Internet Programming & Protocols
Lecture 24

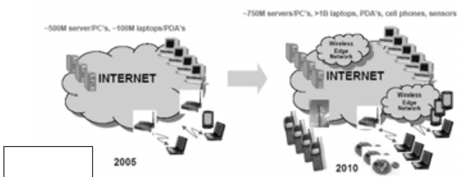
Wireless networks

Mobile/ad hoc networks

www.cs.utk.edu/~dunigan/ipp/

Internet trends

- Wireless key driver for future Internet (end device volume)
- Shift from PC's to mobile computing and embedded devices
  - 2 billion cell phones vs 500 million internet PCs (2005)
  - More than 400 million internet-capable cell phones and growing
  - New data devices (blackberry, iPoD, PDA)
  - Sensor deployment just starting (5 billion by 2010 ?)



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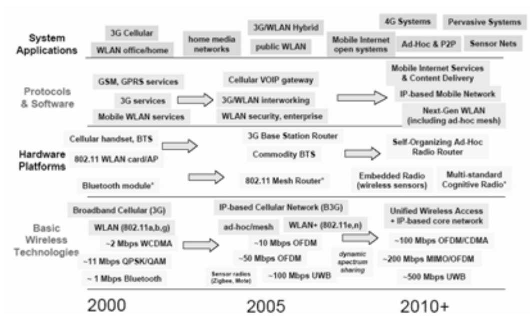
Wireless roadmap



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Wireless architecture

- Most of the interesting issues are in
  - Routing and addressing (mobile IP)
  - Link layer (radio layer protocol)
  - Security
  - Engineering – low power consumption, small memory, limited bandwidth
- Our interest … transport protocol

Wireless networks

- Usually configured with an access point, but can be point-to-point

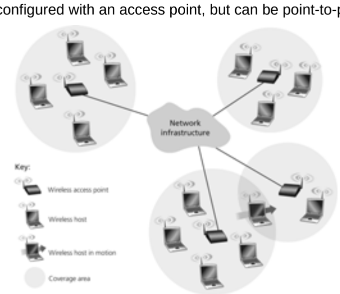
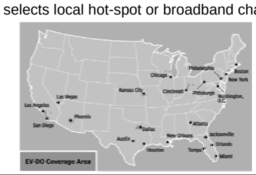
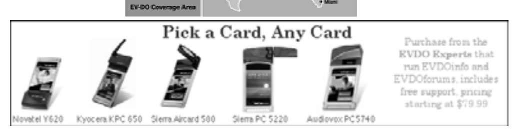


Figure 6.1 • Elements of a wireless network © Kurose

WiMAX (3G) wireless broadband

- Metropolitan area wireless (Verizon, Sprint -- $70/month)
- Always on, personal wireless, 300-512 kbs (IEEE 802.16)
- Future: laptop selects local hot-spot or broadband channel





Link characteristics

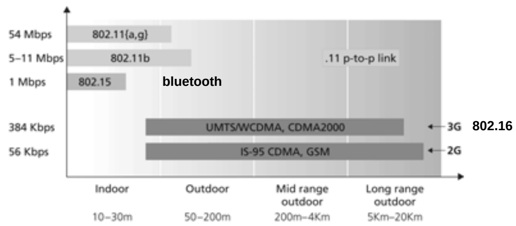
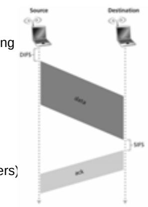


Figure 6.2 ♦ Link characteristics of selected wireless network standards © Kurose

802.11

Figure 6.11 ♦ The 802.11 frame © Kurose

- Physical layer
  - Radio frequency media
  - Shared media, sharing with Code Division Multiple Access (CDMA)
  - Signal strength affected by distance and obstructions
  - Interference from reflections, other RF sources
  - More bit errors than in wired links
- Ethernet-like link layer (MAC protocol)
  - CSMA – make sure channel is not busy before transmitting
    - If busy, wait random delay (DIFS) and check again
  - Ethernet used CSMA/CD
    - transmitter would listen for interference and stop
  - But transmitting and "listening" for RF impractical
    - Transmit signal much stronger than received signal
    - Hidden terminal problem (can't hear some transmitters)
  - CRC and link layer ACKs (ARQ)
    - If CRC OK, receiver waits (SIFS) then sends ACK



