# 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
  - [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

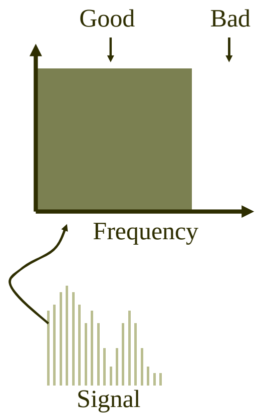


## Overview

- 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

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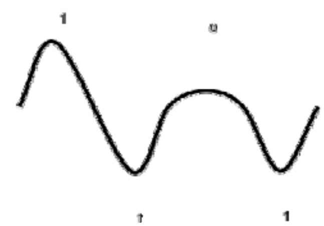
## The Nyquist Limit

- 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



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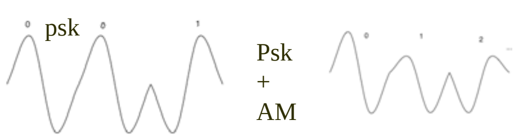
## Past the Nyquist Limit

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

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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.

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## 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

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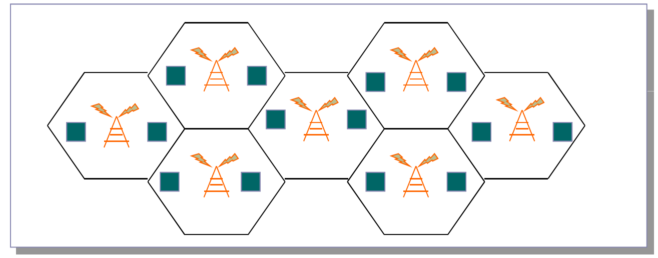
## Cellular Reuse

- 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



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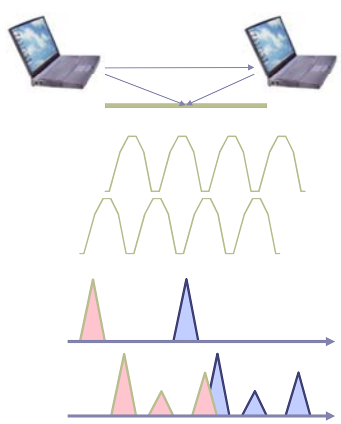
## Multipath Effects

- 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).



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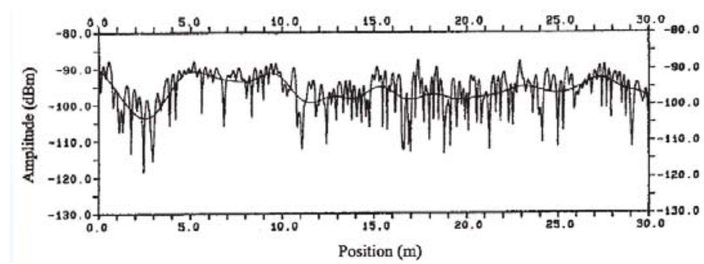
## Fading - Example




- Frequency of 910 MHz or wavelength of about 33 cm

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## 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



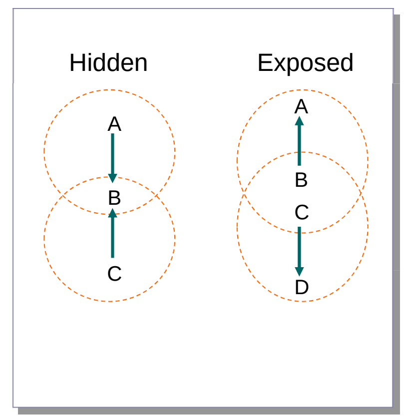
## Example MAC Protocols

- 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



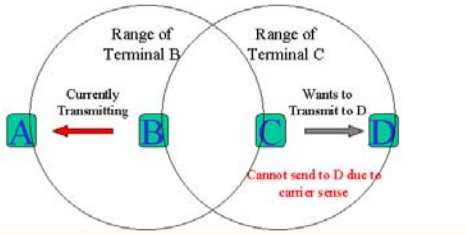
## CSMA/CD Does Not Work

- 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



## MACAW

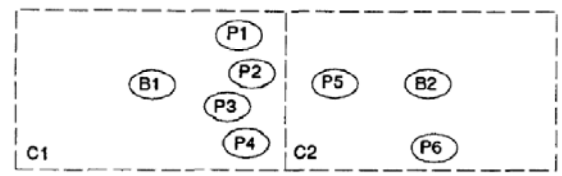
- 4 design details
  1. Contention is at the receiver
  2. Congestion is location dependent
  3. Fairn
  4. Propa conte






