




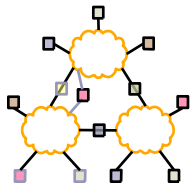
CE693: Adv. Computer Networking

L-9 Wireless Fall 1389

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

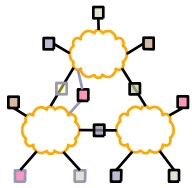


Wireless Intro



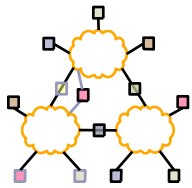
- TCP on wireless links
- Wireless MAC
- Assigned reading
 - [BPSK97] A Comparison of Mechanism for Improving TCP Performance over Wireless Links
 - [BM09] In Defense of Wireless Carrier Sense

Wireless Challenges



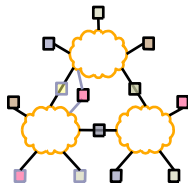
- Force us to rethink many assumptions
- Need to share airwaves rather than wire
 - Don't know what hosts are involved
 - Host may not be using same link technology
- Mobility
- Other characteristics of wireless
 - Noisy → lots of losses
 - Slow
 - Interaction of multiple transmitters at receiver
 -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

Overview

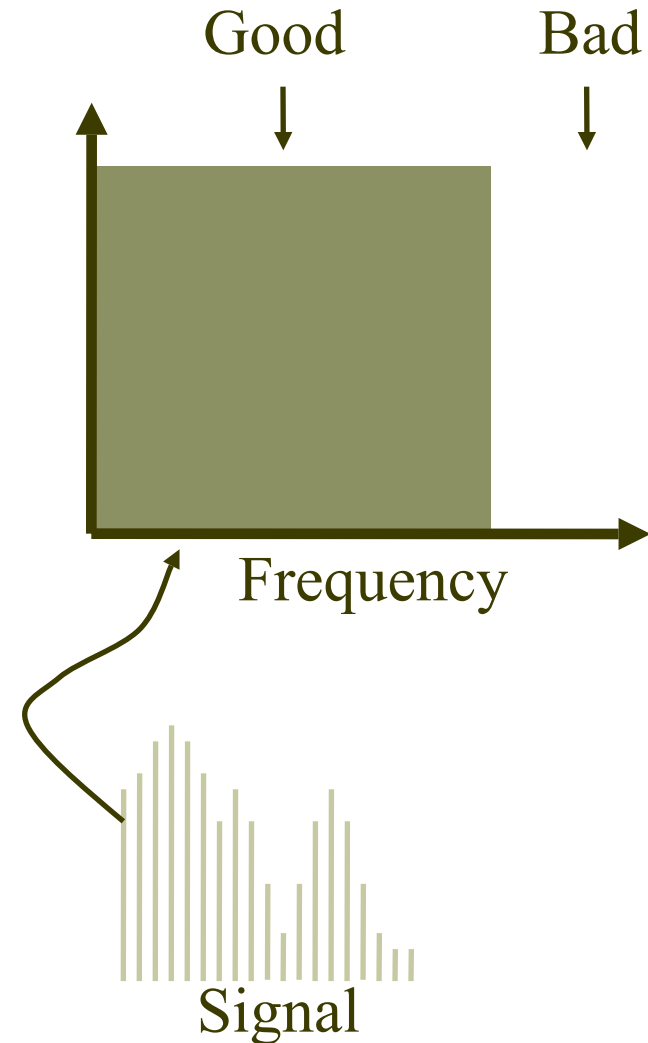


- Wireless Background
- Wireless MAC
 - MACAW
 - 802.11
- Wireless TCP

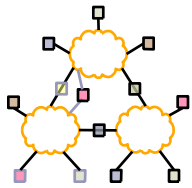
Transmission Channel Considerations



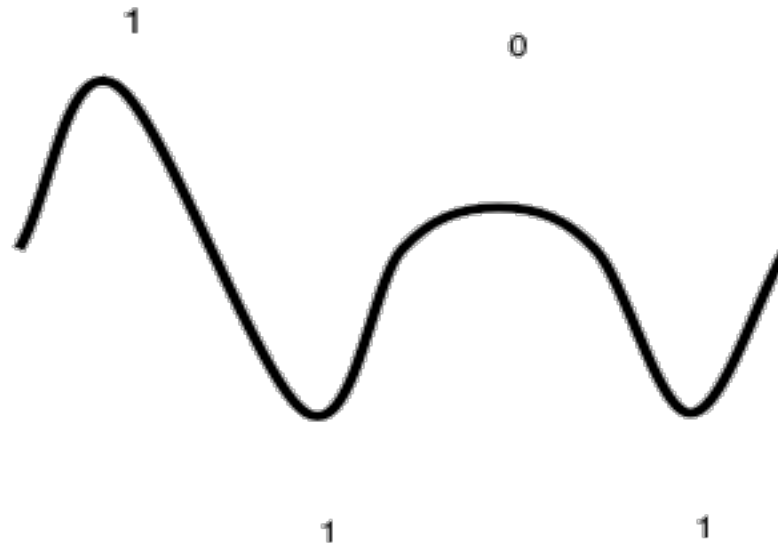
- Every medium supports transmission in a certain frequency range.
 - Outside this range, effects such as attenuation, .. degrade the signal too much
- Transmission and receive hardware will try to maximize the useful bandwidth in this frequency band.
 - Tradeoffs between cost, distance, bit rate
- As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



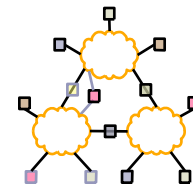
The Nyquist Limit



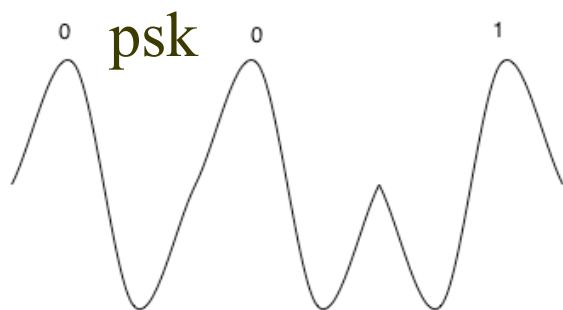
- A noiseless channel of width H can at most transmit a binary signal at a rate $2 \times H$.
 - E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
 - Assumes binary amplitude encoding



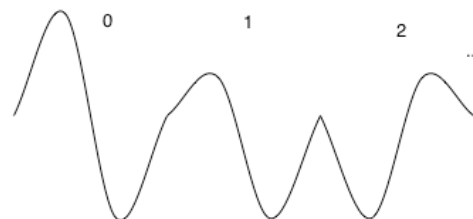
Past the Nyquist Limit



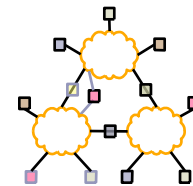
- More aggressive encoding can increase the channel bandwidth.
 - Example: modems
 - Same frequency - number of symbols per second
 - Symbols have more possible values



PsK
+
AM

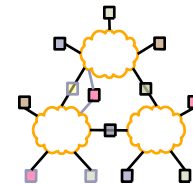


Capacity of a Noisy Channel

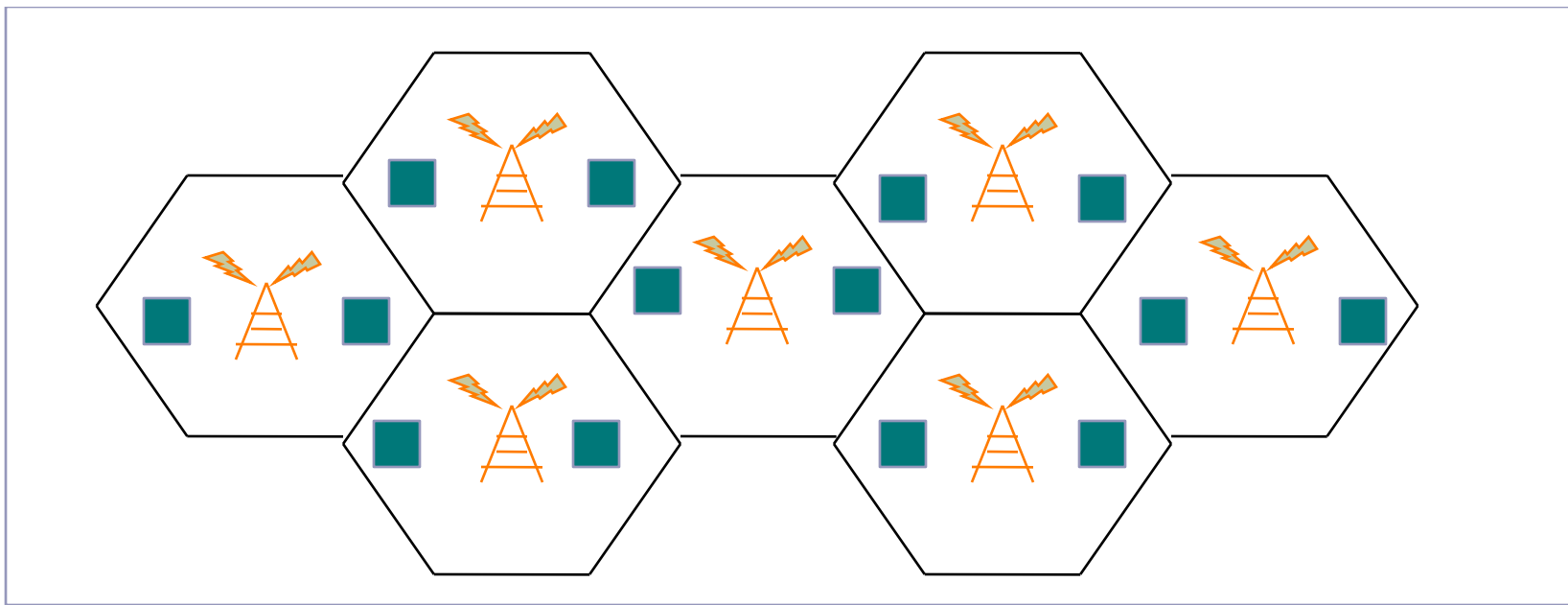


- Can't add infinite symbols - you have to be able to tell them apart. This is where noise comes in.
- Shannon's theorem:
 - $C = B \times \log(1 + S/N)$
 - C: maximum capacity (bps)
 - B: channel bandwidth (Hz)
 - S/N: signal to noise ratio of the channel
 - Often expressed in decibels (db). $10 \log(S/N)$
- 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.

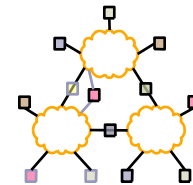
Cellular Reuse



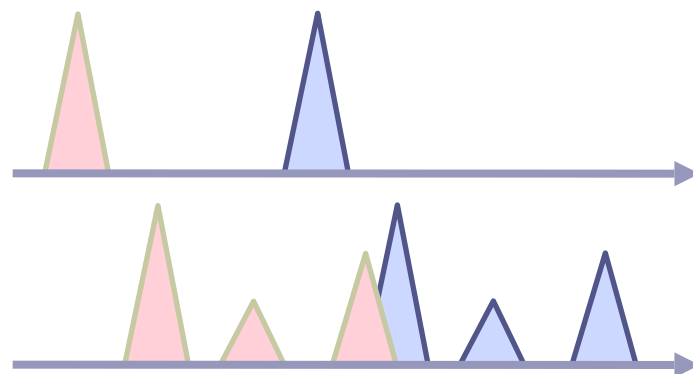
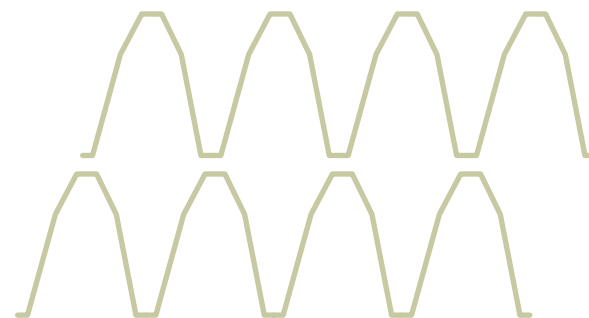
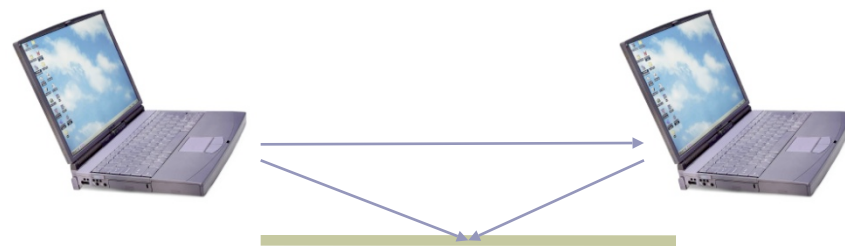
- Transmissions decay over distance
 - Spectrum can be reused in different areas
 - Different “LANs”
 - Decay is $1/R^2$ in free space, $1/R^4$ in some situations



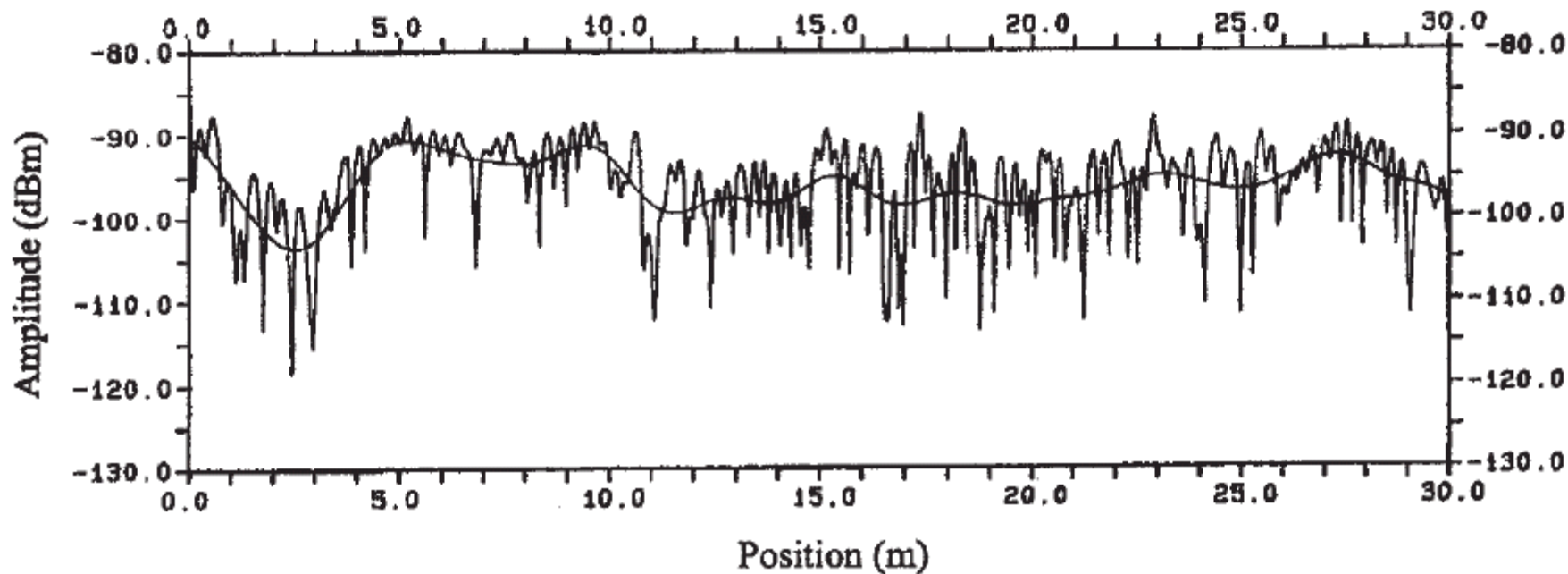
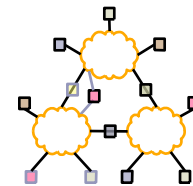
Multipath Effects



- 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).