Network characteristics

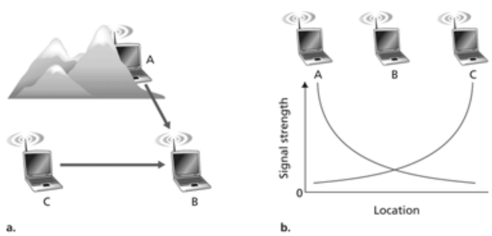
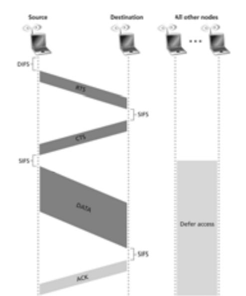


Figure 6.3 ♦ Hidden terminal problem (a) and fading (b) © Kurose

802.11 MAC

- Hidden terminal makes congestion avoidance difficult
- Optional Request to Send (RTS) and Clear to Send (CTS) protocol can be used to "reserve" the channel
  - Used for long data frames
  - Long data frames more likely to encounter interference/loss
  - ☹ introduces delays and reduces channel utilization
- Additional protocols for associating
  - Access (SSID) and beacon frames
  - security



© Kurose

Figure 6.10 ♦ Collision avoidance using the RTS and CTS frames

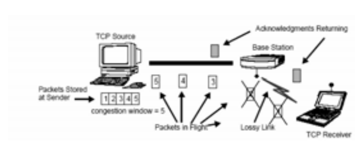
Radio ranges and hidden nodes

- Transmission range (TX_Range): represents the range within which a packet is successfully received if there is no interference from other radios
- Carrier sensing range (CS_Range): is the range within which a transmitter triggers carrier sense detection
- Interference range (IF_Range): is the range within which stations in receive mode will be "interfered with" by an unrelated transmitter and thus suffer a loss
- Relationship of three ranges

  $TX\_Range < IF\_Range_{max} < CS\_Range$

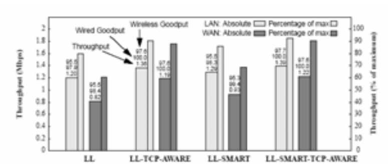
Wireless effects on transport

- Lossy path, usually non-congestive loss
  - ARQ recovery can increase RTT and variance of RTT
    - Multiple retransmits at the link layer
  - Clustered losses (multiple packet drops in a loss "event")
  - BER 10^{-6} translates to frame error rate of 2% for big frames
- Adding link-layer reliability
  - FEC -- reduces throughput
  - ARQ – increases RTT and variance
  - Link layer use TCP ACK/SACK info for smart retransmit (Balakrishnan)



TCP-aware link layer retransmits

- Implemented at wireless gateway (snoop-like)
- Use TCP ACK and SACKs to control link layer retransmits (snoop like)
  - LL uses cumulative ACK and retransmit timer (don't suppress dup ACKs)
  - LL-SMART uses SACK info (don't suppress dup ACKs)
  - LL-TCP-AWARE (snoop protocol, i.e. suppress dup ACKs)
  - LL-SMART-TCP-AWARE (snoop using SACK)
- Performance on testbed (10 mbs wired Ether + Wavelan wireless)
  - Reference Balakrishnan (Berkeley) '97



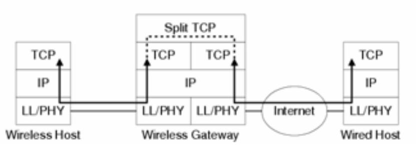
TCP for wireless links

- Proper MSS – bigger MTU may not be best
  - Probability of segment error higher with bigger packets
- Recover fast from packet loss
  - NewReno, SACK
  - Aggressive: HS TCP, STCP (but may not have large window/RTT)
  - Rate-based restart, slow-start
- Resilience to out of order packets
  - DSACK + undo CA
  - adapative dup-threshold (linux)
- Identify non-congestive loss
  - TCPW
  - Explicit loss notification (ELN)
- Isolate lossy path
  - Split or indirect TCP
  - snoop

