18-452/18-750
Wireless Networks and Applications
Lecture 8: Wireless LANs
802.11 Wireless

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Spring Semester 2024

http://www.cs.cmu.edu/~prs/wirelessS24/

Outline

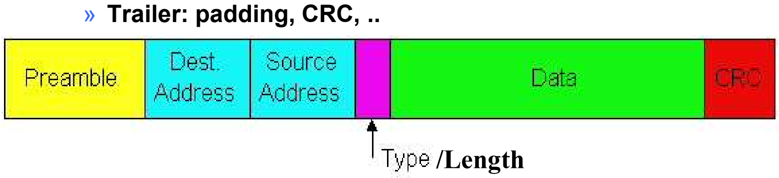
- **Data link fundamentals**
  - » **And what changes in wireless**
- **Aloha**
- **Ethernet**
- **Wireless-specific challenges**
- **802.11 and 802.15 wireless standards**

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

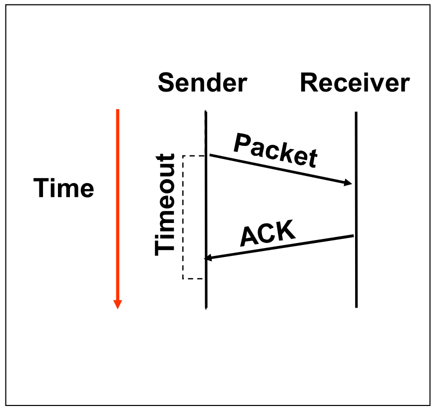
- Detection: only detect errors
  - » Make sure corrupted packets get thrown away, e.g. Ethernet
  - » Use of error detection codes, e.g. CRC
- Recovery: also try to recover from lost or corrupted packets
  - » Option 1: forward error correction (redundancy)
  - » Option 2: retransmissions
- How does 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

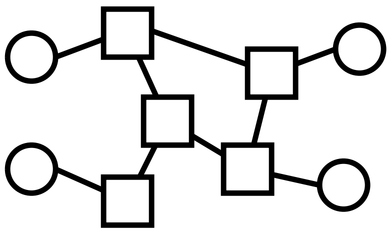
- Simplest ARQ protocol
- Send a packet, stop and wait until acknowledgement arrives
- Will examine ARQ issues later in semester
- Limitations?
- What popular for the datalink?

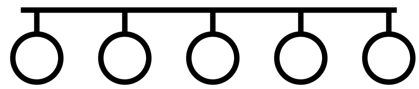


Media Access Control

- 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





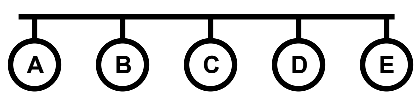
- Routing and packet forwarding.
- Point-to-Point error and flow control.

Switched ethernet, mesh and ad hoc networks

- Media access control.
- Scalability.

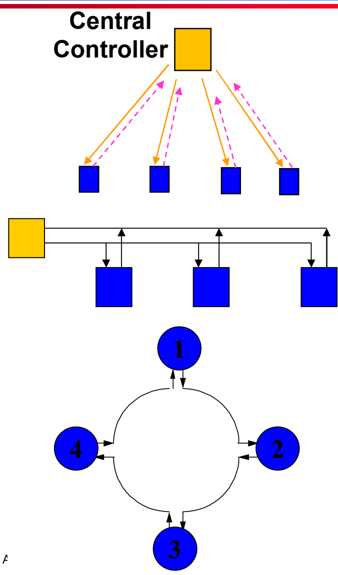
Traditional ethernet, Wifi, Aloha, …

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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- Aloha
- Ethernet
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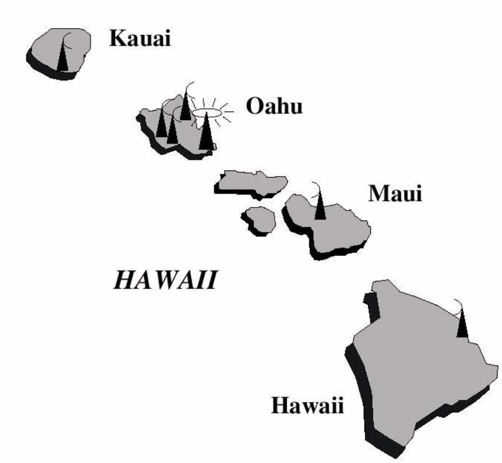
Why ALOHA