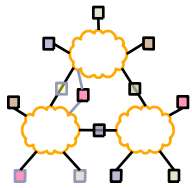


Fading - Example



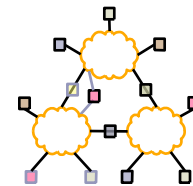
- Frequency of 910 MHz or wavelength of about 33 cm

Overview



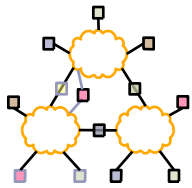
- Wireless Background
- **Wireless MAC**
 - **MACAW**
 - 802.11
- Wireless TCP

Medium Access Control



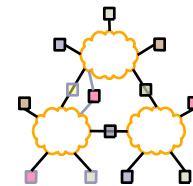
- Think back to Ethernet MAC:
 - Wireless is a shared medium
 - Transmitters interfere
 - Need a way to ensure that (usually) only one person talks at a time.
 - Goals: Efficiency, possibly fairness

Example MAC Protocols

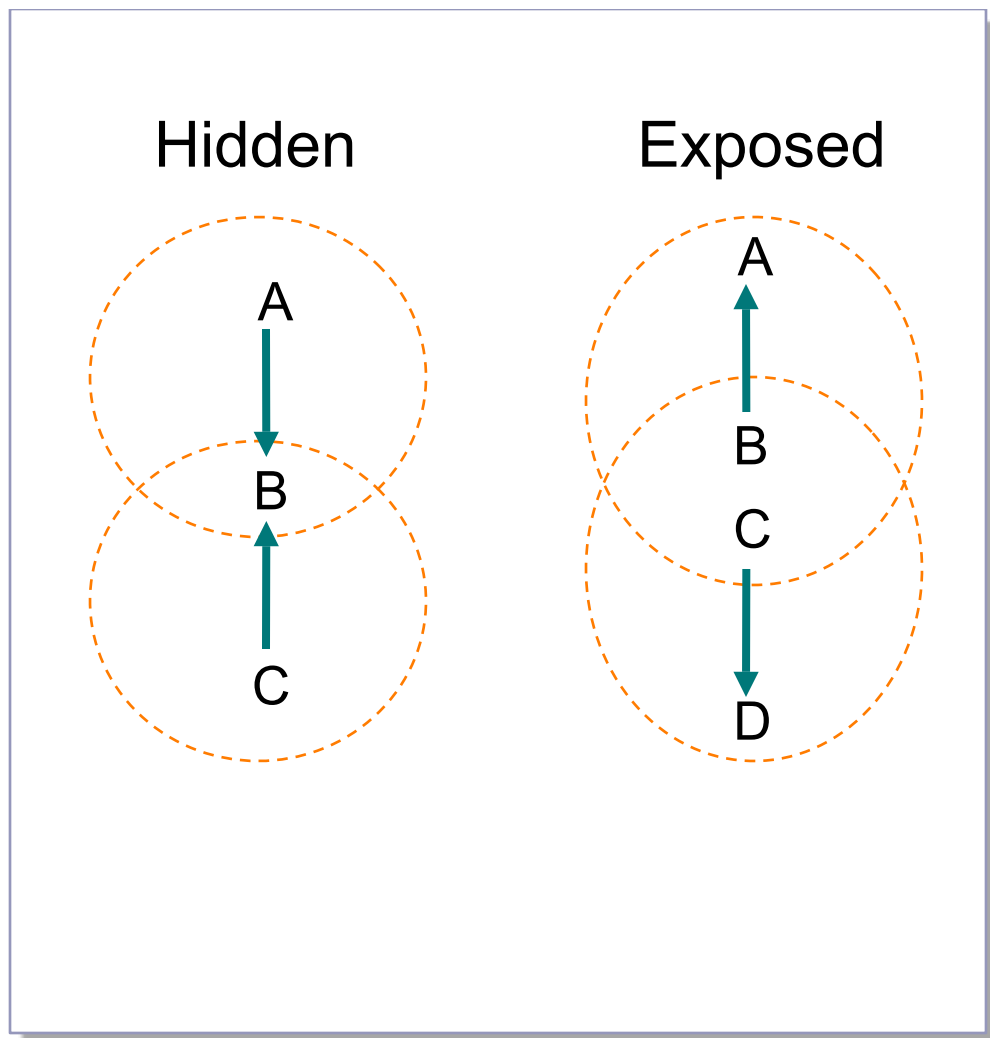


- Pure ALOHA
 - Transmit whenever a message is ready
 - Retransmit when ACK is not received
- Slotted ALOHA
 - Time is divided into equal time slots
 - Transmit only at the beginning of a time slot
 - Avoid partial collisions
 - Increase delay, and require synchronization
- Carrier Sense Multiple Access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

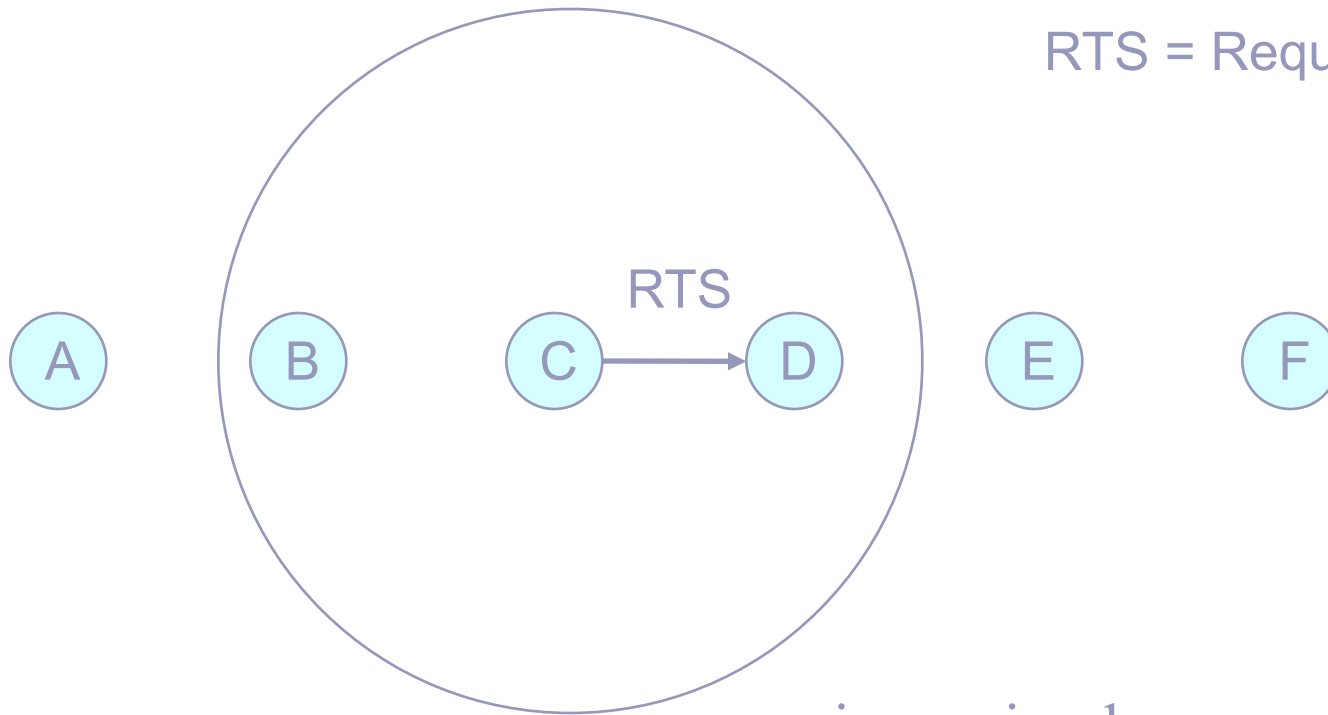
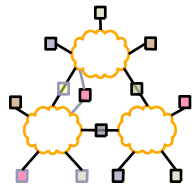
CSMA/CD Does Not Work



- 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



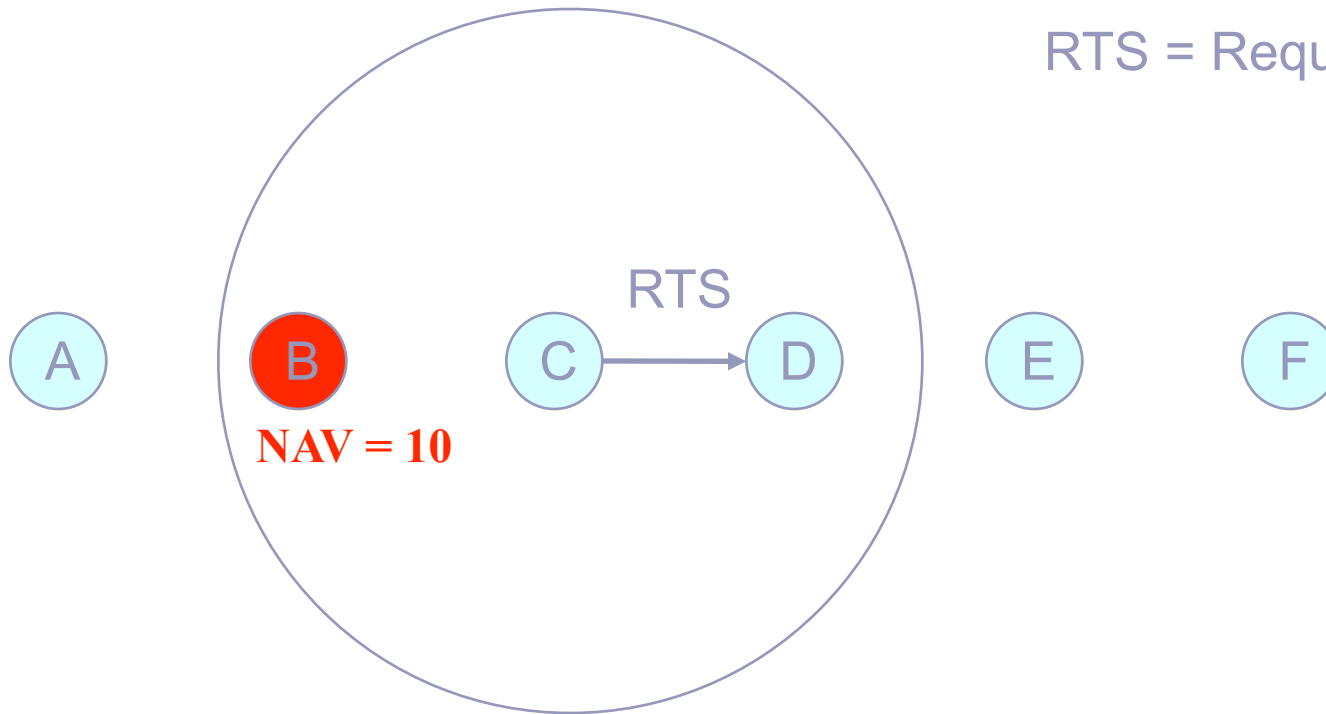
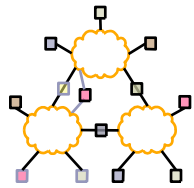
MACA (RTS/CTS)



assuming a circular range

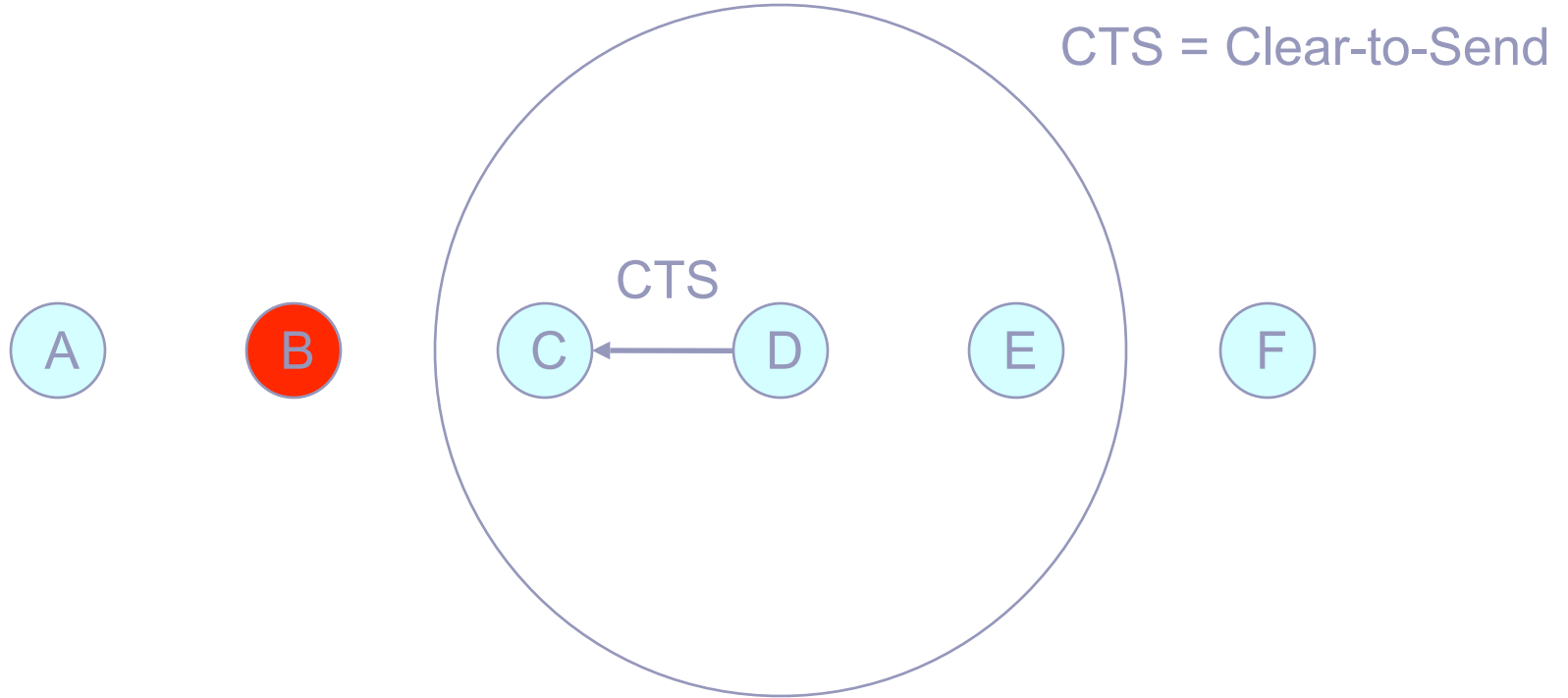
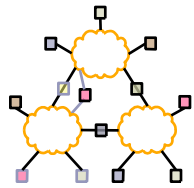


MACA (RTS/CTS)

