CE693: Adv. Computer Networking

L-9 Wireless

Acknowledgments: Lecture slides are from the graduate level Computer Networks course thought by Srinivasan Seshan at CMU. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.

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

Wireless Challenges

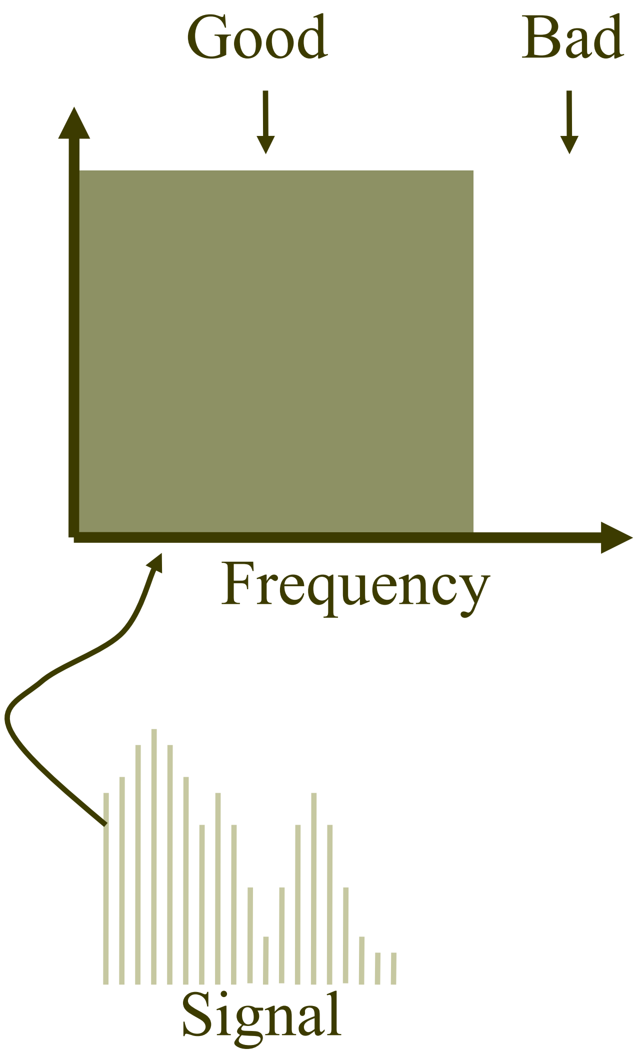
- Force us to rethink many assumptions
- Need to share airwaves rather than wire
  - Don't know what hosts are involved
  - Host may not be using same link technology
- Mobility
- Other characteristics of wireless
  - Noisy → lots of losses
  - Slow
  - Interaction of multiple transmitters at receiver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

Overview

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

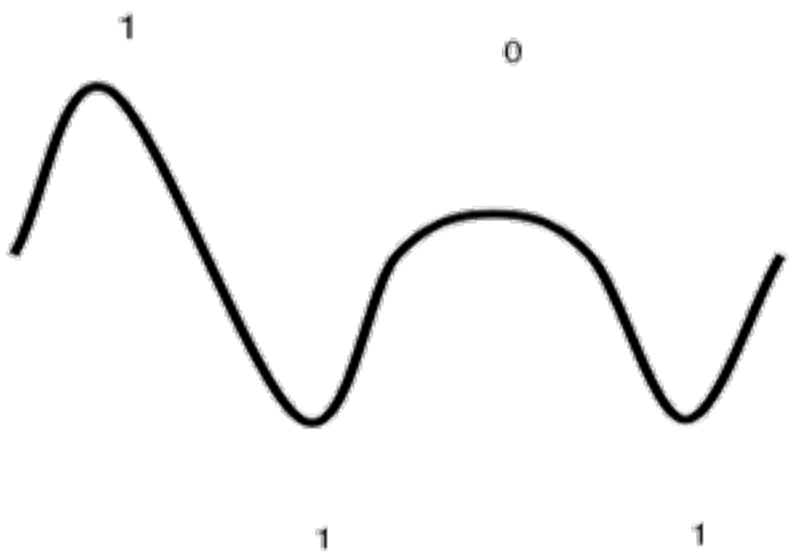
Transmission Channel Considerations

- 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



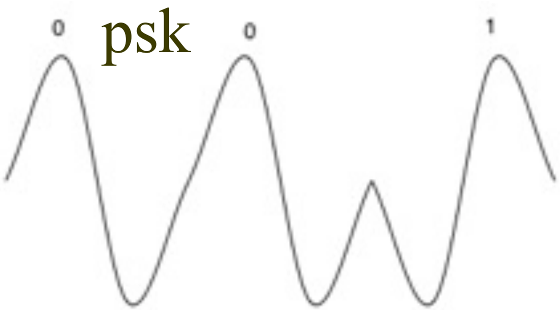
The Nyquist Limit

- 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



Psk
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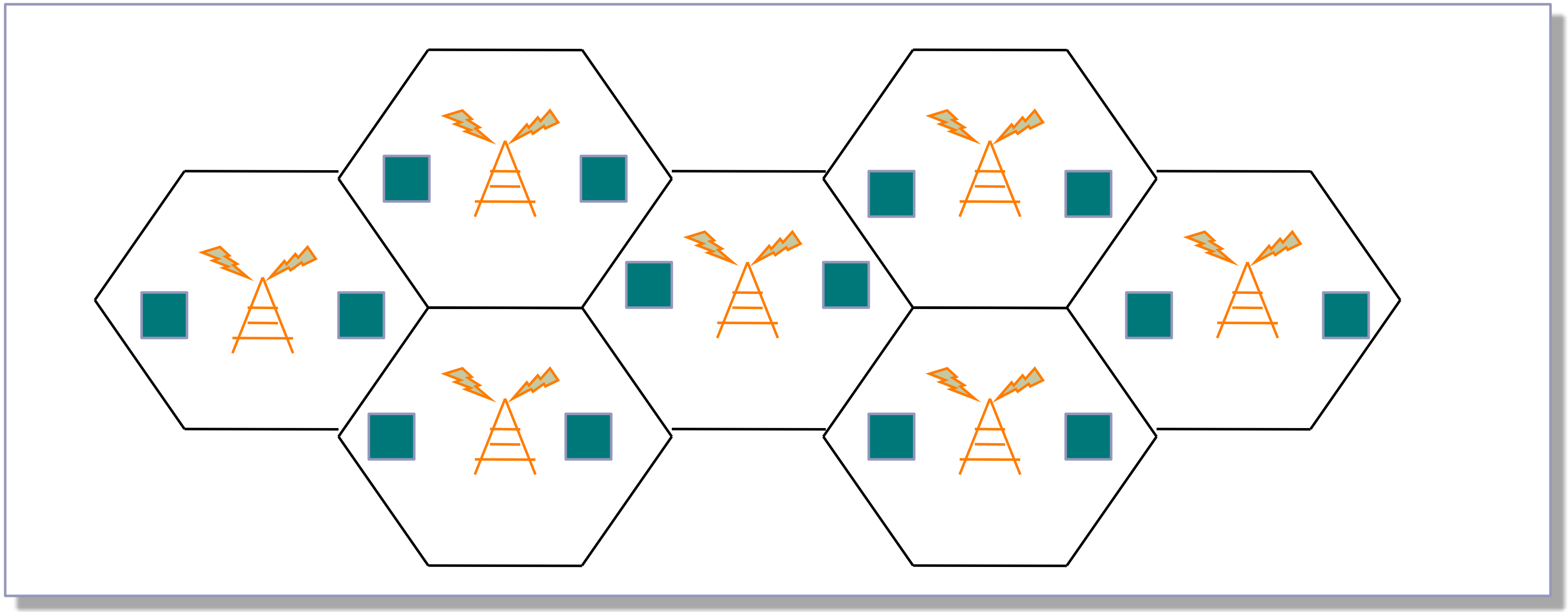
Capacity of a Noisy Channel

- 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.

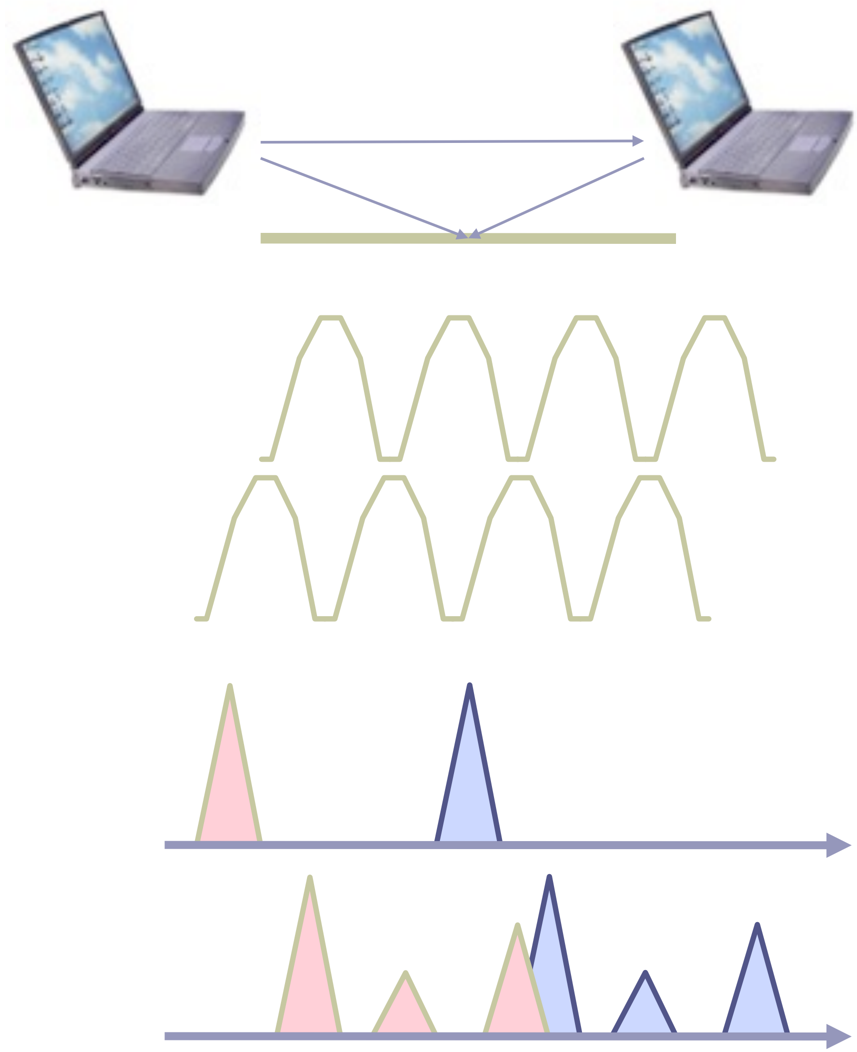
Cellular Reuse

- 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

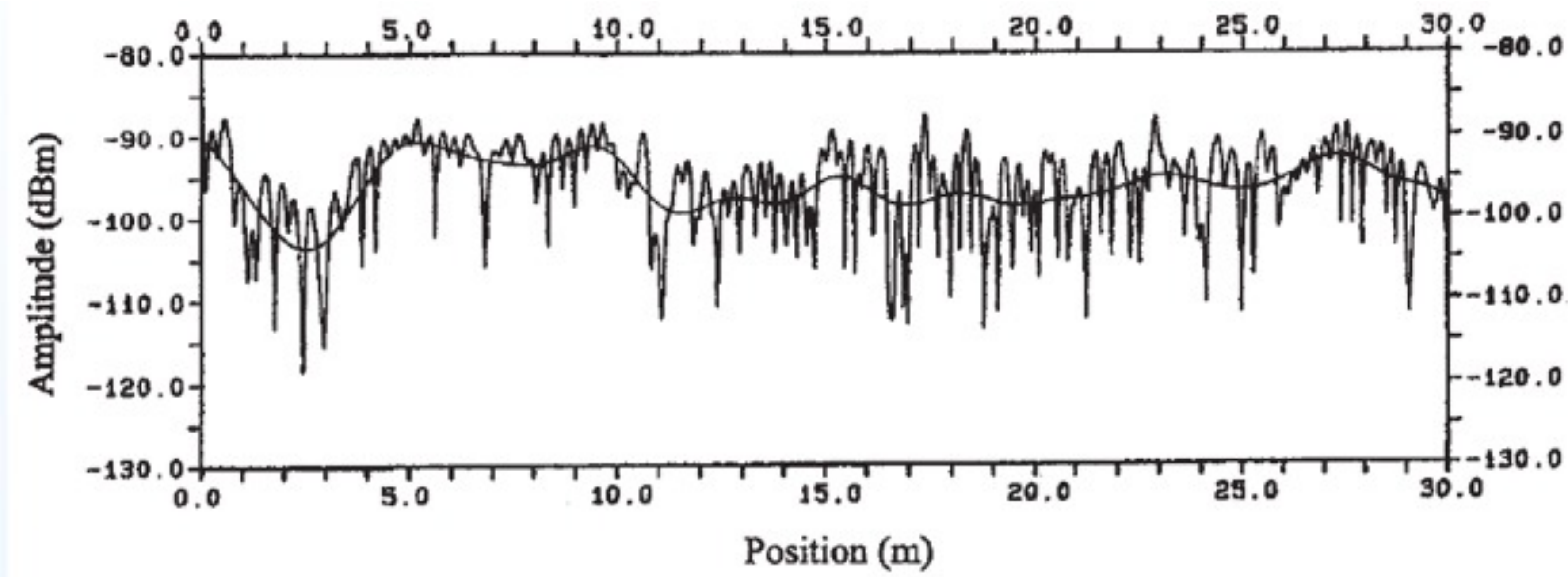


Multipath Effects

- 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 or 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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Medium Access Control