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 $P[a(\Delta t)=0] \cong 1-\lambda\Delta t$

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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

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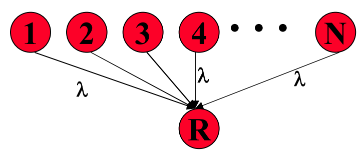
Pure ALOHA: Model

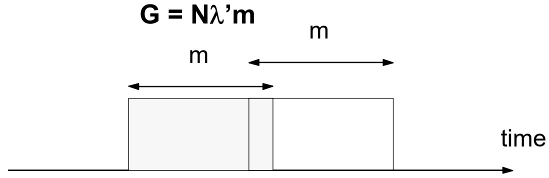
- Let there be N stations contending for use of the channel.
- Each station transmits λ packets/sec on average based on a Poisson arrival process
- All messages transmitted are of the same fixed length, m, in units of time
- Let new traffic intensity be $S \equiv N\lambda m$
- Since all new packets eventually 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(no arrival in 2 x m sec) = $e^{-2N\lambda' m} = e^{-2G}$

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

   λ/λ' = S/G = Fraction of transmissions that are successful

   » S = rate of successful transmissions

   » G = network load – successful transmissions and retransmissions

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

  $S/G = e^{-2G}$

  $S = Ge^{-2G}$ ⟶ **Maximum Throughput of Pure Aloha**

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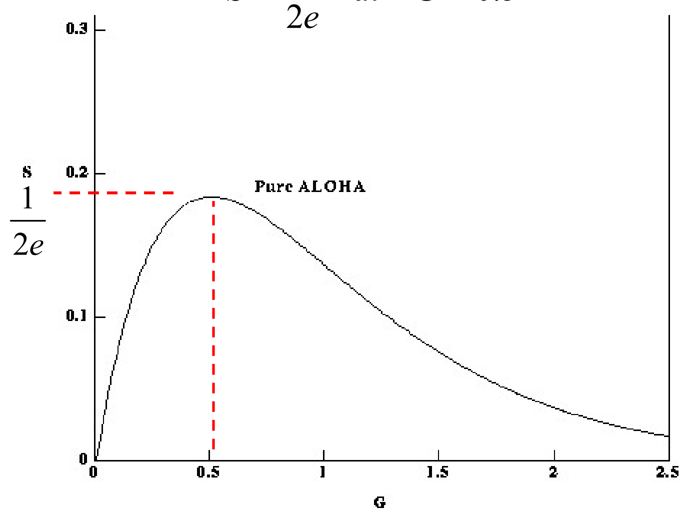
Analysis Conclusion

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



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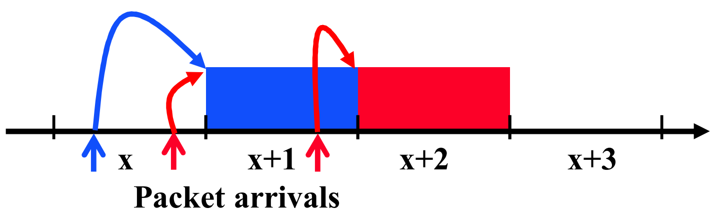
Slotted ALOHA

