Week 8: Multiple Access Links and Protocols

EE3017/IM2003 Computer Communications

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Topic Outline
(Updated in January 2020)

Topic Outline

Multiple Access Links and Protocols

- Point-to-Point Links
- Multiple Access Links and Protocols
- Ideal Multiple Access Protocol
- Channel Partitioning Protocols
- Random Access Protocols
- “Taking-turns” Protocols
- MAC Addresses

Recommended reading:
Section 5.3, Pages 481 to 495 of the recommended textbook
(Page numbers are based on 5^{th} or 2010 Edition.)

Learning Objectives

Learning Objectives

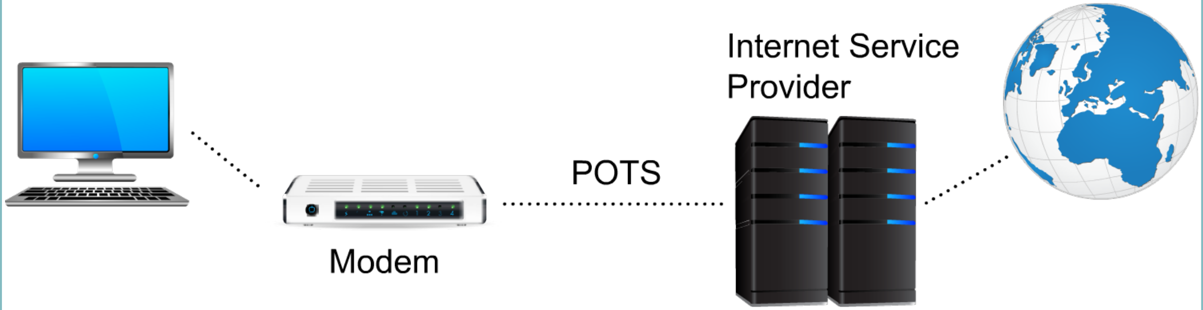
By the end of this topic, you should be able to:

- Explain the differences between point-to-point links and multiple-access links.
- Explain the desired characteristics of an ideal multi-access protocol.
- Explain Channel Partitioning, Random Access, and “Taking Turns” multi-access protocols.
- Analyse various MAC protocols.
- Explain the structure of MAC addresses.

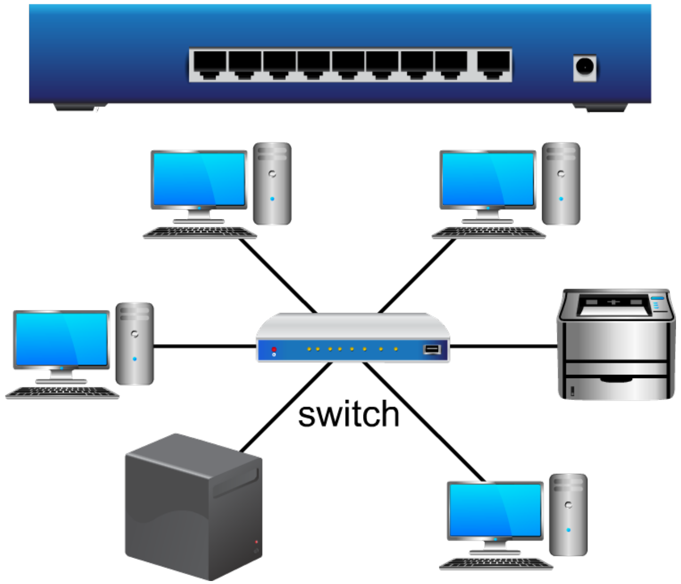
Point-to-Point Links

Point-to-Point Links

Examples of point-to-point links:



Point-to-point link for dial-up access



Point-to-point link between an Ethernet switch and hosts

POTS: Plain old telephone service

Notes: Point-to-Point Links

In any communication system or computer network, the physical connections between network devices could be categorised into point-to-point links or multiple access links.

A point-to-point link connects two network devices at both end of the link. Normally the point-to-point link is bidirectional; hence, the network devices at both ends of the link could transmit simultaneously without interfering with each other's transmission.

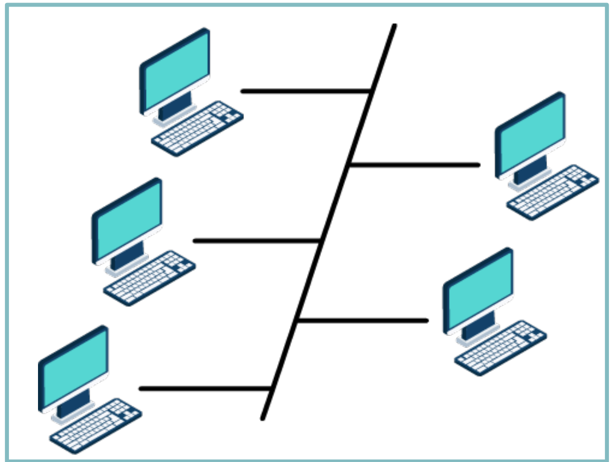
A good example of a point-to-point link is how the plain old telephone is connected to the local telephone exchange. Another good example is computers are connected to a network switch.

Multiple Access Links

Multiple Access Links

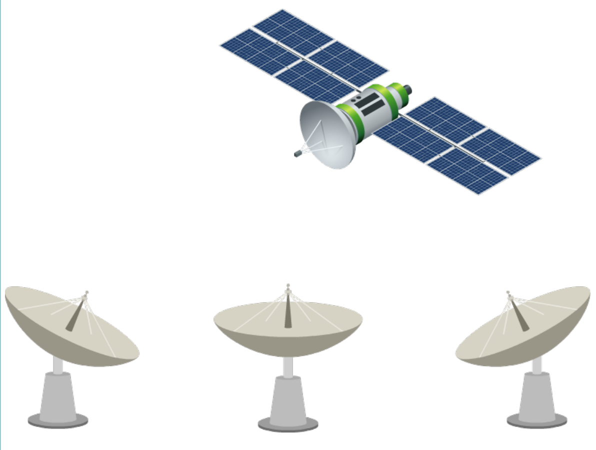
Multiple Access (shared wire or medium)

