CS244a: An Introduction to Computer Networks

Handout 10: Link Layer
CSMA/CD, Ethernet, Token Passing

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The Link Layer

- Application
- Presentation
- Session
- Transport
- Network
- Link
- Physical

The 7-layer OSI Model

The 4-layer Internet Model
Examples of MAC Protocols
(MAC = "Medium Access Control")

<table>
<thead>
<tr>
<th>Single Random</th>
<th>Complex Deterministic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet-Switched Radio Network</td>
<td>Token Passing</td>
</tr>
<tr>
<td>Aloha</td>
<td>Token Ring (IEEE 802.5)</td>
</tr>
<tr>
<td>Carrier Sense Multiple Access/Collision Detection</td>
<td></td>
</tr>
<tr>
<td>Ethernet (IEEE 802.3)</td>
<td></td>
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</tbody>
</table>

Goals of MAC Protocols

MAC Protocols arbitrate access to a common shared channel among a population of users

1. Fair among users
2. High efficiency
3. Low delay
4. Fault tolerant
Outline

- Random Protocols
  - Aloha
  - CSMA/CD
  - Ethernet (CSMA/CD put into practice)

- Token Passing Protocols
  - Common Features
  - Flavor #1: Release After Reception (RAR)
  - Flavor #2: Release After Transmission (RAT)

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Aloha Protocol

Basic operation:
1. All hosts transmit on one frequency.
2. Central node repeats whatever it receives on the other frequency.

If more than one host transmits at the same time

Collision at central node!

If there is a collision, hosts receive corrupted data, and so wait for a randomly chosen time before retransmitting their packets.
Aloha Protocol

- Aloha protocol is very simple, and fairly robust against failure of a host.
- The protocol is distributed among the hosts.
- Under low-load, we can expect the delay to be small.
- Under high-load, a lot of time is “wasted” sending packets that collide.

Improving performance:
- Listen for activity before sending a packet.
- Detect collisions quickly and stop transmitting.
- After a collision, pick the random waiting time so as to maximize throughput.

CSMA/CD Protocol

All hosts transmit & receive on one channel
Packets are of variable size.

When a host has a packet to transmit:
1. Carrier Sense: Check that the line is quiet before transmitting.
2. Collision Detection: Detect collision as soon as possible. If a collision is detected, stop transmitting; wait a random time, then return to step 1.

binary exponential backoff
CSMA/CD Network Size Restriction

To ensure that a packet is transmitted without a collision, a host must be able to detect a collision before it finishes transmitting a packet.

Events:
- \( t=0 \): Host A starts transmitting a packet.
- \( t=PROP \): Just before the first bit reaches Host B, Host B senses the line to be idle and starts to transmit a packet.
- \( t=PROP \): A collision takes place near Host B.
- \( t=PROP \): Host B detects the collision.
- \( t=PROP \): Host A detects the collision.

From example on previous slide we can see that for a Host to detect a collision before it finishes transmitting a packet, we require:

\[ \text{TRANSP} > 2 \times \text{PROP} \]

In other words, there is a minimum length packet for CSMA/CD networks.
Performance of CSMA/CD

We're going to analyze the performance of a CSMA/CD network.

- Our performance metric will be Efficiency, $\eta$. This is defined to be the fraction of time spent sending useful/successful data. The more time spent causing and detecting collisions, the less efficient the protocol is. More precisely:

  \[
  \eta = \frac{\text{Time taken to send data}}{\text{Time taken to send data + overhead}}
  \]

- To make the analysis simple, we'll assume that time is slotted and all packets are the same length. A time slot equals $2 \times \text{PROP}$. In any given time slot, a host will either decide to transmit or not with probability $p$. (This includes packets transmitted for the first time and retransmissions).

- First, we will try and find the value of $p$ that maximizes the throughput (in fact, it's the goodput).

- Then, using the optimal value of $p$, we'll find the efficiency.