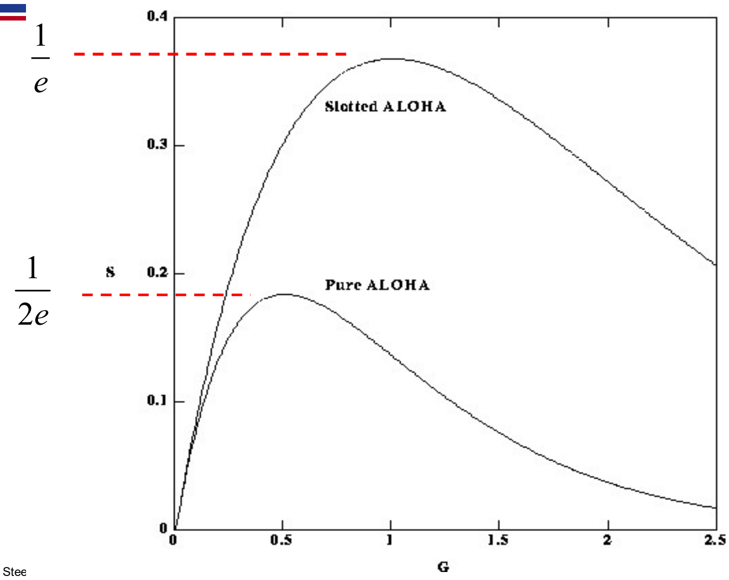
- Transmission can only start at the beginning of each slot of length T
- Vulnerable period is reduced to T
  - » Instead of 2xT in Aloha
- Doubles maximum throughput.



Slotted ALOHA Analysis

- Key point: The "vulnerable period" of the packet of size *m* has been reduced from 2*m* to only *m* !
- Since Poisson arrivals,
  P(successful transmission) = e^{-G} ← Note: Not 2G
- The throughput is then,
  $S = Ge^{-G}$
- The throughput S has maximum value of 1/e = 0.368 at G = 1.

Analysis Results Slotted ALOHA



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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
  - » Inefficient for variable sized packets!
  - » Must synchronize nodes
- 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?

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- Aloha
- Ethernet
- Wireless-specific challenges
- 802.11 and 802.15 wireless standards

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"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

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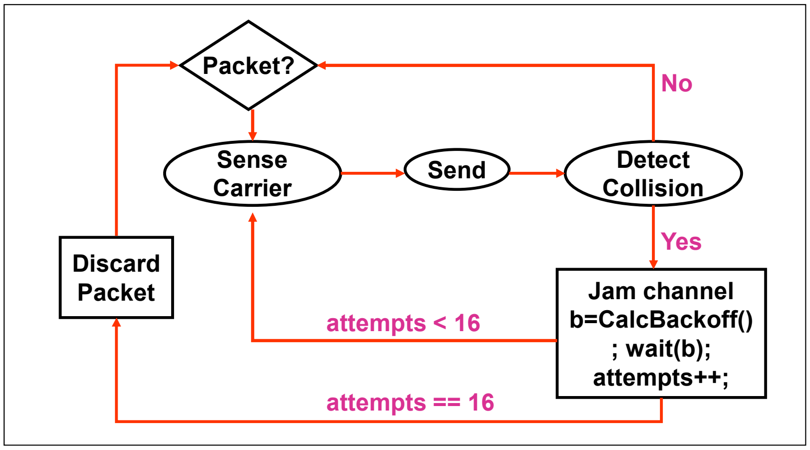
Carrier Sense Multiple Access/ Collision Detection (CSMA/CD)



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?

Ethernet Discussion

- Carrier sense is very reliable
  - » Only fails when nodes transmit "simultaneously"
- Collision detection is very reliable
  - » Guarantees that senders knows about it and retransmits
- Ethernet does not acknowledge packets
  - » Packet loss due to bit errors is rare
  - » Sender "senses losses" and retransmits
  - » ACKs introduced unnecessary overhead
- Today we exclusively use switched Ethernet
  - » Same name, same network properties, same packet format
  - » Completely different technology

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
  - » Potentially very efficient because no or limited coordination overhead
  - » Our focus in the next few lectures
- 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 very different

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So What about Wireless?