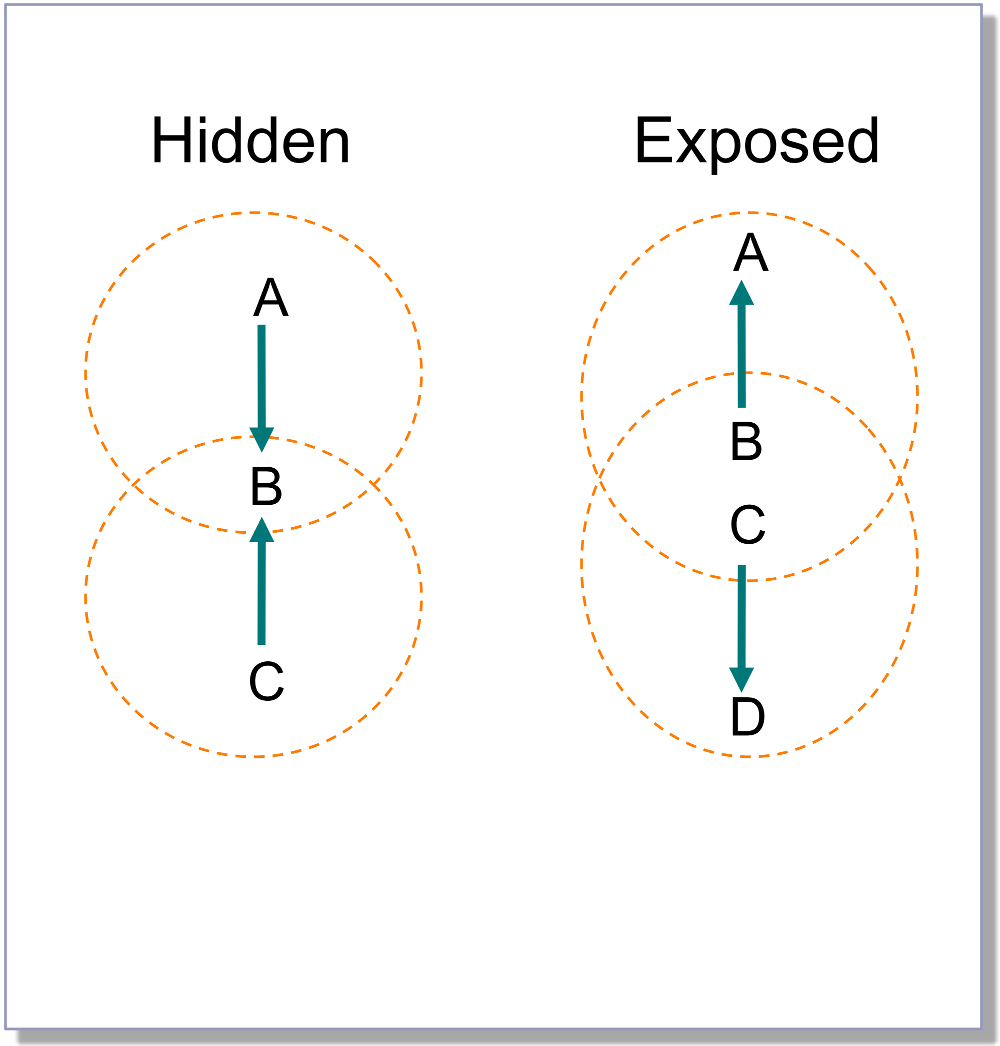
- Think back to Ethernet MAC:
  - Wireless is a shared medium
  - Transmitters interfere
  - Need a way to ensure that (usually) only one person talks at a time.
    - Goals: Efficiency, possibly fairness

Example MAC Protocols

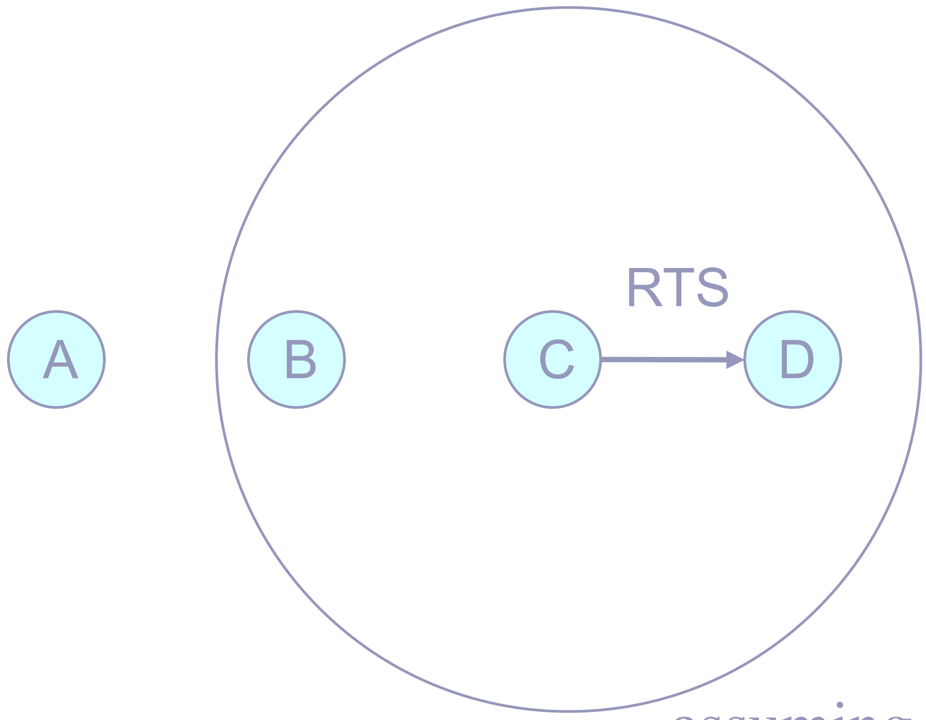
- Pure ALOHA
  - Transmit whenever a message is ready
  - Retransmit when ACK is not received
- Slotted ALOHA
  - Time is divided into equal time slots
  - Transmit only at the beginning of a time slot
  - Avoid partial collisions
  - Increase delay, and require synchronization
- Carrier Sense Multiple 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)

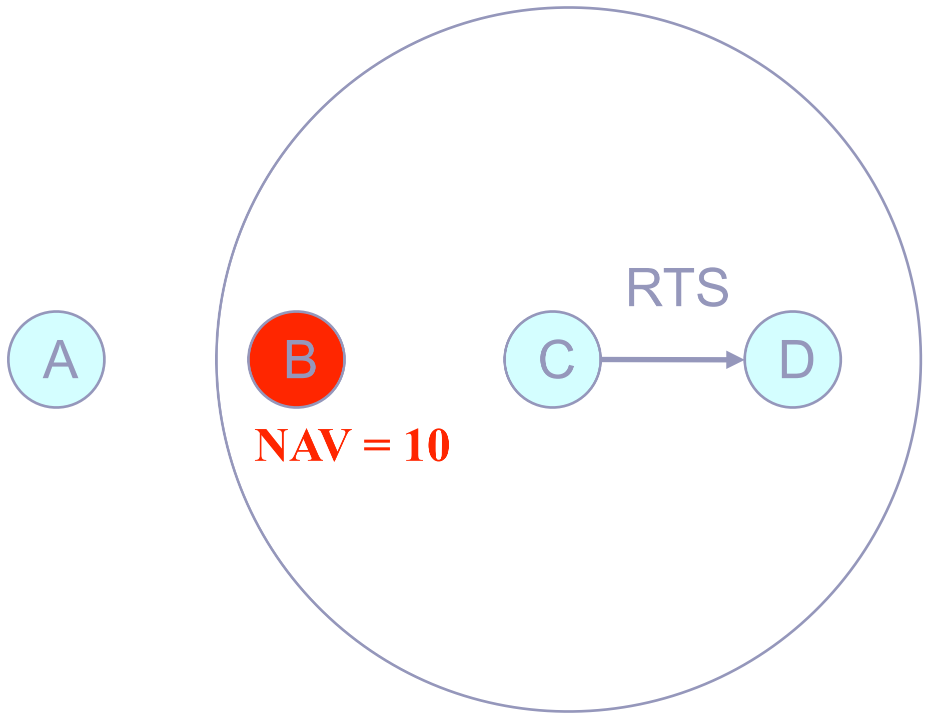


RTS = Request-to-Send

assuming a circular range

MACA (RTS/CTS)

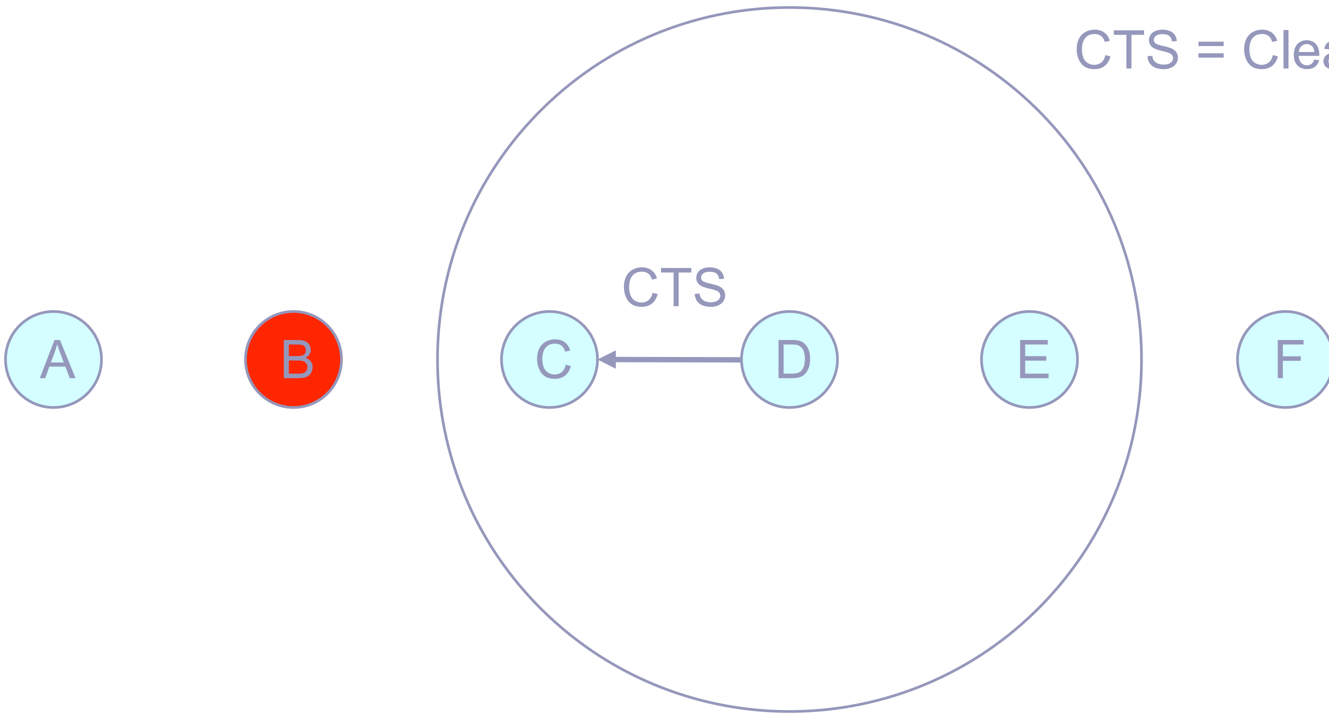
RTS = Request-to-Send



NAV = remaining duration to keep quiet

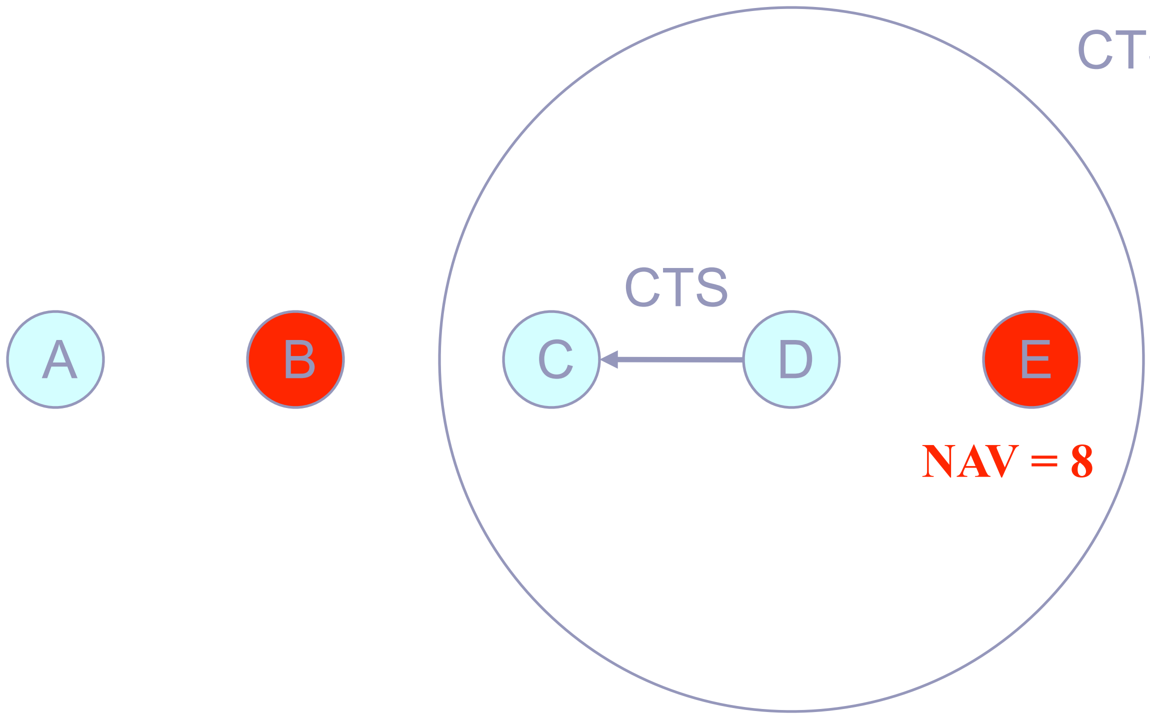
MACA (RTS/CTS)