- old-fashioned Ethernet
- upstream Hybrid Fibre-Coax (HFC)
- 802.11 wireless LAN



shared wire (e.g. cabled Ethernet)

shared RF (e.g. 802.11 WiFi)



shared RF (satellite)

humans at a cocktail party (shared air, acoustical)

RF: Radio frequency

Multiple Access Protocols

- Single shared broadcast medium
- Two or more simultaneous transmissions by nodes: interference
  - collision if node receives two or more signals at the same time

<u>Medium access control</u>

- Distributed algorithm that determines how nodes share medium, i.e. determine when node can transmit
- Communication about medium sharing must use the medium itself!
  - No out-of-band channel for coordination

Notes: Multiple Access Links and Protocols

- A transmission medium is also known as a channel.
- Networks that make use of multiple access links and protocols include old fashion Ethernet, wi-fi and satellite communication.
- A multiple access link connects multiple (typically more than two) network devices with the link being a shared medium – meaning that when one network device transmits on the medium, all the network devices will be able to receive the transmission.
- It also means that when more than one network devices transmit at the same time, their transmissions will interfere and corrupt each other’s transmission – this is known as collision.
- There is the need for a distributed algorithm, known as medium access control protocol – to govern how nodes share the medium such that the nodes could transmit and receive data correctly and efficiently.
- Note that normally the communication among nodes about medium sharing must use the medium itself! This is known as in-band signaling (the opposite is out-of-band signaling).

Ideal Multiple Access Link and Protocol

Broadcast channel of rate *R* bps

1. When one node wants to transmit, it can send at rate *R*
2. When *M* nodes want to transmit, each can send at average rate *R*/*M*
3. Fully decentralised:
   - no special node to coordinate transmissions
   - no synchronisation of clocks, slots
4. Simple

MAC Protocols: A Taxonomy

Three broad classes:

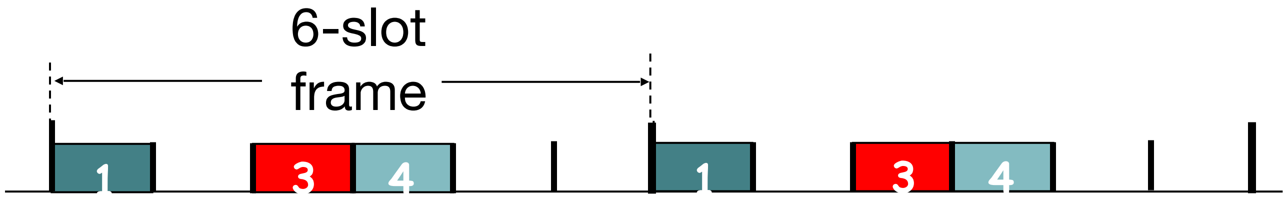
Channel Partitioning	Random Access	"Taking turns"
• Divide channel into smaller "pieces" (time slots, frequency, code) • Allocate piece to node for exclusive use	• Channel not divided, allow collisions • Need to "Recover" from collisions	• Nodes take turns, but nodes with more to send can take longer turns

Channel Partitioning Protocols

Channel Partitioning MAC Protocols: TDMA

TDMA: Time Division Multiple Access

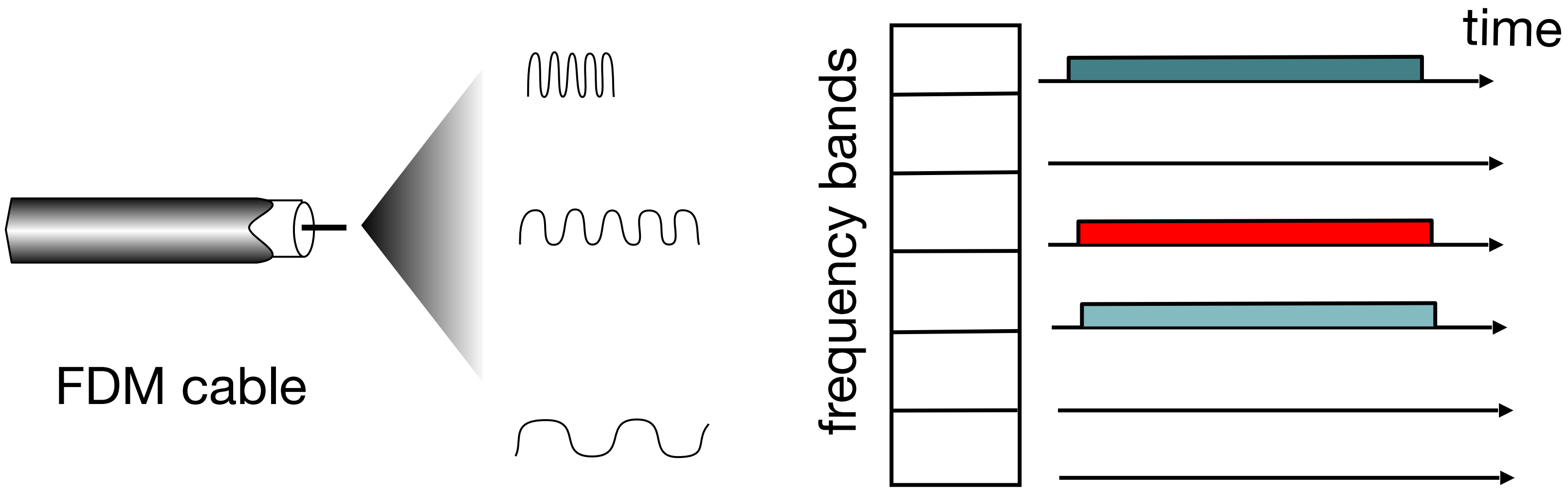
- Access to channel in "rounds"
- Each station gets fixed length slot (length = packet transmission time) in each round
- Unused slots go idle
- E.g. 6-station LAN, 1,3,4 have packets, slots 2,5,6 idle



Channel Partitioning MAC Protocols: FDMA

FDMA: Frequency Division Multiple Access

- Channel spectrum divided into frequency bands
- Each station assigned fixed frequency band
- Unused transmission time in frequency bands go idle
- E.g. 6-station LAN, 1,3,4 have packets, frequency bands 2,5,6 idle



Notes: Channel Partitioning Protocols

- TDMA and FDMA are two techniques that can be used to partition a broadcast channel's bandwidth among all nodes sharing that channel.

