18-452/18-750
Wireless Networks and Applications
Lecture 7: LAN MAC Protocols
Wireless versus Wired

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http://www.cs.cmu.edu/~prs/wirelessS18/

Outline

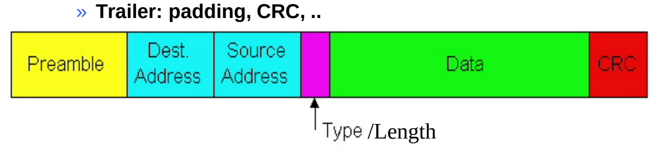
- **Data link fundamentals**
  - » And what changes in wireless
- **Aloha**
- **Ethernet**
- **Wireless-specific challenges**
- **802.11 and 802.15 wireless standards**

Datalink Functions

- **Framing: encapsulating a packet into a bit stream.**
  - » Add header, mark and detect frame boundaries, …
- **Logical link control: managing the transfer between the sender and receiver, e.g.**
  - » Error detection and correction to deal with bit errors
  - » Flow control: avoid that the sender outruns the receiver
- **Media access: controlling which device gets to send a frame next over a link**
  - » Easy for point-to-point links; half versus full duplex
  - » Harder for multi-access links: who gets to send?

Framing

- **Typical structure of a "wired" packet:**
  - » Preamble: synchronize clocks sender and receiver
  - » Header: addresses, type field, length, etc.
  - » The data to be send, e.g., an IP packet
  - » Trailer: padding, CRC, ..



- **How does wireless differ?**
  - » Different transmit rates for different parts of packet
  - » Explicit multi-hop support
  - » Control information for physical layer
  - » Ensure robustness of the header

Error Control: Error Detection and Error Recovery

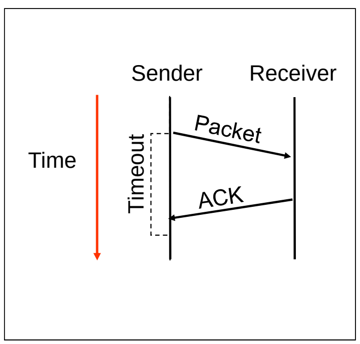
- Detection: only detect errors
  - » Make sure corrupted packets get thrown away, e.g. Ethernet
  - » Use of error detection codes, e.g. CRC
- Recovery: also try to recover from lost or corrupted packets
  - » Option 1: forward error correction (redundancy)
  - » Option 2: retransmissions
- How does wireless differ?
  - » Uses CRC to detect errors, similar to wired
  - » Error recovery is much more important because errors are more common and error behavior is very dynamic
  - » What approach is used?

Error Recovery in Wireless

- Use of redundancy:
  - » Very common at physical layer – see PHY lectures
- Use of Automatic Repeat Request (ARQ)
  - » Use time outs to detect loss and retransmit
- Many variants:
  - » Stop and wait: one packet at a time
    - – The most common at the datalink
  - » Sliding window: receiver tells sender how much to send
    - – Many retransmission strategies: go-back-N, selective repeat, …
- When should what variant be used?
  - » Noise versus bursty (strong) interference

Stop and Wait

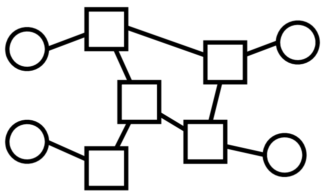
- Simplest ARQ protocol
- Send a packet, stop and wait until acknowledgement arrives
- Will examine ARQ issues later in semester
- Limitations?
- What popular for the datalink?

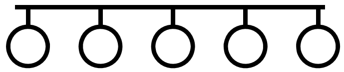


Media Access Control

- How do we transfer packets between two hosts connected to the same network?
- Using point-to-point “links” with “switches” -- store-and-forward
  - » Very common in wired networks, at multiple layers
- Multiple access networks
  - » Multiple hosts are sharing the same transmission medium
  - » Need to control access to the medium
  - » Taking turn versus contention based protocols
- What is different in wireless?
  - » Is store and forward used?
  - » Is multiple access used?

Datalink Architectures





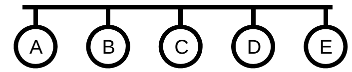
- Routing and packet forwarding.
- Point-to-Point error and flow control.

Switched ethernet, mesh and ad hoc networks

- Media access control.
- Scalability.