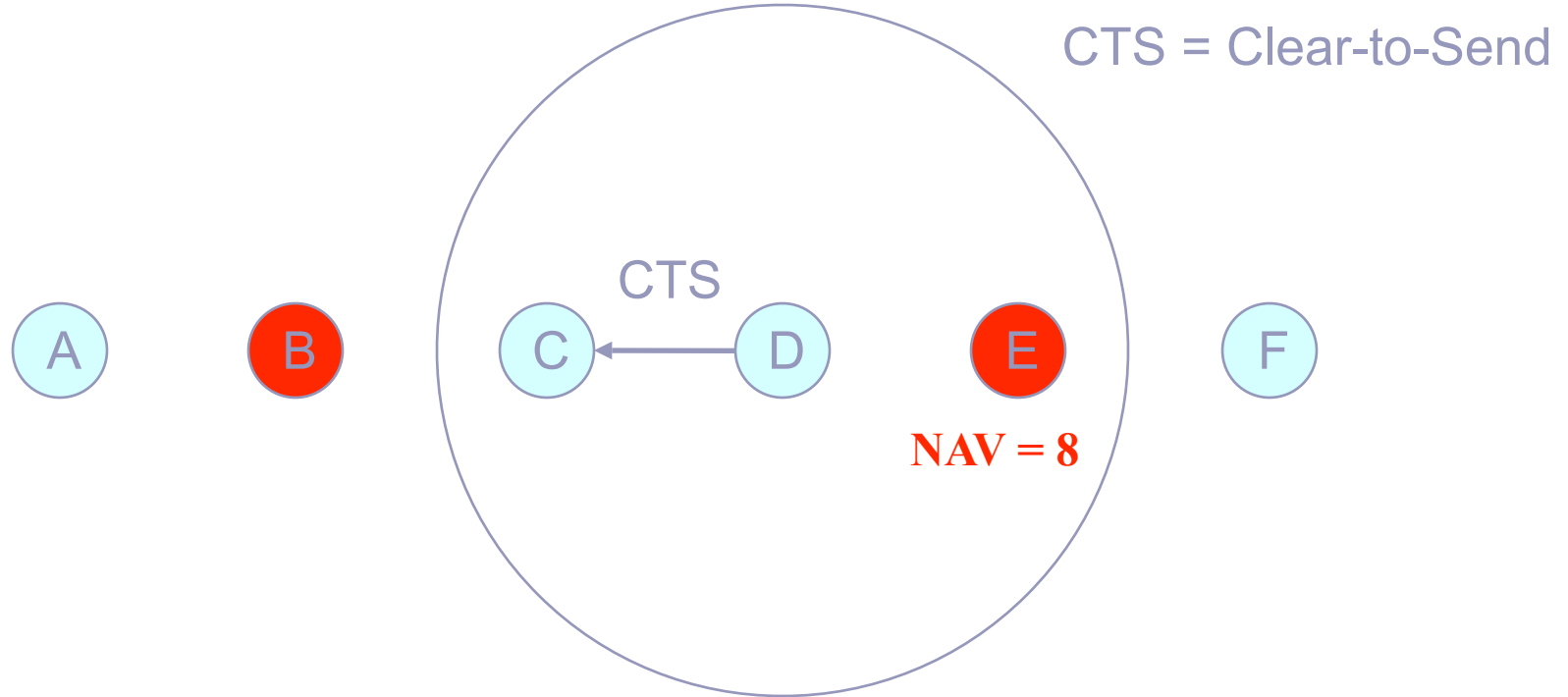
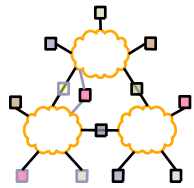


NAV = remaining duration to keep quiet

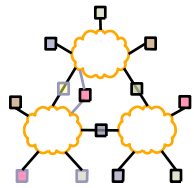
MACA (RTS/CTS)



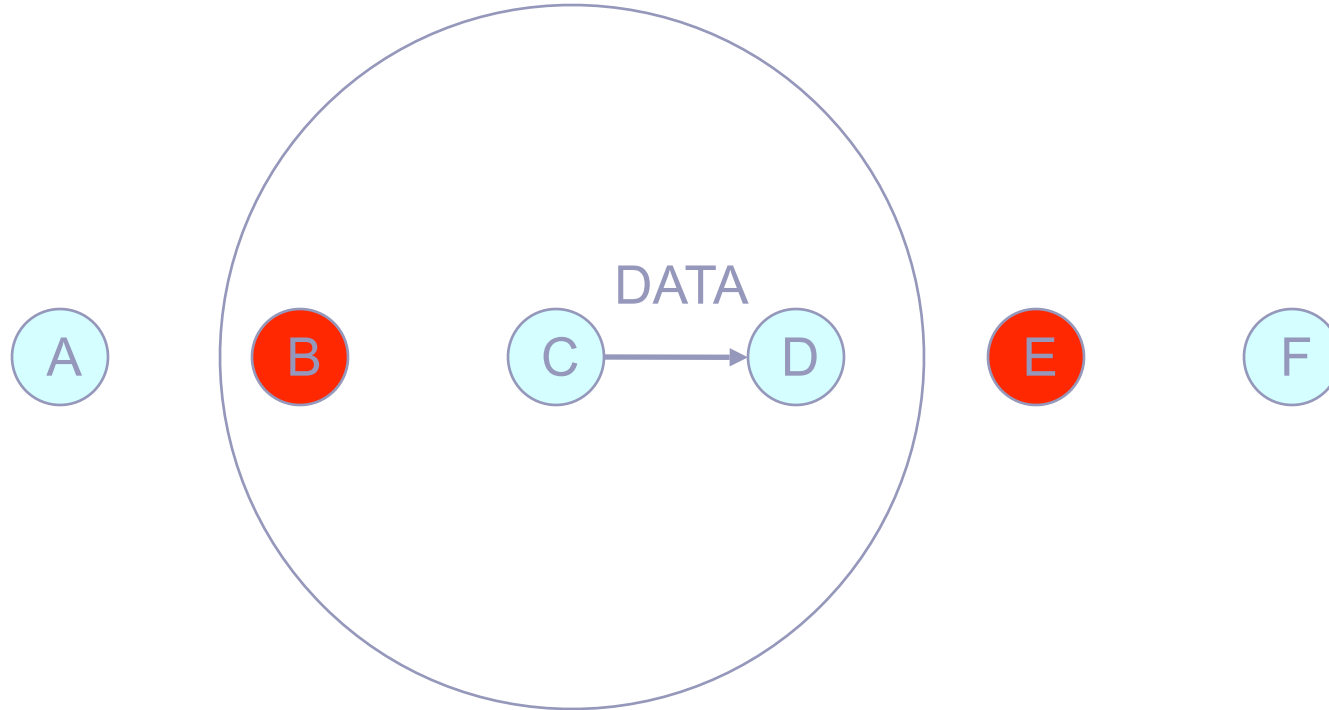
MACA (RTS/CTS)



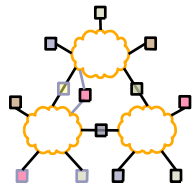
MACA (RTS/CTS)



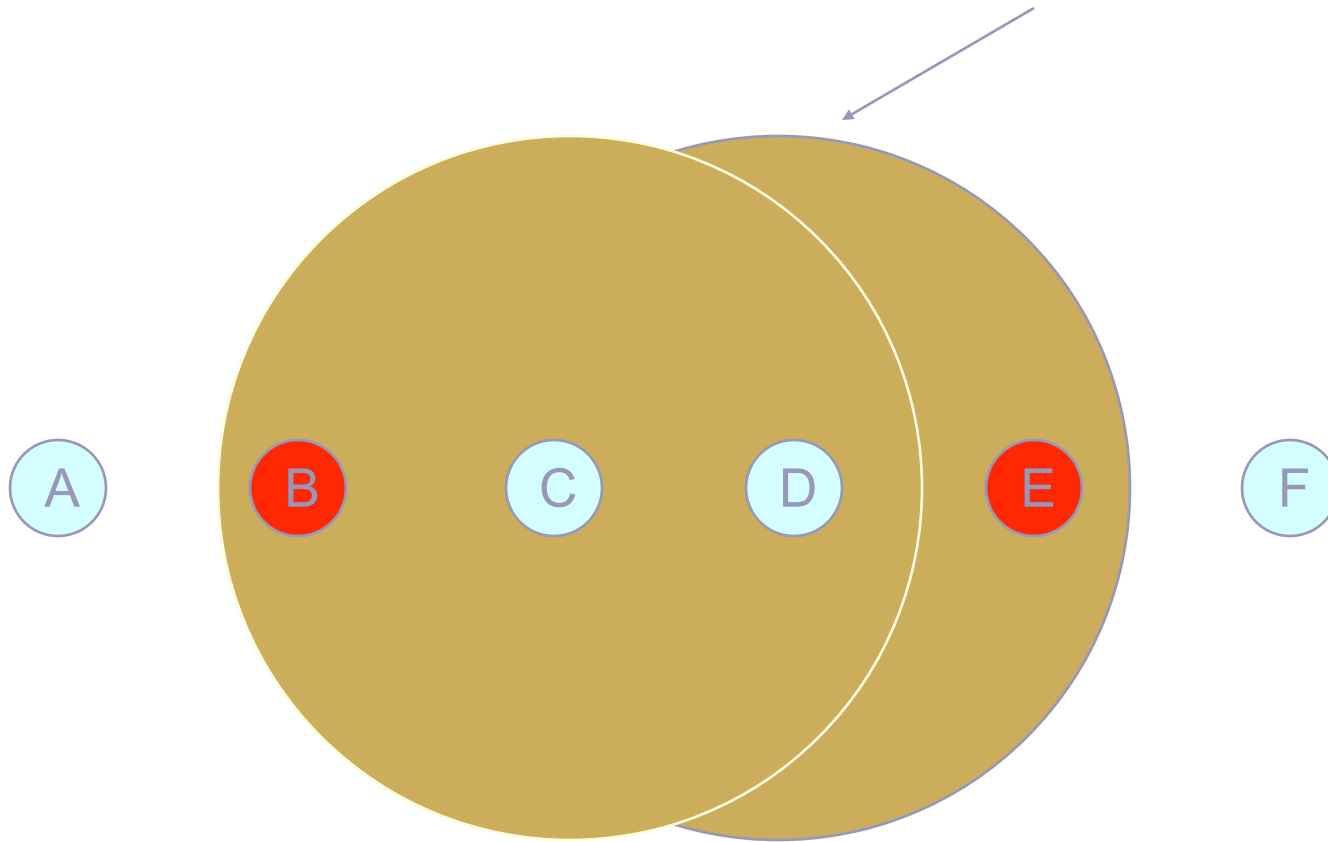
- **DATA** packet follows CTS. Successful data reception acknowledged using **ACK**.

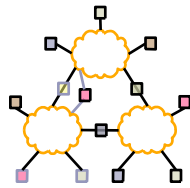


MACA (RTS/CTS)



Reserved area



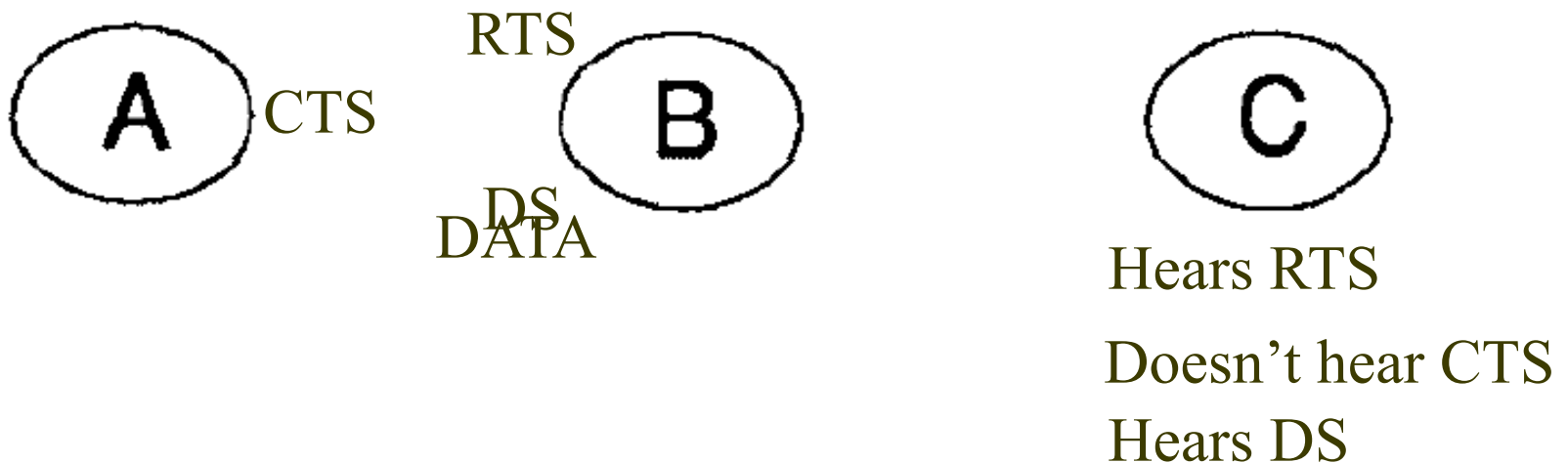


MACAW: Additional Design

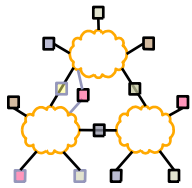
- ACK (needed for faster TCP transfers)

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)

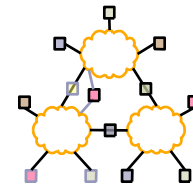


Overview



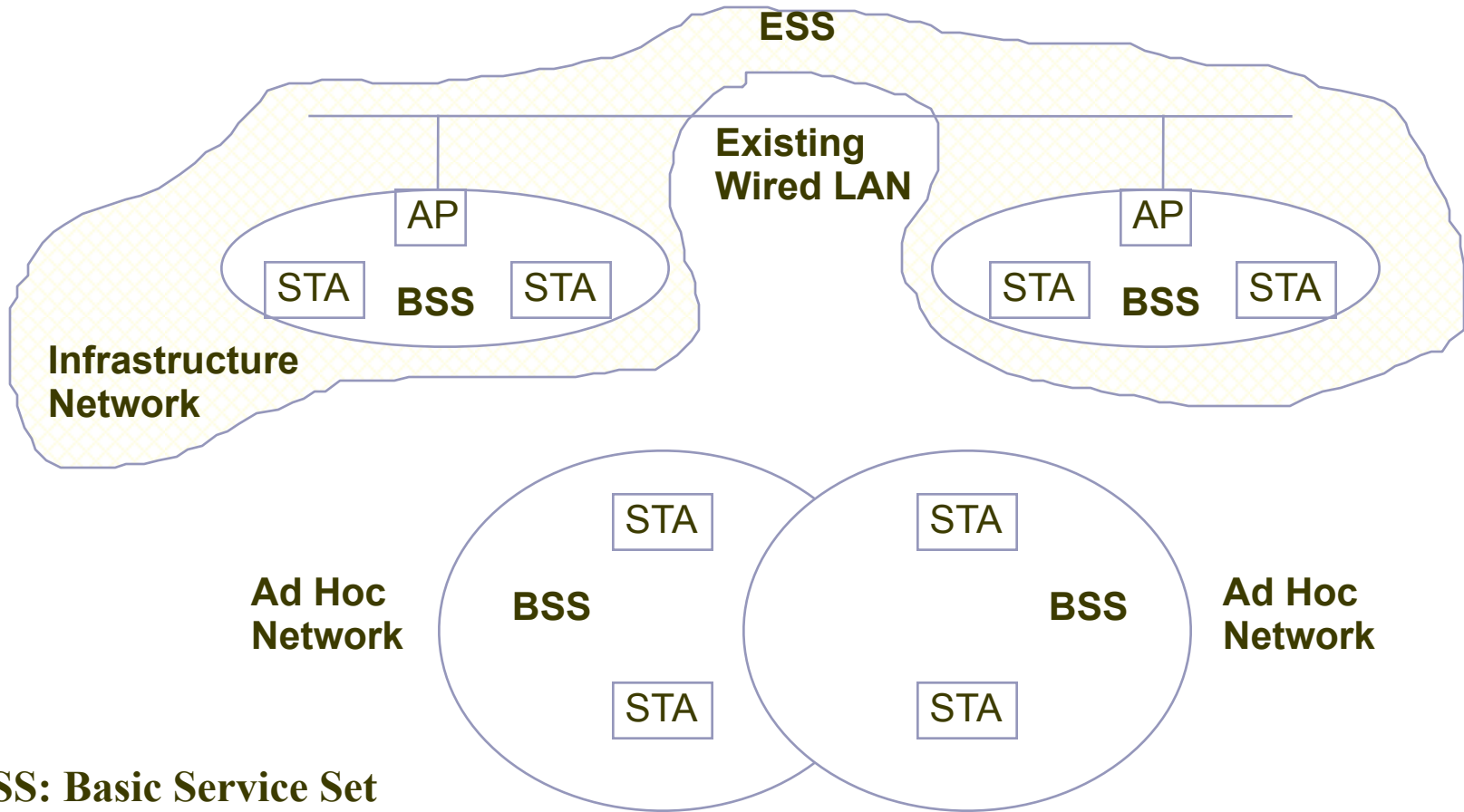
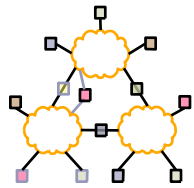
- Wireless Background
- **Wireless MAC**
 - MACAW
 - **802.11**
- Wireless TCP

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)

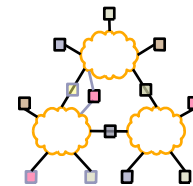
Overview, 802.11 Architecture



BSS: Basic Service Set

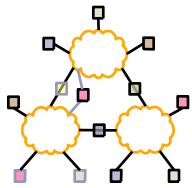
ESS: Extended Service Set

802.11 modes



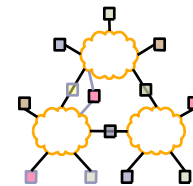
- Infrastructure mode
 - All packets go through a base station
 - Cards associate with a BSS (basic service set)
 - Multiple BSSs can be linked into an Extended Service Set (ESS)
 - Handoff to new BSS in ESS is pretty quick
 - Wandering around CE building
 - Moving to new ESS is slower, may require re-addressing
 - Wandering from Sharif to Tehran U.
- Ad Hoc mode
 - Cards communicate directly.

