15-744: Computer Networking

L-9 Wireless

Wireless Intro

- TCP on wireless links
- Wireless MAC
- Assigned reading
  - [BPSK97] A Comparison of Mechanism for Improving TCP Performance over Wireless Links
  - [BM09] In Defense of Wireless Carrier Sense
- Optional
  - [BDS+94] MACAW: A Media Access Protocol for Wireless LAN's

Wireless Challenges

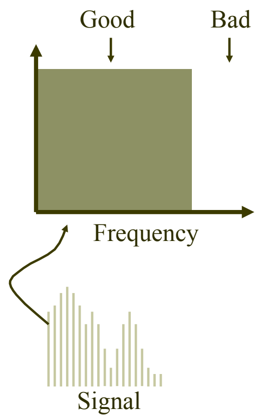
- Force us to rethink many assumptions
- Need to share airwaves rather than wire
  - Don't know what hosts are involved
  - Host may not be using same link technology
- Mobility
- Other characteristics of wireless
  - Noisy → lots of losses
  - Slow
  - Interaction of multiple transmitters at receiver
    - Collisions, capture, interference
  - Multipath interference

Overview

- Wireless Background
- Wireless MAC
  - MACAW
  - 802.11
- Wireless TCP

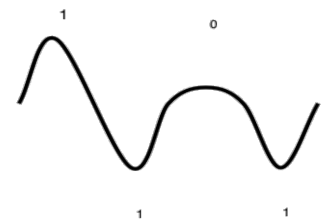
Transmission Channel Considerations

- Every medium supports transmission in a certain frequency range.
  - Outside this range, effects such as attenuation, .. degrade the signal too much
- Transmission and receive hardware will try to maximize the useful bandwidth in this frequency band.
  - Tradeoffs between cost, distance, bit rate
- As technology improves, these parameters change, even for the same wire.
  - Thanks to our EE friends



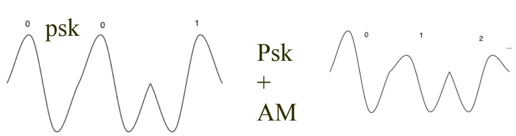
The Nyquist Limit

- A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.
  - E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
  - Assumes binary amplitude encoding



Past the Nyquist Limit

- More aggressive encoding can increase the channel bandwidth.
  - Example: modems
    - Same frequency - number of symbols per second
    - Symbols have more possible values



Capacity of a Noisy Channel

- Can't add infinite symbols - you have to be able to tell them apart. This is where noise comes in.
- Shannon's theorem:
  - C = B x log(1 + S/N)
  - C: maximum capacity (bps)
  - B: channel bandwidth (Hz)
  - S/N: signal to noise ratio of the channel
    - Often expressed in decibels (db). 10 log(S/N).
- Example:
  - Local loop bandwidth: 3200 Hz
  - Typical S/N: 1000 (30db)
  - What is the upper limit on capacity?
    - Modems: Teleco internally converts to 56kbit/s digital signal, which sets a limit on B and the S/N.

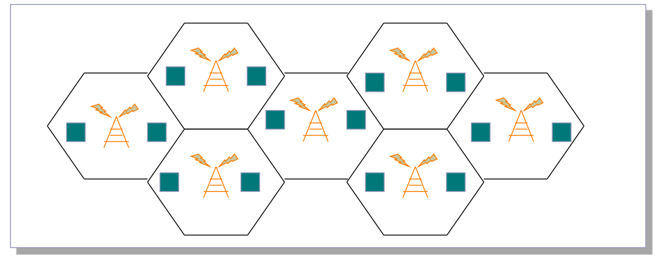
Free Space Loss

$$\text{Loss} = P_t / P_r = (4\pi\, d)^2 / (G_r\, G_t\, \lambda^2)$$

- Loss increases quickly with distance (d^2).
- Need to consider the gain of the antennas at transmitter and receiver.
- Loss depends on frequency: higher loss with higher frequency.
  - But careful: antenna gain depends on frequency too
    - For fixed antenna area, loss decreases with frequency
  - Can cause distortion of signal for wide-band signals

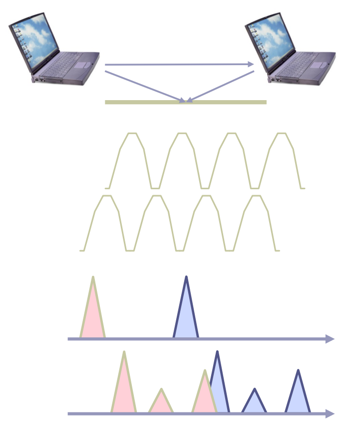
Cellular Reuse

- Transmissions decay over distance
  - Spectrum can be reused in different areas
  - Different "LANs"
  - Decay is $1/R^2$ in free space, $1/R^4$ in some situations

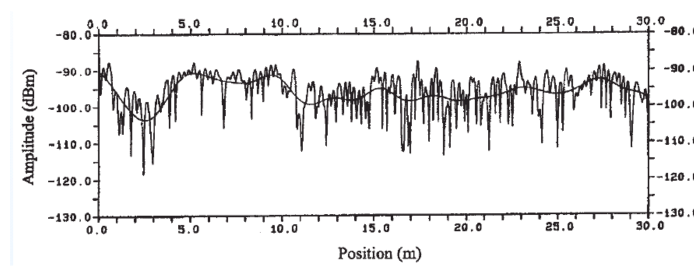


Multipath Effects

- Receiver receives multiple copies of the signal, each following a different path
- Copies can either strengthen or weaken each other.
  - Depends on whether they are in our out of phase
- Small changes in location can result in big changes in signal strength.
  - Short wavelengths, e.g. 2.4 GHz → 12 cm
- Difference in path length can cause inter-symbol interference (ISI).



Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

Overview

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  - MACAW
  - 802.11
- Wireless TCP

Medium Access Control

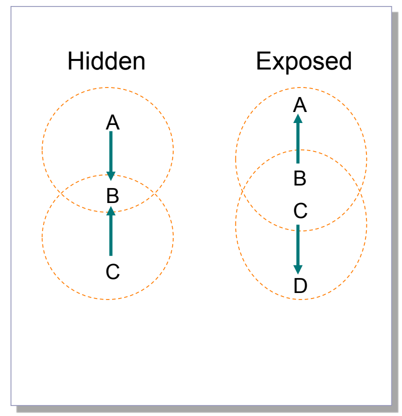
- Think back to Ethernet MAC:
  - Wireless is a shared medium
  - Transmitters interfere
  - Need a way to ensure that (usually) only one person talks at a time.
    - Goals: Efficiency, possibly fairness

Example MAC Protocols

- Pure ALOHA
  - Transmit whenever a message is ready
  - Retransmit when ACK is not received
- Slotted ALOHA
  - Time is divided into equal time slots
  - Transmit only at the beginning of a time slot
  - Avoid partial collisions
  - Increase delay, and require synchronization
- Carrier Sense Multiple Access (CSMA)
  - Listen before transmit
  - Transmit only when no carrier is detected

