Fundamentals of Computer Networking

Guevara Noubir

Lecture 4: Multi-Access Communication

CSG150

Outline

- Introduction
- ALOHA/Slotted ALOHA: mathematical analysis, performance, stability, etc.
- Other MAC protocols: CSMA, Ethernet, Token-Ring
- MAC for wireless

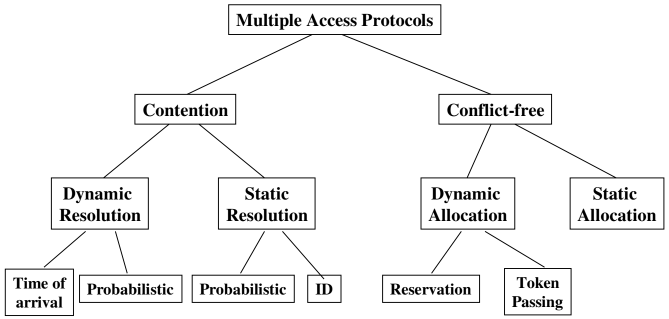
Multiple Access Schemes: Summary

- Stations can communicate if they use different combinations of: frequency, time slot, code, location, polarization
  - Note: it is not always possible to implement all these access schemes
- An atomic resource can be defined as:
  - (freq, time-slot, code, location, polarization)
  - The simultaneous use of an atomic resource results in a “collision” and loss of packets
- Medium Access Protocols define the rules for stations to share these resources
- Algorithms for MAC can be used in other contexts
  - distributed systems (*e.g.,* databases)

Shared Mediums

- Wireless channels (e.g., satellite, WLAN)
- Multi-tapped bus (e.g., ethernet, token bus, CATV)

Classification of MAC Protocols



MAC Protocols: Evaluation

- Throughput
- Delay
- Buffering
- Stability

We also generally assume that:
  - channel is errorless
  - a feedback is available

Slotted Aloha [Abramson1970]

- History: developed by the University of Hawaii to connect data terminals to a central computer using radio channels
- Assumptions on an ideal slotted multi-access model:
  - Slotted system (discrete system, no sensing)
  - Poisson arrivals: λ/m (m is the number of nodes)
  - Collision or perfect reception
  - Feedback: 0, 1, collision
  - Retransmissions: colliding packets are retransmitted until successfully received (=> backlogged nodes)
  - Buffering options:
    - No buffering: packets arriving at backlogged nodes are discarded
    - Infinite set of nodes ($m \to \infty$): packets always arrive at new nodes

Slotted Aloha Algorithm

- Unbacklogged transmits a newly arriving packet in the first slot after the packet arrival

- When a collision occurs, each node sending one of the colliding packets becomes backlogged. Backlogged nodes wait for a random number of slots before retransmitting. Later on we will assume that retransmission will executed with a fixed probability q_r

Performance of Slotted Aloha

- Simplified analysis:
  - Assumption: retransmissions from backlogged nodes are sufficiently randomized to approximate the total transmission by a Poisson process of rate $G > \lambda$.
  - Probability of successful transmission: Ge^{-G}
  - In equilibrium: arrival rate should be equal to departure rate
  - Maximum possible departure rate occurs at $G = 1$ => departure rate = $1/e$.
- This analysis doesn't take into account the dynamic of the system: G changes as a function of the number of backlogged nodes. However it correctly identifies the maximum achievable throughput, and optimum value for G.

Improved Analysis of Slotted Aloha (No-Buffering Assumption)

- At some instant just before the beginning of a slot:
  - n is the number of backlogged nodes
  - Probability that an unbacklogged node transmits is $q_a=1-e^{-\lambda/m}$
  - Probability that a backlogged node transmits is: $q_r > q_a$
  - Expected drift in state n:
    - $D_n = (m-n)q_a - P_{succ}$
    - $P_{succ} = nq_r(1-q_r)^{n-1}(1-q_a)^{m-n} + (m-n)(1-q_r)^n q_a(1-q_a)^{m-n-1}$
  - Expected number of attempted transmissions (attempt rate): $G(n) = (m-n)q_a + nq_r$ => $P_{succ} \approx G(n)\, e^{-G(n)}$