802.11 Management Operations



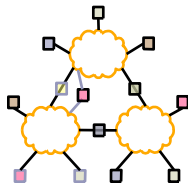
- Scanning
- Association/Reassociation
- Time synchronization
- Power management

Scanning & Joining



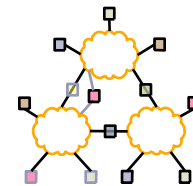
- Goal: find networks in the area
- Passive scanning
 - No require transmission → saves power
 - Move to each channel, and listen for Beacon frames
- Active scanning
 - Requires transmission → saves time
 - Move to each channel, and send Probe Request frames to solicit Probe Responses from a network

Time Synchronization in 802.11



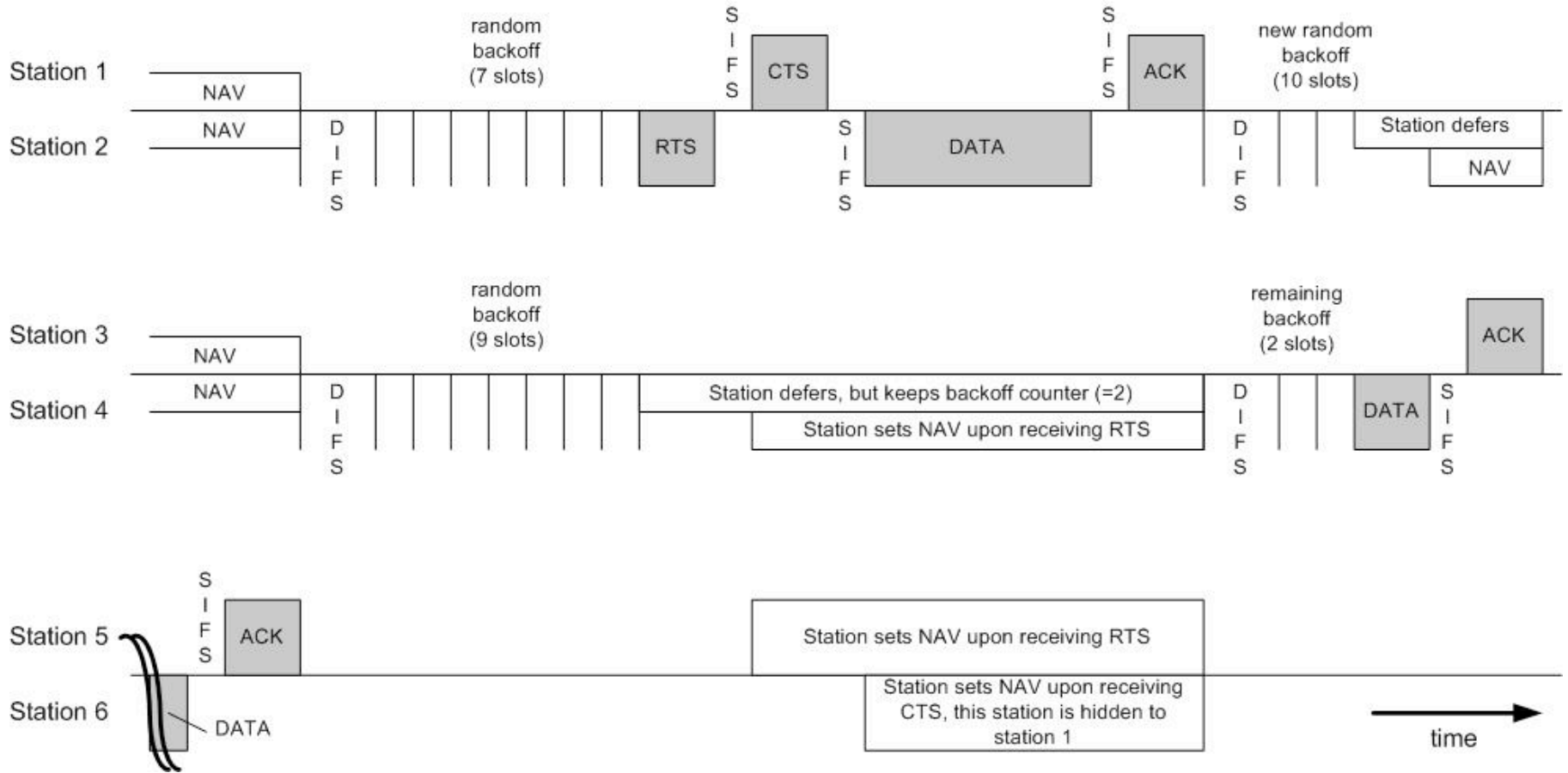
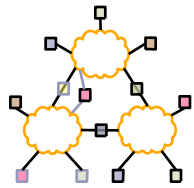
- Timing synchronization function (TSF)
 - AP controls timing in infrastructure networks
 - All stations maintain a local timer
 - TSF keeps timer from all stations in sync
- Periodic Beacons convey timing
 - Beacons are sent at well known intervals
 - Timestamp from Beacons used to calibrate local clocks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

Power Management in 802.11

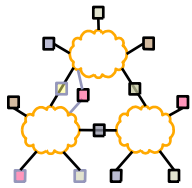


- A station is in one of the three states
 - Transmitter on
 - Receiver on
 - Both transmitter and receiver off (dozing)
- AP buffers packets for dozing stations
- AP announces which stations have frames buffered in its Beacon frames
- Dozing stations wake up to listen to the beacons
- If there is data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

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

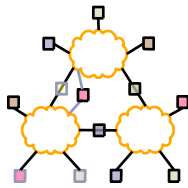


Discussion

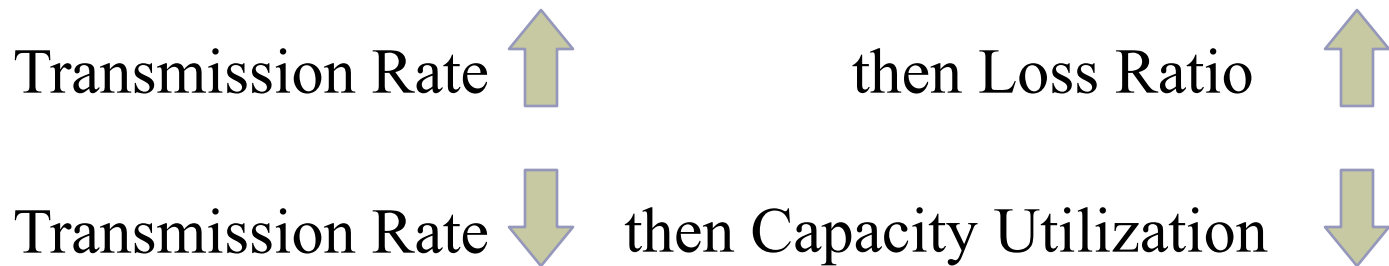


- **RTS/CTS/Data/ACK vs. Data/ACK**
 - Why/when is it useful?
 - What is the right choice
 - Why is RTS/CTS not used?

802.11 Rate Adaptation

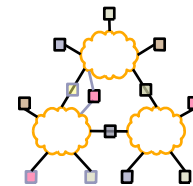


- 802.11 spec specifies rates not algorithm for choices
 - 802.11b 4 rates, 802.11a 8 rates, 802.11g 12 rates
 - Each rate has different modulation and coding



throughput decreases either way – need to get it just right

Carrier Sense



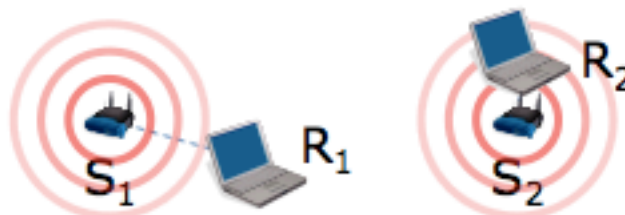
Desired result: concurrency



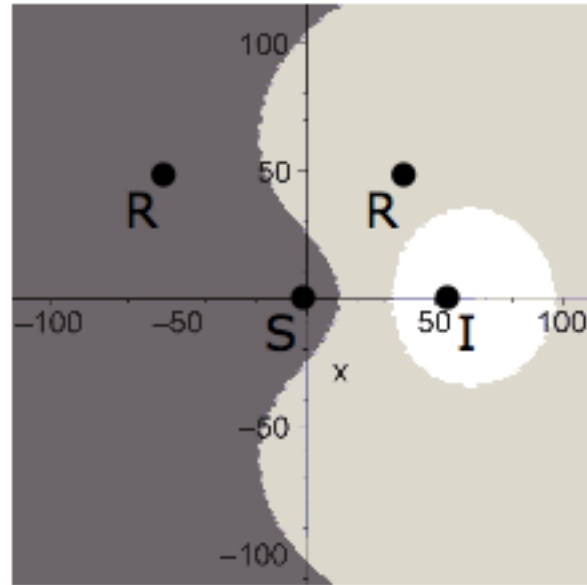
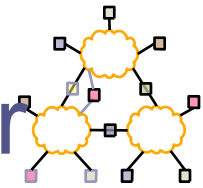
Desired result: time-multiplexing



Desired result: ???



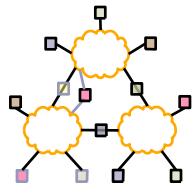
Single Receiver, Sender and Interferer



$D = 55$

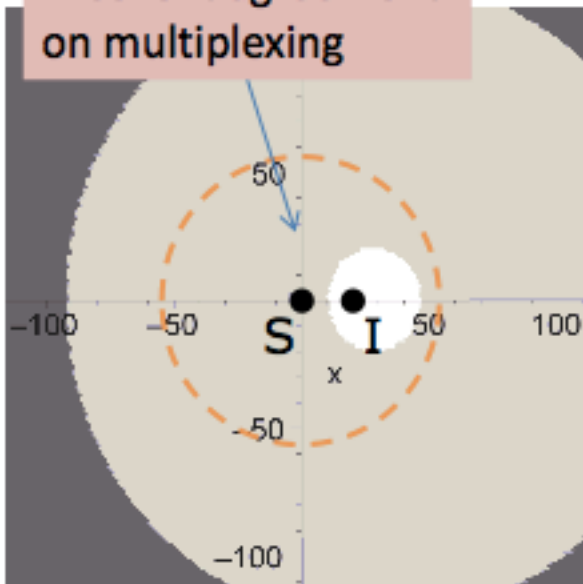
- Prefers concurrency
- Prefers multiplexing
- Starved w/o multiplexing

Interferer Position



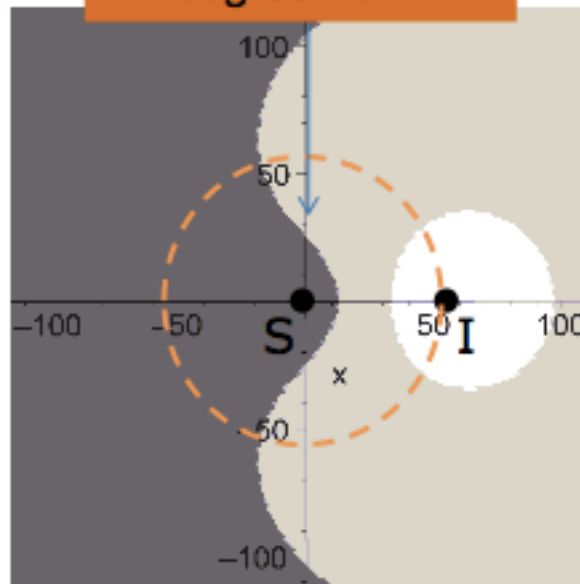
Receiver preference vs. position:

Excellent agreement
on multiplexing



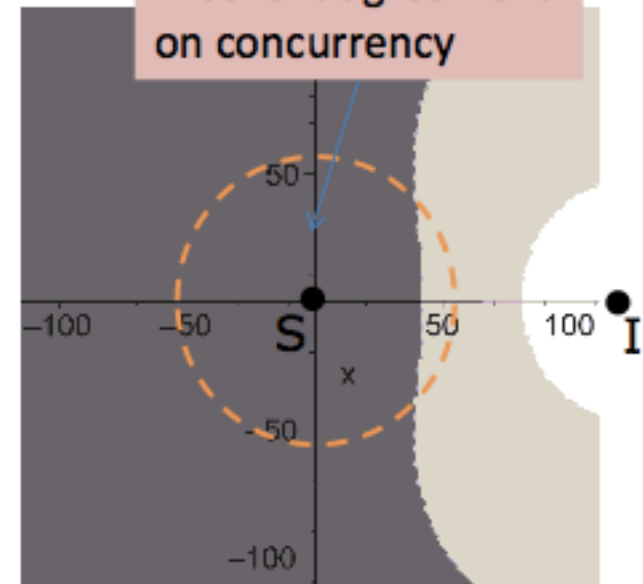
$D = 20$

Disagreement??