## 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 |

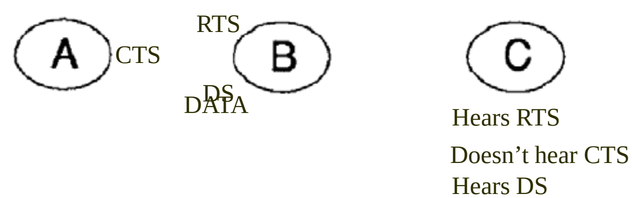
- ACK

| 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 |



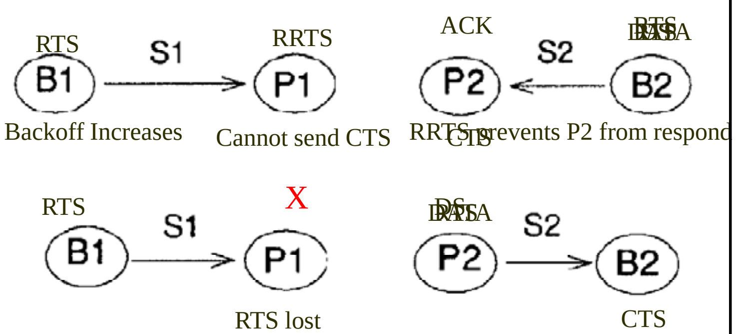
## MACAW: Additional Design

- DS
  - Because carrier sense disabled



## RRTS

- Problem:

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## 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.

- Future work:
  - Multicast support
  - Copying backoff

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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

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## 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

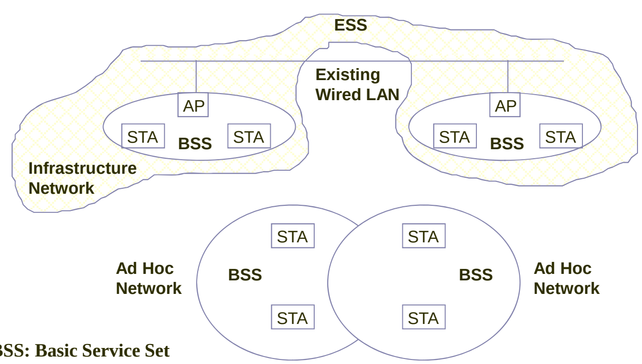


## 802.11 details

- Fragmentation
  - 802.11 can fragment large packets (this is separate from IP fragmentation).
- 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

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## 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
- Joining a BSS
  - Synchronization in TSF and frequency : Adopt PHY parameters : The BSSID : WEP : Beacon Period : DTIM

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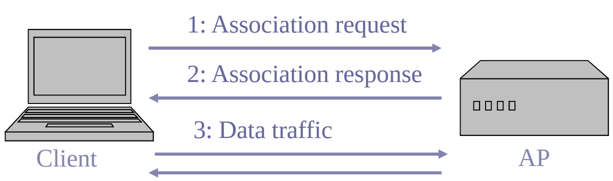
## Association in 802.11

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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



## IEEE 802.11 Wireless MAC

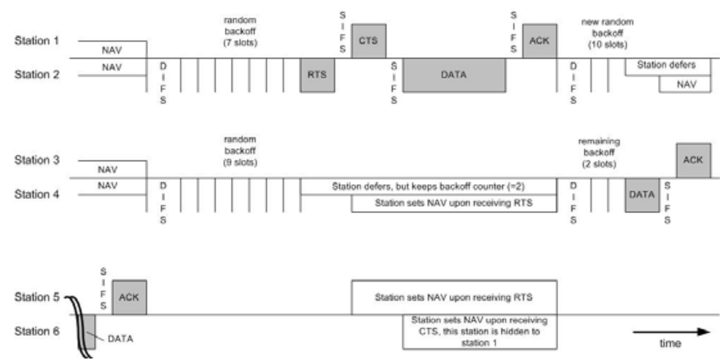
- Support broadcast, multicast, and unicast
  - Uses ACK and retransmission to achieve reliability for unicast frames
  - No ACK/retransmission for broadcast or multicast frames
- Distributed and centralized MAC access
  - Distributed Coordination Function (DCF)
  - Point Coordination Function (PCF)