CTS = Clear-to-Send



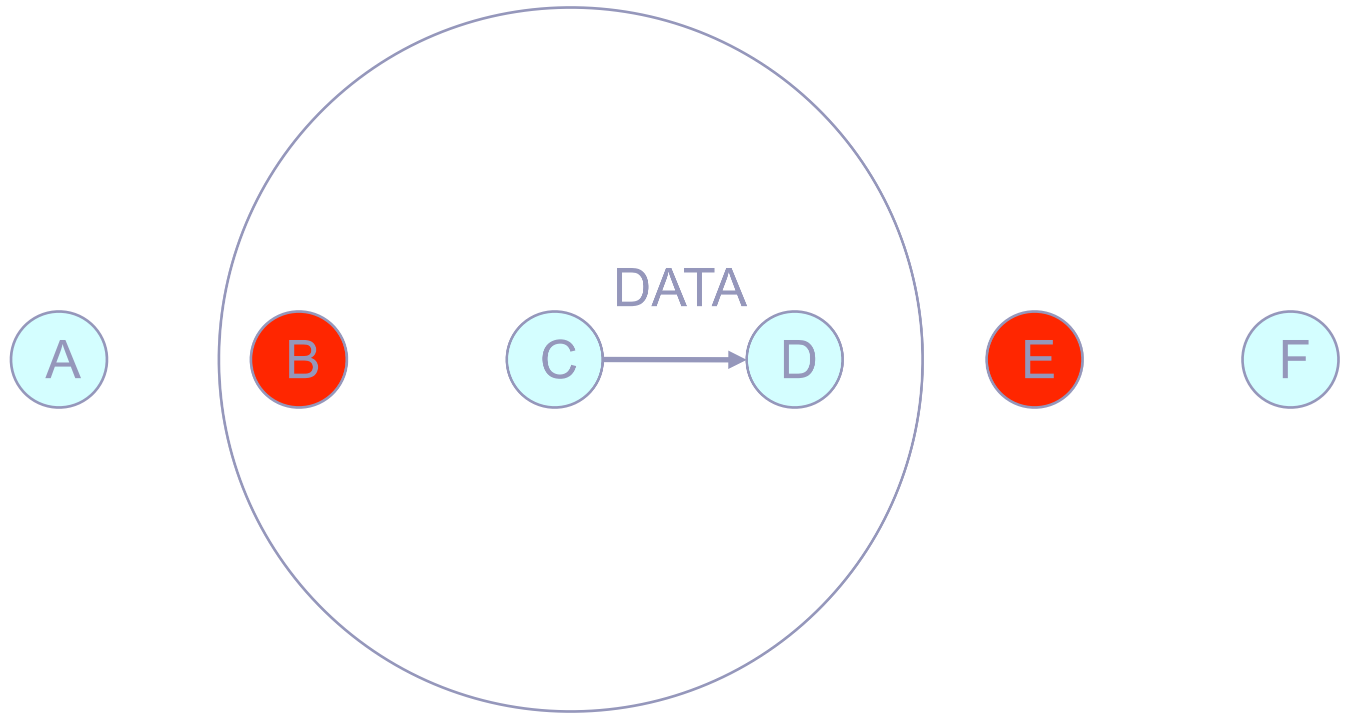
MACA (RTS/CTS)

CTS = Clear-to-Send

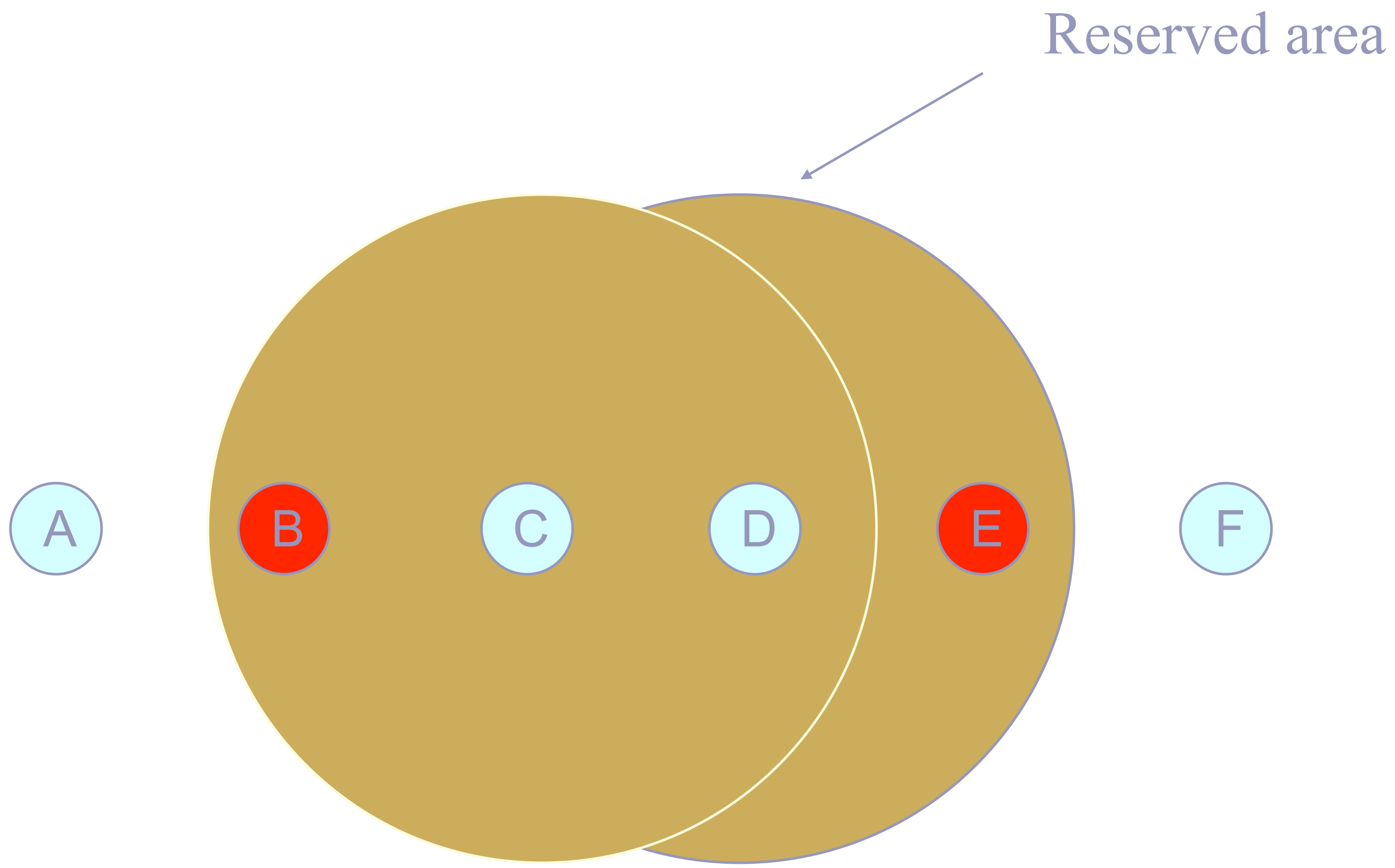


MACA (RTS/CTS)

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



MACA (RTS/CTS)

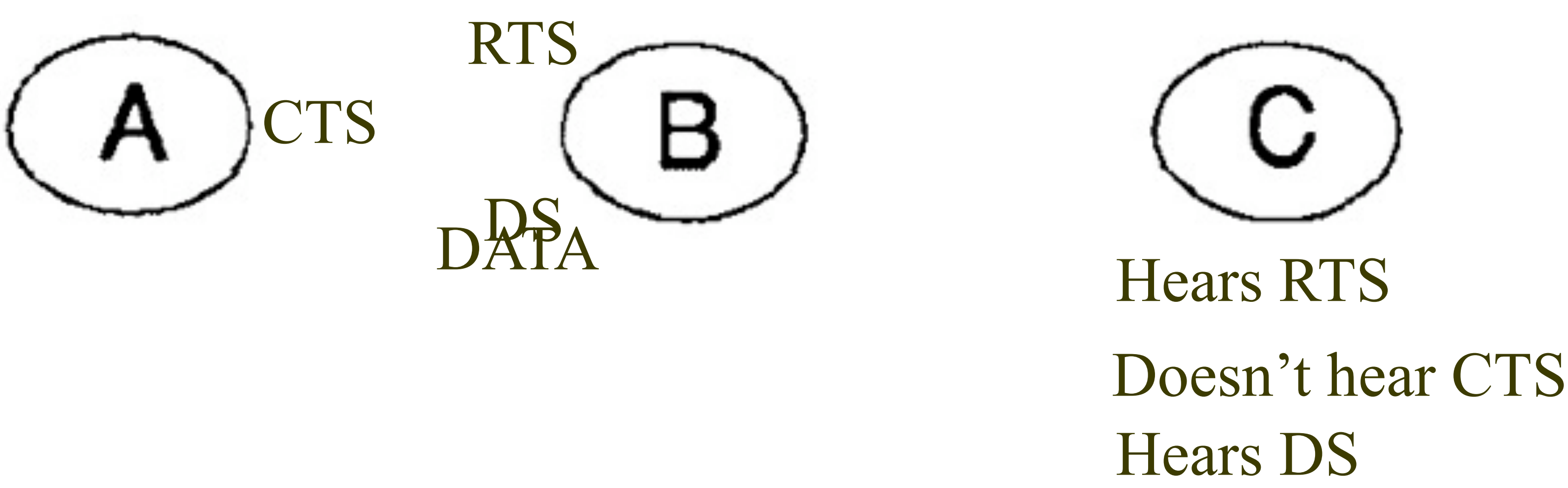


MACAW: Additional Design

- 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)



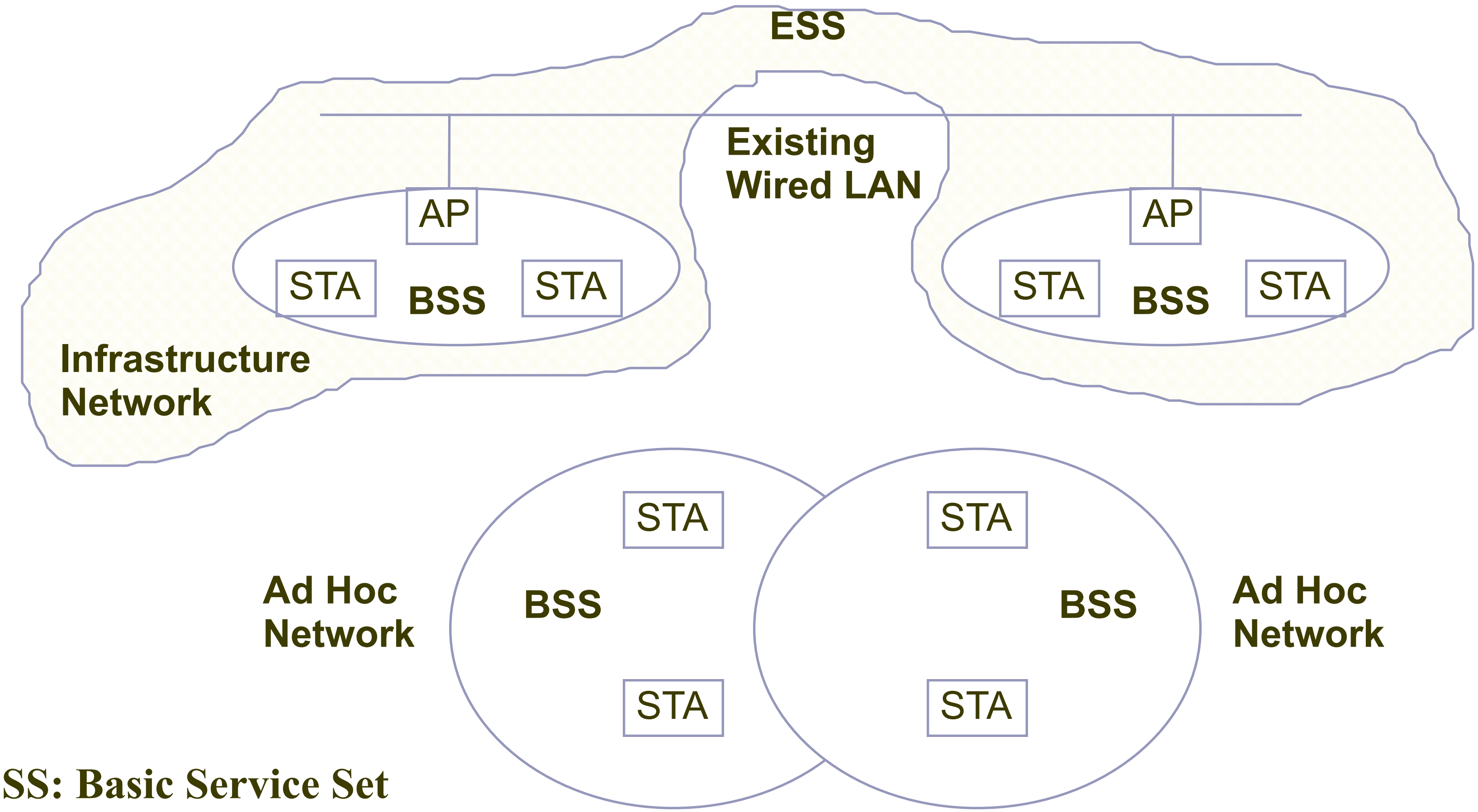
Overview

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

802.11 particulars

- 802.11b (WiFi)
  - Frequency: 2.4 - 2.4835 Ghz DSSS
  - Rates: 1, 2, 5.5, 11 Mbps
- 802.11a: Faster, 5Ghz OFDM. Up to 54Mbps, 19+ channels
- 802.11g: Faster, 2.4Ghz, up to 54Mbps
- 802.11n: 2.4 or 5Ghz, multiple antennas (MIMO), up to 450Mbps (for 3x3 antenna configuration)

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 CE building
    - Moving to new ESS is slower, may require re-addressing
      - Wandering from Sharif to Tehran U.
- Ad Hoc mode
  - Cards communicate directly.