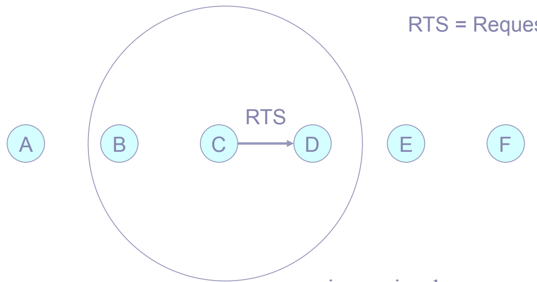
CSMA/CD Does Not Work

- Carrier sense problems
  - Relevant contention at the receiver, not sender
  - Hidden terminal
  - Exposed terminal
- Collision detection problems
  - Hard to build a radio that can transmit and receive at same time



MACA (RTS/CTS)

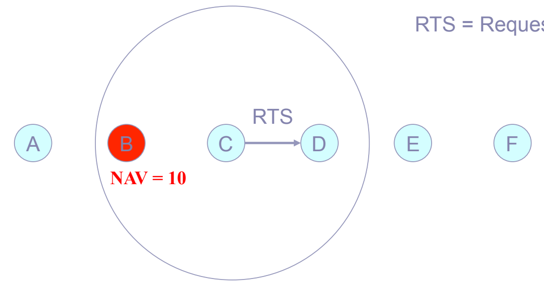
RTS = Request-to-Send



assuming a circular range

MACA (RTS/CTS)

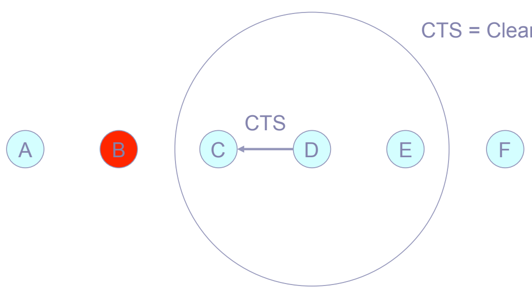
RTS = Request-to-Send



NAV = remaining duration to keep quiet

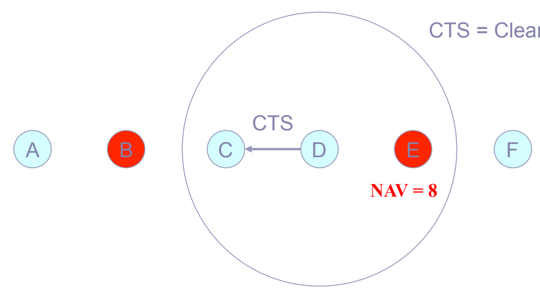
MACA (RTS/CTS)

CTS = Clear-to-Send



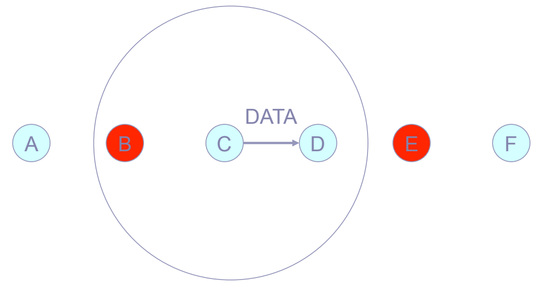
MACA (RTS/CTS)

CTS = Clear-to-Send

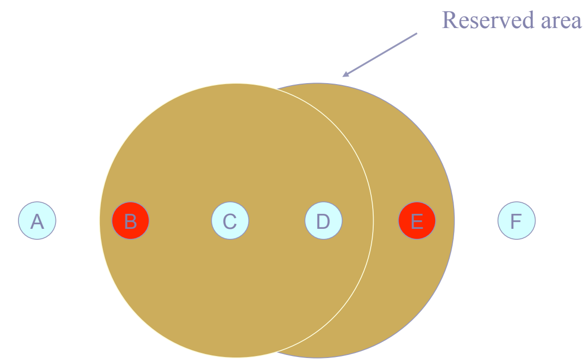


MACA (RTS/CTS)

•DATA packet follows CTS. Successful data reception acknowledged using ACK.



MACA (RTS/CTS)

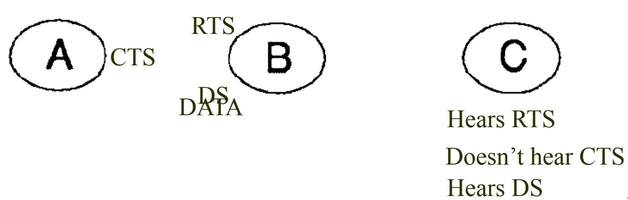


MACAW: Additional Design

- ACK (needed for faster TCP transfers)

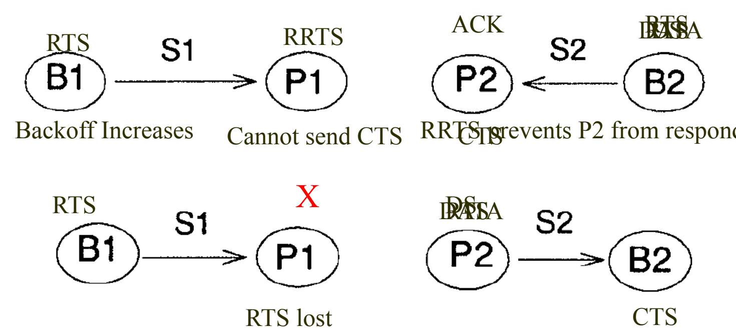
Error Rate	RTS-CTS-DATA	RTS-CTS-DATA-ACK
0	40.41	36.76
0.001	36.58	36.67
0.01	16.65	35.52
0.1	2.48	9.93

- DS (needed since carrier sense disabled)



RRTS

- Problem:



MACAW: Conclusions

- 8% extra overhead for DS and ACK
- 37% improvement in congestion

MACA	RTS-CTS-DATA	53.07
MACAW	RTS-CTS-DS-DATA-ACK	49.07

Table 9: The throughput, in packets per second, achieved by a uncontested single stream.

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IEEE 802.11 Overview

- Adopted in 1997

Defines:

- MAC sublayer
- MAC management protocols and services
- Physical (PHY) layers
  - IR
  - FHSS
  - DSSS

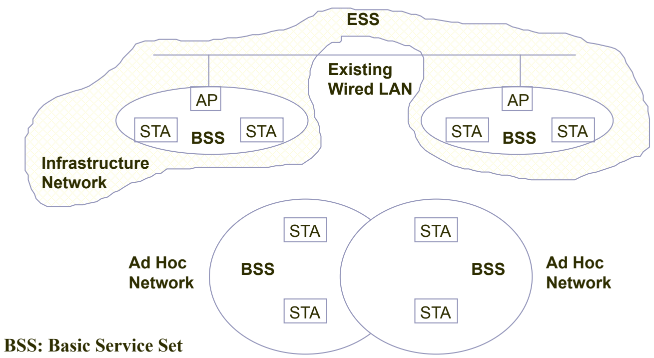
802.11 particulars

- 802.11b (WiFi)
  - Frequency: 2.4 - 2.4835 Ghz DSSS
  - Modulation: DBPSK (1Mbps) / DQPSK (faster)
  - Orthogonal channels: 3
    - There are others, but they interfere. (!)
  - Rates: 1, 2, 5.5, 11 Mbps
- 802.11a: Faster, 5Ghz OFDM. Up to 54Mbps
- 802.11g: Faster, 2.4Ghz, up to 54Mbps
- 802.11n: 2.4 or 5Ghz, multiple antennas (MIMO), up to 450Mbps (for 3x3 antenna configuration)

802.11 details

- Preamble
  - 72 bits @ 1Mbps, 48 bits @ 2Mbps
  - Note the relatively high per-packet overhead
- Control frames
  - RTS/CTS/ACK/etc.
- Management frames
  - Association request, beacons, authentication, etc.