## 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)



## Discussion

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

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## Wireless Challenges

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  - Don't know what hosts are involved
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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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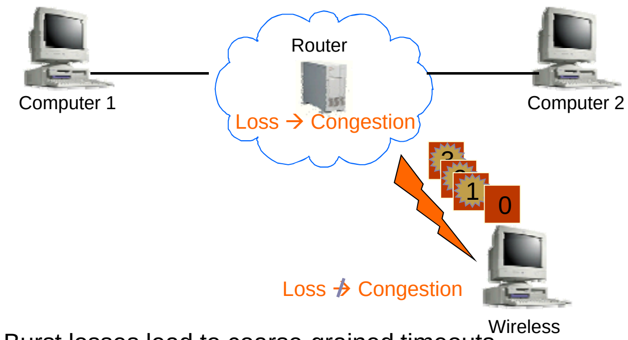
## Constraints & Requirements

- 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



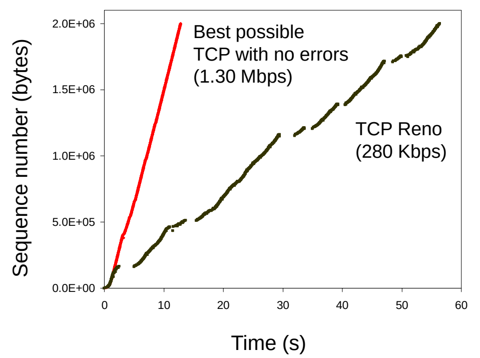
## Challenge #1: Wireless Bit-Errors




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



## Performance Degradation




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

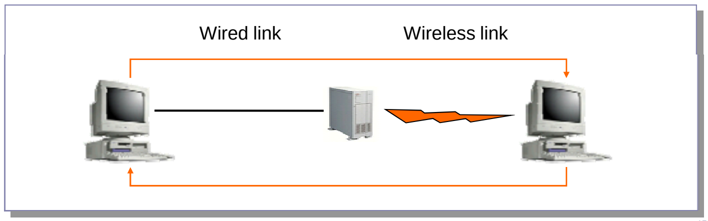


## Proposed Solutions

- 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)

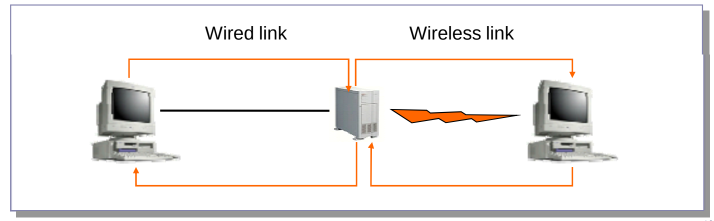
- Improve TCP implementations
  - Not incrementally deployable
  - Improve loss recovery (SACK, NewReno)
  - Help it identify congestion (ELN, ECN)
    - ACKs include flag indicating wireless loss
  - Trick TCP into doing right thing → E.g. send extra dupacks
  - What is SMART?
    - DUPACK includes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





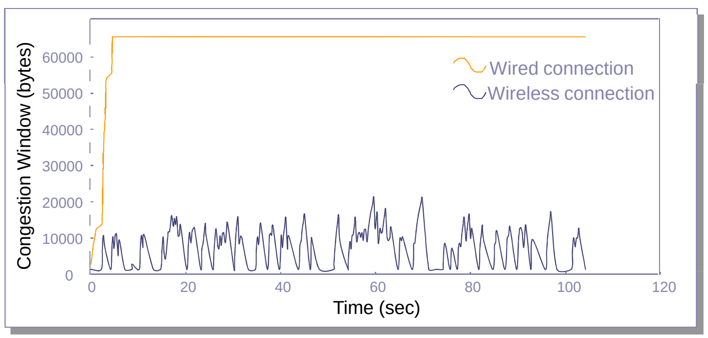

## Approach Styles (Split Connection)

- 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

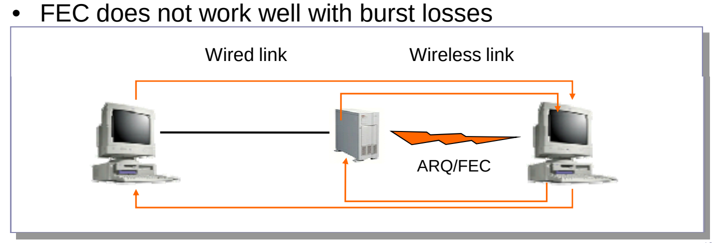



- Wired connection does not shrink congestion window
- But wireless connection times out often, causing sender to stall