802.11 Management Operations

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

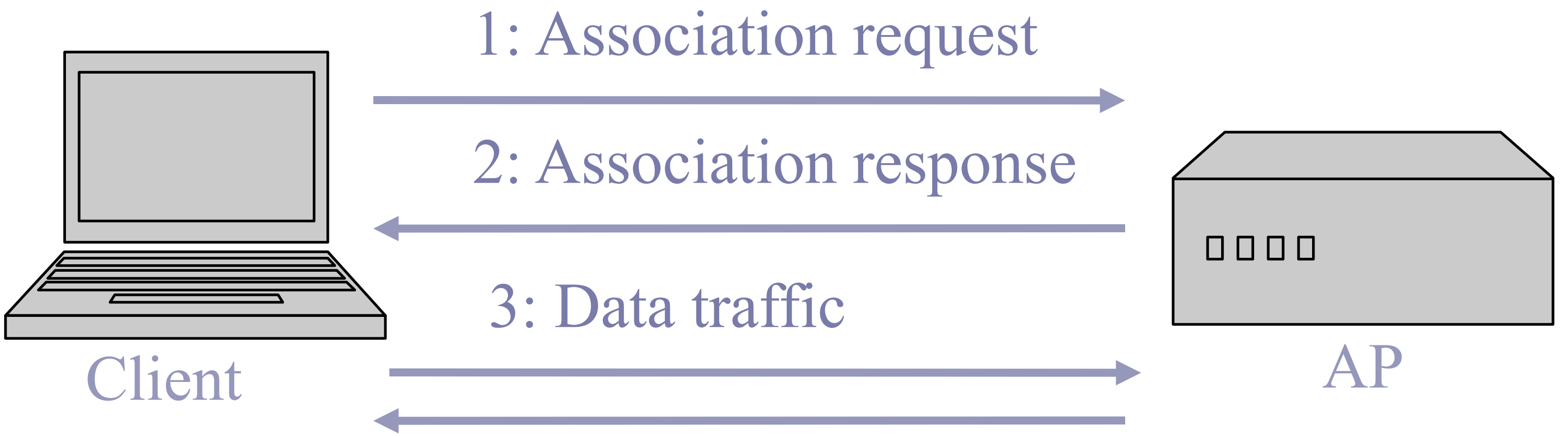
Scanning & Joining

- 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

Association in 802.11



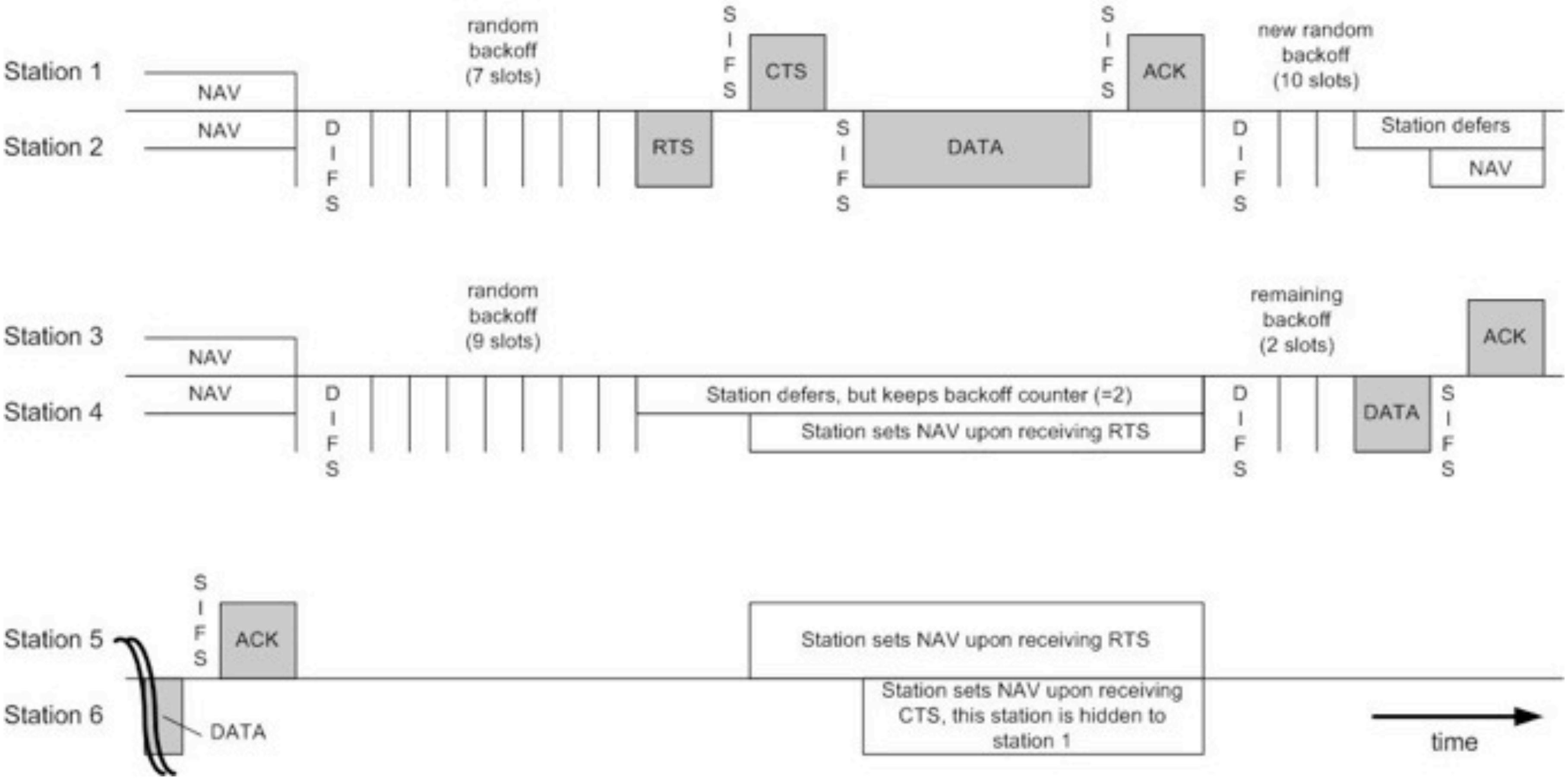
Time Synchronization in 802.11

- 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

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

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 ↑

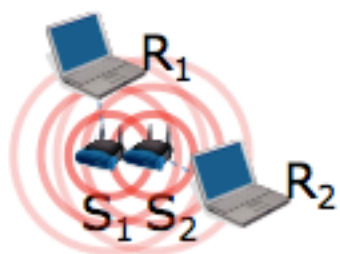
Transmission Rate ↓ then Capacity Utilization ↓

throughput decreases either way – need to get it just right

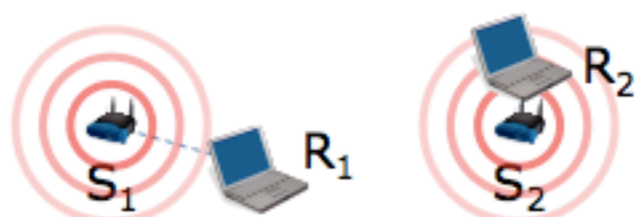
Carrier Sense

Desired result: concurrency

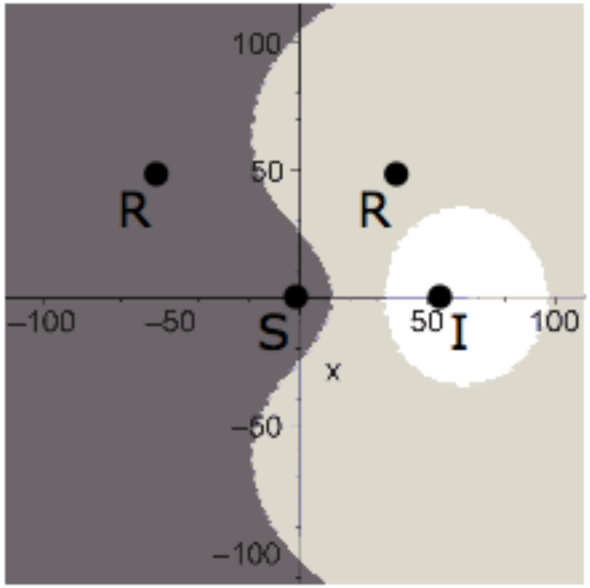
Desired result: time-multiplexing



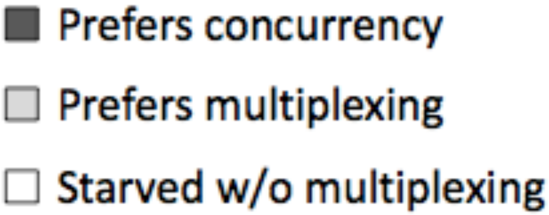
Desired result: ???



Single Receiver, Sender and Interferer

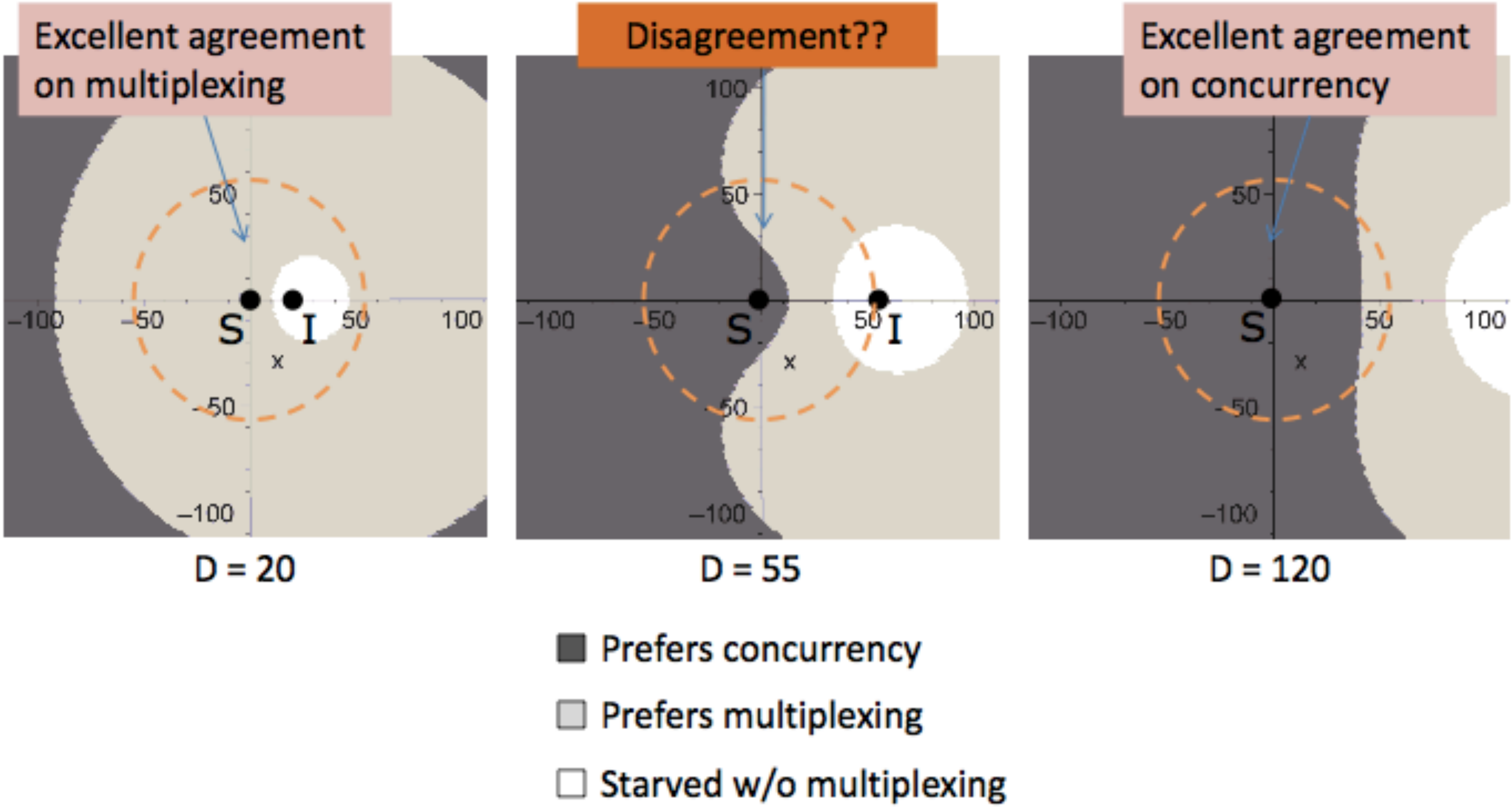


D = 55



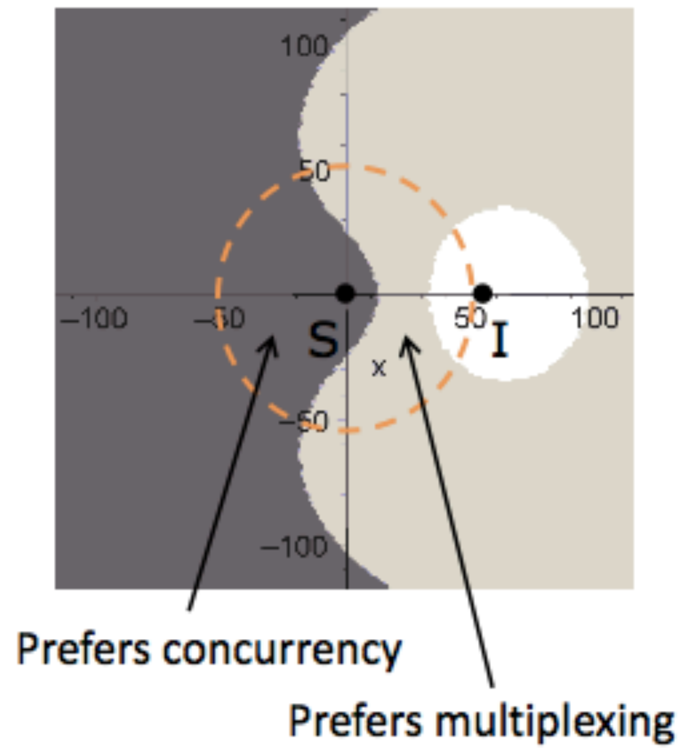
Interferer Position

Receiver preference vs. position:

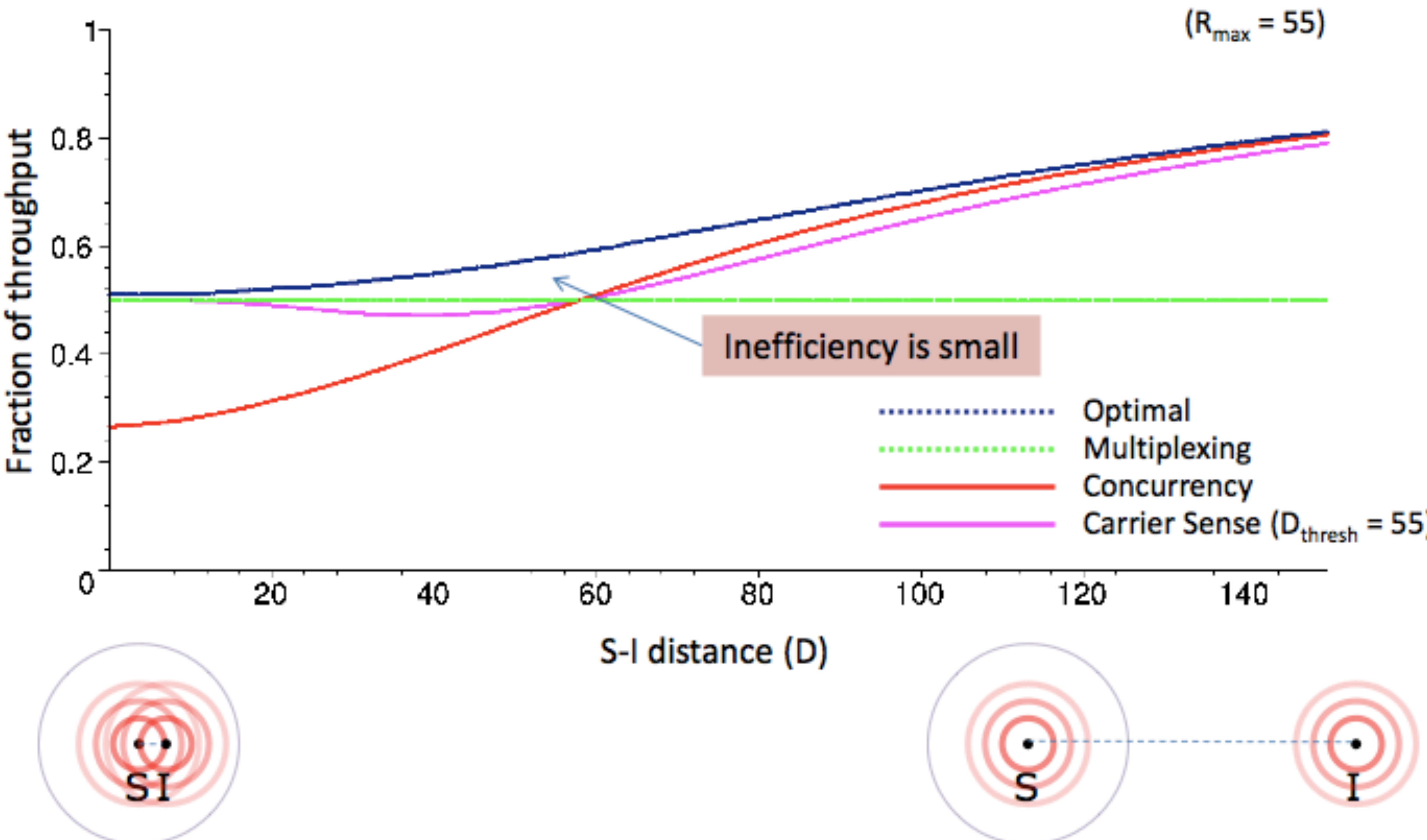


ABR Helps in Disagreements

- 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.



Carrier Sense + ABR Works Well



Key Assumptions

- ABR == Shannon
  - ABR is rarely this good

- Interference and ABR are both stable
  - Interference may be bursty/intermittent

Overview

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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

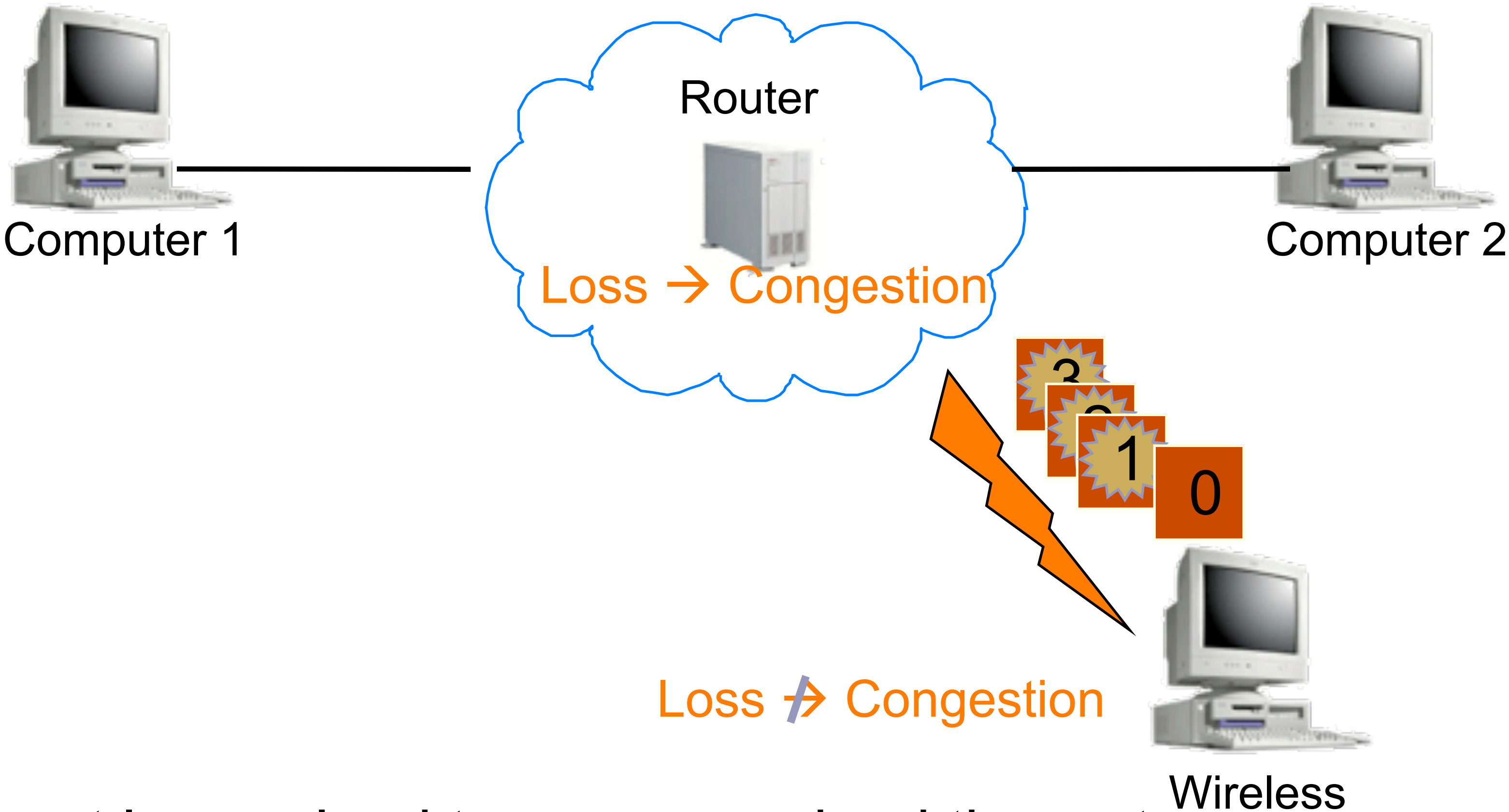
TCP Problems Over Noisy Links

- 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

Constraints & Requirements

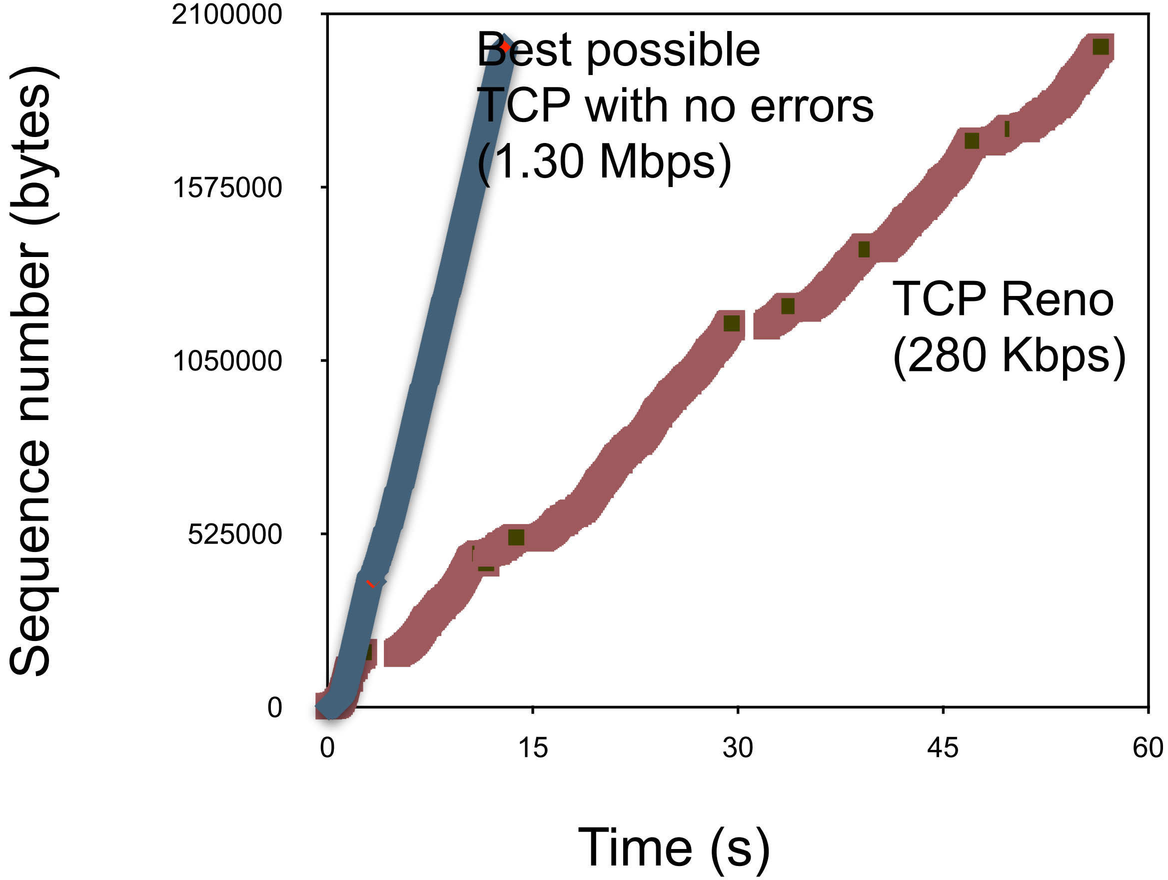
- Incremental deployment
  - Solution should not require modifications to fixed hosts
  - If possible, avoid modifying mobile hosts
- Probably more data to mobile than from mobile
  - Attempt to solve this first

Challenge #1: Wireless Bit-Errors



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

Performance Degradation



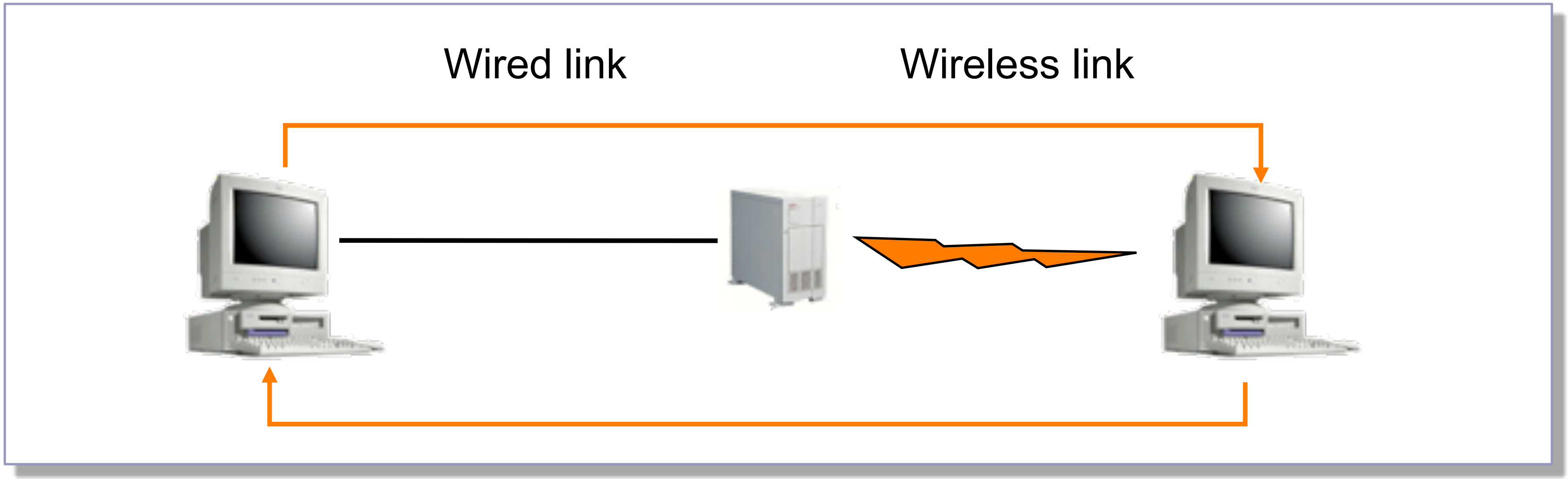
2 MB wide-area TCP transfer over 2 Mbps Lucent WaveLAN