Overview, 802.11 Architecture



BSS: Basic Service Set
ESS: Extended Service Set

802.11 modes

- Infrastructure mode
  - All packets go through a base station
  - Cards associate with a BSS (basic service set)
  - Multiple BSSs can be linked into an Extended Service Set (ESS)
    - Handoff to new BSS in ESS is pretty quick
      - Wandering around CMU
    - Moving to new ESS is slower, may require re-addressing
      - Wandering from CMU to Pitt
- Ad Hoc mode
  - Cards communicate directly.
  - Perform some, but not all, of the AP functions

802.11 Management Operations

- Scanning
- Association/Reassociation
- Time synchronization
- Power management

Scanning & Joining

- Goal: find networks in the area
- Passive scanning
  - No require transmission → saves power
  - Move to each channel, and listen for Beacon frames
- Active scanning
  - Requires transmission → saves time
  - Move to each channel, and send Probe Request frames to solicit Probe Responses from a network

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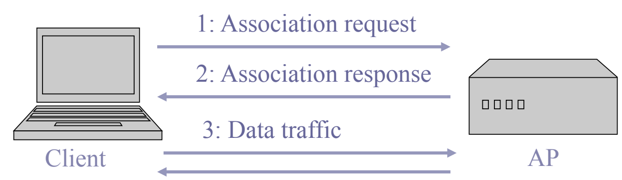
Association in 802.11



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Time Synchronization in 802.11

- Timing synchronization function (TSF)
  - AP controls timing in infrastructure networks
  - All stations maintain a local timer
  - TSF keeps timer from all stations in sync
- Periodic Beacons convey timing
  - Beacons are sent at well known intervals
  - Timestamp from Beacons used to calibrate local clocks
  - Local TSF timer mitigates loss of Beacons

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Power Management in 802.11

- A station is in one of the three states
  - Transmitter on
  - Receiver on
  - Both transmitter and receiver off (dozing)
- AP buffers packets for dozing stations
- AP announces which stations have frames buffered in its Beacon frames
- Dozing stations wake up to listen to the beacons
- If there is data buffered for it, it sends a poll frame to get the buffered data

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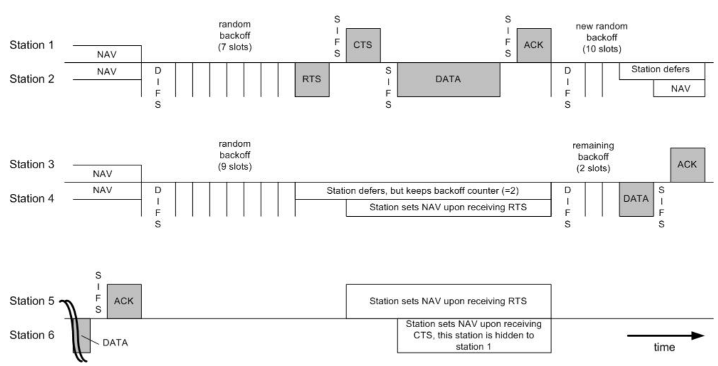
IEEE 802.11 Wireless MAC

- Support broadcast, multicast, and unicast
  - Uses ACK and retransmission to achieve reliability for unicast frames
  - No ACK/retransmission for broadcast or multicast frames
- Distributed and centralized MAC access
  - Distributed Coordination Function (DCF)
  - Point Coordination Function (PCF)

802.11 DCF (CSMA)

- Distributed Coordination Function (CSMA/CA)
- Sense medium. Wait for a DIFS (50 μs)
- If busy, wait ‘till not busy. Random backoff.
- If not busy, Tx.
- Backoff is binary exponential
- Acknowledgements use SIFS (short interframe spacing). 10 μs.
  - Short spacing makes exchange atomic

802.11 DCF ([RTS/CTS/]Data/ACK)



Discussion

- RTS/CTS/Data/ACK vs. Data/ACK
  - Why/when is it useful?
  - What is the right choice
  - Why is RTS/CTS not used?

802.11 Rate Adaptation

- 802.11 spec specifies rates not algorithm for choices
  - 802.11b 4 rates, 802.11a 8 rates, 802.11g 12 rates
  - Each rate has different modulation and coding

Transmission Rate ↑ then Loss Ratio ↑

Transmission Rate ↓ then Capacity Utilization ↓

throughput decreases either way – need to get it just right

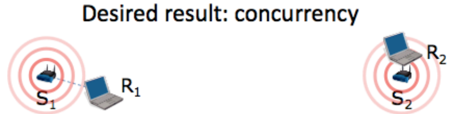
Auto Bit Rate (ABR) Algorithms

- Probe Packets
  - ARF
  - AARF
  - SampleRate
- Consecutive successes/losses
  - ARF
  - AARF
  - Hybrid Algorithm
- Physical Layer metrics
  - Hybrid Algorithm
  - RBAR
  - OAR
- Long-term statistics
  - ONOE

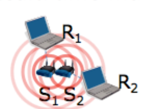
Commercially Deployed: ARF, SampleRate and ONOE

Carrier Sense

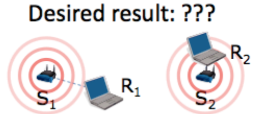
Desired result: concurrency



Desired result: time-multiplexing

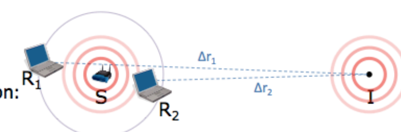


Desired result: ???

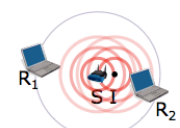


Maybe Carrier Sense is Fine?

- "Far" interference:
  - Small distance variation: $\Delta r_1 \approx \Delta r_2$

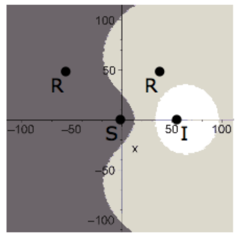


- "Near" interference:
  - Nobody wants concurrency; $SINR_{concurrent} <<< SNR_{multiplexing}$



- In both cases, all receivers agree on preferring either multiplexing or concurrency
  - "Agreement" means CS can perform well
- Intermediate distance will be the hard case
- Also, shadows and obstacles?