- TDMA divides time into time frames and further divides each time frame into *N* time slots. Each time slot is then assigned to one of the *N* nodes. Whenever a node has a packet to send, it transmits the packet's bits during its assigned time slot in the recurring TDM frame. Typically slot sizes are chosen such that a single packet can be transmitted during a slot time.

- TDMA eliminates collisions and is perfectly fair as each node gets a dedicated transmission rate of *R*/*N* bps, where *R* is the data rate of the shared medium.

- The two major drawbacks of TDMA:
  - A node is limited to an average rate of *R*/*N* bps even when it is the only node with data to send.
  - A node must always wait for its turn in the transmission sequence even when it is the only node with data to send.

Notes: Channel Partitioning Protocols

- FDMA divides the *R* bps medium into different frequencies, each with a bandwidth of *R*/*N*, and assigns each frequency to one of the *N* node.

- FDM shares both the advantages and drawbacks of TDMA.

- Other channel partitioning protocols are Code Division Multiple Access (CDMA) and Wavelength Division Multiplexing (WDM), *which are not covered in this course.*

Random Access Protocols

Random Access Protocols

- When node has packet to send:
  - transmit at full channel data rate *R*
  - no *a priori* coordination among nodes

- Two or more transmitting nodes ➜ “collision”

- Random access MAC protocol specifies:
  - how to detect collisions
  - how to recover from collisions (e.g. via delayed retransmissions)

- Examples of random access MAC protocols:
  - Slotted ALOHA
  - ALOHA
  - CSMA, CSMA/CD, CSMA/CA

Notes: Random Access Protocols

- In a random access protocol, a transmitting node always transmits at the full rate of the channel, *R* bps.

- When a node experiences a collision, it waits for a random delay before retransmitting the frame. Each node involved in a collision chooses independent delays to minimise the chances of further collisions.

- Some schemes such as CSMA/CD (old fashion Ethernet) is able to detect collision almost immediately and abort the transmission straightaway while other schemes such as ALOHA and Slotted ALOHA assume that a transmission is unsuccessful unless it receives an acknowledgement with a specific epoch time. CSMA/CA is used in wi-fi and it uses short RTS (Request to Send) and CTS (Clear to Send) frames to secure exclusive access to the medium before transmission. *All these multiple access protocols will be discussed later.*

Slotted ALOHA

Slotted ALOHA

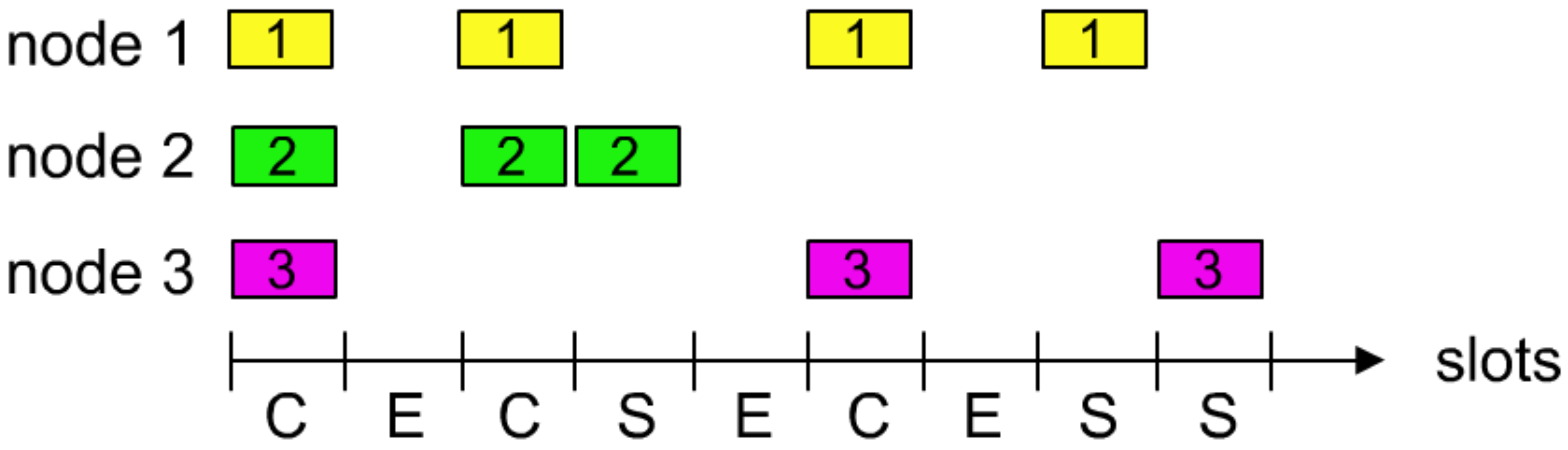
Assumptions

- All frames have the same size.
- Time is divided into equal size slots (time to transmit 1 frame).
- Nodes start to transmit only at beginning of slot.
- Nodes are synchronised.
- If two or more nodes transmit in slot, all nodes detect collision.

Operation

- When node obtains fresh frame, transmits in next slot:
  - *if no collision*: node can send new frame in next slot.
  - *if collision*: node retransmits frame in each subsequent slot with probability p until successful.

Slotted ALOHA



Pros

- Single active node can continuously transmit at full rate of channel
- Highly decentralised: only slots in nodes need to be in sync
- Simple

Cons

- Collisions, wasting slots
- Idle slots
- Slot synchronisation

Slotted ALOHA Efficiency

Efficiency: long-run fraction of successful slots (many nodes, all with many frames to send).

Suppose:

N nodes with many frames to send, each transmits in slot with probability *p* *(Note that this is not exactly how Slotted ALOHA operates but it will keep the analysis simple)*.

- Probability that given node has success in a slot $= p(1-p)^{N-1}$
- Probability that *any* node has success in a slot $= Np(1-p)^{N-1}$
- Max efficiency: Find p^* that maximises $Np(1-p)^{N-1}$
- For many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as *N* goes to infinity, gives:

  Max efficiency = 1/e = 0.37

At best: channel used for useful transmissions 37% of

Notes: Slotted ALOHA

- Note that there is a need for all the nodes in the Slotted ALOHA network to synchronise their slots. One way to do it is for a (master) node to send out a special bit sequence to all nodes on a regular basis for slot synchronisation.