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Performance of CSMA/CD

Maximizing goodput

Find the goodput, $\alpha(p)$:

Probability that exactly one node transmits in a given slot.

\[
\alpha(p) = \binom{N}{1} p(1 - p)^{N-1}
\]

\[
\frac{d\alpha}{dp} = N(1 - p)^{N-1} - pN(N - 1)(1 - p)^{N-2}
\]

\[
\therefore \alpha_{\text{max}} \approx 36\% \approx 40\% \text{ when: } p = 1/N
\]
Performance of CSMA/CD

Finding the overhead

Define $A$ to be the expected number of time slots wasted before a packet is transmitted successfully:

$$A = (\alpha \times 0) + (1 - \alpha)(1 + A)$$

$\therefore$ when: $\alpha = \alpha_{\text{max}}$, $A = 1.5$

[Alternatively, consider a coin with $\text{Pr}(\text{heads}) = \alpha = 0.4$. The expected number of coin tosses until the first head is $1/0.4 = 2.5$, i.e. 1.5 unsuccessful attempts, followed by 1 successful one]

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Performance of CSMA/CD

Finding the efficiency

$$\eta_{\text{CSMA/CD}} = \frac{\text{TRANSP}}{\text{TRANSP} + E[\# \text{ of wasted slots per packet}]}$$

$$= \frac{\text{TRANSP}}{\text{TRANSP} + A(2 \times \text{PROP})}$$

$$= \frac{\text{TRANSP}}{\text{TRANSP} + (3 \times \text{PROP})}$$
Performance of CSMA/CD

\[ \eta_{\text{CSMA/CD}} = \frac{1}{1 + 3a}, \quad \text{where:} \quad a = \frac{\text{PROP}}{\text{TRANSP}} \]

From simulation and more precise models:

\[ \eta_{\text{CSMA/CD}} = \frac{1}{1 + 5a} \]

Outline

- Random Protocols
  - Aloha
  - CSMA/CD
  - Ethernet (CSMA/CD put into practice)
- Token Passing Protocols
  - Common Features
  - Flavor #1: Release After Reception (RAR)
  - Flavor #2: Release After Transmission (RAT)
The Original Ethernet

PROP_{max} = l / c = 1500 / 2.5 \times 10^8 = 6 \mu s

TRANSP > 2 \times PROP \Rightarrow TRANSP > 12 \mu s

\therefore \text{Packet size} \geq (12 \mu s) \times 10 \text{Mb/s} / s = 120 \text{bits}

In practice, minimum packet size = 512 bits.
- allows for extra time to detect collisions.
- allows for "repeaters" that can boost signal.

Original picture drawn by Bob Metcalfe, inventor of Ethernet (1972 - Xerox PARC)
**Ethernet Frame Format**

<table>
<thead>
<tr>
<th>Bytes:</th>
<th>7</th>
<th>1</th>
<th>6</th>
<th>6</th>
<th>2</th>
<th>0-1500</th>
<th>0-46</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamble</td>
<td>SFD</td>
<td>DA</td>
<td>SA</td>
<td>Type</td>
<td>Data</td>
<td>Pad</td>
<td>CRC</td>
<td></td>
</tr>
</tbody>
</table>

1. Preamble: trains clock-recovery circuits
2. Start of Frame Delimiter: indicates start of frame
3. Destination Address: 48-bit globally unique address assigned by manufacturer.
   - 1b: unicast/multicast
   - 1b: local/global address
4. Type: Indicates protocol of encapsulated data (e.g. IP = 0x0800)
5. Pad: Zeros used to ensure minimum frame length
6. Cyclic Redundancy Check: check sequence to detect bit errors.

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**The 10Mb/s Ethernet Standard**

**IEEE 802.3**

**Ethernet MAC Protocol**

- 10Base-5: Original Ethernet: large thick coaxial cable.
- 10Base-2: Thin coaxial cable version.
- 10Base-T: Voice-grade unshielded twisted-pair Category-3 telephone cable.
- 10Base-F: Two optical fibers in a single cable.

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10Base-T
"Twisted pair Ethernet"

- Designed to run over existing voice-grade “Category-3”
  twisted pair telephone wire.
- Centralized management (“managed hubs”) lead to more
  reliability.
- Created a huge increase in Ethernet usage.

Increasing the data rate
10Mb/s -> 100Mb/s -> 1Gb/s -> 10Gb/s

- **Problem:** $TRANSP > 2PROP$
- E.g. CSMA/CD at 100Mb/s over 1500m of
cable: $PROP = \frac{1500}{2.5 \times 10^8} = 6 \mu s$

  $\therefore TRANSP > 12 \mu s \Rightarrow \text{Packetsize} \geq 1200\text{bits}$

- **To overcome this two techniques used:**
  - **Cable length limited to 100m:**
    $PROP = \frac{200}{2.5 \times 10^8} \Rightarrow \text{Packetsize} \geq 160\text{bits}$
  - Use “Ethernet Switching” to prevent collisions (in an
    upcoming lecture).
The 100Mb/s Ethernet Standard
"Fast Ethernet"

Different physical layer options

Ethernet MAC Protocol

100Base-T4 100Base-TX 100Base-FX

Up to 100m of cable per segment.

