**Direct Link Communication:**
**Technology and Access Control**

**Point-to-point communication**

Already seen digital/analog transmission of digital data including coding and error detection.

**Reliable transmission**

Principal methodology: ARQ (Automatic Repeat reQuest) or PAR (Positive Acknowledgment with Retransmission) or backward error correction (BEC).
Three components:

- acknowledgment (ACK)
- timeout
- retransmit
Stop-and-wait

Assumption: Frame is “lost” due to corruption; discarded by NIC after error detection.
Issue of RTT (Round-Trip Time) and timer management:

- what is proper value of timer?
- RTT estimation
- easier for single link than path in an internetwork
- largely independent of queueing effect

More serious problem: Not keeping the pipe full.

\[\rightarrow \text{ bandwidth-delay product}\]

Literally, volume of data in on the link.

To achieve high utilization, want to keep volume of traffic flowing close to the bandwidth limit.
**Example:** Link BW 1.5 Mbps, 45 ms RTT; bandwidth-delay product = 1.5 Mbps × 45 ms = 67.5 kb ≈ 8 kB.

If frame size 1 kB, then (effective) throughput is 1024 × 8/0.045 = 182 kbps; utilization is only 0.125.

Solution: Other things being equal, must increase frame size.

- straightforward increase of frame size is problematic; why?
- send blocks of data, i.e., sequence of frames
- creates management problem
Sliding window protocol

- **SWS**: Send Window Size
- **RWS**: Receiver Window Size
- **LAR**: Last ACK Received
- **LFS**: Last Frame Sent
- **NFE**: Next Frame Expected
- **LFA**: Last Frame Acceptable
Assign sequence number (SeqNum) to individual frames.

Maintain invariants:

- $LFS - LAR + 1 \leq SWS$
- $LFA - NFE + 1 \leq RWS$

Sender: Update LAR, send more frames, then update LFS.

Receiver: Cumulative ACK; let SeqNumToAck denote the largest sequence number not yet acknowledged.

- $NFE \leftarrow SeqNumToAck + 1$
- $LFA \leftarrow SeqNumToAck + RWS$
ACK variants:

- piggyback
- negative ACKs
- selective ACKs

Sequence number wrap-around problem:

\[ SWS < \frac{(\text{MaxSeqNum} + 1)}{2}. \]

\[ \rightarrow \] similar to stop-and-wait (binary)
Further optimization/control variables in end-to-end case?

Why can packets still be lost given that link layer achieves reliability?

Link-based flow/congestion control revival (H. T. Kung). Achieve flow control/multiplexing (buffer sharing)/reliability at link level.
Multi-access communication

Ethernet and CSMA/CD

→ copper, optical fiber

Types:

- 10Base2 (ThinNet): coax, segment length 200 m, 30 nodes/segment
- 10Base5 (ThickNet): coax, segment length 500 m, 100 nodes/segment
- 10Base-T: twisted pair, segment length 100 m, 1024 nodes/segment
- 10Base-F: fiber, segment length 2000 m, 1024 nodes/segment
- 100Base-T (Fast Ethernet): category 5 UTP, fiber (also 100VG-AnyLAN)
- Gigabit Ethernet: fiber, category 5 UTP
Connectivity example:

- bus/star configuration
- multihomed/singlehomed
- unique Ethernet address per NIC
Segments can be hooked up by repeaters, bridges, gateways, (hub) switches.

- maximum of 2 (4 for IEEE 802.3) repeaters between two hosts; 1500 m
- for Fast Ethernet, 2 repeater hops

High-bandwidth Ethernets have shorter network diameter.

- about 2500 m for 10 Mbps Ethernet
- about 200 m for 100 Mbps Ethernet
- even shorter for 1 Gbps Ethernet
DIX Ethernet frame:

<table>
<thead>
<tr>
<th>8</th>
<th>6</th>
<th>6</th>
<th>2</th>
<th>46 - 1500</th>
<th>4</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
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<td>dest. address</td>
<td></td>
<td>body</td>
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--- IEEE 802.2 LLC (Logical Link Control)
Encoding: Manchester

Addressing:

- 48 bit unique address
- point-to-point
- broadcast (all 1’s)

Receiver: Ethernet adaptor accepts frames with relevant address.

- accepts only own frame address
- accepts all frames (promiscuous mode)
MAC (Medium Access Control): CSMA/CD

- **CS (Carrier Sense)**: Can detect if some other node is using the link.

- **MA (Multiple Access)**: Many nodes are allowed to simultaneously access the link.