- When a node in a Slotted ALOHA network has a new frame to send, it waits until the beginning of the next slot and transmits the entire frame in the slot. Note that all frames have the same size and fit exactly in the slot.

- If there is no collision, the node will successfully transmit its frame and thus need not consider retransmitting the frame. The node can prepare a new frame for transmission, if it has one. Note that the sending node knows that its transmission is successful when it receives a short acknowledgement frame from the intended receiving node. This acknowledgement is not illustrated in the diagram but you can imagine that each slot shown is long enough to accommodate the sending node to send its frame as well as for the receiving node to send a short acknowledgement.

Notes: Slotted ALOHA

- If there is a collision, the sending node will know it because it does not receive an acknowledgement from the receiving station within the slot. The sending node then decides whether to retransmit its frame in the following slots with probability p (a number with a value between 0 and 1) until the frame is successfully transmitted with an acknowledgement received.

- By retransmitting with probability p, the node effectively tosses a biased coin; the event “head” corresponds to “retransmit,” which occurs with probability p. The event “tail” corresponds to “skip the slot and toss the coin again in the next slot,” which occurs with probability $(1 - p)$.

- By using an approximate analysis, it can be shown that the efficiency of a Slotted ALOHA network is approximately 1/e = 0.37.

Exercise

Suppose three active nodes: nodes A, B, and C, are competing for access to a channel using slotted ALOHA. Assume each node has an infinite number of frames to send. Each node attempts to transmit in each slot with probability *p*. *(Note that this assumption is made to simplify the analysis. In actual fact, after a node successfully transmits a frame without collision, it will transmit a new frame with certainty, i.e., with probability of 1, in the next slot.)*

For easy reference, assume that the first slot is numbered slot 1, the second slot in numbered slot 2, and so on.

a) What is the probability that node A succeeds in a slot?
b) What is the probability that some node succeeds in a slot?
c) What is the probability that node A succeeds for the first time in slot 4?
d) What is the efficiency of this three-node system?

Answers

a) What is the probability that node A succeeds in a slot?

Let q = Pr{Node A succeeds in a slot}
= Pr{Node A transmits while Nodes B and C do not transmit in the slot}
$= p\,(1-p)^2$

b) What is the probability that some node succeeds in a slot?

Pr{Some node succeeds in a slot}
= ${}^{3}C_{1}$Pr{Node A transmits while Nodes B and C do not transmit in the slot}
$= 3p\,(1-p)^2$

Answers

c) What is the probability that node A succeeds for the first time in slot 4?

Pr{Node A succeeds for the first time in slot 4}
= Pr{Node A fails in slots 1, 2 and 3) x Pr{Node A succeeds in slot 4}
= $(1-q)^3 q$

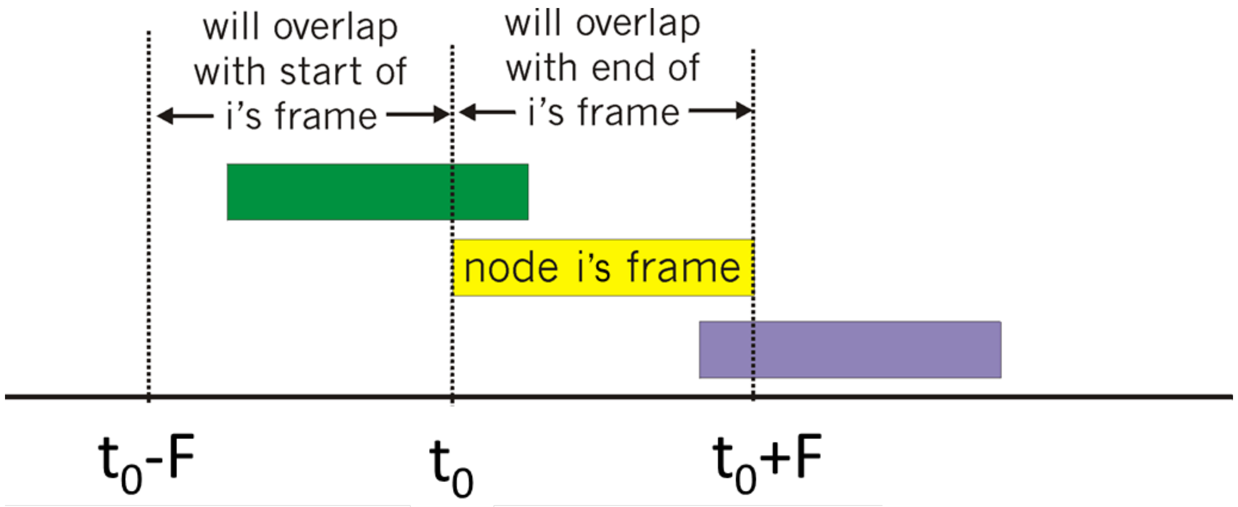
d) What is the efficiency of this three-node system?

Efficiency = Pr{Some node succeeds in a slot}
= $3p\,(1-p)^2$

ALOHA

Pure (Unslotted) ALOHA

- Unslotted ALOHA: simpler, no synchronisation
- When frame first arrives:
  - transmit immediately.
- Collision probability increases:
  - frame sent at t_0 collides with other frames sent in $[t_0 - F, t_0 + F]$, where F is the time required to transmit a frame.



Pure (Unslotted) ALOHA Efficiency

Pr(success by given node) = Pr(node transmits) ·

Pr(no other node transmits in $[t_0-F,t_0]$ ·

Pr(no other node transmits in $[t_0,t_0+F]$

$= p \cdot (1-p)^{N-1} \cdot (1-p)^{N-1}$

$= p \cdot (1-p)^{2(N-1)}$

… choosing optimum p and then letting $N \rightarrow$ infinity …

= 1/(2e) = 0.18

! even *worse* than slotted Aloha!

Notes: Pure ALOHA

- The original ALOHA system proposed by Abramson in 1970 was an unslotted, and fully decentralised protocol.

- In Pure ALOHA, when a frame first arrives, the node immediately transmits the frame in its entirety into the broadcast channel.