Single Receiver, Sender and Interferer



D = 55

- Prefers concurrency
- Prefers multiplexing
- Starved w/o multiplexing

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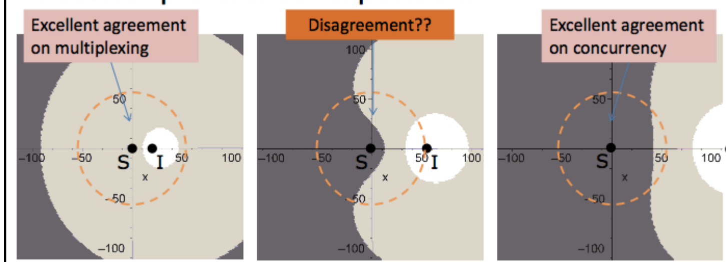
Interferer Position

Receiver preference vs. position:



- Prefers concurrency
- Prefers multiplexing
- Starved w/o multiplexing

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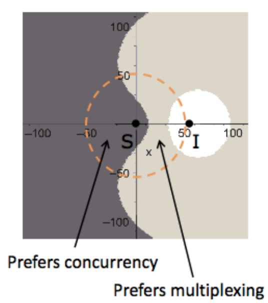
ABR Helps in Disagreements

- Intermediate distance can mean poor agreement! But...
- Does "mistaken" concurrency mean near-zero throughput? No. Adapts with lower bitrate.
- Does "mistaken" multiplexing mean 50%-reduced throughput? No. Adapts with higher bitrate.
- "Exposed" and "hidden" terminals are not very useful concepts with ABR



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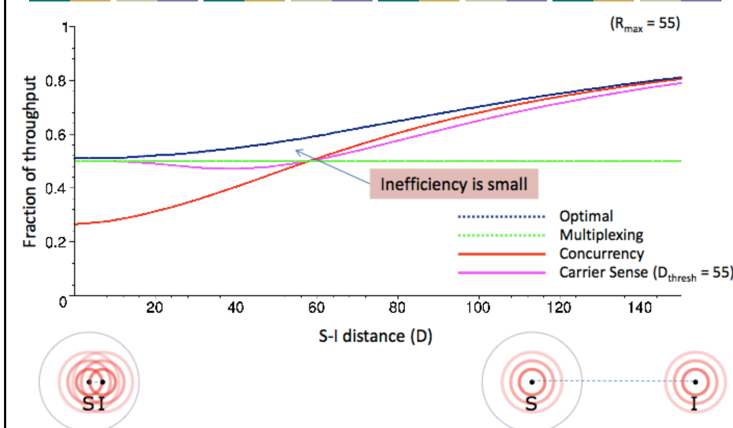
Carrier Sense + ABR Works Well



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Key Assumptions

- ABR == Shannon
  - ABR is rarely this good
- Interference and ABR are both stable
  - Interference may be bursty/intermittent

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TCP Problems Over Noisy Links

- Wireless links are inherently error-prone
  - Fades, interference, attenuation
  - Errors often happen in bursts
- TCP cannot distinguish between corruption and congestion
  - TCP unnecessarily reduces window, resulting in low throughput and high latency
- Burst losses often result in timeouts
- Sender retransmission is the only option
  - Inefficient use of bandwidth

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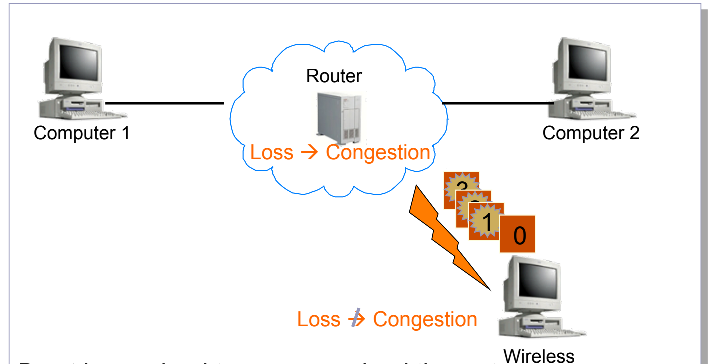
Constraints & Requirements

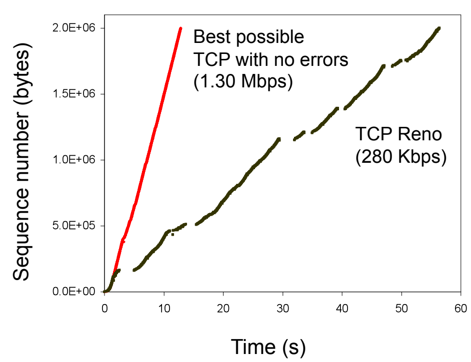
- Incremental deployment
  - Solution should not require modifications to fixed hosts
  - If possible, avoid modifying mobile hosts
- Probably more data to mobile than from mobile
  - Attempt to solve this first

Challenge #1: Wireless Bit-Errors



Burst losses lead to coarse-grained timeouts
Result: Low throughput

Performance Degradation



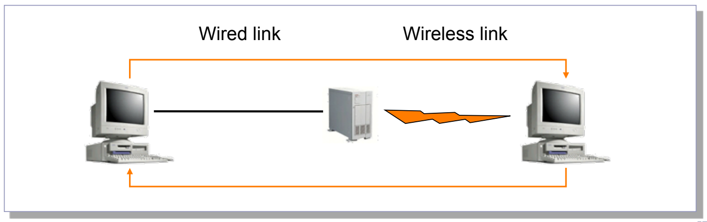
2 MB wide-area TCP transfer over 2 Mbps Lucent WaveLAN

Proposed Solutions

- End-to-end protocols
  - Selective ACKs, Explicit loss notification
- Split-connection protocols
  - Separate connections for wired path and wireless hop
- Reliable link-layer protocols
  - Error-correcting codes
  - Local retransmission

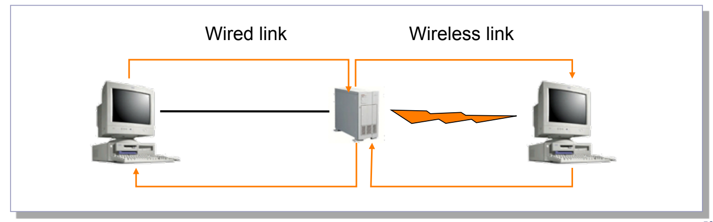
Approach Styles (End-to-End)

- Improve TCP implementations
  - Not incrementally deployable
  - Improve loss recovery (SACK, NewReno)
  - Help it identify congestion (ELN, ECN)
    - ACKs include flag indicating wireless loss
  - Trick TCP into doing right thing → E.g. send extra dupacks
  - What is SMART?
    - DUPACK includes sequence of data packet that triggered it

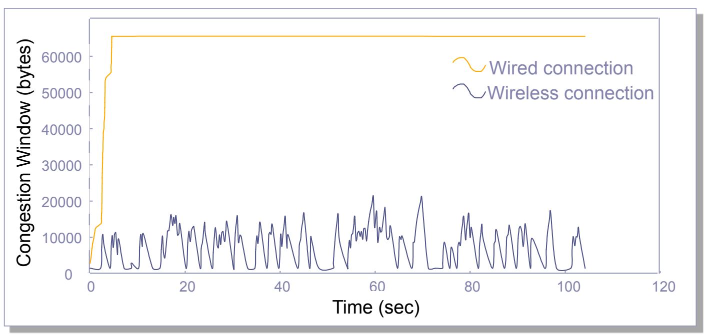


Approach Styles (Split Connection)

- Split connections
  - Wireless connection need not be TCP
  - Hard state at base station
    - Complicates mobility
    - Vulnerable to failures
    - Violates end-to-end semantics



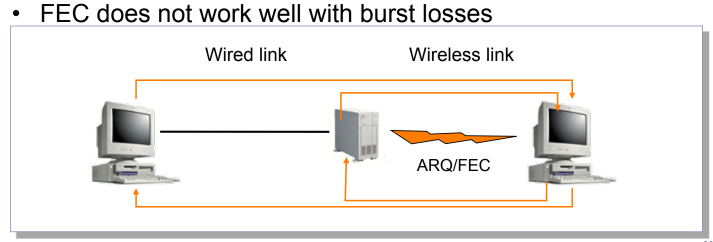
Split-Connection Congestion Window



- Wired connection does not shrink congestion window
- But wireless connection times out often, causing sender to stall