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

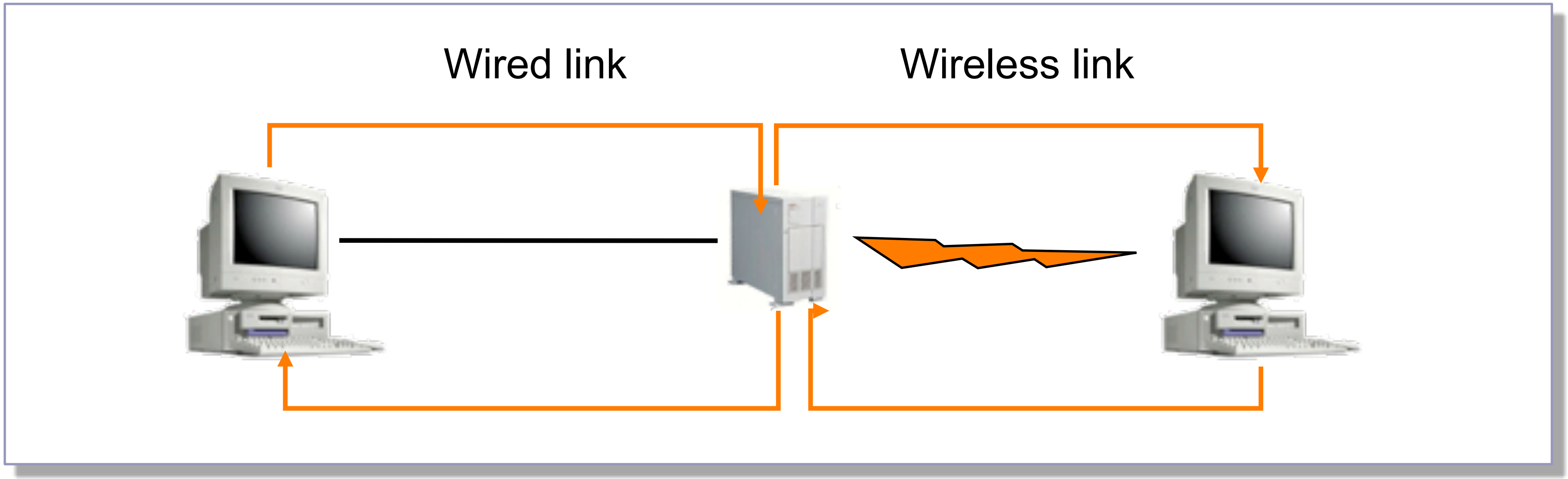
Approach Styles (End-to-End)

- 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

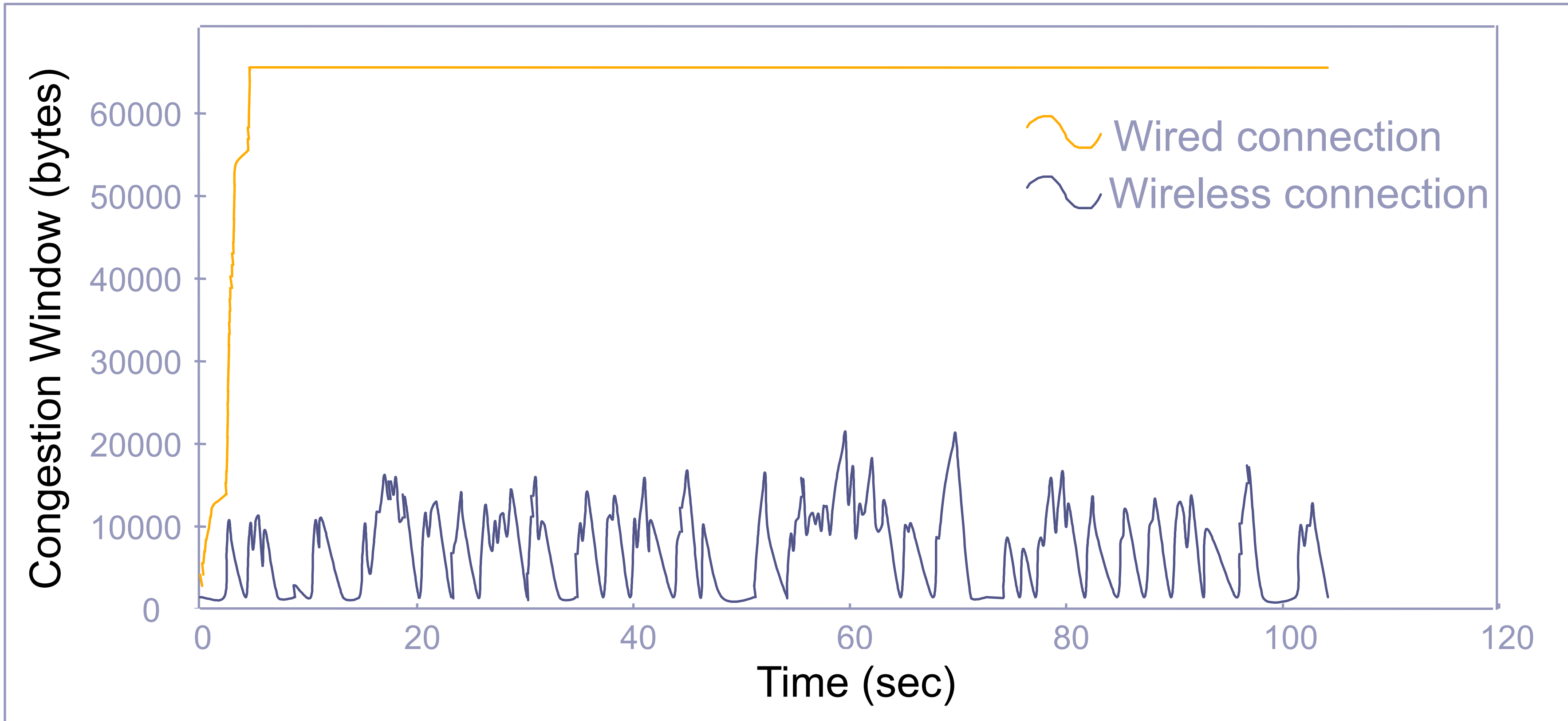


Approach Styles (Split Connection)

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



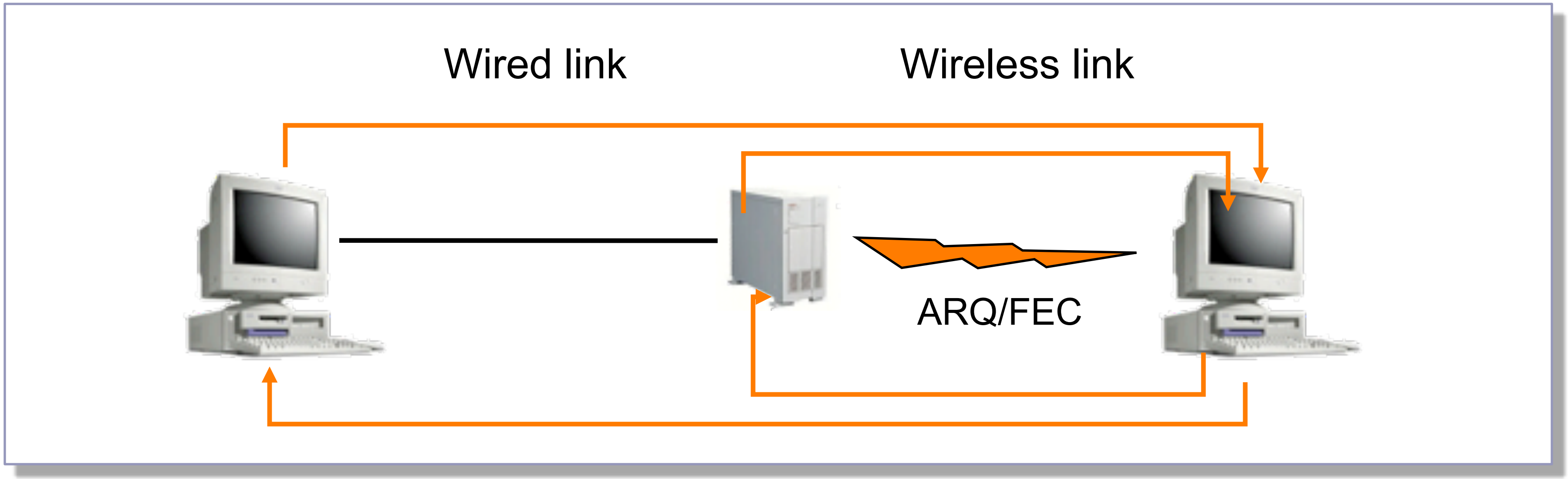
Split-Connection Congestion Window



- 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

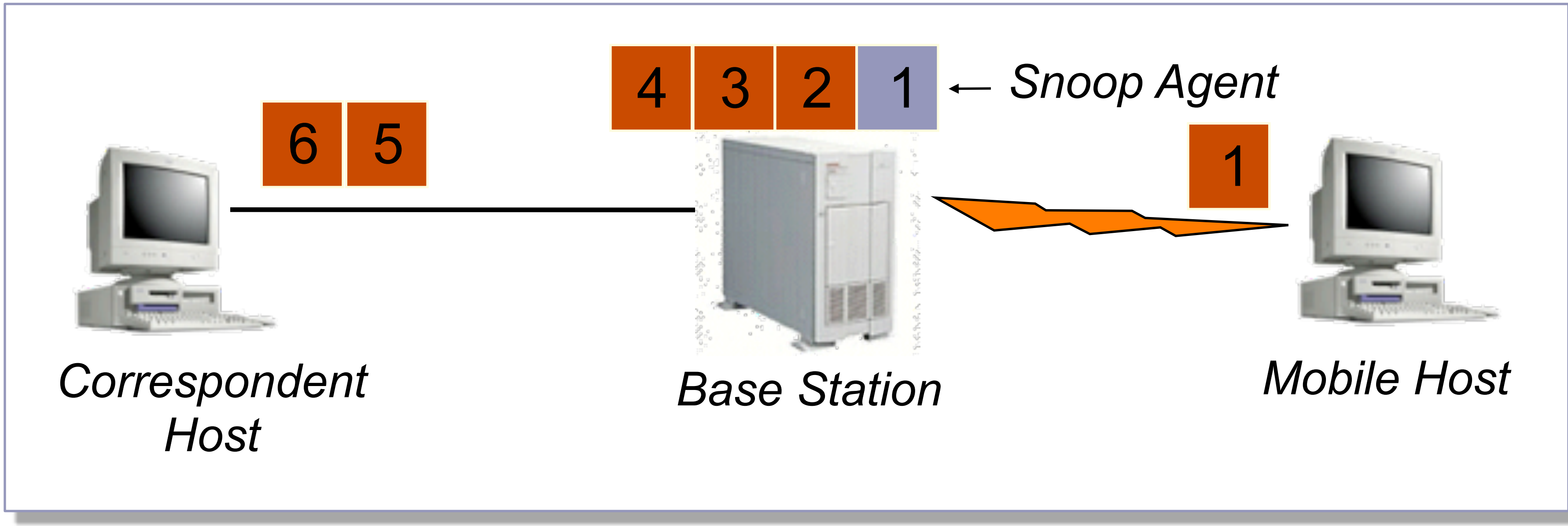
- Shield TCP sender from wireless vagaries
  - Eliminate adverse interactions between protocol layers
  - Congestion control only when congestion occurs
- The End-to-End Argument [SRC84]
  - Preserve TCP/IP service model: end-to-end semantics
- Eliminate non-TCP protocol messages

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

Snoop Overview

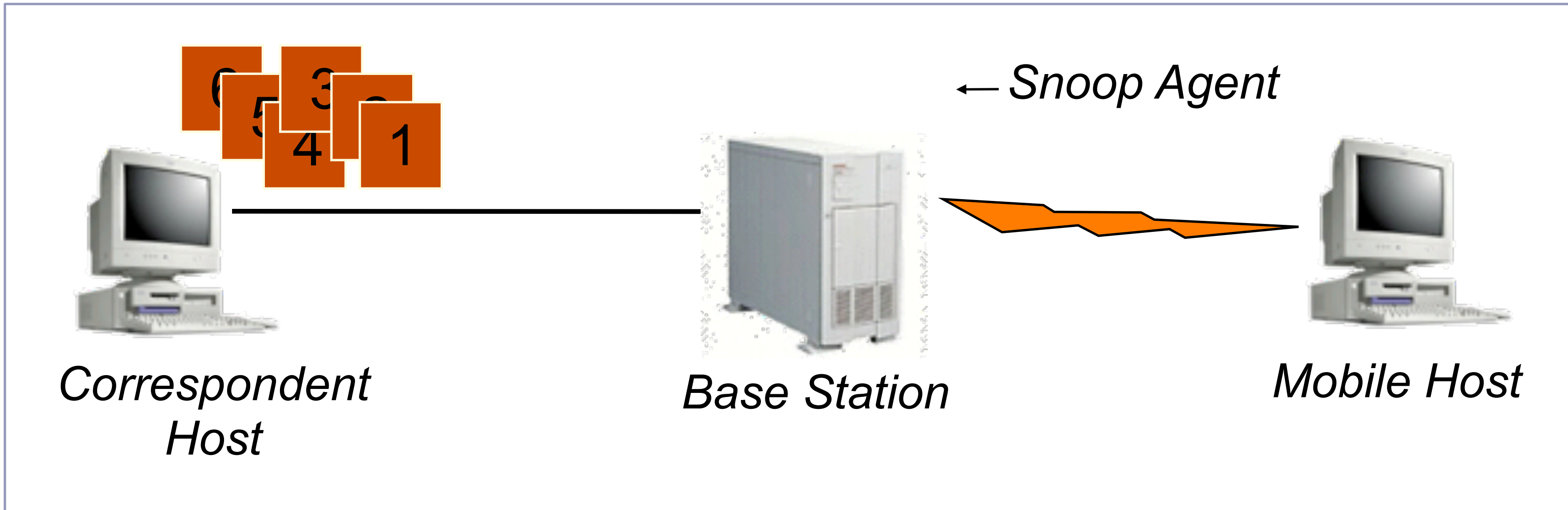
- Modify base station
  - to cache un-acked TCP packets
  - … and perform local retransmissions
- Key ideas
  - No transport level code in base station
  - When node moves to different base station, state eventually recreated there