Stability Slotted Aloha

- Slotted Aloha has two stable points and one unstable point
- System dynamic ($q_r > q_a$):
  - Left of the first stable point, there are more new arrivals than can be successfully transmitted $(m-n)q_a > P_{succ}$. n increases: positive drift.
  - Right of the first stable point (before unstable point), there are less new arrivals than can be handled $(m-n)q_a < P_{succ}$. n decreases: negative drift.
  - Right of the unstable point (before second stable point), there are more new arrivals than can be successfully transmitted $(m-n)q_a > P_{succ}$. n increases: positive drift.
- If we consider the buffering scheme with infinite number of nodes: then attempts' rate = $\lambda + nq_r$ => only one stable equilibrium and once the unstable equilibrium is passed the number of backlogged nodes increases without bound

Stabilizing Slotted Aloha

- Solution: dynamically change the value of q_r. Goal: maintain the attempt rate $G = 1$. How to estimate n?
- Basic strategy: increase q_r on idle slot and reduce q_r on collision.
- Rivest's pseudo-Bayesian algorithm:
  - Both backlogged and unbacklogged nodes behave in the same way: $G(n) = nq_r$, $P_{succ} = nq_r(1-q_r)^{n-1}$. Higher delay delay for new arrivals if q_r is not adequately updated.
  - $q_r(\hat{n}) = \min\{1, 1/\hat{n}\}$ to approach $G = nq_r = 1$

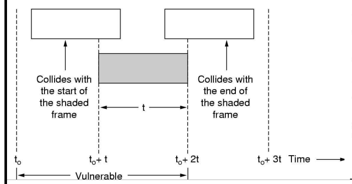
$$\hat{n}_{k+1} = \begin{cases} \max\{\lambda, \hat{n}_k + \lambda - 1\} & \text{for idle or success} \\ \hat{n}_k + \lambda + (e-2)^{-1} & \text{for collision} \end{cases}$$

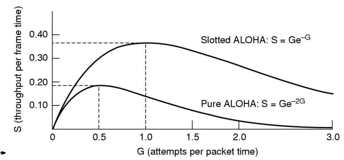
Binary Exponential Backoff

- Sometimes the feedback assumption is unrealistic. However, a node may still be able to know if its own transmissions succeeded (wireless networks). This is insufficient for the pseudo-Bayesian strategy.
- Strategy: if the packet has been transmitted unsuccessfully i times, then probability of transmission in successive slots is set at $q_r = 2^{-i}$ (uniformly distributed over the next 2^i slots). Newly arrived packets are transmitted immediately in the next slot.
- For infinite nodes this strategy is unstable.

Un-slotted Aloha

- No more slots boundaries. Retransmissions are executed after a random amount of time.
- Throughput per slot: $S = Ge^{-2G}$. Maximized for G =0.5





Reservation Aloha

- Time is divided into a reservation interval and a data interval:
  - Slotted Aloha is executed over the reservation interval
  - Effective transmissions are carried over the data interval
- Applications:
  - Satellite systems (satellite provides feedback)
  - Random Access Channel for cellular telephone systems
  - Wireless ATM

Carrier Sense Protocols

Use the fact that in some networks you can *sense* the medium to check whether it is currently free

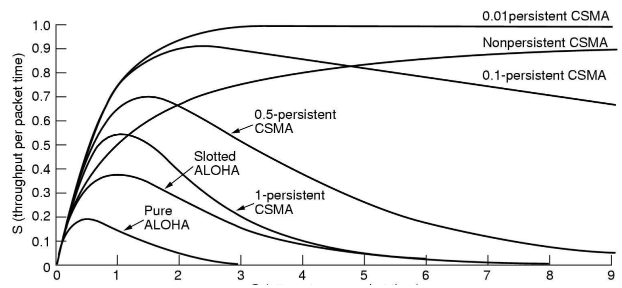
- 1-persistent CSMA
- non-persistent CSMA
- p-persistent protocol
- CSMA with collision Detection (CSMA/CD)

- 1-persistent CSMA
  - when a station has a packet:
    - it waits until the medium is free to transmit the packet
    - if a collision occurs, the station waits a random amount of time
  - first transmission results in a collision if several stations are waiting for the channel

Carrier Sense Protocols (*Cont'd*)

- non-persistent CSMA
  - when a station has a packet:
    - if the medium is free, transmit the packet
    - otherwise wait for a random period of time and repeat the algorithm
  - higher delays, but better performance than pure ALOHA
- p-persistent protocol
  - when a station has a packet wait until the medium is free:
    - transmit the packet with probability *p*
    - wait for next slot with probability 1-*p*
  - better throughput than other schemes but higher delay
- CSMA with collision Detection (CSMA/CD)
  - stations abort their transmission when they detect a collision
  - e.g., Ethernet, IEEE802.3