## 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

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## 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

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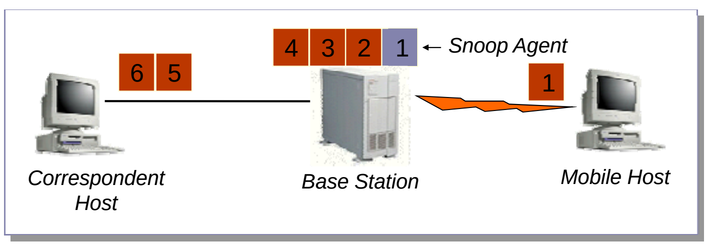
## Snoop Protocol: CH to MH




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

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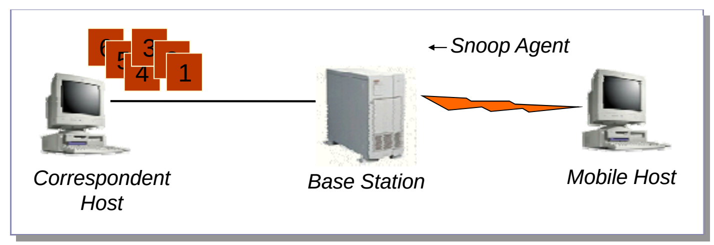
## Snoop Protocol: CH to MH




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

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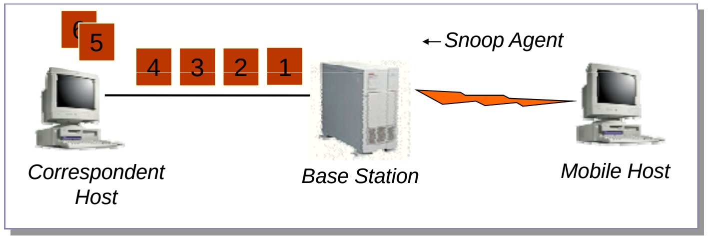
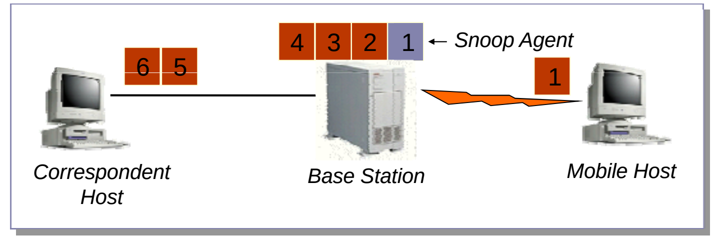
## Snoop Protocol: CH to MH