- **CD (Collision Detection)**: Can detect if simultaneous access has occurred (corrupted signal).
Ethernet is 1-*persistent* MA scheme; more generally, *p*-persistent where \( 0 < p \leq 1 \).

Worst-case collision scenario:

- sender (worst case) needs to wait \( 2\tau \) sec before detecting collision
- for 2500 m length, 51.2 \( \mu \)s round-trip time (\( 2\tau \))
- enforce 51.2 \( \mu \)s slot (jam) time
- at 10 Mbps, 512 bits; i.e., minimum frame size
Hence, upon collision detection:

- Make sure to transmit at least 512 bits

  \[ \text{\(2 \times \text{bandwidth-delay product}\)} \]

  \[ \text{\(6 + 6 + 2 + 46 + 4 = 64 \text{ B} = 512 \text{ bits}\)} \]

- exponential backoff; wait for \(0 \leq X \leq 51.2 \mu s\) before next attempt

- on \(i\)'th collision, wait for \(0 \leq X \leq (2^i - 1)51.2 \mu s\) before next attempt, \(i \leq 16\)

- \(X = 0 \mu s, 51.2 \mu s, 2 \times 51.2 \mu s, 3 \times 51.2 \mu s, \ldots\)

  \[ \text{\(\rightarrow \text{distributed bus arbitration mechanism}\)} \]
Performance (approximate) analysis of CSMA/CD

Assumptions:

- *contention slot* (or mini slot) of duration $2\tau$ ($\tau$: end-to-end propagation delay)

- $k$ hosts transmitting with constant probability $p$ at every contention slot—slotted system

Fix contention slot; probability that a fixed host acquires slot successfully $p(1 - p)^{k-1}$.

Hence, probability that some host acquires a given slot

$$\eta = kp(1 - p)^{k-1}.$$ 

Fact: $\eta$ is maximized at $p = 1/k$. Also,

$$\lim_{k \to \infty} \eta = 1/e.$$
Probability that contention time interval $T$ (multiple of $2\tau$) lasts for exactly $i$ contention slots $\eta(1 - \eta)^{i-1}$.

Hence, mean contention duration (in units of $2\tau$)

$$E(T) = \sum_{i=0}^{\infty} i\eta(1 - \eta)^{i-1} = 1/\eta.$$ 

Mean contention duration $2\tau/\eta \approx 2\tau e$ (sec).

If mean frame transmission time is $t_0$ (sec), then

$$\rho = \frac{t_0}{t_0 + 2\tau e}$$

If mean frame length is $F$, bandwidth $B$, length of medium $L$, signal propagation speed $c$,

$$\rho = \frac{1}{1 + (2e/c)BL/F}$$
If $B$ is increased, then either $L$ must decrease and/or $F$ must increase.

\[ \rightarrow \text{ bad news for high-bandwidth media} \]

In practice: debate on actual throughput of Ethernet (above 90% vs. much lower).
Current trend: use switching hubs (Ethernet switches).

- multiple collision domains ("multi-port bridge")
- switching (buffering at Ethernet switches)
- conceptually little distinction with full-fledged switching (e.g., ATM)
- realization of virtual LANs
Gigabit and Fast Ethernet: use compendium of tricks. However, subject to intrinsic limitations.

- Fast Ethernet (100Base-T) uses various physical layer options including that of FDDI (emulate CSMA/CD)
- 100Base-T uses same frame size
- 100VG-AnyLAN (IEEE 802.12) uses priority scheduling (not CSMA/CD)
- gigabit Ethernets use broadband signalling
- maintaining consistent frame format & backward compatibility is an important factor
ALOHA: ’70s Abramson et al. (Univ. of Hawaii); simplest form of multi-access system using radio waves.

- send frame (pure or slotted).
- upon collision, retry after random waiting time.
- missing component: carrier sense (CS)
- subject to perils of long propagation time (in msec)
- 37% utilization limit (slotted)
Wireless LAN: short-range radio.

\[ \rightarrow \text{two problems with using simple CSMA} \]

- hidden station problem
- exposed station problem
Hidden station problem

1. $A$ transmits to $B$
2. $C$ does not sense $A$; transmits to $B$
3. interference occurs at $B$

Exposed station problem

1. $B$ transmits to $A$
2. $C$ wants to transmits to $D$ (to its right) but senses $B$
3. $C$ refrains from transmitting although ok
MACA (Multiple Access with Collision Avoidance)

- sender sends short RTS (request to send) frame
- receiver sends short CTS (clear to send) frame to sender
- others sensing RTS or CTS wait for suitable duration
- collision can still occur on control messages
- exponential backoff

Next: collision-free (reservation-based) protocols
FDDI (Fiber Distributed Data Interface)

→ token ring architecture

High-bandwidth extension of IBM 4 Mbps token ring and 16 Mbps IEEE 802.5 token ring standard.