- Wireless datalink protocols similar to those used in wired networks
- Wireless is inherently multiple access
- The specifics depend on many factors, but ..
- Random access solutions are a good fit for data in the unlicensed spectrum
  - » Low control complexity, especially for contention-based protocols (e.g., Ethernet)
  - » No control over the shared spectrum band
- Cellular uses scheduled access
  - » Need to be able to guarantee performance
  - » Have control over spectrum – simplifies scheduled access
  - » There is always a central controller

Next

Later

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Wireless Ethernet is a Good Idea, but …

- Attenuation is very different from that of a wire
  - Depends strongly on distance, frequency
- Wired media have exponential attenuation
  - Received power at d meters proportional to 10^{-kd}
  - Attenuation in dB = *k d*, where *k* is dB/meter
- Wireless attenuation is quadratic in d
  - 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
  - So signal level more slowly with distance?
- No! We cannot igenore the constants!
  - Wireless attenuation at 2.4 GHz: 60-100 dB
  - In practice numbers are much lower for wired

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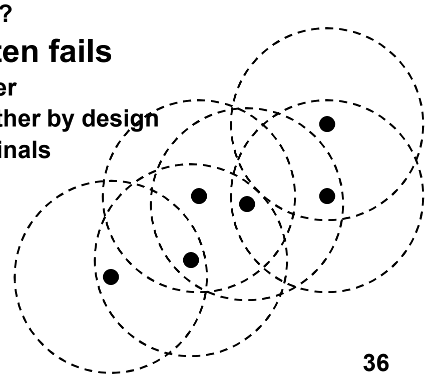
Implications for Wireless Ethernet

- 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?
- "Listen before you talk" often fails
  - Not all nodes can hear each other
  - Ethernet nodes can hear each other by design
  - Hidden terminals, exposed terminals
  - Capture effects
- Made worse by fading
  - Changes over time!



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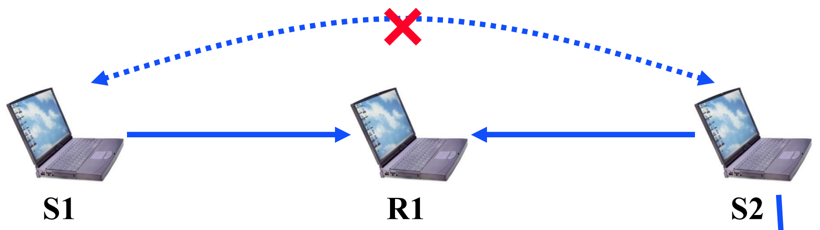
Hidden Terminal Problem



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

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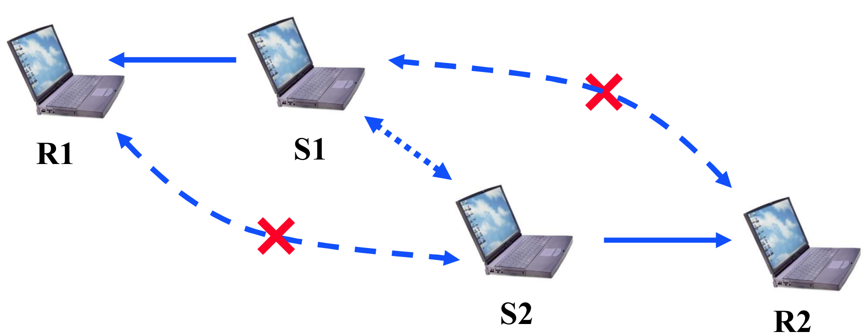
Exposed Terminal Problem



- Carrier sense prevents two senders from sending at the same time even when they cannot reach each other's receiver
- Severity again depends on CCA threshold
  - Higher CCA reduces occurrence of exposed terminals, but can create hidden terminal scenarios