Windows XP
wireless enhancements
•New Reno (RFC 2582)
•SACK (RFC 2883)
•FACK (RFC 3517)

TCP splitting

- Intercept the SYN and opens a separate TCP connection over the lossy link (sort of like what NAT does) … indirect TCP
- Gateway maps packets from one flow to the other
  - Could use different flavor of TCP for lossy link (TCPW)
  - Use different buffer sizes, MSS, etc.
- Faster recovery on lossy segment
  - Wired side appears to have shorter RTT
- Violates end-to-end semantics, more TCP packet handling overhead



Split performance

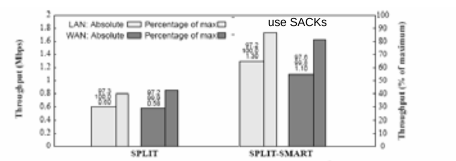


Figure 9. Performance of split-connection protocols: bit error rate = 1.9x10^{-6} (1 error/65536 bytes).

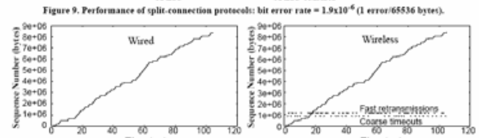
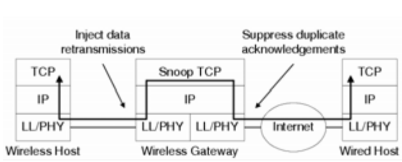


Figure 10. Packet sequence trace for the wired and wireless parts of the SPLIT protocol. The wireless part has two rows of horizontal dots: the top one shows the times of fast retransmissions and the bottom one the times of the timeout-based ones.

TCP snooping

- Objective: confine retransmissions to the lossy link
- Snoop the connection and transparently retransmit lost packets
  - Cache packets from wired side to use in case retransmit needed
  - Release when ACK comes back from lossy path
- Doesn't break end-to-end semantics
- Usually outperforms split TCP



Explicit Loss Notification (ELN)

- Notify TCP sender of non-congestive loss
- Snoop agent sets an ELN bit in TCP header for non-congestive loss
- Receiver forwards ELN bit back to sender
- When sender receives ELN, retransmits lost packet without invoking congestion control
- Slower than direct intervention of snoop agent (takes a RTT to do retransmit)
- Requires modification to wireless gateway and host's TCP

ELN performance

- TCP Reno vs TCP Reno + ELN

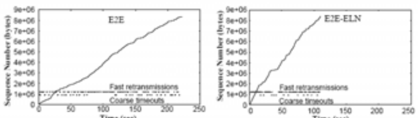


Figure 7. Packet sequence traces for E2E (TCP Reno) and E2E-ELN. The top row of horizontal dots shows the times when fast retransmissions occur; the bottom row shows the coarse timeouts.

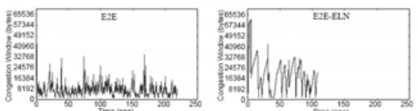


Figure 8. Congestion window size as a function of time for E2E (TCP Reno) and E2E-ELN. This figure clearly shows the utility of ELN in preventing rapid fluctuations, thereby maintaining a larger average congestion window size.

Testbed performance of TCP enhancements (Balakrishnan)

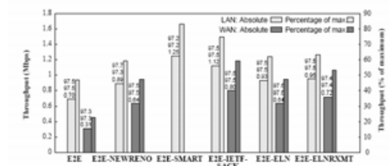


Figure 6. Performance of end-to-end protocols: bit error rate = 1.9×10^{-6} (1 error/65536 bytes).

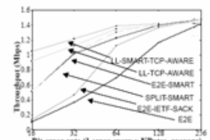


Figure 12. Performance of six protocols (LAN case) across a range of bit-error rates, ranging from 1 error every 16 KB to 1 every 256 KB shown on a log-scale.