Comparison

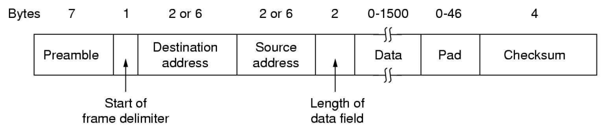


Ethernet

- History: evolution from Aloha, CSMA, CSMA/CD (by Xerox PARC) => Ethernet, => IEEE802.3 (Digital, Intel, Xerox)
  - There are slight differences between ethernet and 802.3 (e.g., 802.3 length field is used for packet type in ethernet, various transmission speeds for 802.3 from 1 to 10Mbps)
- Physical layer (10Mbps ethernet):
  - Manchester encoding (bit syncro, no-dc component)
  - Cabling: maximum 500 meters with up to 4 repeaters (max 2500m)

10Base5	Thick coax	500 m	100 nodes	Good for backbones
10Base2	Thin coax	200 m	30	Cheapest system
10Base-T	Twisted pair	100 m	1024	Easy maintenance
10Base-F	Fiber optics	2000 m	1024	Between buildings

Frame Format

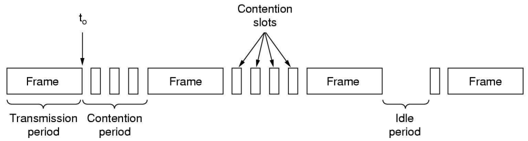


- Preamble : 7x10101010…
  - allows the receiver's clock to synchronize
- SF: 10101011
- 10Mbps=> 6bytes addresses:
  - Broadcast: FF:FF:FF:FF:FF:FF
  - Multicast: 01:00:5e:00:00:00 -to- 01:00:5e:7f:ff:ff
  - Unicast: unique per adaptor (ranges are allocated to manufacturers)
- Pad: minimum frame length of 64 bytes

Ethernet Algorithm

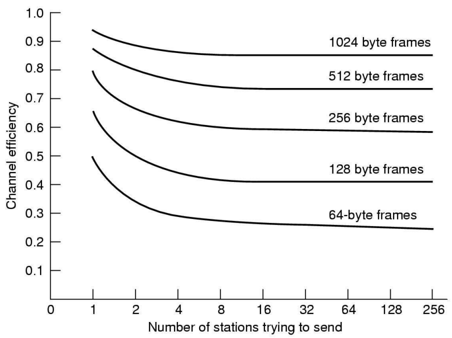
- Receiver: accepts frames with a correct CRC
- Sender: CSMA/CD 1-persistent algorithm
  - If the adaptor has a frame and the line is idle: transmit
  - If a collision occurs:
    - When detected a 32-bit jamming sequence is sent
    - Binary exponential backoff: select a random number $\in [0, 2^i-1]$
    - After ten collisions the randomization interval is frozen to max 1023
    - After 16 collisions the controller throws away the frame
- What is the reasons for having a minimal frame length? (Hint RTT: 51.2µs)

Simplified Ethernet Performance



- Assume that retransmissions occur with probability *p*, *k* stations ready to transmit:
  - Probability that a station acquires the channel: $A=kp(1-p)^{k-1}$
  - Maximum: when $p=1/k$, $k\to\infty$ $A\to 1/e$
  - Probability that a contention interval has exactly *j* intervals is: $A(1-A)^{j-1}$
  - Mean number of slots per contention is: $1/A$
  - Slot duration: $2\tau = 51.2\mu s$
  - Channel efficiency: $P/(P+2\tau/A)$

Ethernet Performance



Ethernet Capture Effect

- A and B have a large queue of packets
- There exists a situation were B will keep increasing its backoff interval (and finally dropping its packet) while A is transmitting its packets

Other MAC Protocols

- Bit-map protocol
  - reservation slots + transmission slots
- Broadcast Recognition with Alternating Method (BRAM) = Mini Slotted Alternating Priorities (MSAP)
  - permission to transmit rotates between stations
  - reserve and transmit right after
- Binary Countdown
  - inputs from different stations are Boolean ORed: binary 1 overwrites 0
  - stations with lower address are physically discarded
- Adaptive Tree Walk Protocol (inspired from blood testing for syphilis in the army) a special case of the general class of splitting algorithms

Splitting Algorithms

- The basic idea is to continuously split the set of contending nodes (using: a unique ID, arrival time, random number, etc.)
- Tree Algorithms (generalization of the random walk):
  - Binary tree:
  - J-ary tree:
- First-Come First-Serve Algorithms