Snoop Protocol: CH to MH



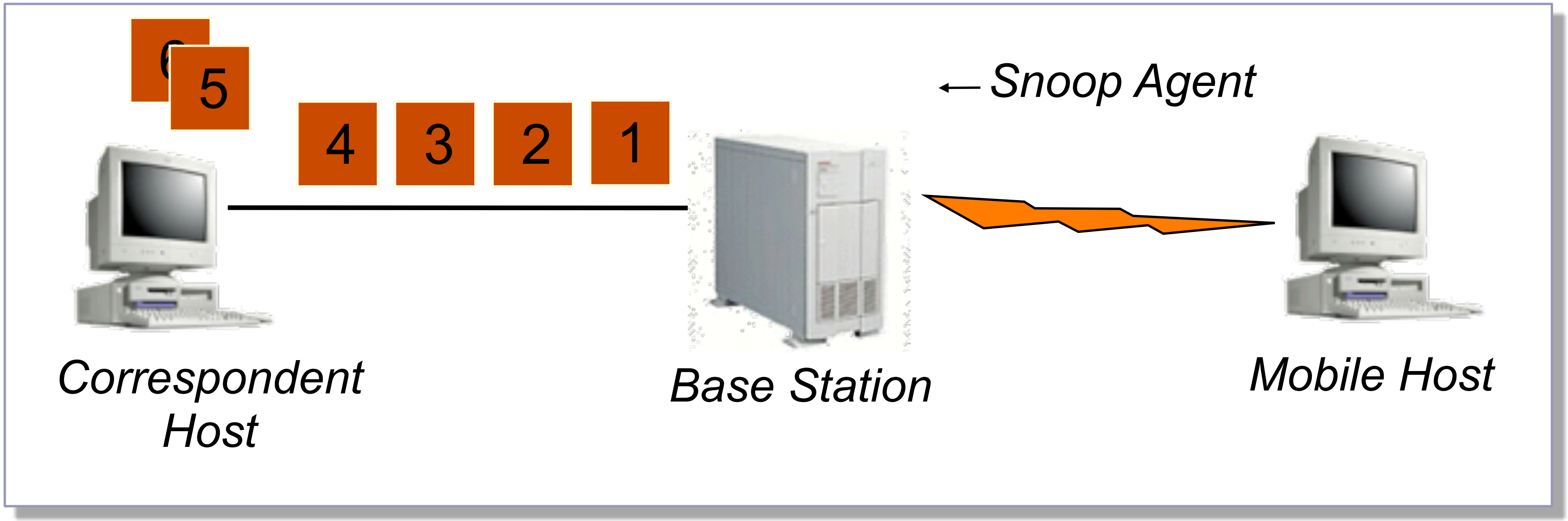
- Snoop agent: *active interposition agent*
  - Snoops on TCP segments and ACKs
  - Detects losses by duplicate ACKs and timers
  - Suppresses duplicate ACKs from MH

Snoop Protocol: CH to MH



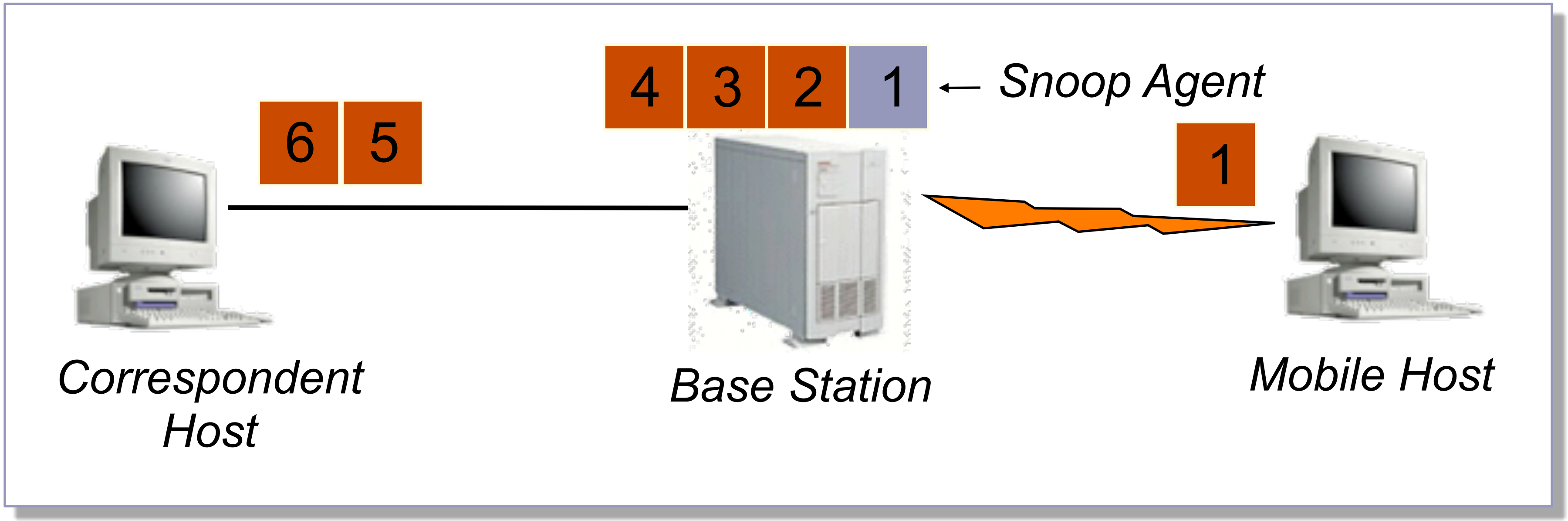
- Transfer of file from CH to MH
- Current window = 6 packets

Snoop Protocol: CH to MH



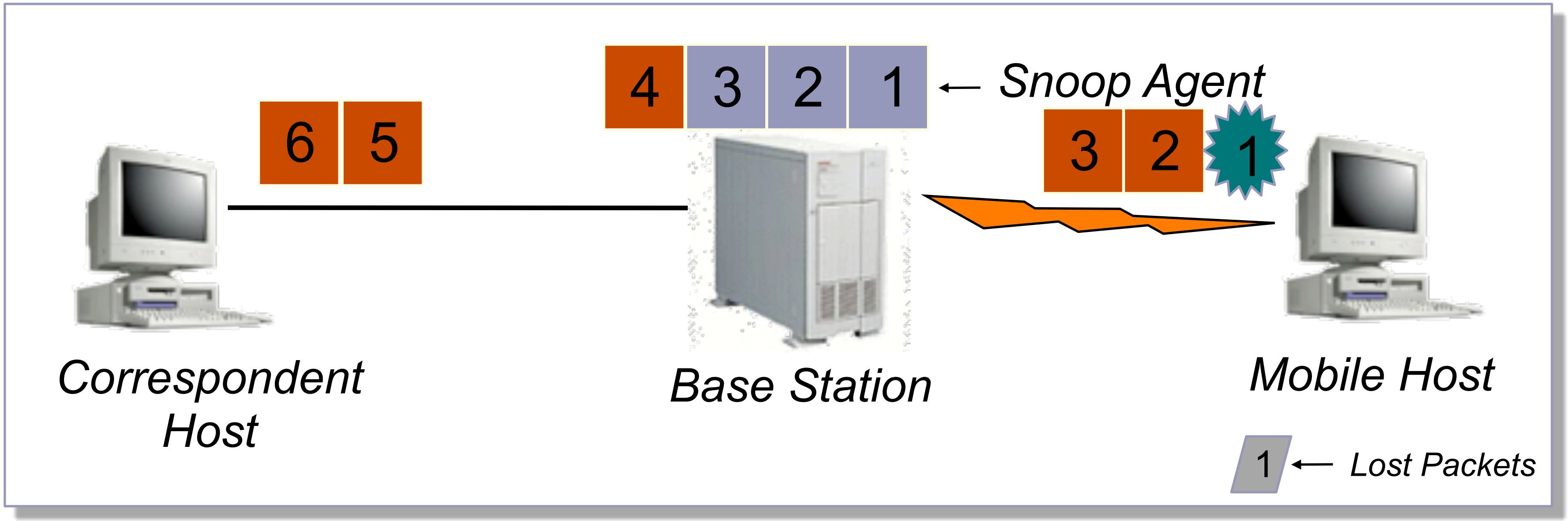
- Transfer begins

Snoop Protocol: CH to MH



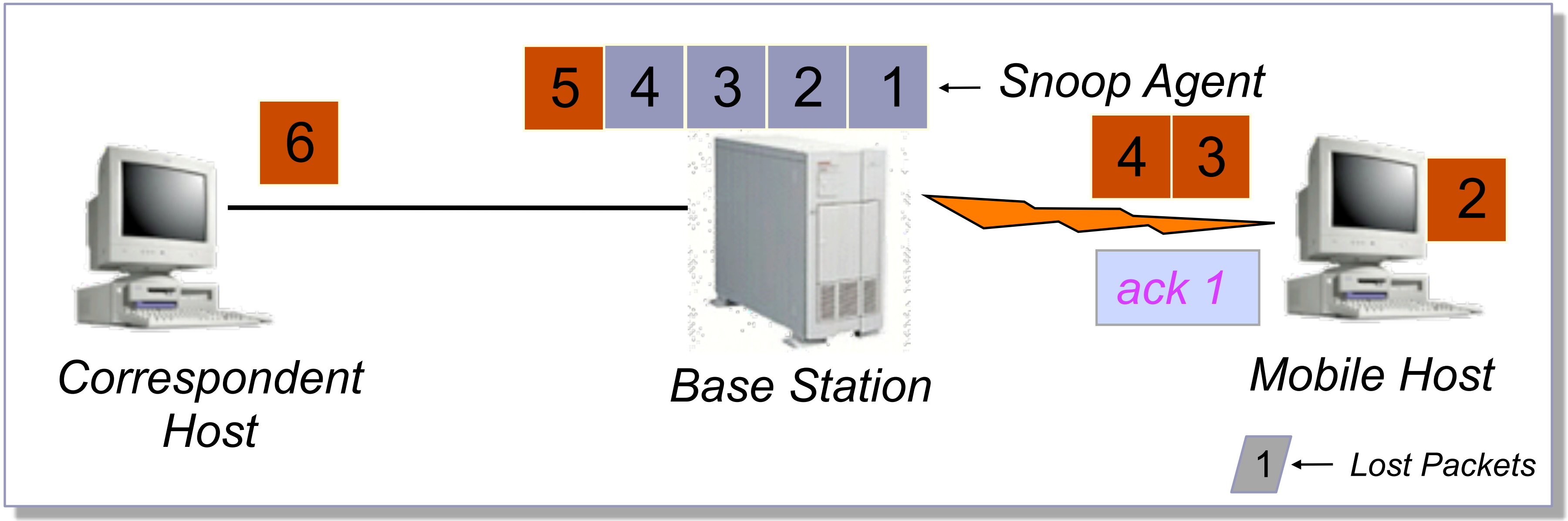
- Snoop agent caches segments that pass by