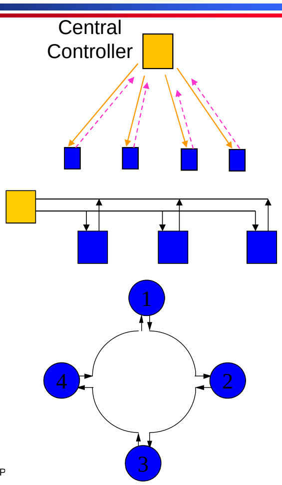
Traditional ethernet, Wifi, Aloha, …

Multiple Access Networks



- Who gets to send a packet next?
- Scheduled access: explicit coordination ensures that only one node transmits
  - » Looks cleaner, more organized, but …
  - » Coordination introduces overhead – requires communication (oops)
- Random access: no explicit coordination
  - » Potentially more efficient, but …
  - » How does a node decide whether it can transmit?
  - » Collisions are unavoidable – also results in overhead
  - » How do you even detect a collision?

Scheduled Access MACs



- Polling: controller polls each nodes
- Reservation systems
  - » Central controller
  - » Distributed algorithm, e.g. using reservation bits in frame
- Token ring: token travels around ring and allows nodes to send one packet
  - » Distributer version of polling
  - » FDDI, …

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- Ethernet
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Why ALOHA

Pure ALOHA

- Developed in University of Hawaii in early 1970's.
- It does not get much simpler:
  1. A user transmits at will
  2. If two or more messages overlap in time, there is a collision – receiver cannot decode packets
  3. Receive waits for roundtrip time plus a fixed increment – lack of ACK = collision
  4. After a collision, colliding stations retransmit the packet, but they stagger their attempts randomly to reduce the chance of repeat collisions
  5. After several attempts, senders give up
- Although very simple, it is wasteful of bandwidth, attaining an efficiency of at most 1/(2e) = 0.18

Poisson Process

Informal: memory less

- A Poisson process of "rate" $\lambda > 0$ is a counting process a(t) which satisfies the following conditions:
  1. The process has independent increments in disjoint intervals
     - i.e., $a(t_1+\Delta t)-a(t_1)$ is independent of $a(t_2+\delta t)-a(t_2)$ if $[t_1, t_1+\Delta t]$ and $[t_2, t_2+\delta t]$ are disjoint intervals
  2. The increments of the process are stationary.
     - i.e., $a(t_1+\Delta t)-a(t_1)$ does not depend on t_1
  3. The probability of exactly one event occurring in an infinitesimal interval Δt is $P[a(\Delta t)=1] \cong \lambda\Delta t$
  4. The probability that more than one event occurs in any infinitesimal interval Δt is $P[a(\Delta t)>1] \cong 0$
  5. The probability of zero events occurring in Δt is $P[a(\Delta t)=0] \cong 1-\lambda\Delta t$

Poisson Distribution

- Above definitions lead to: Probability P(k) that there are exactly k events in interval of length T is,

$$P(k) = \frac{(\lambda T)^k e^{-\lambda T}}{k!}$$

- We call the above probability the "Poisson distribution" for arrival rate λ
- Its mean and variance are:

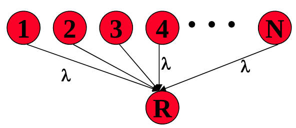
$$E(k) = \lambda T$$

$$\sigma_k^2 = E(k^2) - E^2(k) = \lambda T$$

- Many nice properties, e.g. sum of a N independent Poisson processes is a Poisson process

Pure ALOHA: Model

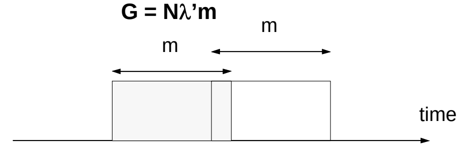
- Let there be N stations contending for use of the channel.
- Each station transmits λ packets/sec on average based on a Poisson arrival process
- All messages transmitted are of the same fixed length, m, in units of time
- Let new traffic intensity be $S \equiv N\lambda m$
- Since all new packets eventually get through, 'S' is also the network throughput



Pure Aloha: Vulnerability

- Simplification: assume the retransmitted messages are independent Poisson process as well
- The total rate of packets attempting transmission = newly generated packets + retransmitted ones = $\lambda' > \lambda$
- The total traffic intensity (including retransmissions) is ,

$$G = N\lambda' m$$



Collision between two messages

- The "vulnerable period" in which a collision can occur for a given packet is 2 x m sec

Pure Aloha: Analysis

- Calculate the "Probability of no collision" two ways:

1. Probability that there is no arrival in interval 2 x m:

   $P(\text{no arrival in } 2 \times m \text{ sec}) = e^{-2N\lambda' m} = e^{-2G}$

2. Since all new arrivals eventually get through, we have

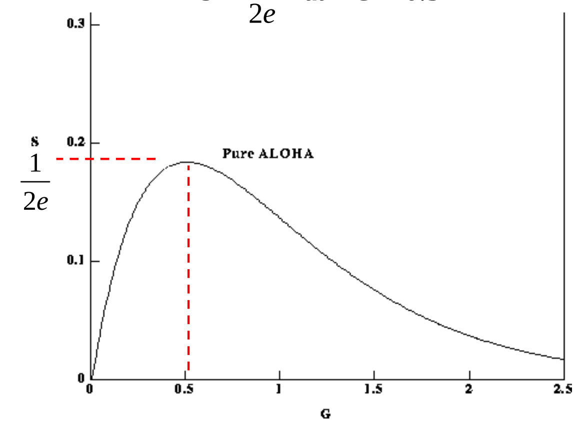
   $\lambda/\lambda' = S/G$ = Fraction of transmissions that are successful

- So, S/G = Probability of no collision = P(no arrival in 2m sec)
- Thus,

$$S/G = e^{-2G}$$
$$S = Ge^{-2G} \longrightarrow \text{Maximum Throughput of Pure Aloha}$$

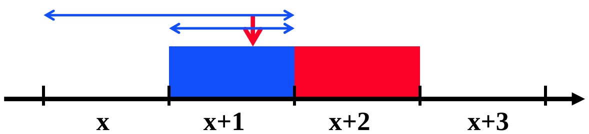
Analysis Conclusion

- S is maximum at $S = \dfrac{1}{2e}$ at $G = 0.5$

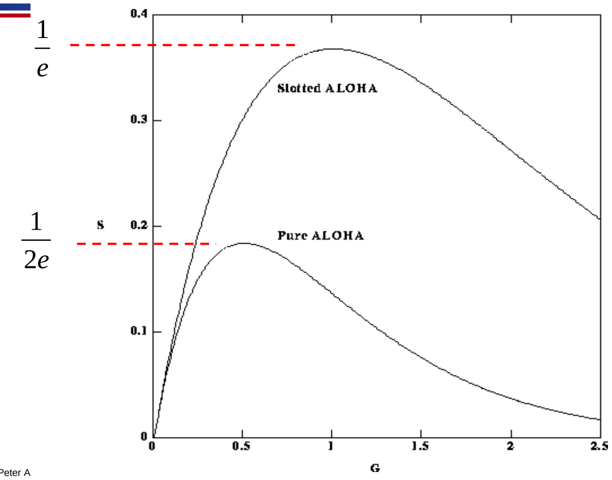


Slotted ALOHA

- Transmission can only start at the beginning of each slot of length T
- Vulnerable period is reduced to T
  - » Instead of 2xT in Aloha
- Doubles maximum throughput.



Analysis Results Slotted ALOHA



Discussion of ALOHA

- Maximum throughput of ALOHA is very low 1/(2e) = 18%, but
  - » Has very low latency under light load
- Slotted Alohas has twice the performance of basic Aloha, but performance is still poor
  - » Slightly longer delay than pure Aloha
  - » Slotted design is also not very efficient when carrying variable sized packets!
- Still, not bad for an absolutely minimal protocol!
  - » Good solution if load is low – used in some sensor networking technologies (cheap, simple)
- How do we go faster?

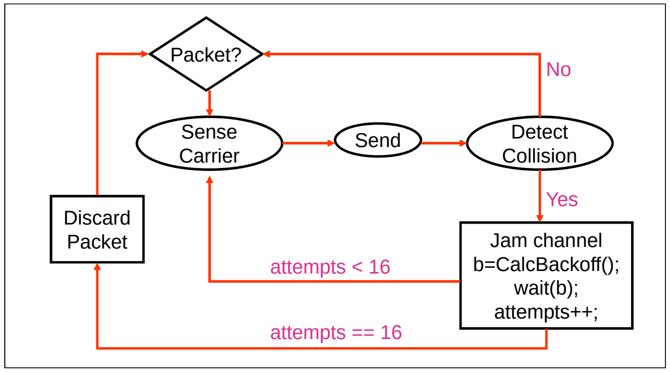
Outline

- Data link fundamentals
  - » And what changes in wireless
- Aloha
- Ethernet
- Wireless-specific challenges
  - » Ethernet review
  - » How wireless differs
- 802.11 and 802.15 wireless standards

"Regular" Ethernet CSMA/CD

- Multiple Access: multiple hosts are competing for access to the channel
- Carrier-Sense: make sure the channel is idle before sending – "listen before you send"
- Collision Detection: collisions are detected by listening on the medium and comparing the received and transmitted signals
- Collisions results in 1) aborting the colliding transmissions and 2) retransmission of the packets
- Exponential backoff is used to reduce the chance of repeat collisions
  - » Also effectively reduces congestion