100Base-T4: Uses four pairs of voice grade Category-3 cable.
100Base-TX: Uses two pairs of data grade Category-5 cable.
100Base-FX: Uses two optical fibers.

The 1Gb/s Ethernet Standard
"Gigabit Ethernet"

Ethernet MAC Protocol

1000Base-TX 1000Base-FX

1000Base-TX: Uses four pairs of data grade Category-5 cable.
1000Base-FX: Uses two optical fibers.
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  - Ethernet (CSMA/CD put into practice)
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Token Passing
Common Features

- A token rotates around a ring to each node in turn. We will define:
  \[ PROP = \text{minimum rotation time around ring.} \]
- All nodes (computers, routers, etc.) copy all data and tokens, and repeat them along the ring.
- When a node wishes to transmit packet(s), it grabs the token as it passes.
- It holds the token while it transmits.
- When it is done, it releases the token again and sends it on its way.
Flavor #1: Release After Reception (RAR)

- Computer captures token, transmits data, waits for data to successfully travel around ring, then releases token again.
- Allows computer to detect errored frames and retransmit them.

Example time evolution in which host 1 and host 3 have packets to transmit:

<table>
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<tr>
<th>Time</th>
<th>Host 1</th>
<th>Host 2</th>
<th>Host 3</th>
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<tr>
<td>0</td>
<td>Data</td>
<td>Token</td>
<td>Data</td>
</tr>
<tr>
<td>1/c</td>
<td>Token</td>
<td>Data</td>
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Efficiency of RAR

Recall: Efficiency, $\eta$, is the fraction of time spent sending useful data.

Define: $T_{ij}$ to be the time from when the token arrives at host $i$ until it next arrives at host $j$.

\[ T_{12} \leq \text{TRANSP} + \text{PROP} + \text{TRANST} + \frac{l_i}{c} \]
\[ \therefore T_{1i} \leq N(\text{TRANSP} + \text{PROP} + \text{TRANST}) + \sum \frac{l_i}{c} \]
\[ = N(\text{TRANSP} + \text{PROP} + \text{TRANST}) + \text{PROP} \]

\[ \therefore \eta_{RAR} \leq \frac{N(\text{TRANSP})}{N(\text{TRANSP} + \text{PROP} + \text{TRANST}) + \text{PROP}} \]
\[ = \frac{1}{1 + a}, \quad a = \frac{\text{PROP}}{\text{TRANSP}}, \quad \text{TRANSP} >> \text{TRANST} \]

Flavor #2: Release After Transmission (RAT)

- Computer captures token, transmits data, then releases token again.

Example time evolution in which host 1 and host 3 have packets to transmit:

<table>
<thead>
<tr>
<th>Time Evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRANSP</strong></td>
</tr>
<tr>
<td>Data</td>
</tr>
<tr>
<td><strong>l_i/c</strong></td>
</tr>
</tbody>
</table>

- Token arrives at host 1
- Token departs from host 1
- Token arrives at host 3
- Token arrives at host 2
Efficiency of RAT

\[ T_{1,2} \leq \text{TRANSP} + \text{TRANST} + l_i / c \]
\[ \therefore T_{1,1} \leq N(\text{TRANSP} + \text{TRANST}) + \sum l_i / c \]
\[ = N(\text{TRANSP} + \text{TRANST}) + \text{PROP} \]

\[ \therefore \eta_{\text{RAT}} \leq \frac{N(\text{TRANSP})}{N(\text{TRANSP} + \text{TRANST}) + \text{PROP}} \]
\[ a = \frac{\text{PROP}}{\text{TRANSP}}, \quad \text{TRANSP} >> \text{TRANST} \]

Comparison of Efficiencies

Example: 100 node network
- PROP = 1000m/c
- TRANSP = (1000bits)/ (100Mb/s)

\[ a = \frac{4}{10} = 0.4 \]
\[ \eta_{\text{CSMA/CD}} = \frac{1}{1 + 5a} = \frac{1}{1 + 2} = 33.3\% \]
\[ \eta_{\text{RAR}} \leq \frac{1}{1 + a} = 71\% \]
\[ \eta_{\text{RAT}} \leq \frac{1}{1 + a / N} = 99.6\% \]
Token Rings

Techniques:
- Release After Reception (RAR)
- Release After Transmissions (RAT)

Examples:
- RAR: IEEE 802.5 Token Rings
- RAT: Fiber Distributed Data Interface (FDDI)