Approach Styles (Link Layer)

- More aggressive local rexmit than TCP
  - Bandwidth not wasted on wired links
- Adverse interactions with transport layer
  - Timer interactions
  - Interactions with fast retransmissions
  - Large end-to-end round-trip time variation
- FEC does not work well with burst losses



Hybrid Approach: Snoop Protocol

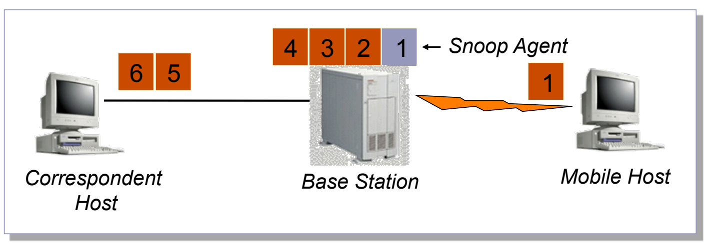
- Shield TCP sender from wireless vagaries
  - Eliminate adverse interactions between protocol layers
  - Congestion control only when congestion occurs
- The End-to-End Argument [SRC84]
  - Preserve TCP/IP service model: end-to-end semantics
  - *Is connection splitting fundamentally important?*
- Eliminate non-TCP protocol messages
  - *Is link-layer messaging fundamentally important?*

Fixed to mobile: transport-aware link protocol
Mobile to fixed: link-aware transport protocol

Snoop Overview

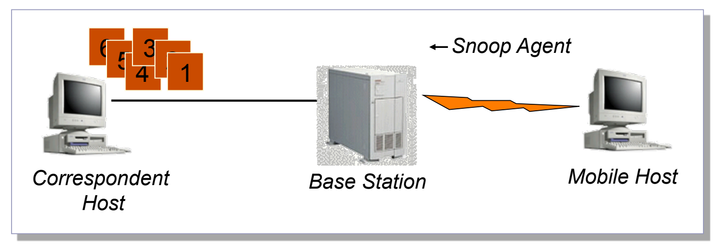
- Modify base station
  - to cache un-acked TCP packets
  - … and perform local retransmissions
- Key ideas
  - No transport level code in base station
  - When node moves to different base station, state eventually recreated there

Snoop Protocol: CH to MH



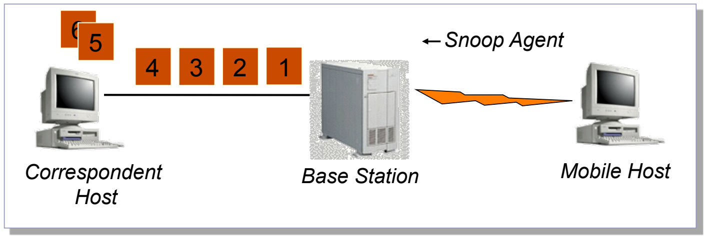
- Snoop agent: *active interposition agent*
  - Snoops on TCP segments and ACKs
  - Detects losses by duplicate ACKs and timers
  - Suppresses duplicate ACKs from MH

Snoop Protocol: CH to MH



- Transfer of file from CH to MH
- Current window = 6 packets

Snoop Protocol: CH to MH



- Transfer begins

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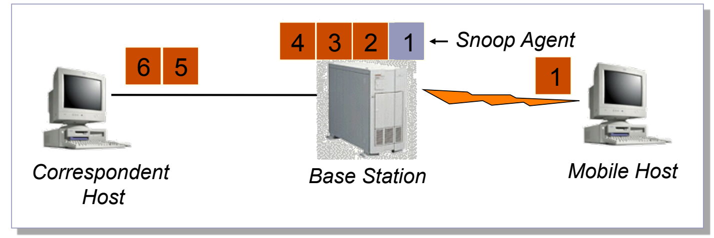
Snoop Protocol: CH to MH



- Snoop agent caches segments that pass by

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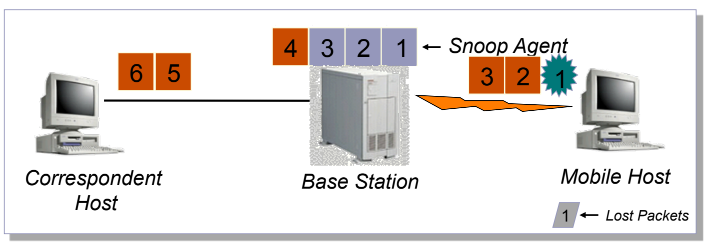
Snoop Protocol: CH to MH



- Packet 1 is Lost

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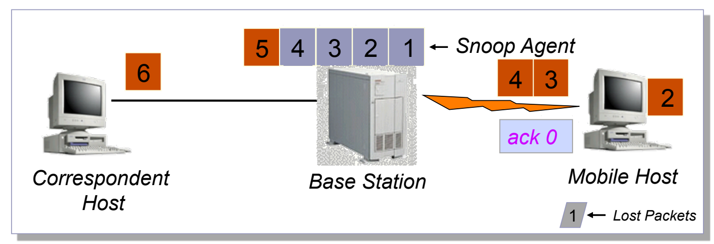
Snoop Protocol: CH to MH



- Packet 1 is Lost
  - Duplicate ACKs generated

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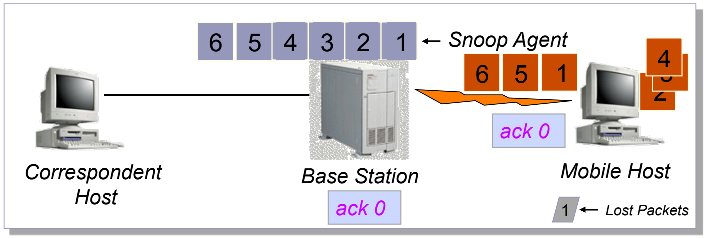
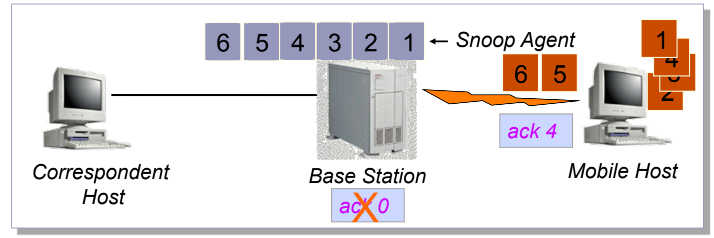
Snoop Protocol: CH to MH



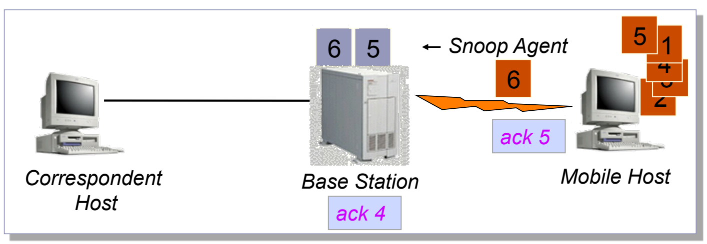
- Packet 1 is Lost
  - Duplicate ACKs generated
- Packet 1 retransmitted from cache at higher priority