Mobile nets

- Mobile wireless
  - Also satellite (LEO/MEO) nets
- Cellular nets
- Ad hoc nets

mobility

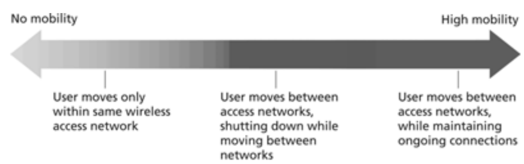


Figure 6.16 ♦ Various degrees of mobility, from the network layer's point of view © Kurose

Mobile IP

- Moving between base stations in same subnet, easy
- Moving into different subnets a bit tricky
  - Shutdown, reboot (nomadicity)
  - Or maintain active connections
    - IP address is part of UDP and TCP packets
    - Keep IP address the same!
- Whole lot of research on “mobile IP”
  - Issues at addressing and routing layers
  - Agent discovery and registration
  - Transparent, efficient, secure

© urose

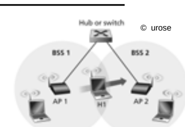


Figure 6.13 ♦ Mobility in the same subnet

Mobile IP functional entities

- **Mobile Node** (MN): a node which can change its point of attachment while maintaining any ongoing communications and using only its home (permanent) IP address.
- **Home Agent** (HA): a router with at least one interface on the MN’s home link which:
  - MN keeps informed of its current location, i.e., its care-of-address (COA),
  - intercepts packets destined to the MN’s home address and tunnels them to the MN’s current location
- **Foreign Agent** (FA): a router on a foreign link which:
  - assists the MN in informing its HA of its current COA,
  - sometimes, provides a COA and de-tunnels packets for the MN,
  - acts as the default router for packets generated by the MN while connected to this foreign link.
- Routing for the mobile node can be indirect or direct

Mobile routing

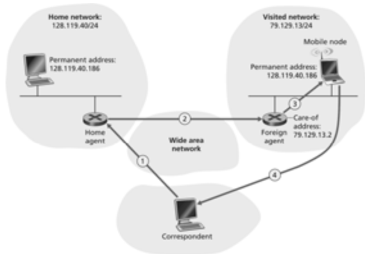


Figure 6.18 • Indirect forwarding to a mobile node © Kurose

Direct routing

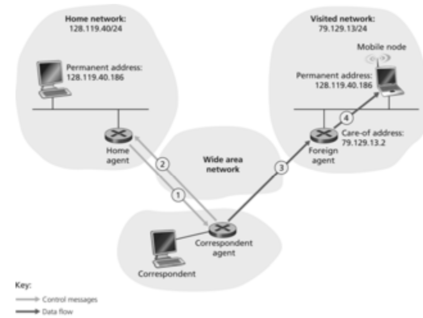
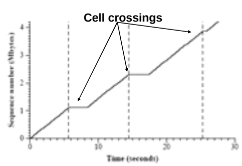


Figure 6.20 • Direct routing to a mobile user © Kurose

Cellular nets

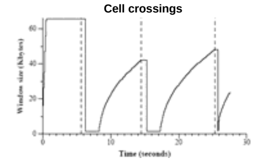
- 1G (first generation) – analog, voice only
- 2G – digital
  - IS-136, FDM/TDM (North America)
  - GSM, FDM/TDM (European)
  - IS-95, CDMA (code division multiplexing, Qualcomm) 9.6 to 14 kbs
- 2.5 G
  - GPRS (son of GSM), 9.6 kbs
  - EDGE, 384 kbs
  - CDMA2000 (son of IS-95), 144 kbs
- 3G
  - 144 kbs driving, 384 kbs stationary outside, 2 mbs indoors
  - UMTS (son of GSM), DS-WCDMA
  - CDMA-2000
- Frame error rates of 1% to 2%



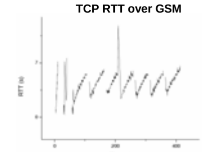
Mobile IP – transport issues

- Usual wireless problems
- motion effects
  - Blackouts (long pauses)
    - Burst losses
  - Packet loss and/or reordering
  - RTT variations (triangular routing)
- TCP tuning
  - Longer retransmit timeout (500 secs to hours?)
  - Network layer feedback to TCP to distinguish loss
    - Notification of link loss (ELFN) or "motion"
  - Aggressive recovery or TCPW