- If a transmitted frame experiences a collision with one or more other transmissions, it will not receive an acknowledgment from the receiving node. The sending node will then retransmit the frame with probability *p*, Otherwise, the node waits for a frame transmission time. After the wait, it then transmits the frame with probability *p*, or waits (remain idle) for another frame time with probability 1-*p*.

- Let the needed to transmit a frame be F. A frame sent at t_0 will collide with other frames sent in the period of $[t_0 - F, t_0 + F]$.

- It can be shown that the probability that a given node has a successful transmission is $p \cdot (1-p)^{2(N-1)}$. By choosing an optimal value of *p* and let *N* approach infinity, it can be shown that the efficiency of the Pure ALOHA network is 1/(2e) = 0.18.

Exercise

You wish to use the pure ALOHA protocol for a field communications system. The data transmission rate of the system is 10 Mbps. Each field station is estimated to need to transmit 40 frames per second with an average frame size of 1000 bytes. Estimate the maximum number of field stations the network can support. If the slotted ALOHA protocol is used, what is the maximum number of field stations the network can support?

Answers

Maximum efficiency of Pure ALOHA network is approximately 1/(2e) = 0.18.

1. The maximum throughput the Pure ALOHA network can support is
   10 Mbps x 0.18 = 1.8 Mbps.

2. Traffic generated by each field station
   = 40 Fps * 1000 bytes * 8 bits = 0.32 Mbps

3. 1.8 Mbps / 0.32 Mbps = 5.6

Hence, the maximum number of stations that can be supported is only 5.

If Slotted ALOHA network is used, the maximum efficiency is about 1/e = 0.37.

3.7 Mbps / 0.32 Mbps = 11.6

Hence, the maximum number of stations that can be supported is 11.

Carrier Sense Multiple Access (CSMA)

Carrier Sense Multiple Access (CSMA)

CSMA

listen before transmit

If channel sensed idle, transmit entire frame

If channel sensed busy, defer transmission

Human analogy:
Don’t interrupt others!

CSMA Collisions

Collisions *can* still occur:

Propagation delay means two nodes may not hear each other's transmission.

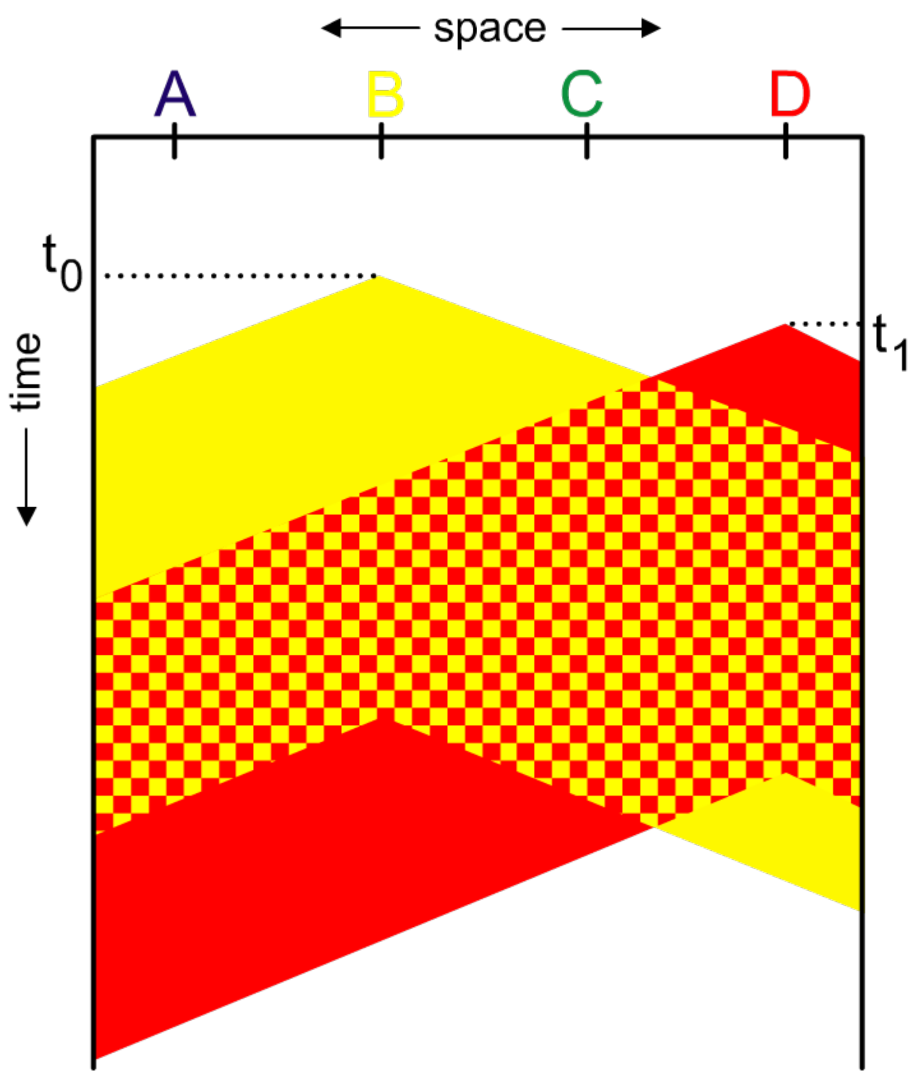
Collision:

Entire packet transmission time wasted.

Note:

Role of distance and propagation delay in determining collision probability.

Spatial layout of nodes



Notes: CSMA

- In both Slotted and Pure ALOHA, a node's decision to transmit is made independently of the activity of the other nodes attached to the broadcast channel. A node neither pays attention to whether another node happens to be transmitting when it begins to transmit, nor stops transmitting if another node begins to interfere with its transmission.

- In CSMA network, a node listens to the channel before transmitting. This is known as carrier sensing. If a frame from another node is currently being transmitted into the channel, a node then waits ("backs off") a random amount of time and then senses the channel again. If the channel is sensed to be idle, the node then begins frame transmission. Otherwise, the node waits for another random amount of time and repeats the process.

- In the time space diagram, at time t_0, Node B senses the channel is idle and begins transmitting a frame, with its bits propagating in both directions along the broadcast medium. Due to propagation delay, the first bit of B's transmission will only reach Node D at time t_2.