Carrier Sense Multiple Access/ Collision Detection (CSMA/CD)



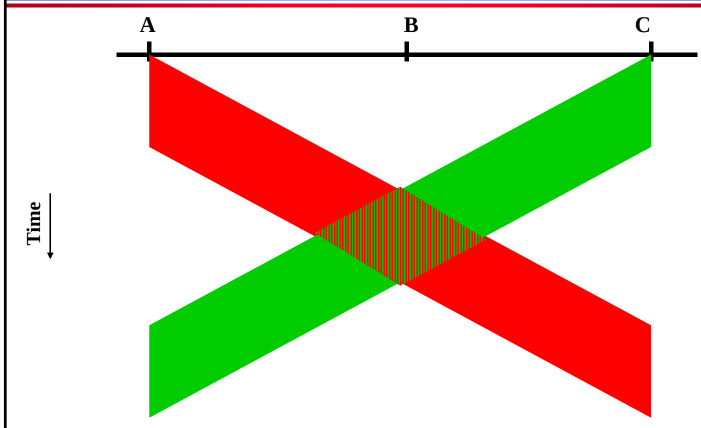
Ethernet Backoff Calculation

- Challenge: how do we avoid that two nodes retransmit at the same time collision
- Exponentially increasing random delay
  - » Infer "number" senders from # of collisions
  - » More senders → increase wait time
- First collision: choose K from {0,1}; delay is K x 512 bit transmission times
- After second collision: choose K from {0,1,2,3}
- After ten or more collisions, choose K from {0,1,2,3,4,…,1023}

How to Handle Transmission When Line is Sensed Busy

- ***p-persistent scheme***:
  - » Transmit with probability p once the channel goes idle
  - » Delay the transmission by t_{prop} with the probability (1-p)
- ***1-persistent scheme***: p = 1
  - » E.g. Ethernet
- ***nonpersistent scheme***:
  - » Reschedule transmission for a later time based on a retransmission delay distribution (e.g. exp backoff)
  - » Senses the channel at that time
  - » Repeat the process
- When is each solution most appropriate?

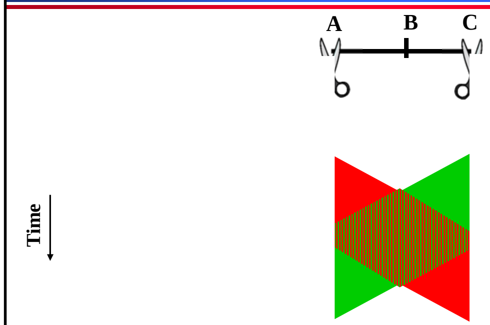
Collisions



Dealing with Collisions

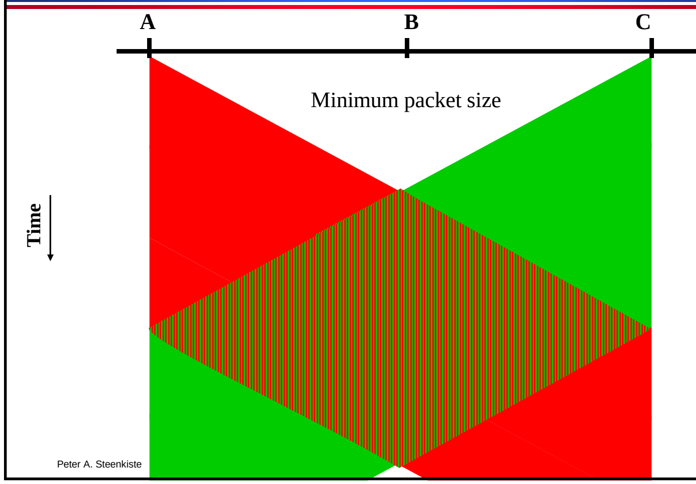
- Collisions will happen: nodes can start to transmit “simultaneously”
  - » Vulnerability window depends on length of wire
- Recovery requires that both transmitters can detect the collision reliably
  - » Clearly a problem as shown on previous slide
- How can we guarantee detection?

Detect Collisions



Limit length wire

Detect Collisions



So What about Wireless?