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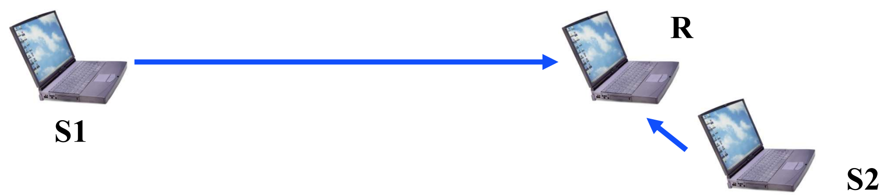
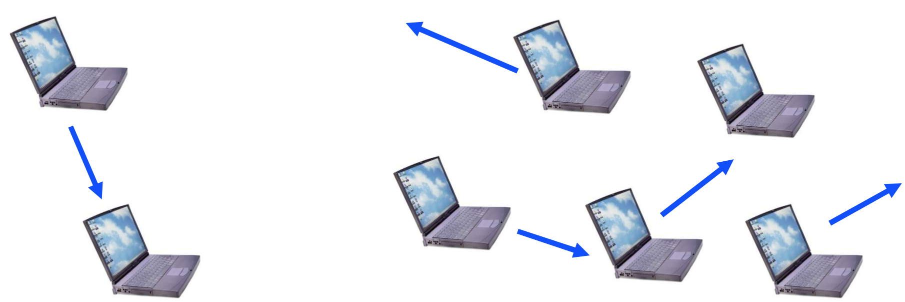
Capture Effect



- 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

Summary
Wireless Challenges

- Wireless signal propagation creates problems for "wireless Ethernet"
  - » Collision Detection is not possible
  - » Hidden and exposed terminals
  - » Capture effect
- Aloha uses a very simple protocol: offers low latency but has terrible capacity
- Ethernet has much better performance but its key features do not work for wireless
- How can we do better for wireless?

Outline

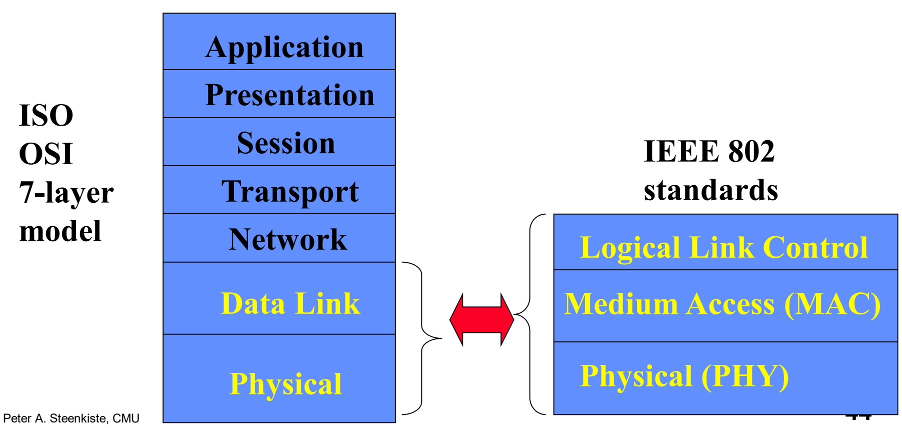
- Data link fundamentals
  - » And what changes in wireless
- Ethernet
- Aloha
- Wireless-specific challenges
- 802.11 and 802.15 wireless standards
  - » 802 protocol overview
  - » Wireless LANs – 802.11
  - » Personal Area Networks – 802.15

History

- Aloha wireless data network
- Car phones
  - » Big and heavy "portable" phones
  - » Limited battery life time
  - » But introduced people to "mobile networking"
  - » Later turned into truly portable cell phones
- Wireless LANs
  - » Originally in the 900 MHz band
  - » Later evolved into the 802.11 standard
  - » Later joined by the 802.15 and 802.16 standards
- Cellular data networking
  - » Data networking over the cell phone
  - » Many standards – throughput is the challenge