Snoop Protocol: CH to MH



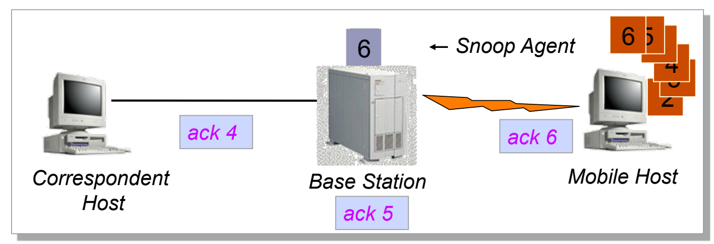
- Duplicate ACKs suppressed

Snoop Protocol: CH to MH



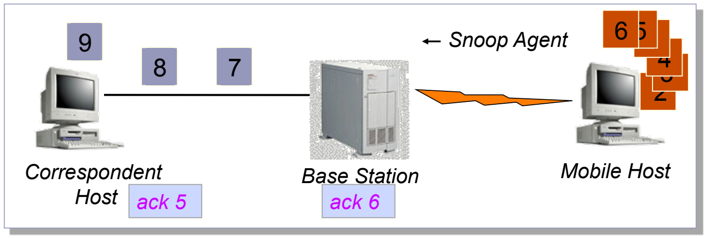
- Clean cache on new ACK

Snoop Protocol: CH to MH



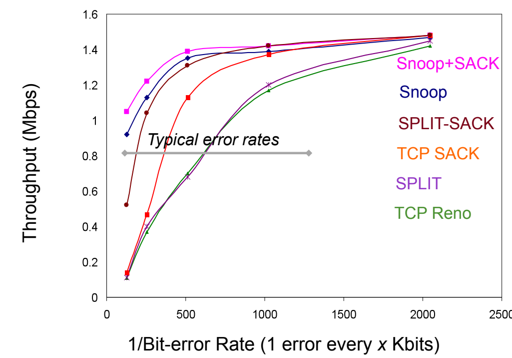
- Clean cache on new ACK

Snoop Protocol: CH to MH



- Active soft state agent at base station
- Transport-aware reliable link protocol
- Preserves end-to-end semantics

Performance: FH to MH



- Snoop+SACK and Snoop perform best
- Connection splitting *not* essential
- TCP SACK performance disappointing

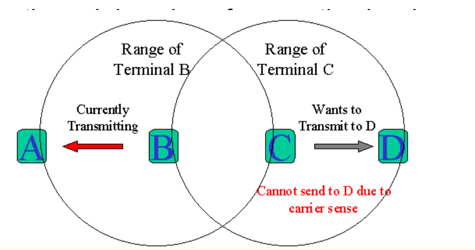
2 MB local-area TCP transfer over 2 Mbps Lucent WaveLAN

Discussion

- Real link-layers aren't windowed
  - Out of order delivery not that significant a concern
- TCP timers are very conservative

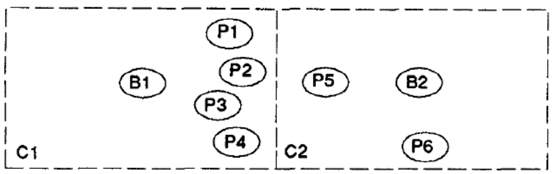
MACAW

- 4 design details
  1. Contention is at the receiver
  2. Congestion is location dependent
  3. Fairn
  4. Propa conte



Fairness in MACAW

- Channel capture in MACA
  - Backoff doubled every collision
  - Reduce backoff on success
- Solution: Copy backoffs
  - This does not always work as wanted



MACAW: Additional Design

- Multiple Stream Model

	Single Stream	Multiple Stream
B-P1	11.42	15.07
B-P2	12.34	15.82
P3-B	22.74	15.64

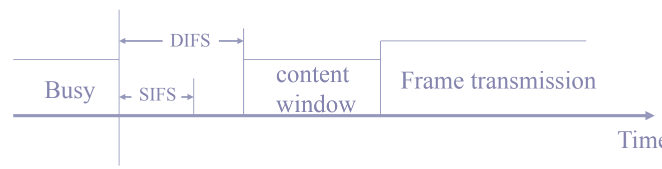
- ACK (TCP transfer!)

Error Rate	RTS-CTS-DATA	RTS-CTS-DATA-ACK
0	40.41	36.76
0.001	36.58	36.67
0.01	16.65	35.52
0.1	2.48	9.93

802.11 Glossary

- Station
- BSS - Basic Service Set
  - IBSS : Infrastructure BSS
- ESS - Extended Service Set
  - A set of infrastructure BSSs.
  - Connection of APs
  - Tracking of mobility
- DS – Distribution System
  - AP communicates with another

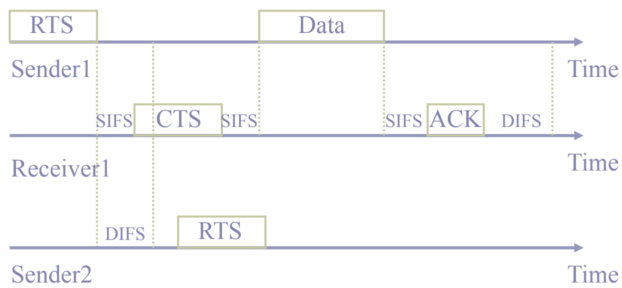
802.11 Frame Priorities



- Short interframe space (SIFS)
  - For highest priority frames (e.g., RTS/CTS, ACK)
- DCF interframe space (DIFS)
  - Minimum medium idle time for contention-based services

SIFS/DIFS

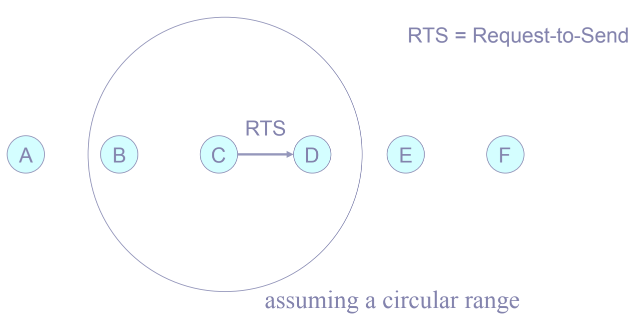
SIFS makes RTS/CTS/Data/ACK atomic



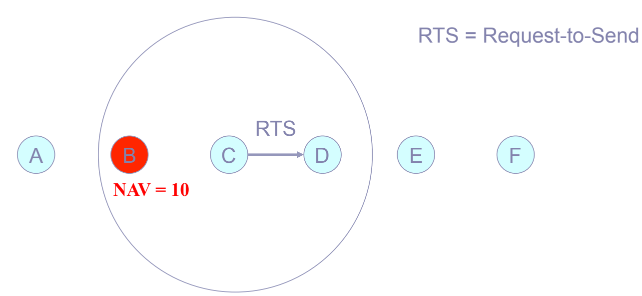
802.11 RTS/CTS

- RTS sets "duration" field in header to
  - CTS time + SIFS + CTS time + SIFS + data pkt time
- Receiver responds with a CTS
  - Field also known as the "NAV" - network allocation vector
  - Duration set to RTS dur - CTS/SIFS time
  - This reserves the medium for people who hear the CTS