- Depends on many factors, but high level:
- Random access solutions are a good fit for data in the unlicensed spectrum
  - » Lower control complexity, especially for contention-based protocols (e.g., Ethernet)
  - » There may not always be a centralized controller
  - » May need to support multi-hop
  - » Also used in many unlicensed bands
- Cellular uses scheduled access
  - » Need to be able to guarantee performance
  - » Have control over spectrum – simplifies scheduled access
  - » More on this later in the course

Summary

- Wireless uses the same types of protocols as wired networks
  - » But it is inherently a multiple access technology
- Some fundamental differences between wired and wireless may result in different design choices
  - » Higher error rates
  - » Must support variable bit rate communication
  - » Signal propagation and radios are different

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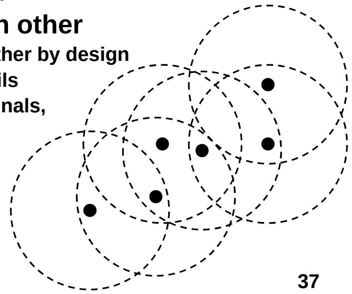
Wireless Ethernet is a Good Idea, but …

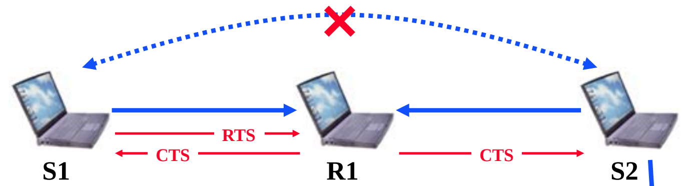
- Attenuation varies with media
  - » Also depends strongly on distance, frequency
- Wired media have exponential dependence
  - » Received power at d meters proportional to 10^{-kd}
  - » Attenuation in dB = *k d*, where *k* is dB/meter
- Wireless media has logarithmic dependence
  - » Received power at d meters proportional to d^{-n}
  - » Attenuation in dB = *n log d*, where *n* is path loss exponent; *n=2* in free space
  - » Signal level maintained for much longer distances?
- But we are ignoring the constants!
  - » Wireless attenuation at 2.4 GHz: 60-100 dB
  - » In practice numbers can be much lower for wired

Implications for Wireless Ethernet

- Collision detection is not practical
  - » Ratio of transmitted signal power to received power is too high at the transmitter
  - » Transmitter cannot detect competing transmitters (is deaf while transmitting)
  - » So how do you detect collisions?
- Not all nodes can hear each other
  - » Ethernet nodes can hear each other by design
  - » “Listen before you talk” often fails
  - » Hidden terminals, exposed terminals,
  - » Capture effects
- Made worse by fading
  - » Changes over time!

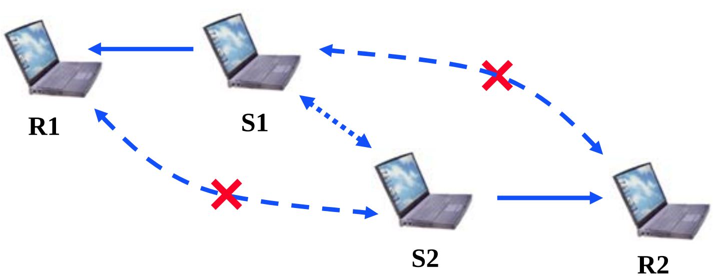


Hidden Terminal Problem



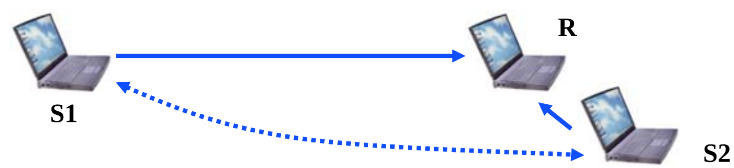
- Lack signal between S1 and S2 and cause collision at R1
- Severity of the problem depends on the sensitivity of the carrier sense mechanism
  - » Clear Channel Assessment (CCA) threshold

Exposed Terminal Problem



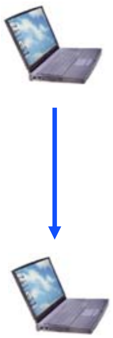
- Carrier sense prevents two senders from sending simultaneously although they do not reach each other’s receiver
- Severity again depends on CCA threshold
  - » Higher CCA reduces occurrence of exposed terminals, but can create hidden terminal scenarios

Capture Effect



- Sender S2 will almost always “win” if there is a collision at receiver R.
- Can lead to extreme unfairness and even starvation.
- Solution is power control
  - » Very difficult to manage in a non-provisioned environment!

Wireless Packet Networking Problems



- Some nodes suffer from more interference than others
  - » Node density
  - » Traffic volume sent by neighboring nodes
- Leads to unequal throughput
- Similar to wired network: some flows traverse tight bottleneck while others do not