$D = 55$

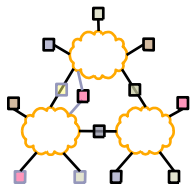
Excellent agreement
on concurrency



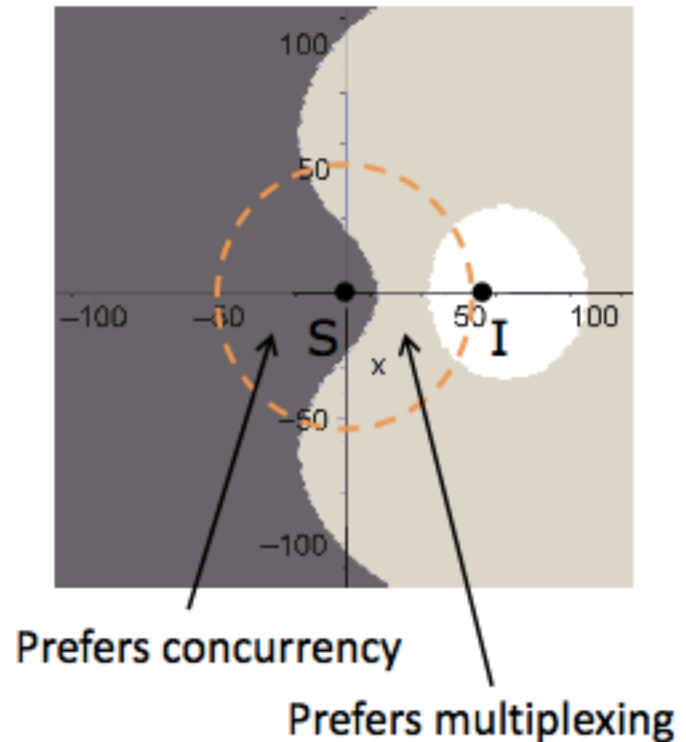
$D = 120$

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

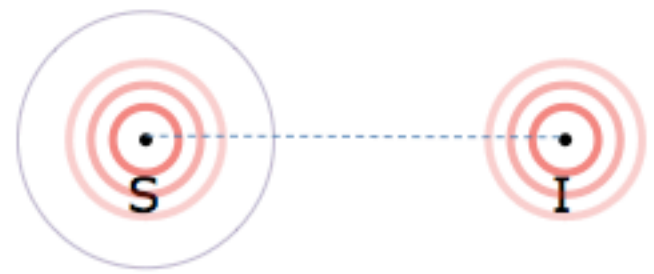
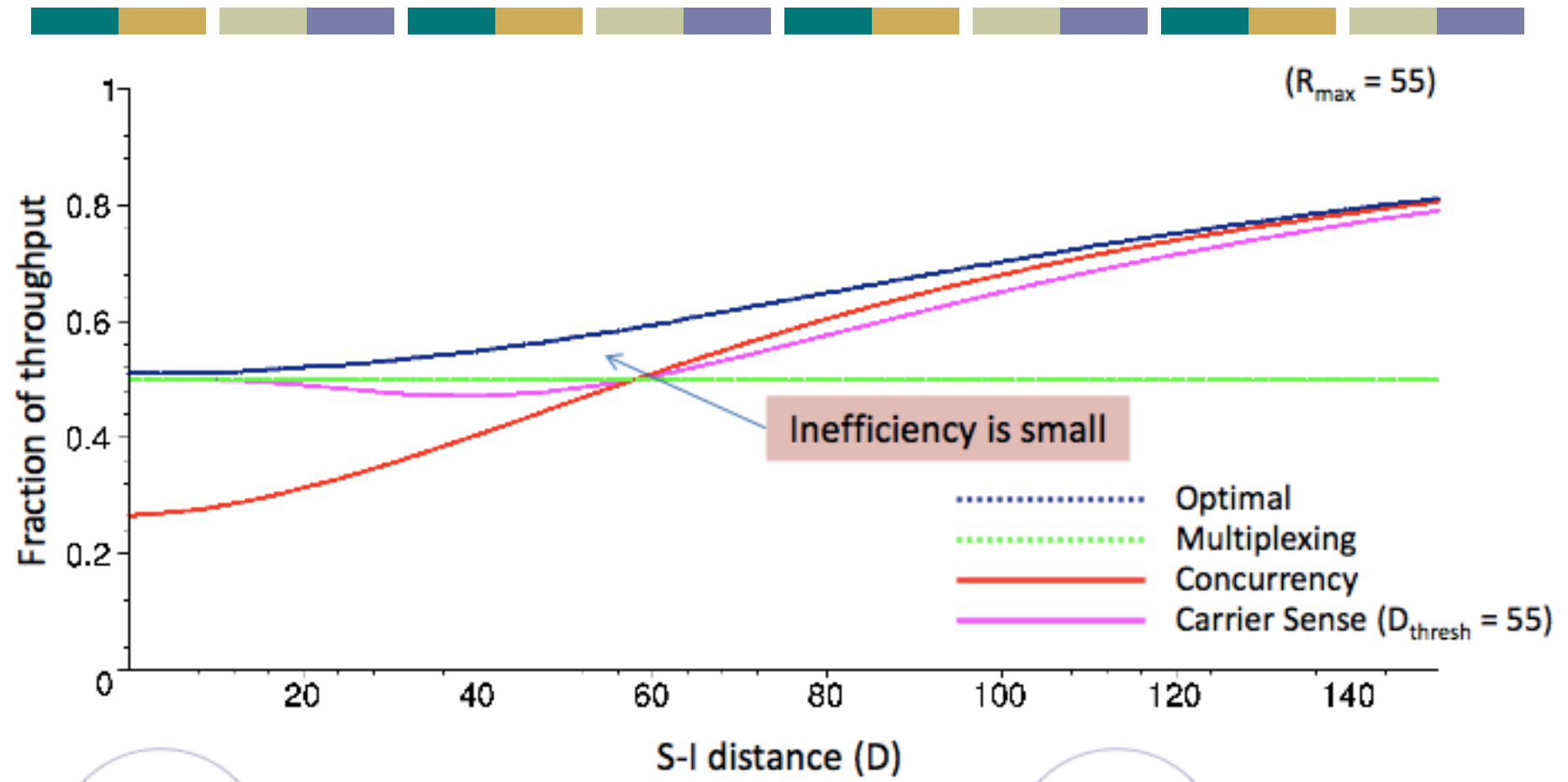
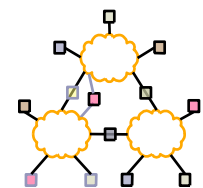
ABR Helps in Disagreements



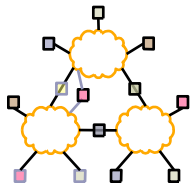
- Intermediate distance can mean poor agreement! But...
- Does “mistaken” concurrency mean near-zero throughput? No. Adapts with lower bitrate.
- Does “mistaken” multiplexing mean 50%-reduced throughput? No. Adapts with higher bitrate.



Carrier Sense + ABR Works Well

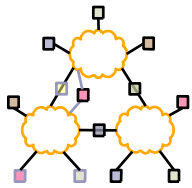


Key Assumptions



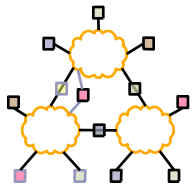
- ABR == Shannon
 - ABR is rarely this good
- Interference and ABR are both stable
 - Interference may be bursty/intermittent

Overview



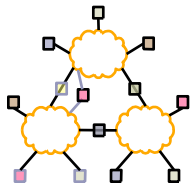
- Wireless Background
- Wireless MAC
 - MACAW
 - 802.11
- Wireless TCP

Wireless Challenges



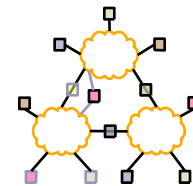
- Force us to rethink many assumptions
- Need to share airwaves rather than wire
 - Don't know what hosts are involved
 - Host may not be using same link technology
- Mobility
- Other characteristics of wireless
 - **Noisy → lots of losses**
 - **Slow**
 - Interaction of multiple transmitters at receiver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

TCP Problems Over Noisy Links



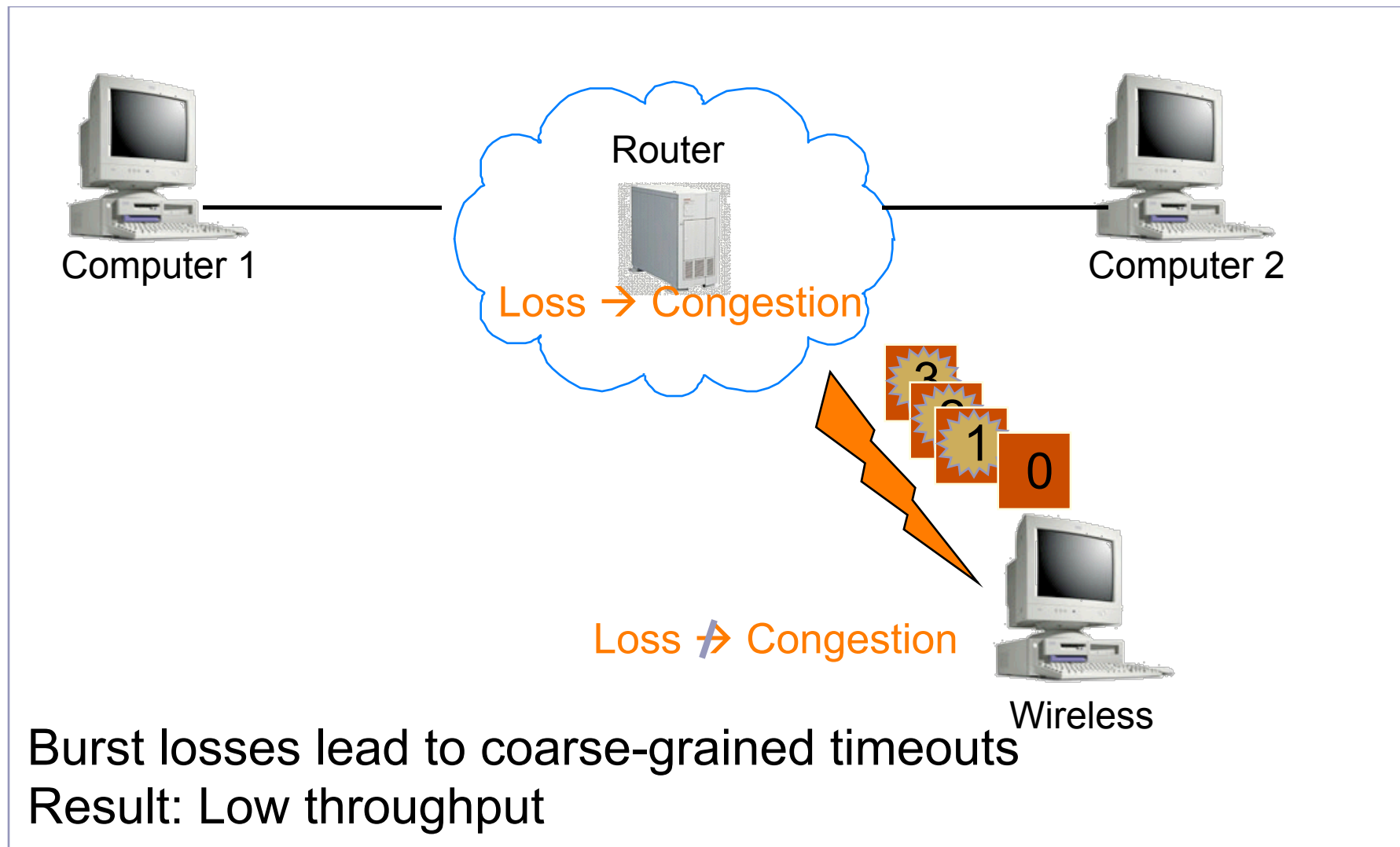
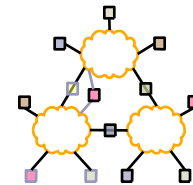
- Wireless links are inherently error-prone
 - Fades, interference, attenuation
 - Errors often happen in bursts
- TCP cannot distinguish between corruption and congestion
 - TCP unnecessarily reduces window, resulting in low throughput and high latency
- Burst losses often result in timeouts
- Sender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

Constraints & Requirements

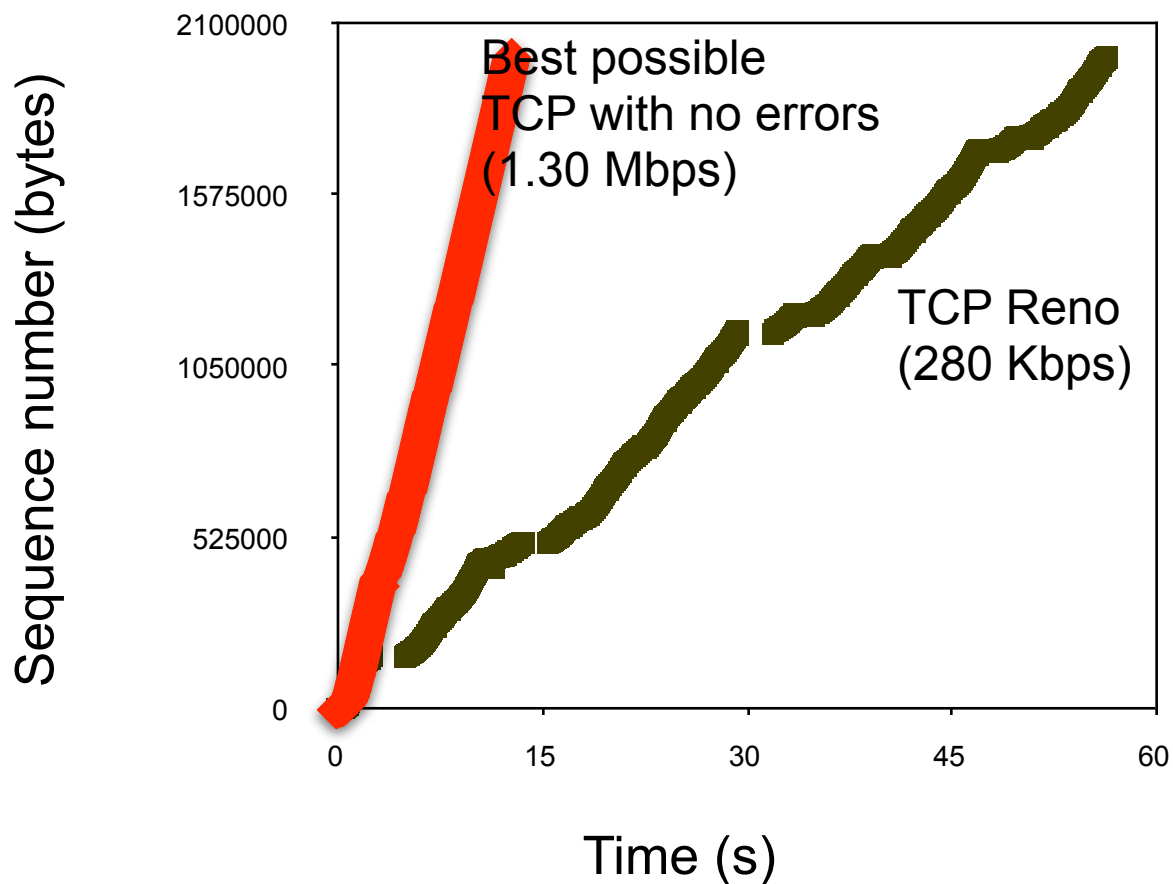
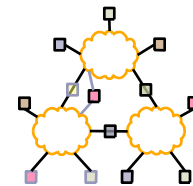


- Incremental deployment
 - Solution should not require modifications to fixed hosts
 - If possible, avoid modifying mobile hosts
- Probably more data to mobile than from mobile
 - Attempt to solve this first

Challenge #1: Wireless Bit-Errors

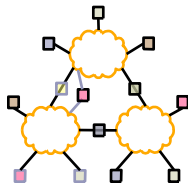


Performance Degradation



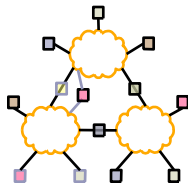
2 MB wide-area TCP transfer over 2 Mbps Lucent WaveLAN

