CSMA/CD Throughput

\[ \rightarrow \text{ approximate analysis in simplified setting} \]

Assumptions:

- time is slotted
  \[ \rightarrow \text{ slot duration: } 2\tau \]
- \( k \) hosts; each host transmits with probability \( p \) at every slot
  \[ \rightarrow \text{ transmission behavior among hosts independent} \]
  \[ \rightarrow \text{ transmission behavior across slots independent} \]

Note:

- independence among users: typical assumption
- independence across time: strong assumption
CSMA/CD is a feedback control:

\[\rightarrow \text{ modify future behavior depending on present/past}\]

That is:

\[\rightarrow \text{ upon collision more to send in the future: } p \uparrow\]
\[\rightarrow \text{ upon backoff: } p \downarrow\]
\[\rightarrow \text{ more general: backlog}\]
We will consider fixed, independent $p$

→ no backlogs

→ no feedback adaptation of $p$

New performance metric: utilization ($\varrho$)

→ fraction of total bandwidth attained

→ $0 \leq \varrho \leq 1$

→ captures efficiency and wastage

In slotted CSMA/CD:

→ fraction of usefully used slots

→ what are “uselessly used” slots?
Ex.: snapshot of baseband channel over 10 time slots
→ blue: successfully transmitted frames
→ brown: collided frames
→ utilization $\varrho$?

One more viewpoint:

→ note: useful and useless “periods” alternate
In the long run,

\[ \varrho = \frac{E[\text{good}]}{E[\text{good}] + E[\text{bad}]} \]

→ avrg. length of adjacent “good” and “bad” periods
→ formula holds under mild conditions

Next: calculate \( E[\text{good}] \) and \( E[\text{bad}] \)
Fix time slot. Probability that a fixed host acquires the slot successfully
\[ p(1 - p)^{k-1} \]

Probability that some host acquires the slot
\[ \eta = kp(1 - p)^{k-1} \]

\[ \longrightarrow \] why?

Now, let’s be generous and find \( p \) that maximizes \( \eta \)

\[ \longrightarrow \] upper bounding

Fact: \( \eta \) is maximized at \( p = 1/k \). Also,
\[ \lim_{k \to \infty} \eta = \lim_{k \to \infty} \left( 1 - \frac{1}{k} \right)^{k-1} = 1/e. \]

\[ \longrightarrow \] many user assumption

\[ \longrightarrow \] common practice to simplify expression (valid?)
Probability bad period persists for exactly $i$ slots

$$(1 - \eta)^{i-1}\eta$$

Therefore average bad period

$$E[\text{bad}] = \sum_{i=0}^{\infty} i(1 - \eta)^{i-1}\eta = 1/\eta$$

$E[\text{bad}]$ is in unit of slots. Convert to second:

$$2\tau/\eta = 2\tau e$$

Similarly calculate $E[\text{good}]$; call it $\gamma$.

Convert $\gamma$ to second:

$$\gamma F/B$$

where

$F$: frame size (bits)

$B$: bandwidth (bps)
Putting everything together

\[ \varrho = \frac{E[\text{good}]}{E[\text{good}] + E[\text{bad}]} \]

\[ = \frac{\gamma F/B}{\gamma F/B + 2\tau e} \]

\[ = \frac{\gamma F/B}{\gamma F/B + 2Le/c} \]

\[ = \frac{1}{1 + (2e/c\gamma)BL/F} \]

where

- \( L \): length of wire (meters)
- \( c \): speed of light (m/s)

What does the formula say?

For example, if \( B \) is increased, what must be done to maintain high utilization?
Note: $BL/F$ comes into play during unit conversion from slots to seconds

$\rightarrow$ holds for different $E[\text{good}]$ and $E[\text{bad}]$

$\rightarrow$ invariant

Recall: to minimize probability of collision we set

$$p = \frac{1}{k}$$

$\rightarrow$ $p$-persistent version of CSMA/CD

$\rightarrow$ depends on knowledge of number of users

$\rightarrow$ today’s Ethernet: 1-persistent

For fixed $p$, as a function of $k$ CSMA/CD throughput is unimodal, i.e., dome-shaped

$\rightarrow$ under excessive load, throughput goes down
In practice today: switched Ethernet

- contention moved from bus to “single point”
  → switch: star topology
  → analogous to old telephone switch-boards

- Ethernet frames are logically scheduled
  → includes buffering

Diagram of output-buffered switch:

[Diagram of output-buffered switch]

→ interconnection networks (e.g., shuffle-exchange)

→ switching fabric: hardware
• Ethernet switch emulates CSMA/CD
  → backward compatibility
  → use same frame format
• upon buffer overflow: send collision signal
  → transparent to legacy host NIC
  → awkward: instituted for incremental deployment
  → Internet: new technology must respect legacy

Ex.: 10Base-T, 100Base-T, 1000Base-T and 1000Base-X

  — FE: 802.3u; GigE: 802.3ab and 802.3z
  — negotiation: e.g., full/half duplex
  — how can GigE overcome length limitation?
  — e.g., supports 200 m as in FE
Slot time extension:

- frame format remains the same
- minimum slot time extended from 64 B to 512 B
  → padding: transparent to legacy CSMA/CA
  → also called carrier extension
  → reconciliation sublayer between MAC and PHY

Packet bursting:

- slot time extension alone problematic
  → small frames: marginal increase in throughput
- allow burst of packets
  → only first packet is padded & burst limit
Longer distances?

→ e.g., 1000Base-LX

Medium-haul GigE/10GigE (802.3ae): 500m, 5km, 40km

• CSMA/CD disabled
  → purely point-to-point link
  → switch-to-switch
  → simpler
  → backward compatibility: not an issue

• flow control
  → pause frame to prevent buffer overflow

QoS: 802.3p

→ frame tagging conveys priority

→ priority classes supported at switches
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

Used as high-bandwidth campus/city backbone.

→ metropolitan/campus distance: MAN
Basic operation:

→ B wants to send to D
Fault-tolerance:

- DAS (dual attachment station)
- SAS (single attachment station)
- frame size < 4500 B
- 4B/5B encoding
- 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)

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

To increase efficiency: increase THT

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

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):

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

\[\rightarrow\] token claim process

\[\rightarrow\] 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.

\[\rightarrow\] leader election

At the end of the day, consistent TTRT value among all stations.

\[\rightarrow\] consensus problem
Compare against Ethernet’s CSMA/CD.

→ round-robin reservation
→ absence of MA and collision
→ determinism vs. indeterminism
→ imperfect QoS assurance
→ performance vis-à-vis CSMA/CD?

Cooperative vs. noncooperative protocols

→ robust if some users use selfish MAC
→ could be malicious