→ 100 Mbps bandwidth

Mostly used as high-bandwidth LAN backbone.
Basic operation:
Fault-tolerance:

- DAS (dual attachment station)
- SAS (single attachment station)
- frame size < 4500 B
- 4B/5B encoding
- ANSI
- supports IEEE 802.2 LLC
- synchronous/asynchronous data
- 2 km inter-station distance
- 200 km diameter (multimode fiber); 100 km circumference
Performance issues: fairness and efficiency

- TRT (token rotation time)
- THT (token holding time)

\[ TRT = \text{no. of nodes} \times \text{THT} + \text{link latency} \]

To increase efficiency: increase THT

\[ \rightarrow \text{let station send as much as it needs} \]
\[ \rightarrow \text{THT} \uparrow \implies \rho \uparrow \]

To increase fairness: limit THT

\[ \rightarrow \text{limit station’s one-time sending of data} \]
To facilitate fairness: introduce TTRT (target token rotation time).

THT determining factor (assume TTRT is given):

- If TRT > TTRT, then late; don’t send asynchronous data.
- If TRT ≤ TTRT, then early; send asynchronous data for max \( \{ \text{TTRT} - \text{TRT}, \text{single frame time} \} \) duration.
- Synchronous frames get always sent.
How to set TTRT?

→ token claim process

→ initiate when needed (e.g., start-up)

• Each station submits *claim frame* containing TTRT bid.

• Smaller TTRT bid overrides higher TTRT bids.
  
  – Compare claim frame bid against own desired TTRT.
  
  – If less, then reset own TTRT to lower value.
  
  – If larger, then put lower bid on claim frame and forward.

• Winner: same bid value when claim frame makes full circle.
At the end of the day, consistent TTRT value among all stations.

\[ \rightarrow \text{consensus problem} \]

Last problem: When to reinsert token after sending data frame?

- immediate release (FDDI)
- delayed release (IEEE 802.5 token ring); problem of bit time and draining
“Easier” to implement quality of service (QoS).

→ real-time issues and QoS guarantees

→ partial solution only

Compare against Ethernet’s CSMA/CD.

→ determinism vs. indeterminism
Throughput: under \textit{infinite-source model}, as long as THT is not “too small,” can approach close to 100% utilization.

\[\text{\textrightarrow \quad \text{what is "not too small"?}}\]

\textit{Bit length} (duration of single bit on medium):

- Bandwidth \(x\) Mbps, a bit sent every \(1/x\) \(\mu\text{sec}\) (bit time).
- Signal propagation speed \(c\) m/\(\mu\text{sec}\), bit length \(c/x\) m.
- If \(c = 300\), \(x = 100\), then bit length 3 m.

What about infinite-source model in the case of Ethernet?

IEEE 802.4 Token bus

- Physical bus, logical ring.
- Token-based bus arbitration.
Distributed queue dual bus (DQDB)

Specifications:

- Two 150 Mbps unidirectional buses.
- 150 km.
- 53 B frames.
- IEEE 802.6.

Performance: Under infinite source model, very efficient.

→ slotted system (cf. STDM)
Issue: fairness.

\[\rightarrow \text{ achieve FIFO queue scheduling}\]

Method (assume sending to the right):

- Keep two counters RC (request counter), CD (count-down counter).
- To send to the right, mark request bit in frame of left bus.
- If request frame passes by on the left bus, increment RC.
- If request was made and CD = 0, then seize next free frame.
- If request was made but CD > 0, then decrement CD upon seeing next unoccupied frame.

Intuitive meaning of RC, CD?
So far, we have looked at architecture (hardware) and algorithms of direct-link media, i.e., data link layer.

Protocol specification of data link layer:
Logical link control: Isolation of common generic mechanisms including reliability and flow control.

→ similar to HDLC (point-to-point)

Medium access control: random access, deterministic access.
Lessons to be drawn:

- Although theory of direct-link communication exists, oftentimes, implementation is arbitrary and technology dependent (e.g., dual ring of FDDI, baseband/broadband & switched Ethernet).

- Emphasis on ease of standardization, implementation, and cost over efficiency.

- Efficiency pressure is a recent phenomenon. Integrated performance measure (QoS) has become important.

- Industry trend: increase bandwidth more and more; problematic fix to the problem.

- Computer networking tendency: shift away from data link issues (e.g., ATM over TCP/IP).