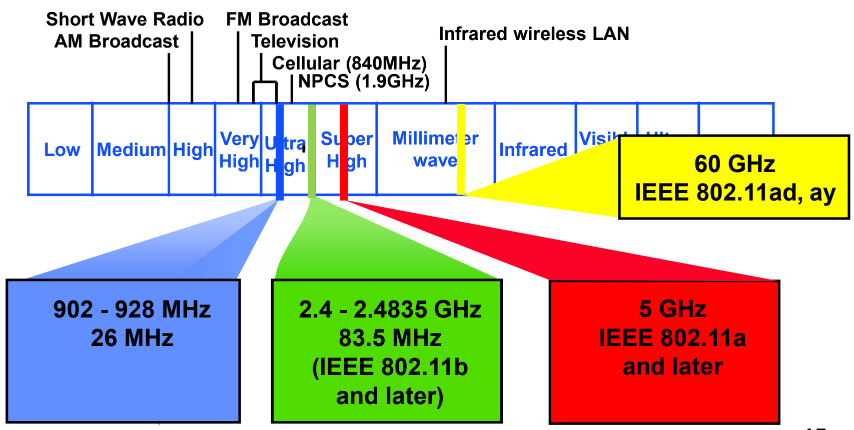
Standardization of Wireless Networks

- Wireless networks are standardized by IEEE
- Under 802 LAN MAN standards committee



Frequency Bands

- Industrial, Scientific, and Medical (ISM) bands
- Generally called "unlicensed" bands



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The 802 Class of Standards

- List on next two slides
- Some standards apply to all 802 technologies
  - » E.g. 802.2 is LLC
  - » Important for inter operability
- Some standards are for technologies that are outdated
  - » Not actively deployed anymore
  - » Many of the early standards are obsolete

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802 Standards – Part 1

Name	Description	Note
IEEE 802.1	Higher Layer LAN Protocols (Bridging)	active
IEEE 802.2	LLC	disbanded
IEEE 802.3	Ethernet	active
IEEE 802.4	Token bus	disbanded
IEEE 802.5	Token ring MAC layer	disbanded
IEEE 802.6	MANs (DQDB)	disbanded
IEEE 802.7	Broadband LAN using Coaxial Cable	disbanded
IEEE 802.8	Fiber Optic TAG	disbanded
IEEE 802.9	Integrated Services LAN (ISLAN or isoEthernet)	disbanded
IEEE 802.10	Interoperable LAN Security	disbanded
IEEE 802.11	Wireless LAN (WLAN) & Mesh (Wi-Fi certification)	active
IEEE 802.12	100BaseVG	disbanded
IEEE 802.13	Unused[2]	Reserved for Fast Ethernet development[3]
IEEE 802.14	Cable modems	disbanded
IEEE 802.15	Wireless PAN	active
IEEE 802.15.1	Bluetooth certification	active
IEEE 802.15.2	IEEE 802.15 and IEEE 802.11 coexistence	
IEEE 802.15.3	High-Rate wireless PAN (e.g., UWB, etc.)	
IEEE 802.15.4	Low-Rate wireless PAN (e.g., ZigBee, WirelessHART, MiWi, etc.)	active
IEEE 802.15.5	Mesh networking for WPAN	

802 Standards – Part 2

IEEE 802.15.6	Body area network	active
IEEE 802.15.7	Visible light communications	
IEEE 802.16	Broadband Wireless Access (WiMAX certification)	
IEEE 802.16.1	Local Multipoint Distribution Service	
IEEE 802.16.2	Coexistence wireless access	
IEEE 802.17	Resilient packet ring	hibernating
IEEE 802.18	Radio Regulatory TAG	
IEEE 802.19	Coexistence TAG	
IEEE 802.20	Mobile Broadband Wireless Access	hibernating
IEEE 802.21	Media Independent Handoff	
IEEE 802.22	Wireless Regional Area Network	
IEEE 802.23	Emergency Services Working Group	
IEEE 802.24	Smart Grid TAG	New (November, 2012)
IEEE 802.25	Omni-Range Area Network	