Splitting: Tree Algorithms

- Binary tree: when a collision occurs in the k^{th} slot:
  - All nodes not involved in the collision go into a waiting mode
  - All nodes involved in the collision split into two subsets
    - The first subset transmits on slot $k+1$.
    - If a collision occurs, the first subset resolves the collision by splitting again and the second subset waits for the resolution of the last collision
    - If no collision occurs, the second subset transmits
  - Algorithm behaves like a stack where two sets are pushed on the stack at each collision
- J-ary tree algorithm: split set of nodes into *j* subsets (with an expected number of packet = 1 per subset) => 0.43 packets/slot
- Improvements of binary tree:
  - an empty slot following a collision results in the splitting of the second subset => 0.46 packets/slot
  - New arrivals join at the head of the stack

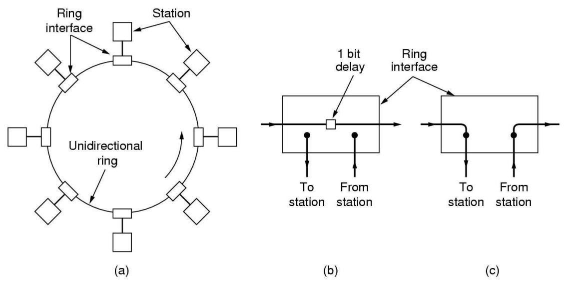
Splitting: First-Come First-Serve

- In the tree splitting algorithm, nodes are differentiated using a random number or a unique ID
- In the FCFS algorithms the nodes are differentiated on the basis of the arrival time of their packets
  - Each node records the arrival time of its packets
  - At each integer time *k* the algorithm specifies the packet to be transmitted during the next slot *k*: these are the packets that arrived within $[T(k), T(k)+\alpha]$
  - When a collision occurs the interval is divided into 2 intervals

Token Passing MAC

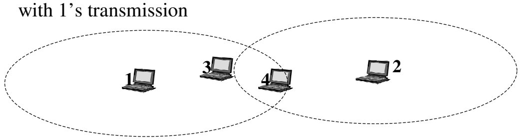
- Token Bus (IEEE802.4):
  - broadcast bus
  - logical ring
  - token: special control frame
  - only the token holder station can transmit frames
  - 0, 2, 4, 6: traffic priority classes
- Token Ring (IEEE802.5):
  - token regenerated/modified at each node
  - stations have two modes:
    - listen (forwards bits with delay 1)
    - transmit (seizes the first token by transforming into the start of frame)

Token Ring



Constraints on MAC Protocols for Wireless LANs

- Stations cannot detect collisions while transmitting
- Stations may not be able to detect transmission even if it is not transmitting (hidden station problem)
  - e.g., 2 cannot hear 1 transmitting to 3, so 2 may transmit to 4 and collide with 1's transmission



- Stations may wrongfully think that communication is taking place: exposed terminal problem
- Others: higher BER: Rayleigh fading channel but low delay spread, mobile users but low speed

Types of Wireless LANs

- Ad-Hoc networks:
  - any station can communication directly with any other station (peer-to-peer communication)
- Infrastructure networks:
  - communication between wireless terminals go through a central station

Multiple Access with Collision Avoidance (MACA 1990)

- MACA is designed for ad-hoc wireless networks
- When a station S_1 has a packet to transmit to station S_2
  - S_1 senses the channel. If the channel is busy defers the transmission until idle
  - if channel is idle S_1 sends a special packet called Request-To-Send (RTS) to the S_2
  - (if the RTS is correctly received by S_2) S_2 sends a Clear-To-Send (CTS), CTS includes the frame length
  - (if the CTS is correctly received by S_1) S_1 starts the data transmission
- Stations which sense:
  - RTS: defer transmission until after CTS
  - CTS: defer transmission until the transmission of data completes
- If a station does not receive CTS in response to its RTS, it invokes an exponential backoff

MACAW (1994)

- Based on MACA
- MILD backoff: multiplicative increase with factor 1.5 and linear decrease
- The receiver sends an ACK if the data is received correctly
- To allow the exposed terminal to be aware of active tranmissions the sender issues a Data-Send (DS) packet in response to CTS
- Separate backoff parameter is maintained for each stream in a station
- To improve fairness a special packet Request-Request-To-Send is used

Conclusion

- Multiple access schemes: how to share an atomic resource?
- Classification of Medium Access Control protocols
- Analysis of Slotted-Aloha
- Description of other MAC protocols