts transmission immediately.
  - If a busy channel is sensed a station waits a random period of time before sensing the channel again.

- **p-persistent CSMA (applies to slotted channels):**
  - If a ready station senses an idle channel, it transmits with probability $p$
  - or defers transmission to the next time slot with probability $q = 1 - p$
  - If the next slot is idle it transmits or defers again with probabilities $p$, $q$
  - The process continues until the frame has been transmitted or another station has seized the channel.
CSMA with Collision Detection (CSMA/CD)

• If two stations begin transmitting simultaneously and detect a collision, both stations abort their transmission immediately.
• Once a collision is detected each ready stations waits a random period of time before attempting to retransmit.
• Worst-case contention interval (the duration of a collision lasts) is equal to $2\tau$ ($\tau$ is the propagation time between the two farthest stations).

Possible states of CSMA/CD channels
• **N** stations with addresses 0 to **N-1**
• **N** one-bit contention slots.
• If a station _i_ has a frame to send, it sends a one during contention slot _i_.
• Once all stations indicated frame availability, ready frames are transmitted in address order.
• Representative of reservation protocols (where each station broadcasts its desire to transmit before actual transmission).
• Efficiency per frame:
  - With low load = \( \frac{d}{N + d} \)  With high load = \( \frac{d}{1 + d} \)
  
  \( d \) = number of bits in one frame
• Binary station address is used to form $\log N$ one-bit contention slots.

• Address bits from all stations are Boolean ORed.

• If a station has a frame to send, it transmits its binary address starting with the high-order bit.

• The station with the highest-numbered address gets to transmit.

• Efficiency per frame
  
  \[
  \text{Efficiency per frame} = \frac{d}{d + \log N}
  \]
IEEE Standard 802.3 (Ethernet)

• 1-persistent CSMA/CD LAN. 10-1000Mbps.

• Broadcast to several destinations possible using addresses with high-order bit = 1.

• Random number of waiting slots upon a collision is chosen by binary exponential backoff algorithm:
  – First collision: wait 0 or 1 slots
  – After \( i \) collisions wait a random number of slots between 0 and \( 2^i - 1 \) with a maximum of 1023.
  – After 16 collisions, failure is reported to higher layers.

• Simplified Channel efficiency = \( \frac{P}{P + 2\tau/A} \) where:
  • \( A = kp(1-p)^{k-1} \) \( k \) stations each with \( p \) probability to transmit in a contention slot.
  • \( P \) time to transmit a frame
  • \( \tau \) worst case propagation delay.
Collision Detection Delay in Ethernet, CSMA/CD

As a result, the time to transmit a frame on the media must be longer than $2\tau$ otherwise collisions will be undetectable to some stations. This determines the minimum frame size.
The 802.3 (Ethernet) Frame Format

- Preamble: 7 bytes 10101010 to synchronize station clocks
- Start of frame byte: 10101011
- Destination address
- Source address
- Length of data field
- Data: 0-1500 bytes
- Pad: padding bits to make frame size more than the minimum size (~64 bits)
- Checksum

Minimum frame size:
The time to transmit a frame on the media must be longer than 2τ otherwise collisions will be undetectable to some stations.
IEEE Standard 802.4: Token Bus

- A linear or tree-shaped bus with N stations
- Stations are organized as a logical ring where each station knows the address of its logical right and left neighbors.
- Only the station in possession of a special control packet “token” is allowed to transmit.
- Once a station is done transmitting it passes the token to one of its two logical neighbors.
- A station in possession of the token and data to transmit passes it on.
- Collision-free protocol; no starvation
IEEE Standard 802.5: Token Ring

- N stations connected using point-to-point links to form a ring.
- A 3 byte token circulates around the ring
- A station desiring to transmit removes the token from the ring and once it passes by and converts a single bit in the token to 1 indicating the start of a frame.
Fiber Distributed Data Interconnect (FDDI)

- FDDI is another ring LAN technology. Transmits data at 100Mbps
- Uses pairs of fiber optic cables to form two counter-rotating concentric rings in which data flows in opposite directions.
- In case of fiber or station failure, remaining stations loop back and reroute data through spare ring
- All stations automatically configure loop back by monitoring data ring