Outline

- 802 protocol overview
- Wireless LANs – 802.11
  - » Overview of 802.11
  - » 802.11 MAC, frame format, operations
  - » 802.11 management
  - » 802.11*
  - » Deployment example
- Personal Area Networks – 802.15

IEEE 802.11 Overview

- Adopted in 1997 with the following goal of providing
  - » Access to services in wired networks
  - » High throughput
  - » Highly reliable data delivery
  - » Continuous network connection, e.g. while mobile
- The protocol defines
  - » MAC sublayer
  - » MAC management protocols and services
  - » Several physical (PHY) layers: IR, FHSS, DSSS, OFDM
- Wi-Fi Alliance is industry group that certifies interoperability of 802.11 products

Infrastructure and Ad Hoc Mode

- Infrastructure mode: stations communicate with one or more access points which are connected to the wired infrastructure
  - » What is deployed in practice
- Two modes of operation:
  - » Distributed Control Functions - DCF
  - » Point Control Functions – PCF
  - » PCF is rarely used - inefficient

Our Focus

- Alternative is "ad hoc" mode: multi-hop, assumes no infrastructure
  - » Rarely used, e.g. military
  - » Hot research topic!

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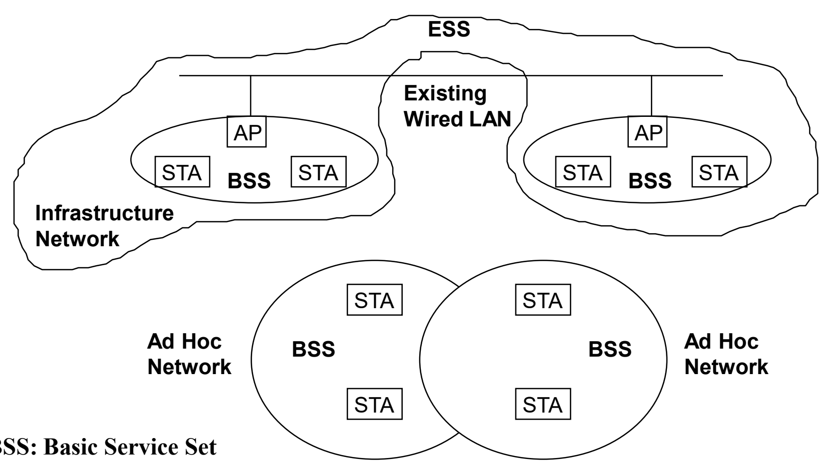
802.11 Architecture



BSS: Basic Service Set

ESS: Extended Service Set

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Terminology for DCF

- Stations and access points
- BSS - Basic Service Set
  - » One access point that provides access to wired infrastructure
  - » Infrastructure BSS
- ESS - Extended Service Set
  - » A set of infrastructure BSSs that work together
  - » APs are connected to the same infrastructure
  - » Tracking of mobility
- DS – Distribution System
  - » AP communicates with each other
  - » Thin layer between LLC and MAC sublayers

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- 802 protocol overview
- Wireless LANs – 802.11
  - » Overview of 802.11
  - » 802.11 MAC, frame format, operations
  - » 802.11 management
  - » 802.11*
  - » Deployment example
- Personal Area Networks – 802.15

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How Does WiFi Differ from Wired Ethernet?

- Signal strength drops off quickly with distance
  - » Path loss exponent is highly dependent on context
- Should expect higher error rates
  - » Solutions?
- Makes it impossible to detect collisions
  - » Difference between signal strength at sender and receiver is too big
  - » Solutions?
- Senders cannot reliably detect competing senders resulting in hidden terminal problems
  - » Solutions?