Snoop Protocol: CH to MH



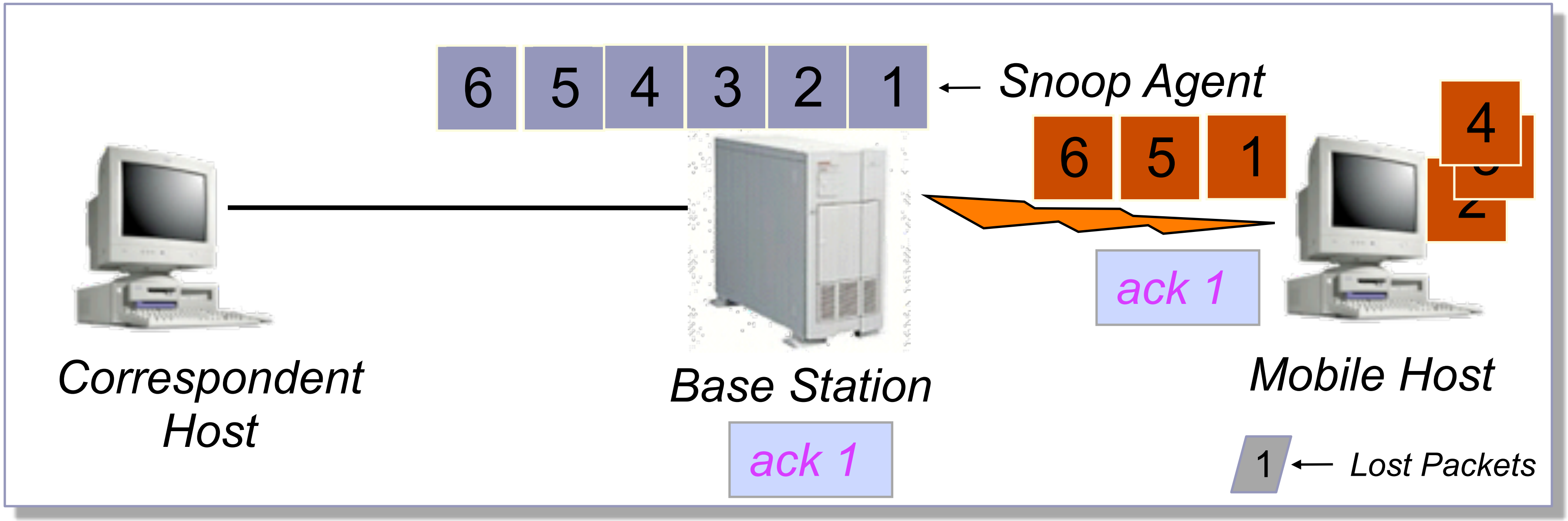
- Packet 1 is Lost

Snoop Protocol: CH to MH



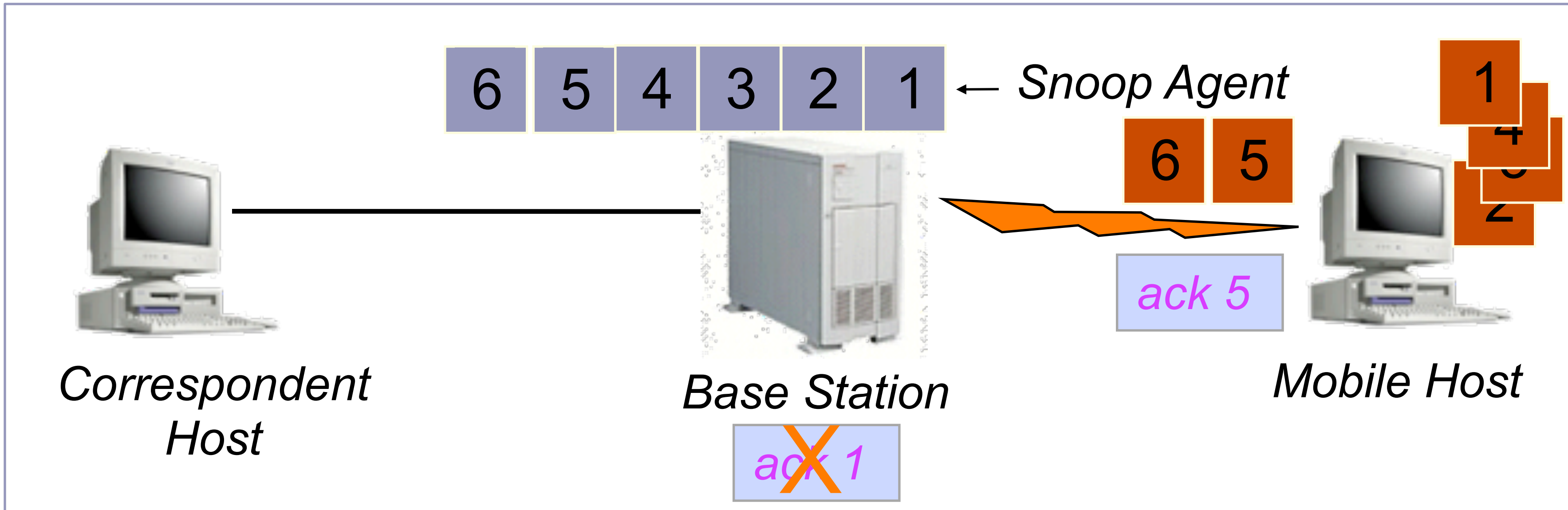
- Packet 1 is Lost
  - Duplicate ACKs generated

Snoop Protocol: CH to MH



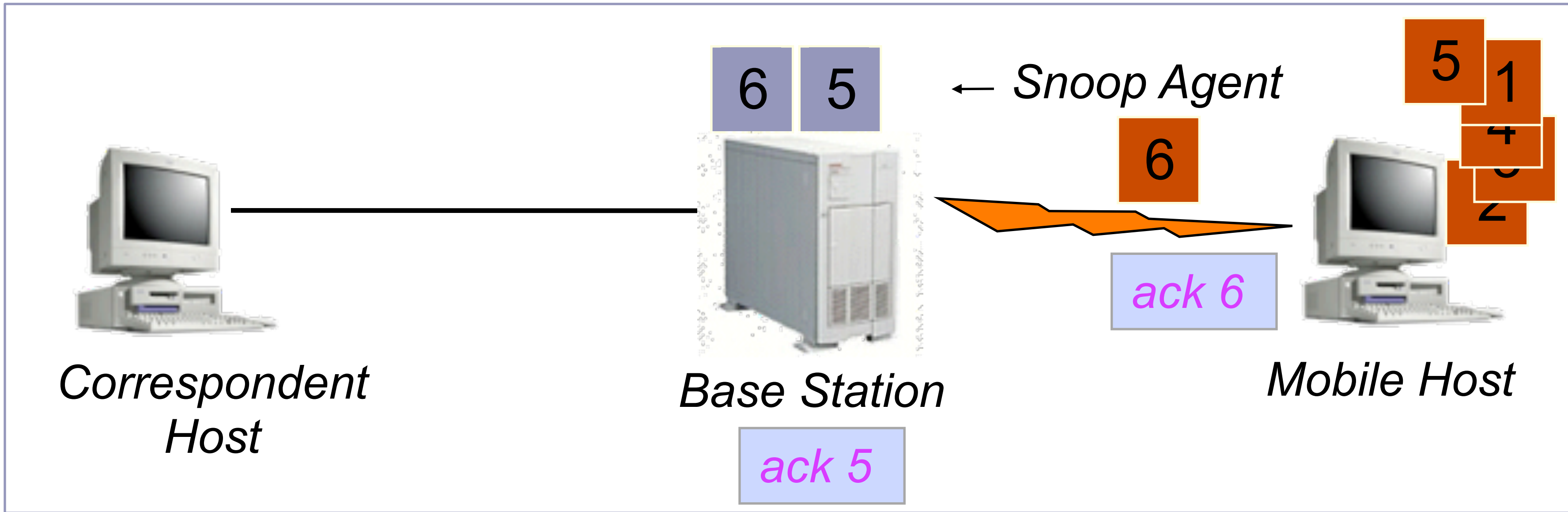
- Packet 1 is Lost
  - Duplicate ACKs generated
- Packet 1 retransmitted from cache at higher priority

Snoop Protocol: CH to MH



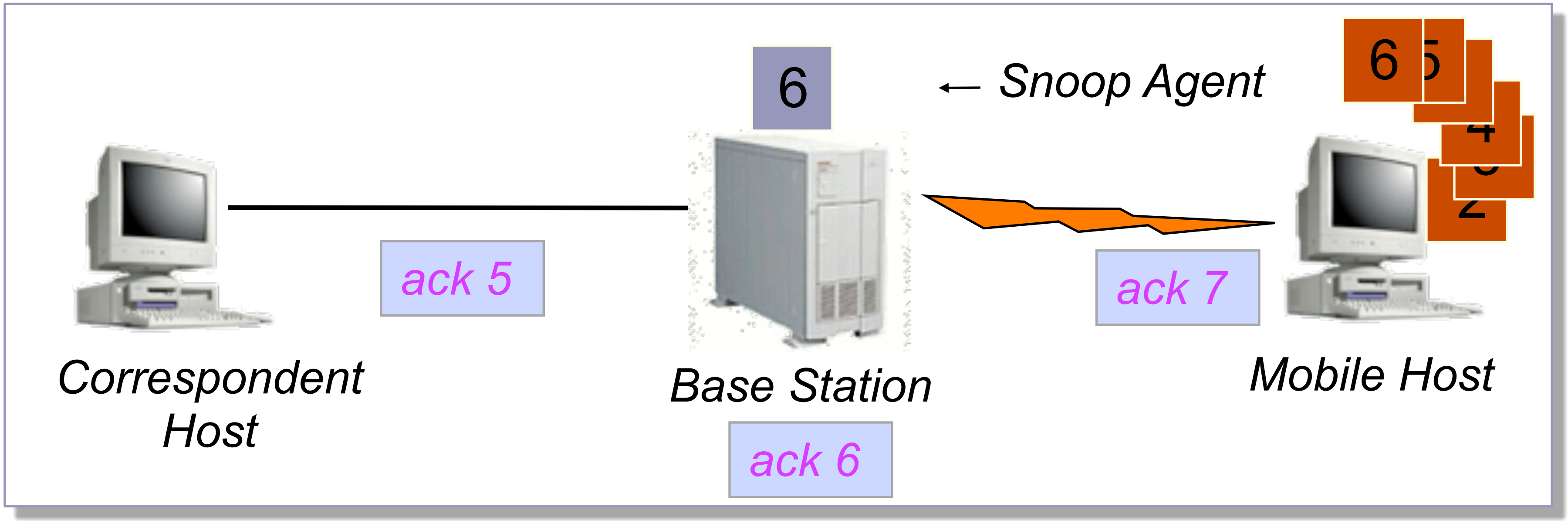
- Duplicate ACKs suppressed

Snoop Protocol: CH to MH



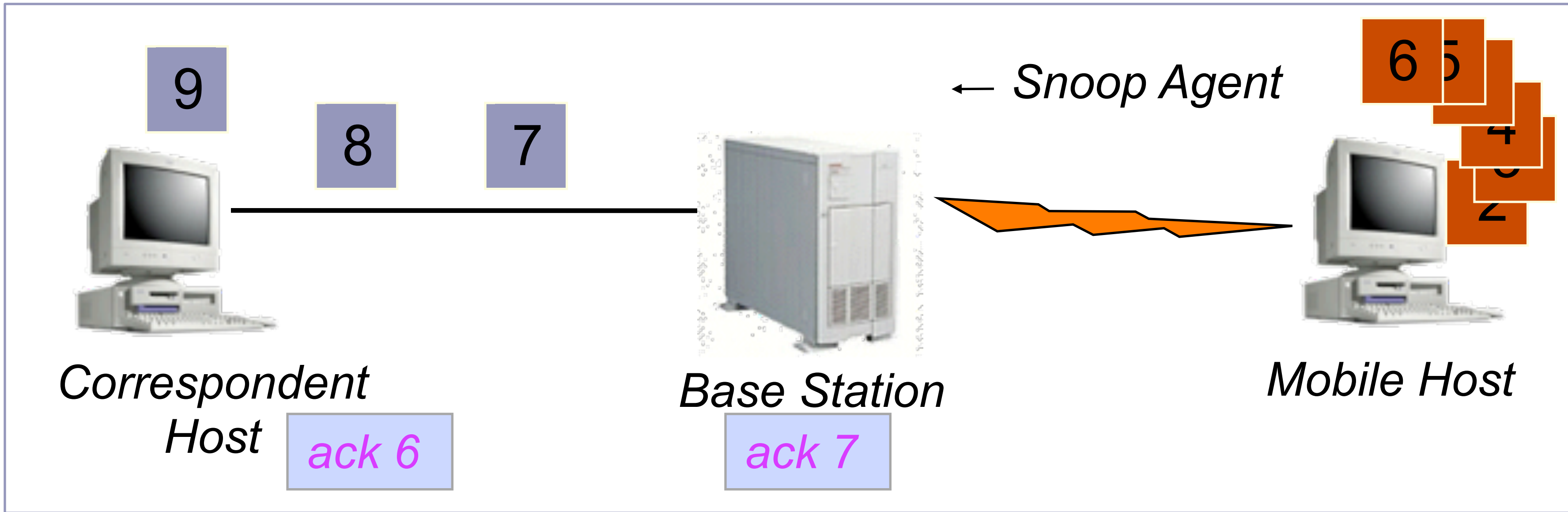
- Clean cache on new ACK

Snoop Protocol: CH to MH



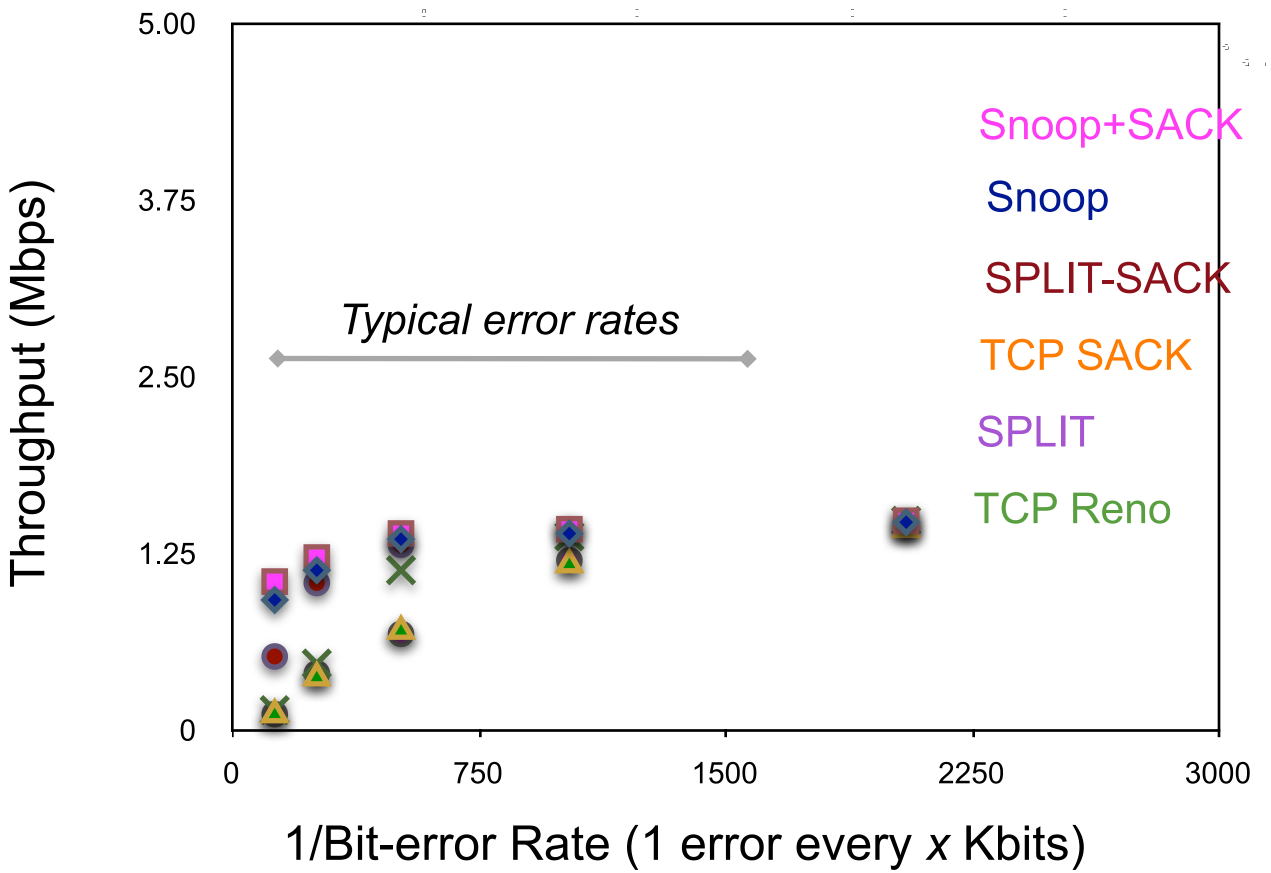
- Clean cache on new ACK

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