Proposed Solutions

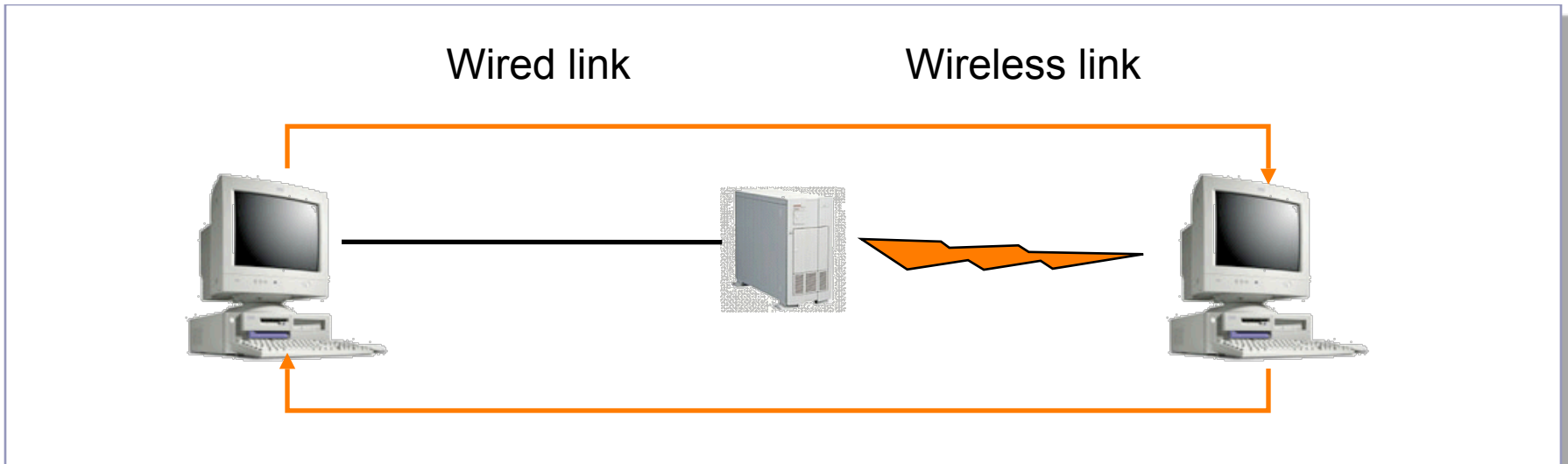


- End-to-end protocols
 - Selective ACKs, Explicit loss notification
- Split-connection protocols
 - Separate connections for wired path and wireless hop
- Reliable link-layer protocols
 - Error-correcting codes
 - Local retransmission

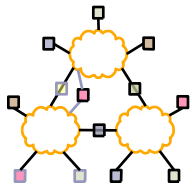
Approach Styles (End-to-End)



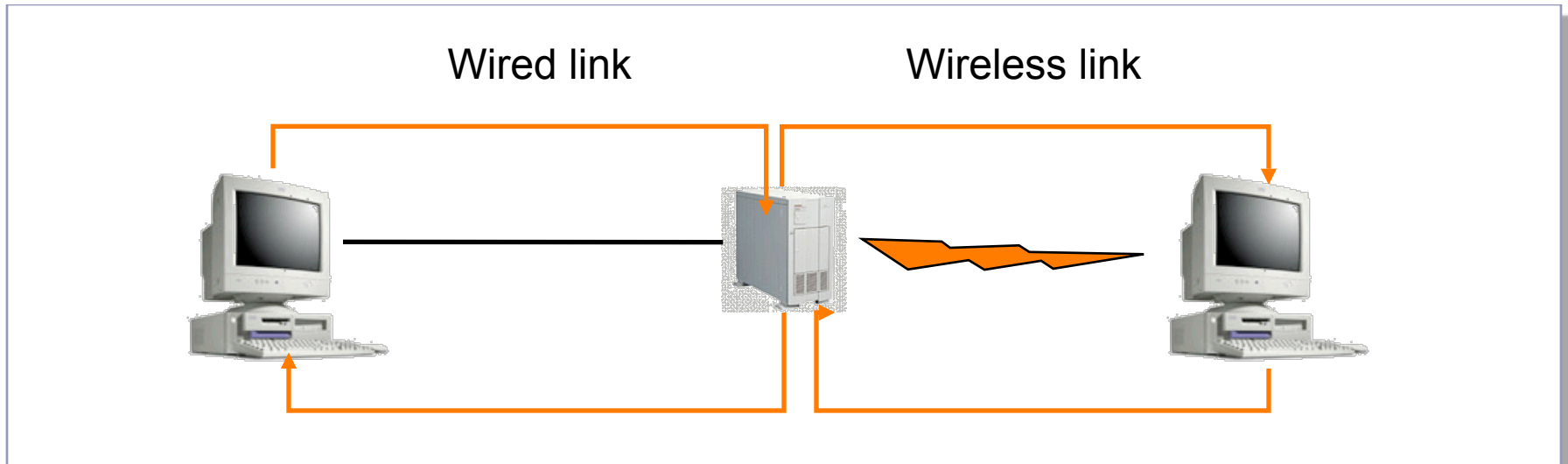
- Improve TCP implementations
 - Not incrementally deployable
 - Improve loss recovery (SACK, NewReno)
 - Help it identify congestion (ELN, ECN)
 - ACKs include flag indicating wireless loss
 - Trick TCP into doing right thing → E.g. send extra dupacks
 - What is SMART?
 - DUPACK includes sequence of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



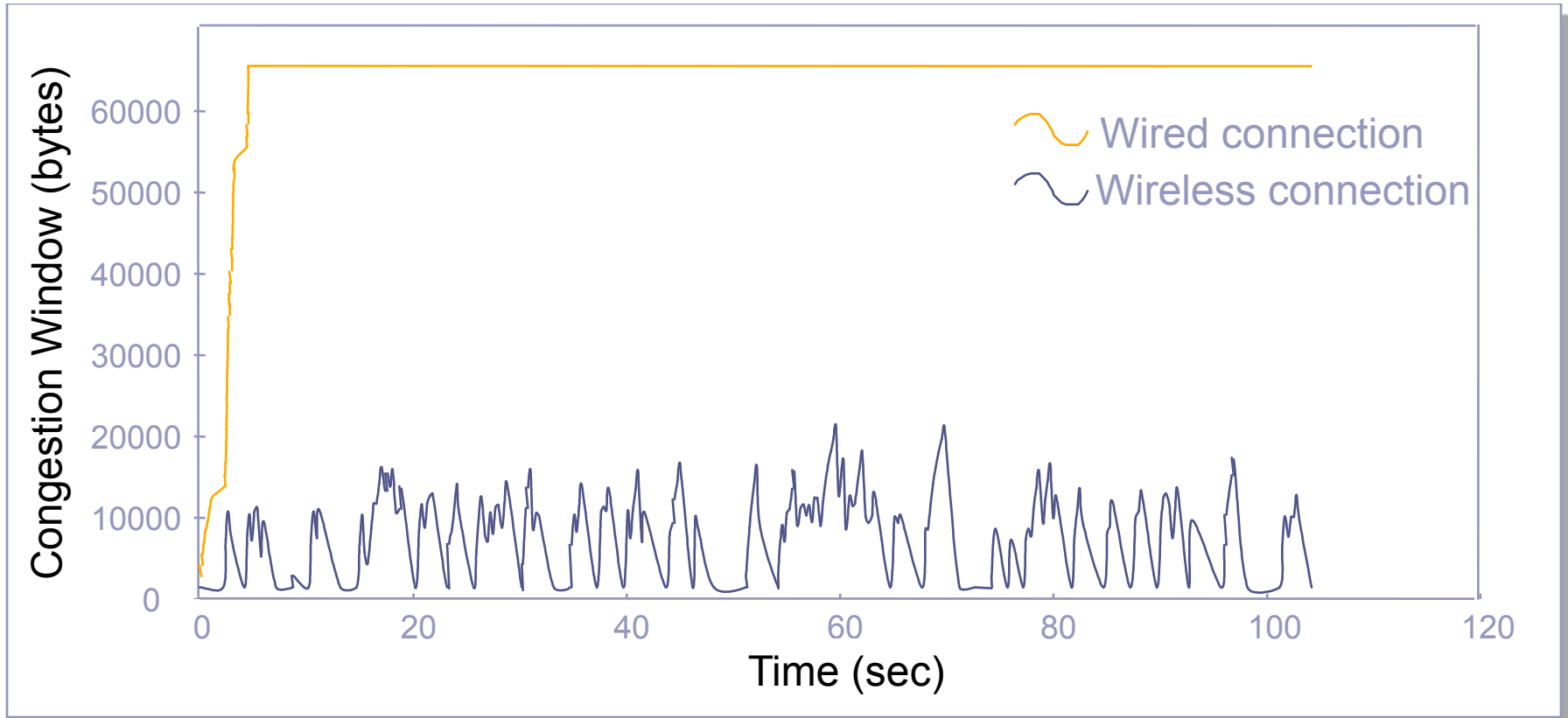
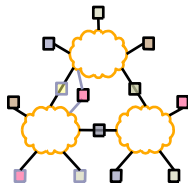
Approach Styles (Split Connection)



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

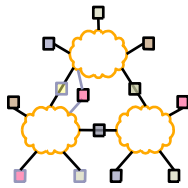


Split-Connection Congestion Window

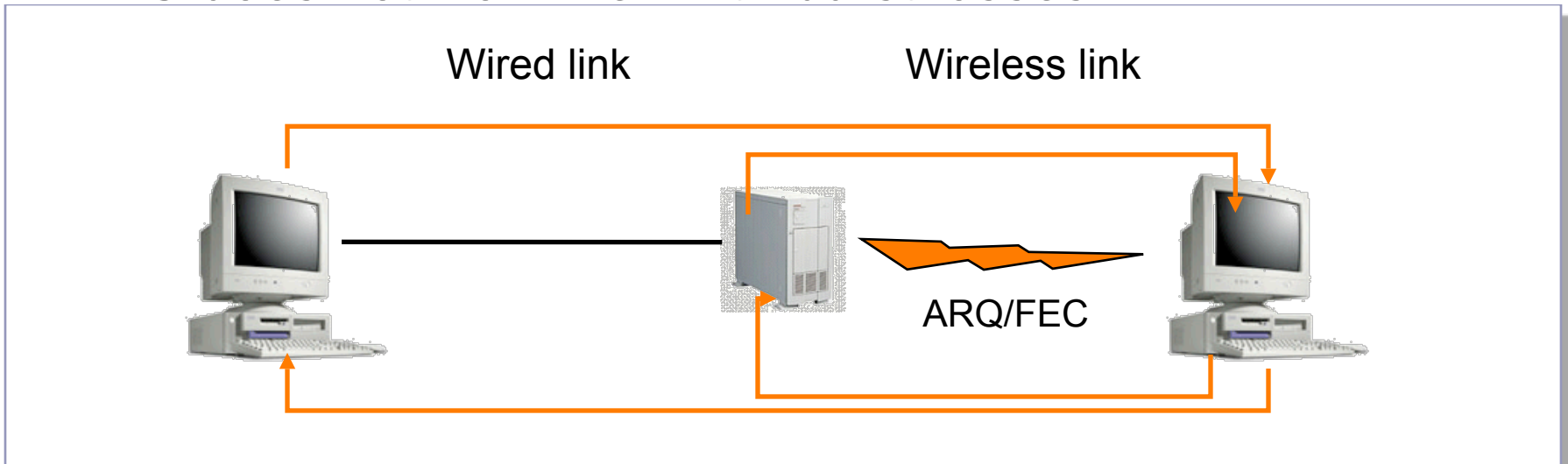


- Wired connection does not shrink congestion window
- But wireless connection times out often, causing sender to stall

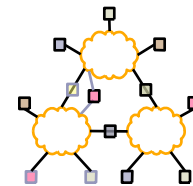
Approach Styles (Link Layer)



- More aggressive local retransmit 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



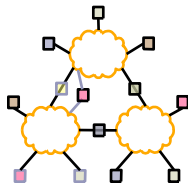
Hybrid Approach: Snoop Protocol



- 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

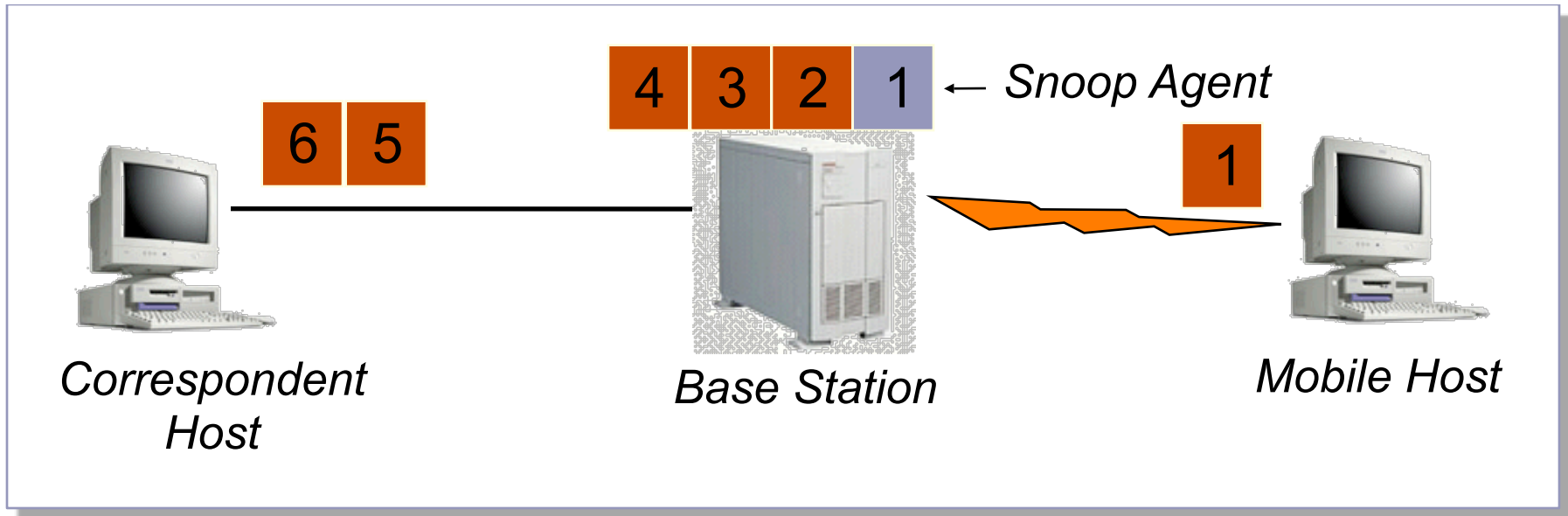
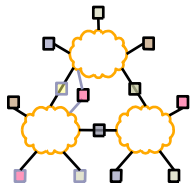
Fixed to mobile: transport-aware link protocol
Mobile to fixed: link-aware transport protocol