Notes: CSMA

- However, at time t_1, Node D still senses the channel to be idle and thus begins transmitting its frame. As a result, the transmissions from B and D will interfere with each other and cause collision.
- The effect of the collision will be felt by different nodes at different times depending on their positions in the network relative to B and D. Regardless of how short the duration the two transmissions interfere with each other, some bits in the two frames will be corrupted and rendered both frames to be in errors and have to be discarded and retransmitted.
- The channel propagation delay (CPD) has an impact on the performance of a CSMA network because the longer the CPD, the larger the chance that a carrier-sensing node is not yet able to sense a transmission that has already begun at another node in the network.
- In the CSMA network, nodes do not perform collision detection; hence, B and D continue to transmit their frames in their entirety even though a collision has occurred.

CSMA/CD

Carrier Sense Multiple Access (CSMA)

CSMA/CD

Carrier sensing,
deferral as in CSMA

Collisions detected within a short time

Colliding transmissions aborted, reducing channel wastage

Human analogy:
The polite conversationalist

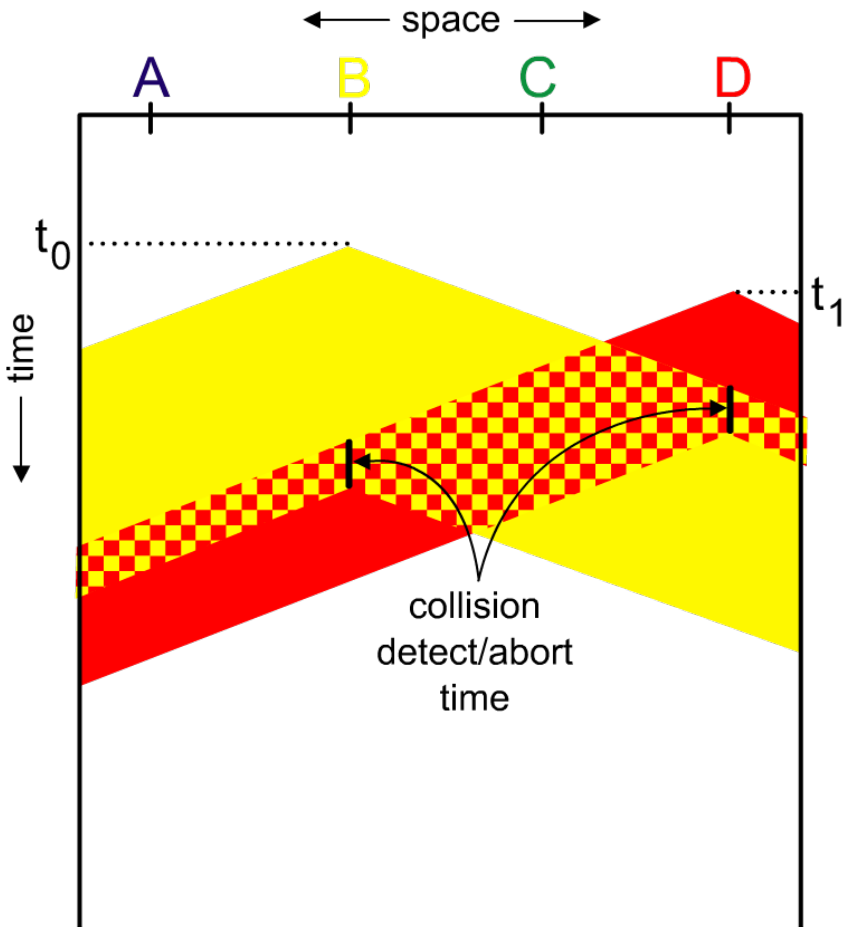
Collision detection:

- Easy in wired LANs:
  Measure signal strengths, or compare transmitted and received signals.

- Difficult in wireless LANs:
  Received signal strength overwhelmed by local transmission strength.

CSMA/CD Collision Detection

Spatial layout of nodes



Notes: CSMA/CD

- CSMA/CD is the multi-access protocol used in the old fashion Ethernet and is standardised under IEEE802.3.

- Unlike CSMA, CSMA/CD nodes are able to perform collision detection. When a node detects collision, it ceases transmission. By ceasing transmission after collision is detected, CSMA/CD frees up the channel almost immediately. Hence, it has better performance compared to CSMA, which continues to transmit the entire frame even after the frame is corrupted by collision.

- In the next module when the Ethernet is discussed in detail, you will find out that the efficiency of a CSMA/CD network is approximately $1/(1 + 5a)$ where a is the ratio of the maximum end-to-end delay of the network segment (t_{prop}) and the average frame transmission time (t_{frame}).

“Taking Turns” Protocols

“Taking Turns” Protocols

Channel Partitioning	Random Access	“Taking turns”
• Share channel *efficiently* and *fairly* at high load • Inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only one active node!	• Efficient at low load: single node can fully utilise channel • High load: collision overhead	• Look for best of both worlds!

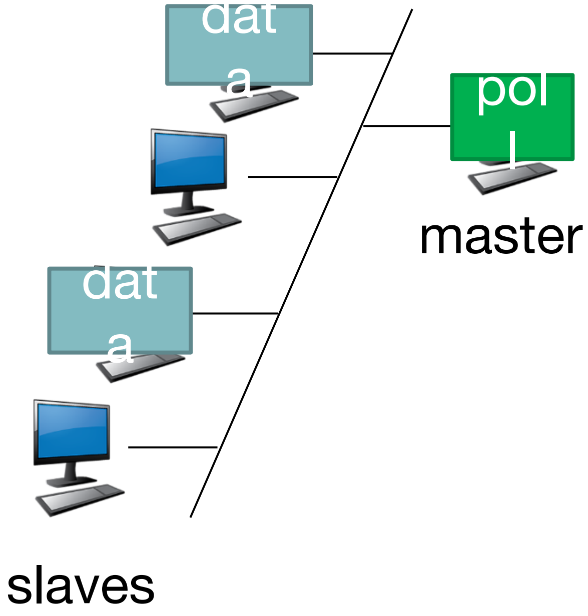
“Taking Turns” Protocols

Polling:

- Master node “invites” slave nodes to transmit in turn.
- Typically used with “dumb” slave devices.