IEEE 802.11

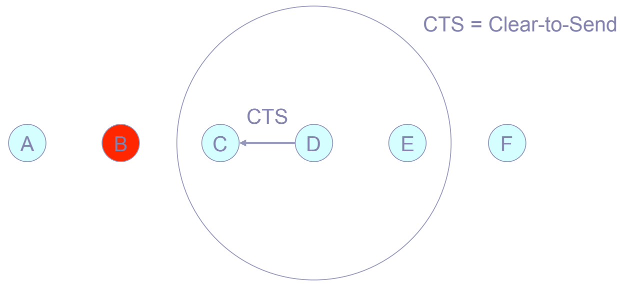


IEEE 802.11

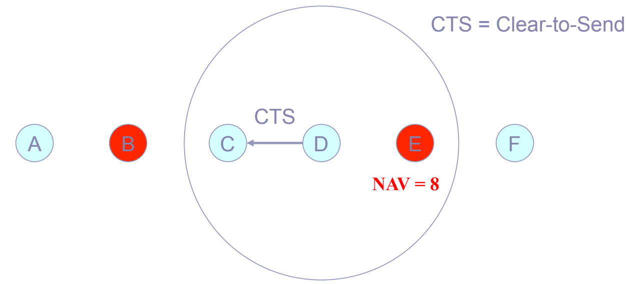


NAV = remaining duration to keep quiet

IEEE 802.11

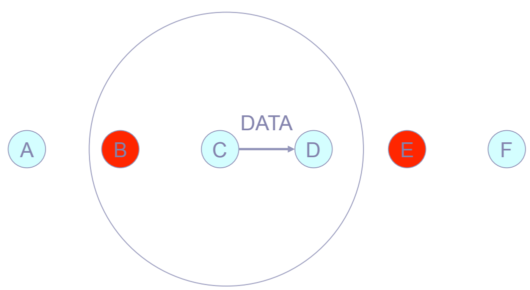


IEEE 802.11

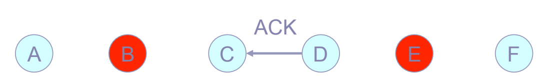


IEEE 802.11

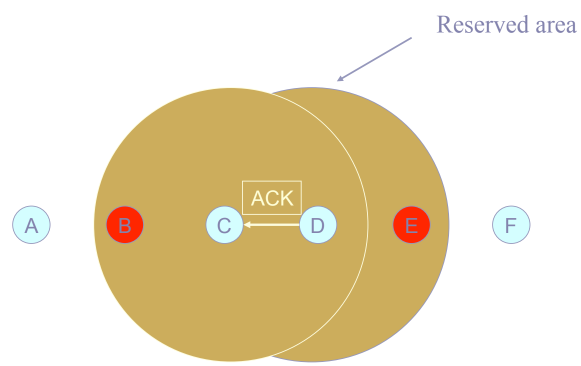
- DATA packet follows CTS. Successful data reception acknowledged using ACK.



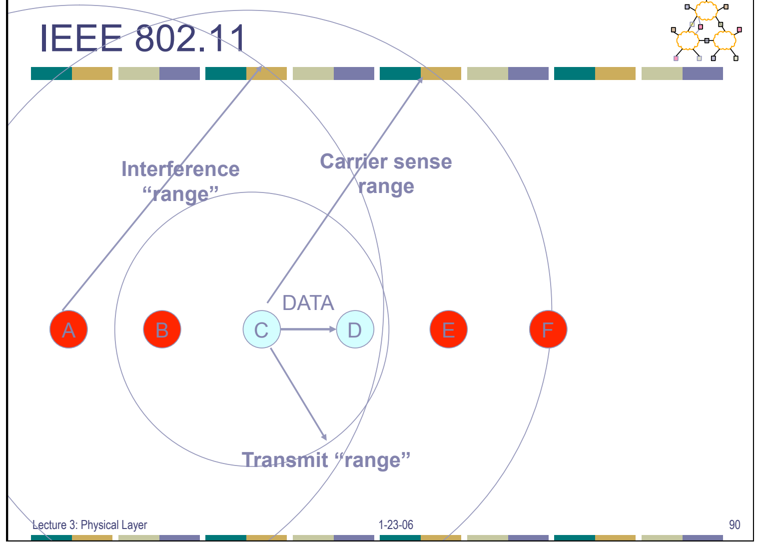
IEEE 802.11



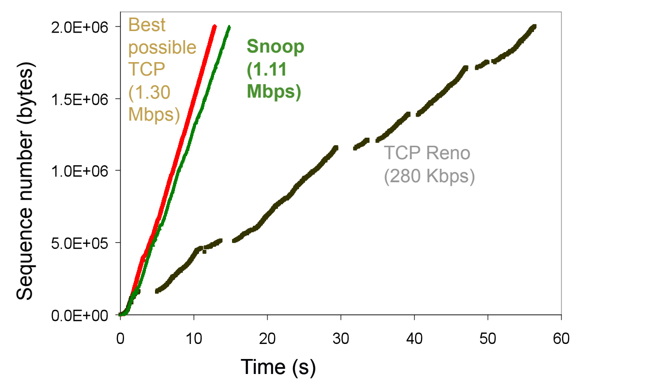
IEEE 802.11



IEEE 802.11

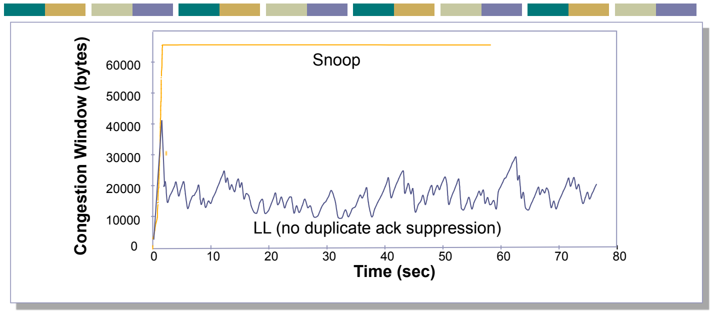


Snoop Performance Improvement



2 MB wide-area TCP transfer over 2 Mbps Lucent WaveLAN

Benefits of TCP-Awareness



- 30-35% improvement for Snoop: LL congestion window is small (but no coarse timeouts occur)
- Connection bandwidth-delay product = 25 KB
- Suppressing duplicate acknowledgments and TCP-awareness leads to better utilization of link bandwidth and performance

Other Issues

- What about mobility?
- What about mobile-to-fixed communication?

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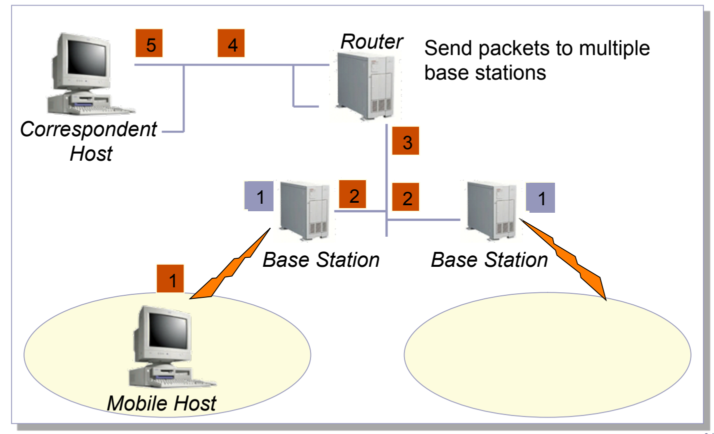
Handling Mobility