Snoop Overview



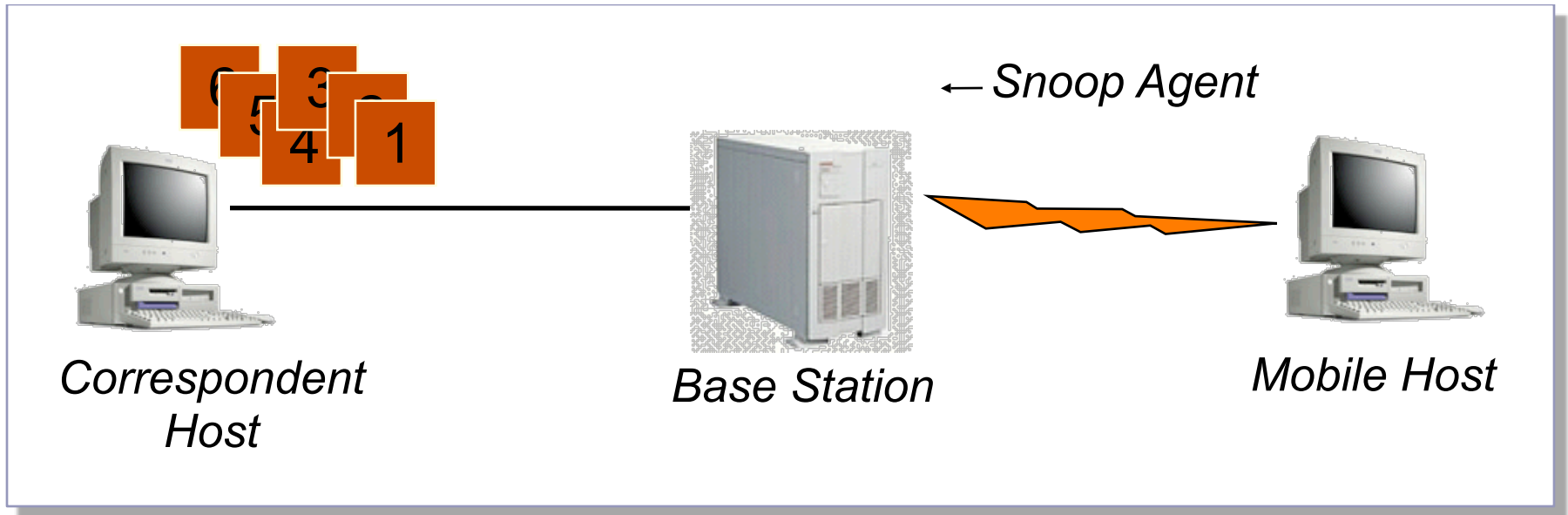
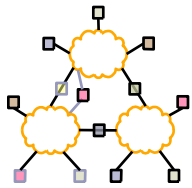
- Modify base station
 - to cache un-acked TCP packets
 - ... and perform local retransmissions
- Key ideas
 - No transport level code in base station
 - When node moves to different base station, state eventually recreated there

Snoop Protocol: CH to MH



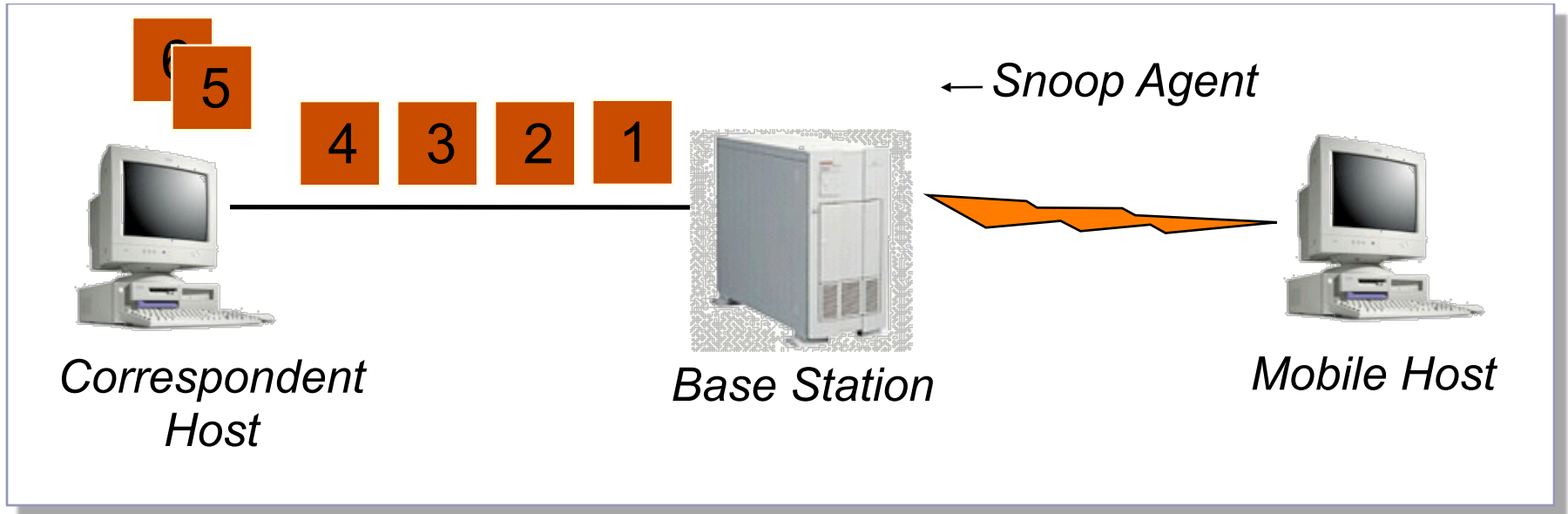
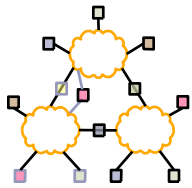
- Snoop agent: *active interposition agent*
 - Snoops on TCP segments and ACKs
 - Detects losses by duplicate ACKs and timers
 - Suppresses duplicate ACKs from MH

Snoop Protocol: CH to MH



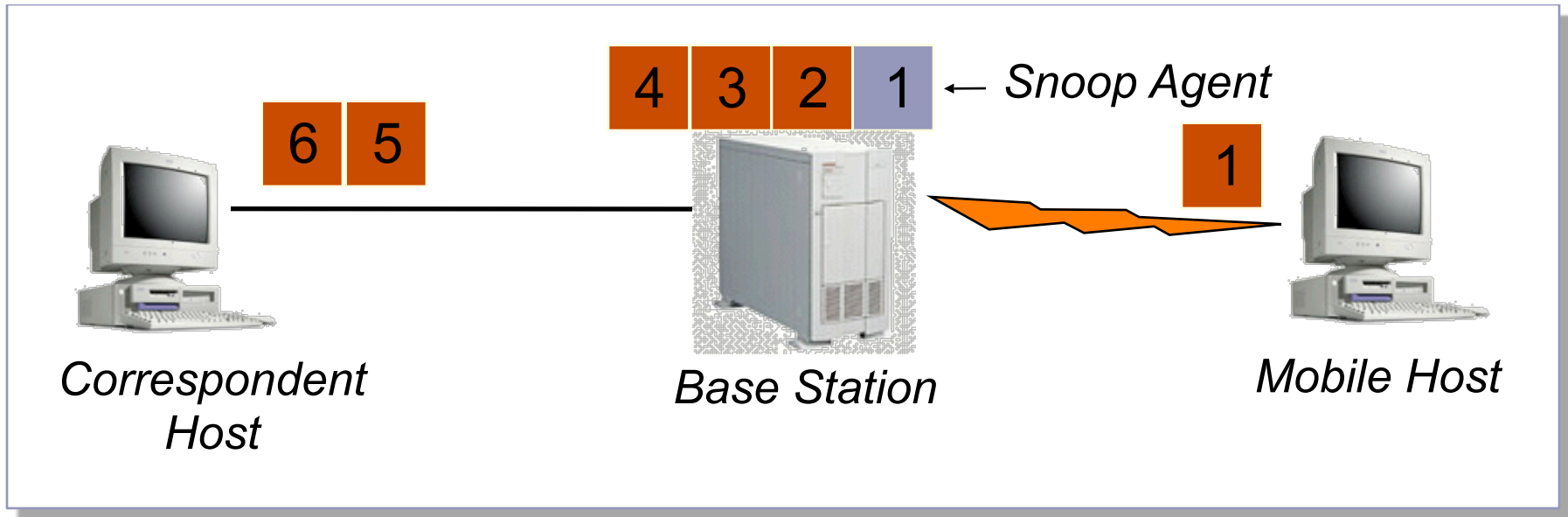
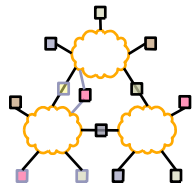
- Transfer of file from CH to MH
- Current window = 6 packets

Snoop Protocol: CH to MH



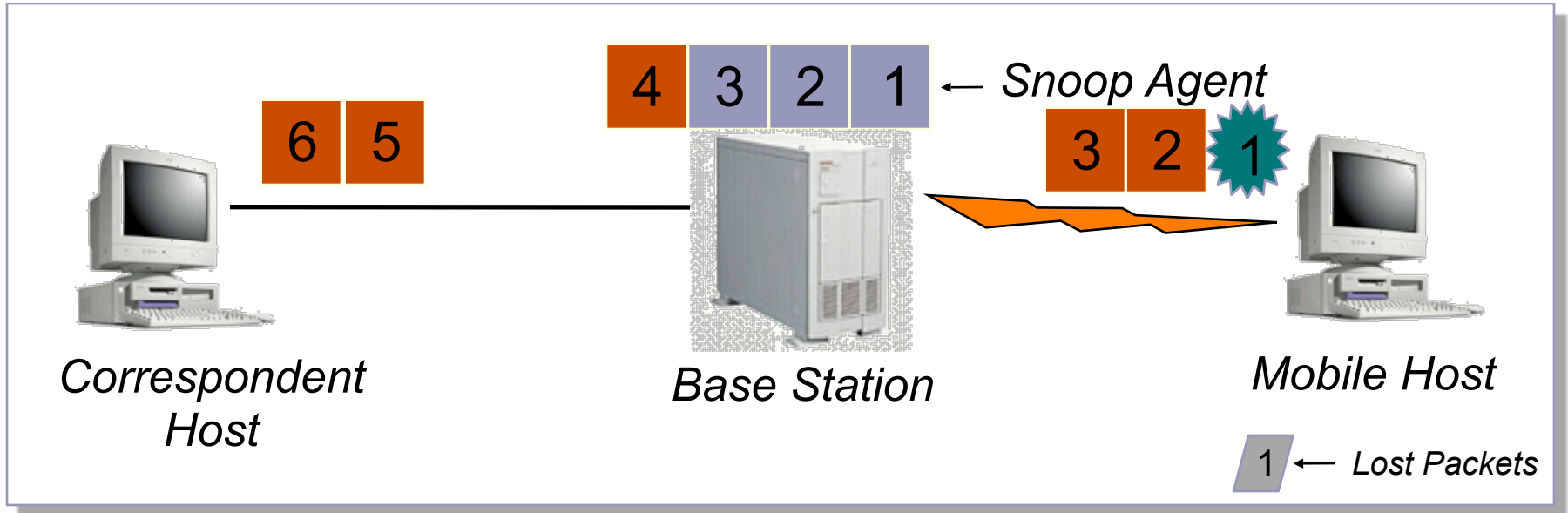
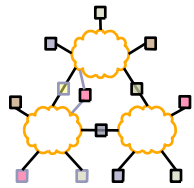
- Transfer begins

Snoop Protocol: CH to MH



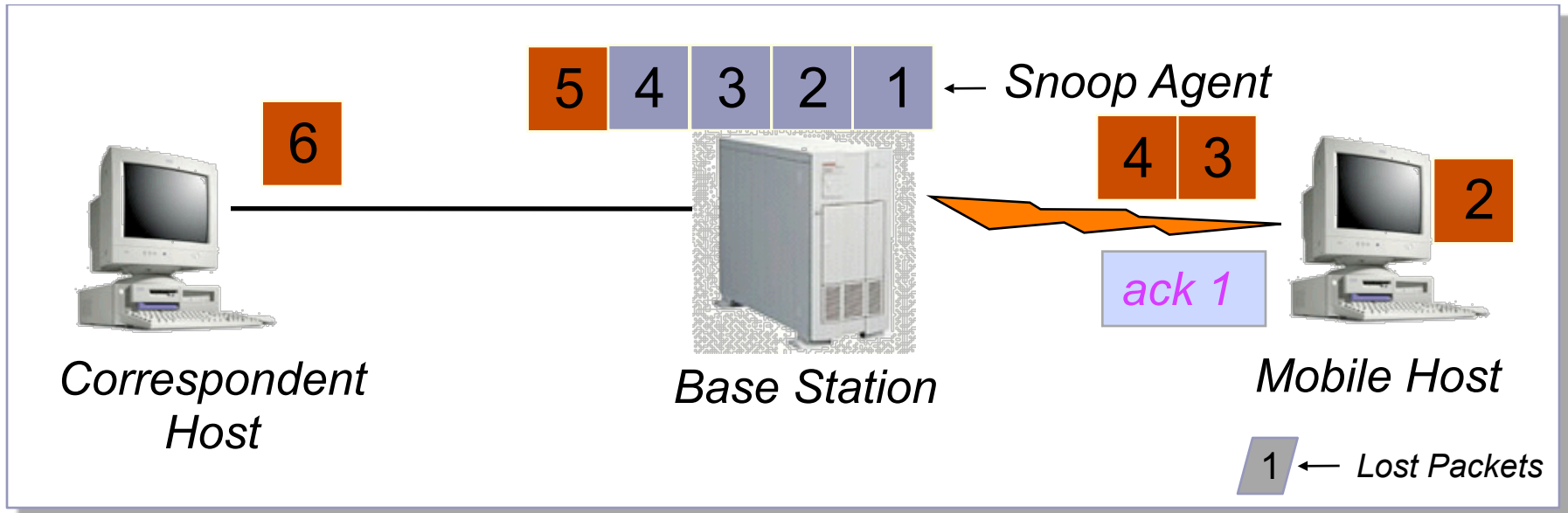
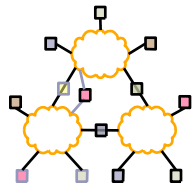
- Snoop agent caches segments that pass by

Snoop Protocol: CH to MH



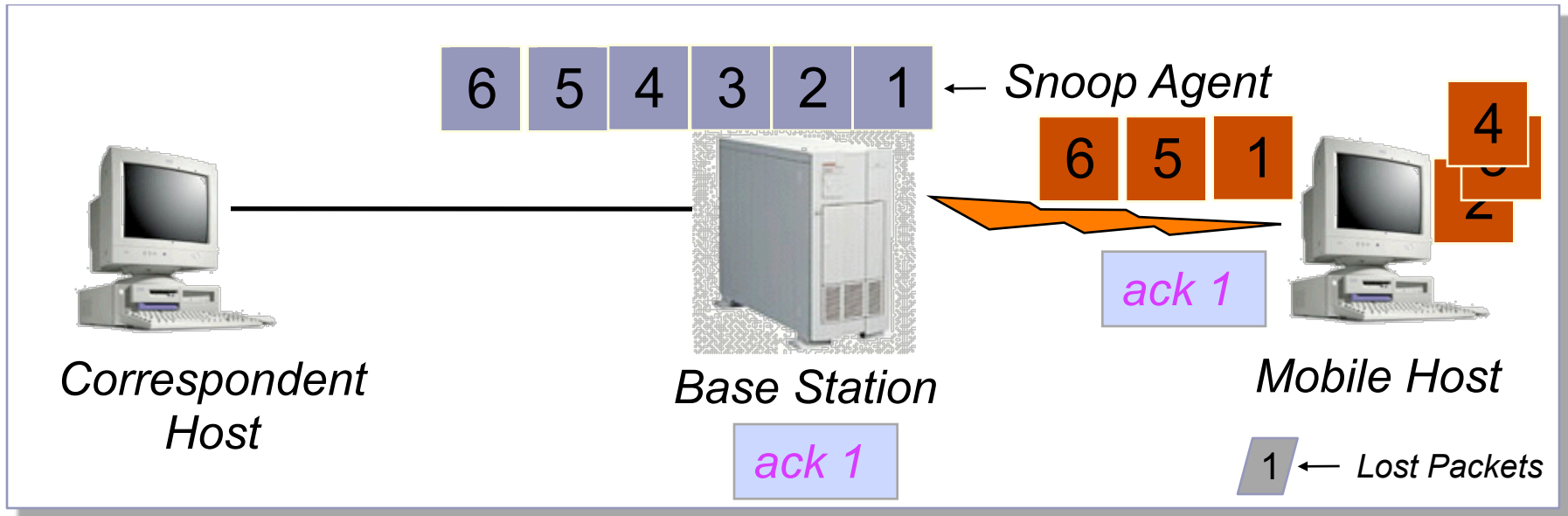
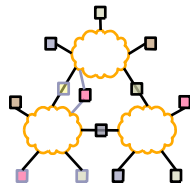
- Packet 1 is Lost