Concerns:

- Polling overhead
- Latency
- Single point of failure (master)



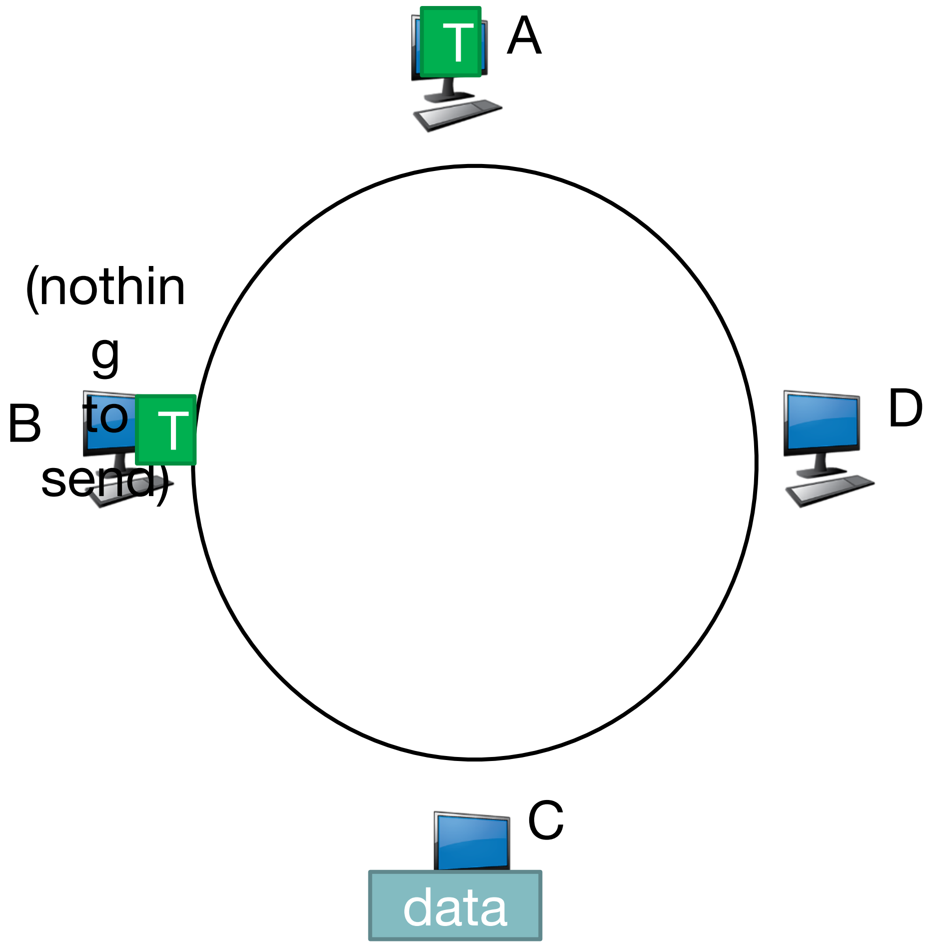
“Taking Turns” Protocols

Token passing:

- Control token passed from one node to next sequentially.
- Token is a special frame

Concerns:

- Token overhead
- Latency
- Single point of failure (token)



Notes: “Taking Turns” Protocols

- Recall that two desirable properties of a multiple access protocol are
  (1) when only one node is active, the active node has a throughput of *R* bps, and
  (2) when *M* nodes are active, then each active node has a throughput of nearly *R*/*M* bps.
  Channel Partitioning Protocols could achieve the second property but not the first. On the other hand, the Slotted ALOHA, Pure ALOHA, CSMA and CSMA/CD protocols could achieve the first property but not the second. This motivated researchers to create the “Taking Turns” protocols.

- There are many variations of “Taking Turns” protocols and we will briefly discuss only the Polling Protocol and the Token-Passing Protocol.

- The polling protocol requires one of the nodes to be designated the master node. The master node polls each of the nodes in a round-robin fashion. The master could inform a station being polled up to how many frames or bytes it could transmit. The master station can determine when a node has finished sending its frames by observing the lack of a signal on the channel.

Notes: “Taking Turns” Protocols

- The polling protocol eliminates the collisions and empty slot that plague random access protocols. This allows polling to achieve much higher efficiency.

- Drawbacks of Polling: 1) Polling overhead; 2) Latency - a node can only send a limited number of frames each time and must wait to be polled many rounds if it is the only node that has many frames to send; 3)The master node is the single point of failure.

- In token-Passing, there is no master node. A short token frame is circulated among the nodes. When a node receives a token, it will release the token immediately if it does not have any frames to transmit; otherwise it sends up to a maximum number of frames and then releases the token.

- Token passing is higher decentralised and efficient. Its drawbacks are: 1) The failure of one node can crash the entire network; 2) If the token is corrupted or a station fails to release the token, some recovery procedure must be invoked to recover the token.

MAC Addresses

Medium Access Control (MAC) Addresses

MAC (or LAN or physical or Ethernet) address:

Function: get frame from one interface to another physically-connected interface (same network).

48 bit MAC address (for most LANs)

- burned in NIC ROM, also sometimes software settable.

Example: E0-18-77-46-F4-34.

- The first six hexadecimal numbers E0-18-77 reveal that the NIC was manufactured by Fujitsu.

MAC Addresses

More…

MAC address allocation administered by IEEE.

Organisationally Unique Identifier (OUI) -- manufacturer buys portion of MAC address space (to assure uniqueness); for example:

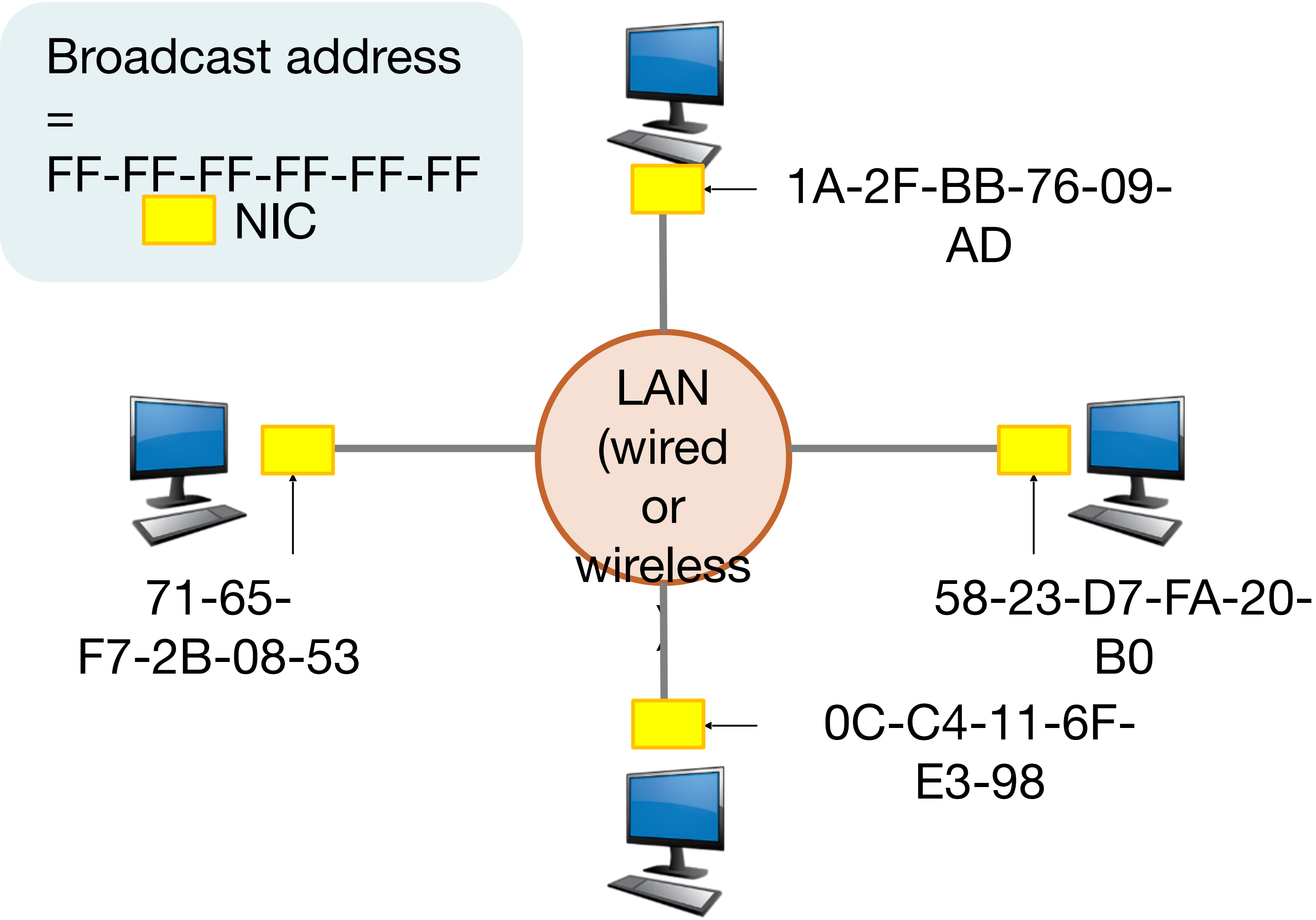
- Dell: 00-14-22
- Cisco: 00-40-96
- Fujitsu: E0-18-77

Flat address ➜ portability

- Can move LAN card from one LAN to another.

MAC Addresses

Each adapter on LAN has a unique LAN address.



Notes: MAC Addresses

- Every host (computer, laptop, smart phone etc.) is connected to the local area network (Ethernet or wi-fi etc.) via one or more network interface cards (NICs). For example, a laptop will normally have a Fast Ethernet NIC and a wi-fi NIC.

- MAC addresses are formed according to the rules of one of three numbering spaces managed by the Institute of Electrical and Electronics Engineers (IEEE): MAC-48, EUI-48, and EUI-64. In this course, we will discuss only the MAC-48 addressing scheme.

- MAC-48 addresses are 48 bits and usually expressed as 6 pairs of two hexadecimal numbers separated by ‘-’; e.g., E0-18-77-46-F4-34

- MAC addresses are normally assigned by the manufacturer of an NIC and are stored in its hardware, such as the card's read-only memory. If assigned by the manufacturer, a MAC address usually encodes the manufacturer's registered identification number and may be referred to as the burned-in address (BIA).

Notes: MAC Addresses

- The first 24 bits in the MAC address are collectively called the Organisationally Unique Identifier (OUI), which identifies the manufacturer. For example, E0-18-77-46-F4-43 is a NIC manufactured by Fujitsu because E0-18-77 is Futjitsu's OUI.

- MAC address has a flat structure and does not change no matter where the NIC goes.

- When an NIC wants to send a frame to some destination NIC, the sending NIC inserts the destination NIC's MAC address into the frame and then sends the frame into the LAN. If the LAN is a broadcast LAN, the frame is received and processed by all other NICs on the LAN. Each NIC will check to see if the destination MAC address in the frame matches its own MAC address. If there is a match, the NIC extracts the enclosed datagram; otherwise, the frame is discarded.

- FF-FF-FF-FF-FF-FF is a special MAC address that is used by a NIC to broadcast to all the NICs on the LAN.

Summary

Summary

Key points discussed in this topic:

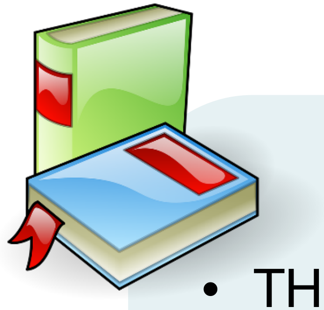
- Channel partitioning, by time, frequency or code
  - Time Division, Frequency Division, Code Division

- Random access (dynamic)
  - ALOHA, Slotted ALOHA, CSMA, CSMA/CD
  - Carrier sensing: easy in some technologies (wire), hard in others (wireless)
  - CSMA/CD used in Ethernet
  - CSMA/CA used in 802.11

- “Taking turns”
  - Polling from central site, token passing, etc.
  - FDDI, IBM Token Ring, etc.

Recommended Readings

Recommended Readings



- THE ALOHA SYSTEM — Another alternative for computer communications
  by NORMAN ABRAMSON, University of Hawaii, Honolulu, Hawaii

- AFIPS '70 (Fall) Proceedings of the November 17-19, 1970, Fall Joint Computer Conference, Pages 281-285
  This paper has been uploaded is available for download at
  https://www.clear.rice.edu/comp551/papers/Abramson-Aloha.pdf