- Transfer begins



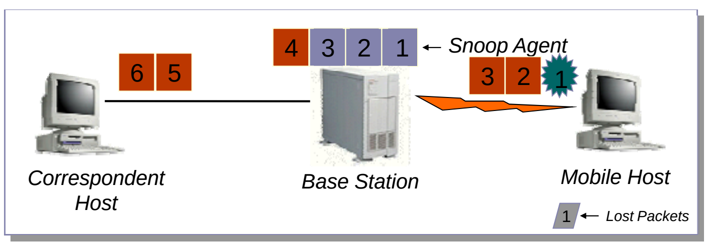
## Snoop Protocol: CH to MH




- Snoop agent caches segments that pass by



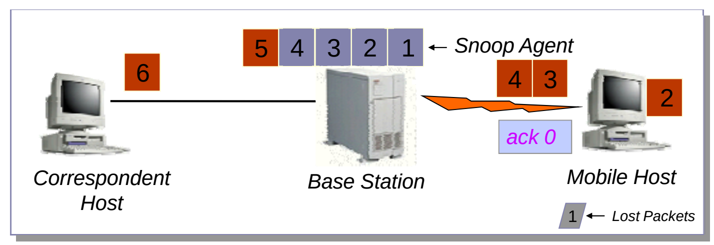
## Snoop Protocol: CH to MH




- Packet 1 is Lost

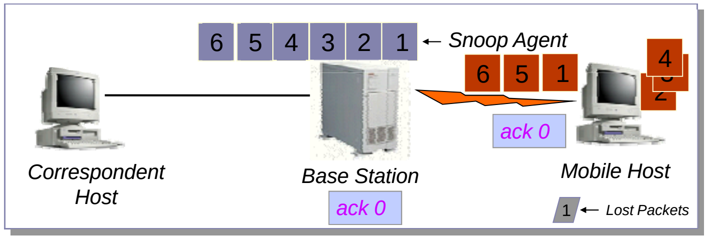


## Snoop Protocol: CH to MH




- Packet 1 is Lost
  - Duplicate ACKs generated

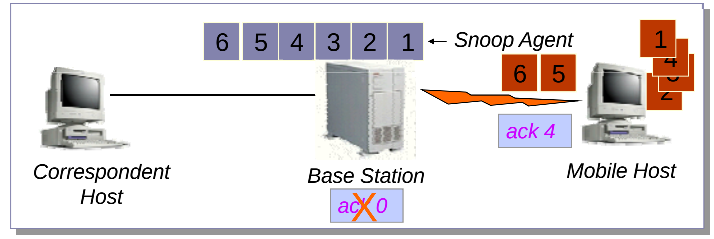
## Snoop Protocol: CH to MH




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



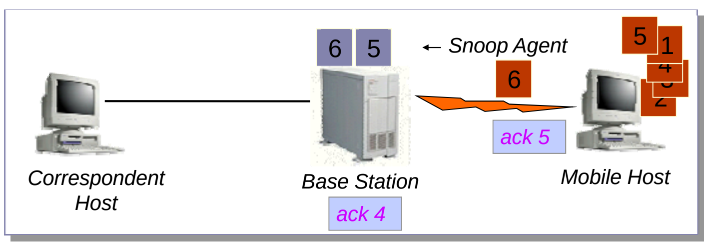
## Snoop Protocol: CH to MH




- Duplicate ACKs suppressed



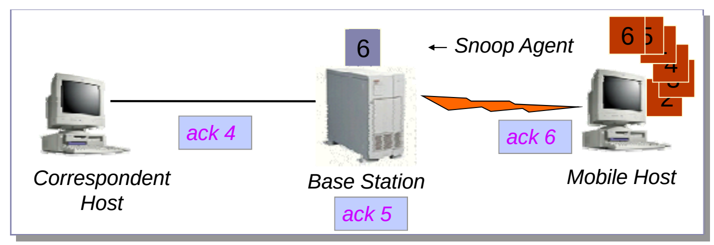
## Snoop Protocol: CH to MH




- Clean cache on new ACK



## Snoop Protocol: CH to MH




- Clean cache on new ACK

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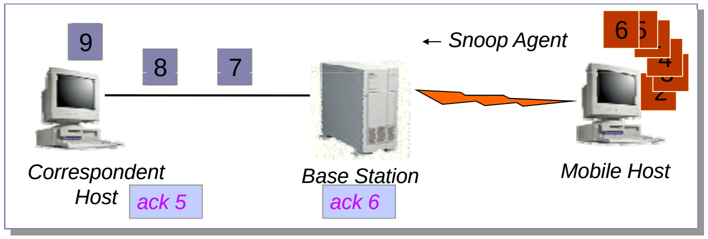
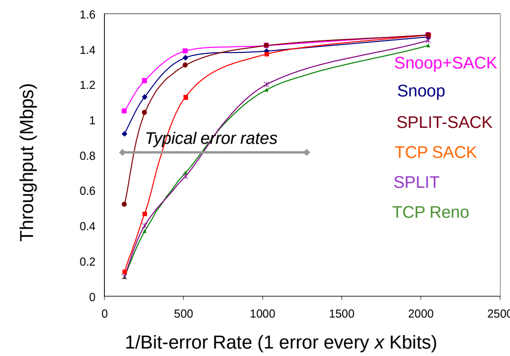



- Active soft state agent at base station
- Transport-aware reliable link protocol
- Preserves end-to-end semantics



## 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