Snoop Protocol: CH to MH



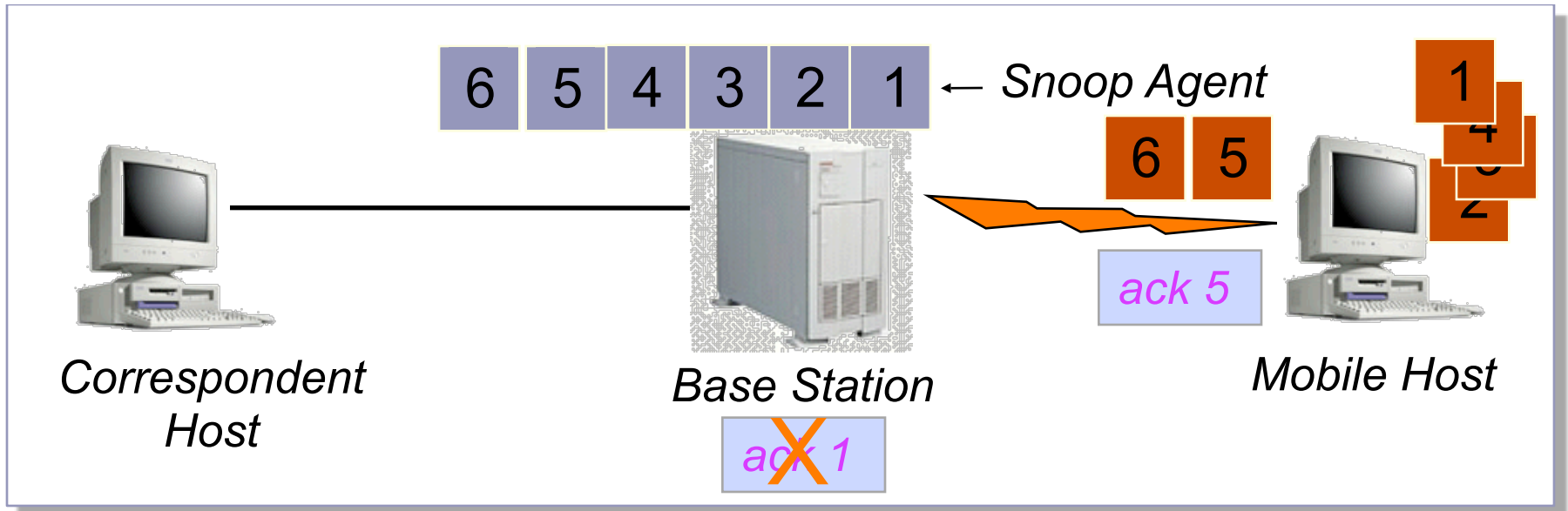
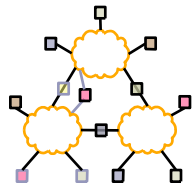
- Packet 1 is Lost
 - Duplicate ACKs generated

Snoop Protocol: CH to MH



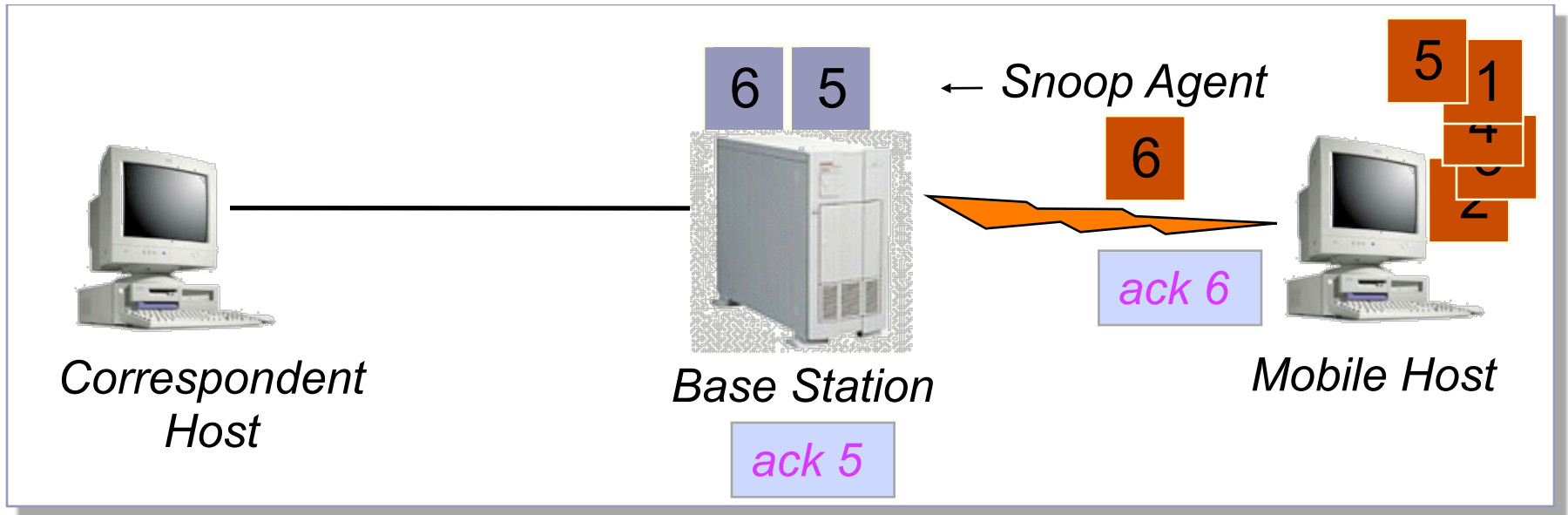
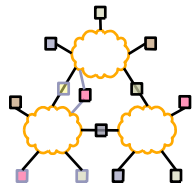
- Packet 1 is Lost
 - Duplicate ACKs generated
- Packet 1 retransmitted from cache at higher priority

Snoop Protocol: CH to MH



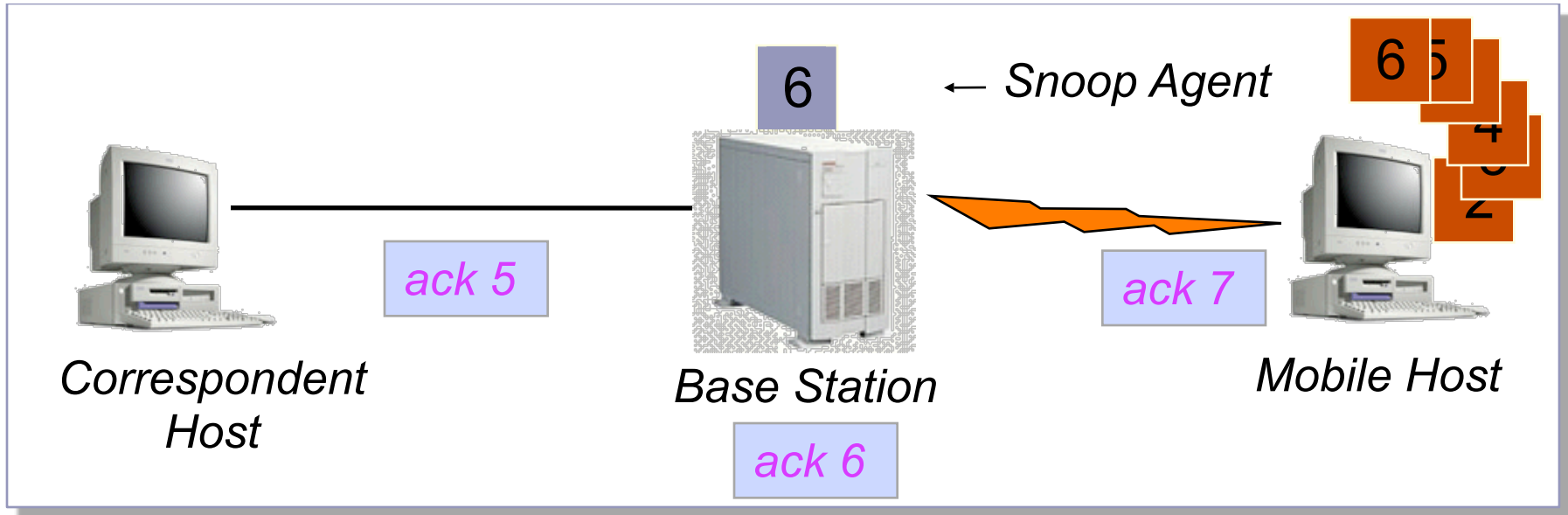
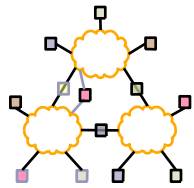
- Duplicate ACKs suppressed

Snoop Protocol: CH to MH



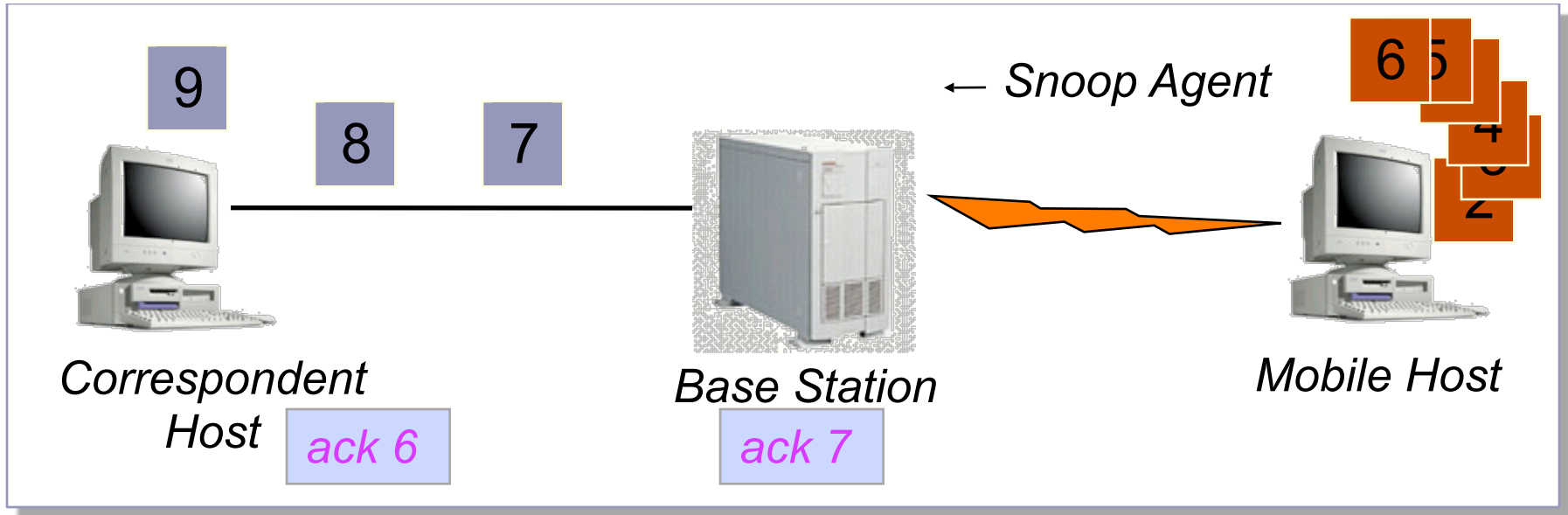
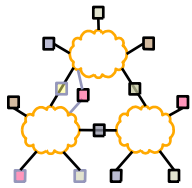
- Clean cache on new ACK

Snoop Protocol: CH to MH



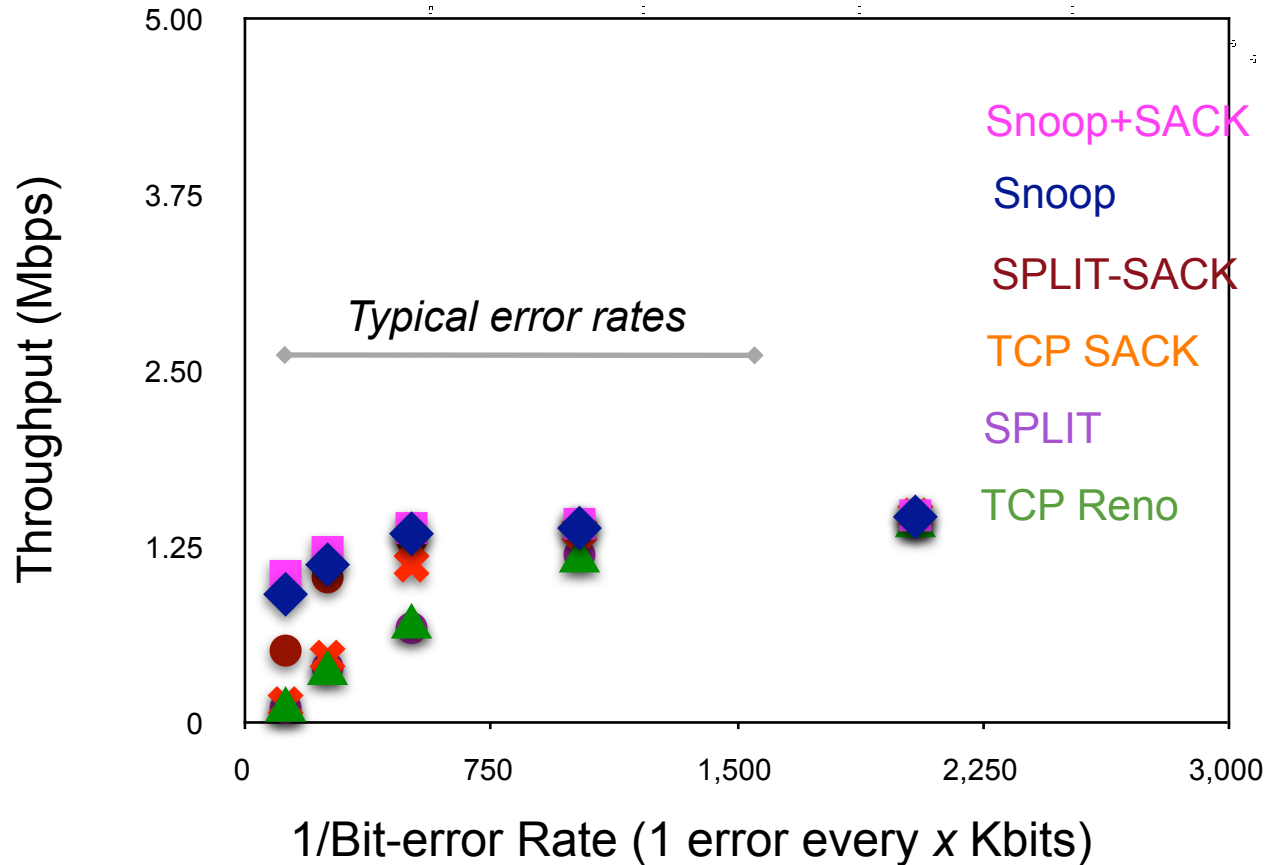
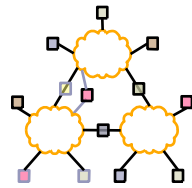
- Clean cache on new ACK

Snoop Protocol: CH to MH



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

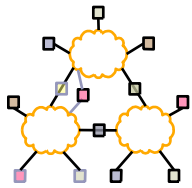
Performance: FH to MH



- 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