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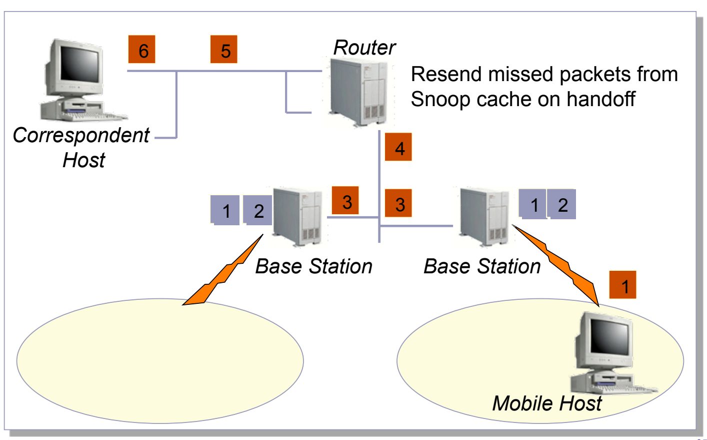
Handling Mobility



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Outline

- Bluetooth

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Bluetooth basics

- Short-range, high-data-rate wireless link for personal devices
  - Originally intended to replace cables in a range of applications
  - e.g., Phone headsets, PC/PDA synchronization, remote controls
- Operates in 2.4 GHz ISM band
  - Same as 802.11
  - Frequency Hopping Spread Spectrum across ~ 80 channels

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Bluetooth Basics cont.

- Maximum data rate of up to 720 Kbps
  - *But, requires large packets (> 300 bytes)*
- Class 1: Up to 100mW (20 dBm) transmit power, ~100m range
  - *Class 1 requires that devices adjust transmit power dynamically to avoid interference with other devices*
- Class 2: Up to 2.4 mW (4 dBm) transmit power
- Class 3: Up to 1 mW (0 dBm) transmit power

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Usage Models

- Wireless audio
  - e.g., Wireless headset associated with a cell phone
  - Requires guaranteed bandwidth between headset and base
  - No need for packet retransmission in case of loss
- Cable replacement
  - Replace physical serial cables with Bluetooth links
  - Requires mapping of RS232 control signals to Bluetooth messages
- LAN access
  - Allow wireless device to access a LAN through a Bluetooth connection
  - Requires use of higher-level protocols on top of serial port (e.g., PPP)
- File transfer
  - Transfer calendar information to/from PDA or cell phone
  - Requires understanding of object format, naming scheme, etc.

Lots of competing demands for one radio spec!

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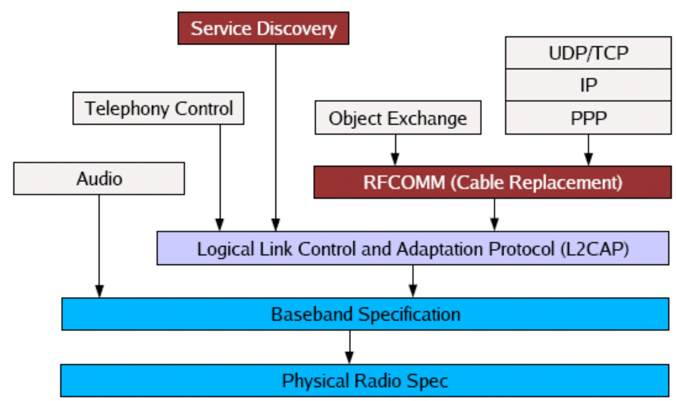
Protocol Architecture



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Piconet Architecture

- One master and up to 7 slave devices in each *Piconet*:

- Master contr e Piconet
  - Time Division Multiple Access (*TDMA*): Only one device transmits at a time
- Frequency hopping used to avoid collisions with other Piconets
  - 79 physical channels of 1 MHz each, hop between channels 1600 times a sec

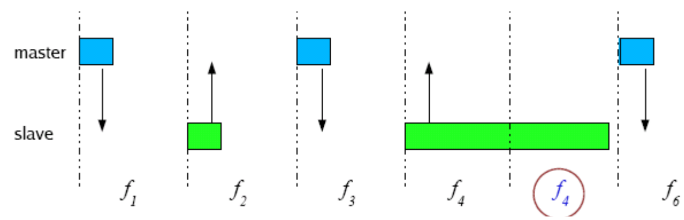
Scatternets

- Combine multiple Piconets into a larger Scatternet
  - Device may act as master in one Piconet and slave in another
  - *Each Piconet using different FH schedule to avoid interference*
- Can extend the range of Bluetooth, can route across Piconets

Baseband Specification

- 79 1-MHz channels defined in the 2.4 GHz ISM band
  - Gaussian FSK used as modulation, 115 kHz frequency deviation
- Frequency Hopping Spread Spectrum
  - Each Piconet has its own FH schedule, defined by the master
  - 1600 hops/sec, slot time 0.625 ms
- Time Division Duplexing
  - Master transmits to slave in one time slot, slave to master in the next
- TDMA used to share channel across multiple slave devices
  - Master determines which time slots each slave can occupy
  - Allows slave devices to sleep during inactive slots

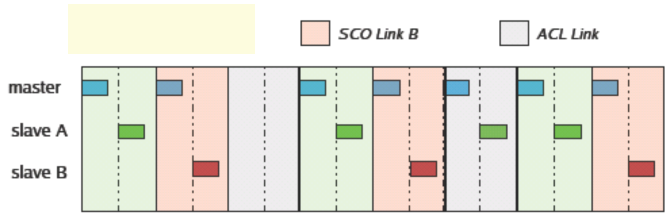
Time slots



- Each time slot on a different frequency
  - According to FH schedule
- Packets may contain ACK bit to indicate successful reception in the *previous* time slot
  - Depending on type of connection...
  - e.g., Voice connections do not use ACK and retransmit
- Packets may span multiple slots – stay on same frequency

Physical and Logical Links

- Bluetooth supports two types of physical links.
- Synchronous Connection Oriented (SCO):
  - Slave assigned to two consecutive slots at regular intervals
    - *Just like TDMA...*
  - No use of retransmission ... *why??*
- Asynchronous Connectionless (ACL)
  - Allows non-SCO slots to be used for "on demand" transmissions
  - Slave can only reply if it was addressed in previous slot by master



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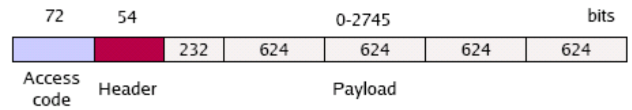
Packet Formats

- Bluetooth supports 14 different payload formats!
  - Different formats for control, voice, and data packets
  - Frames can span 1, 3, or 5 slots
  - Different levels of error coding: No coding, 1/3, or 2/3 FEC



- What is the maximum bandwidth that Bluetooth can achieve?
  - Counting only application payload bytes, no CRC or FEC
  - 5-slot packet, no protection: 341 payload bytes
  - Total time = 5 * (0.625) ms = 3.125 ms
    - But ... need to count an extra slot from the master for ACK!
  - Total bandwidth is therefore 341 bytes / (6 * 0.625 ms) = 721 kbps

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Discussion

- Nice points
  - A number of interesting low power modes
  - Device discovery
    - Must synchronize FH schemes
    - Burden on the searcher
- Some odd decisions
  - Addressing
  - Somewhat bulky application interfaces
    - Not just simple byte-stream data transmission
    - Rather, complete protocol stack to support voice, data, video, file transfer, etc.
      - *Bluetooth operates at a higher level than 802.11 and 802.15.4*

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