Cell crossings



TCP RTT over GSM

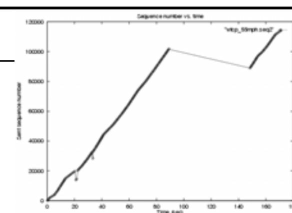


Wireless transmission control protocol

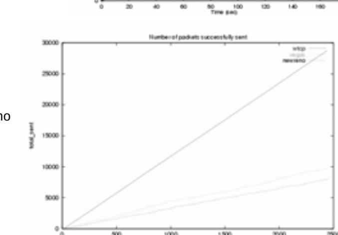
- Not a TCP variant, a new protocol for wide-area wireless nets (WTCP)
- Rate-based
- No transmission timers, uses SACK plus probes during blackouts
- Rate-based recovery and startup based on bandwidth estimation using packet pairs
- Uses interpacket separation to distinguish between congestive and random loss
  - Measured at receiver
  - e.g., receives packet 102 and 107, measures the interpacket arrival times
    - Compares to "expected" arrival rate
    - If arrival rate is bigger than expected, then assumes congestive loss (queuing delays caused longer time), sending rate cut in half
  - Rate adjustment info conveyed to sender in ACKs
- Testbed implementation and ns mods

WTCP performance

- Blackout period during a test of WTCP in Chicago at 55 mph
  - CPPD packet data net over cellular
  - 19.2 Kbs with FEC

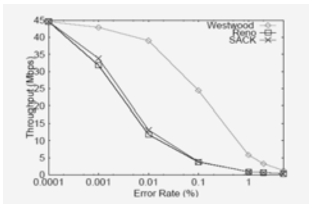


- ns simulation
  - 6% error, 50 Kbs
  - WTCP, vegas, newreno

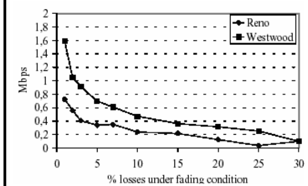


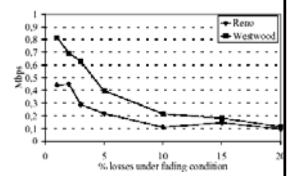
TCP Westwood (TCPW)

- sthresh set to recent fair share estimate
- If non-congestive loss, fast recovery
- Use it for mixed (fixed/wireless) flow
- use it on wireless segment (split)



TCPW and burst losses



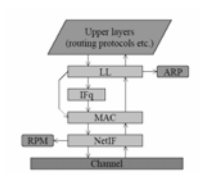


In Bad state packet loss is varied from 0 to 30%. TCPW throughput improvement in single connection is from 66 to 578%

For loss rate greater than 20% TCPW and Reno tend to the same throughput for multiple connections

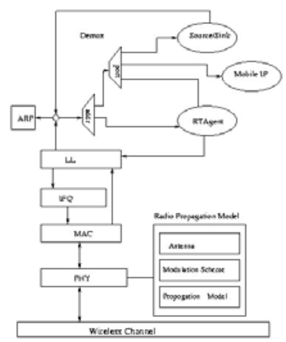
Wireless features of ns

- Mobile node (ad-hoc node)
- Air interface
- Radio propagation model
- Adhoc routing protocols
- Mobile IP



- Wireless model
  - Mobile nodes can move in a given topology
  - Nodes communicate over wireless channels
  - Wireless stack consists of link layer, ARP, MAC, IFQ, …
- Can simulate mobile IP, wireless nets, sensor nets

Structure of a wireless node in *ns*



Sample script for a wireless simulation

```
# Set up hierarchical routing.
# Specify topology.
# Create 'God'

# Create a Base Station
$ns_ node-config -adhocRouting DSR
                 -llType       LL
                 -macType      802.11
                 -ifqType      DropTail
                 -ifqLen       100
                 -antType      OmniAntenna
                 -propType     TwoRayGround
                 -phyType      WirelessPhy
                        -topoInstance $topo
                 -wiredRouting ON
                        -agentTrace   ON
                 -routerTrace  ON
                 -macTrace     ON
                        -movementTrace OFF
                        -channel $chan_
```

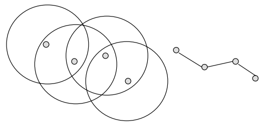

Sample script for a wireless simulation

```
set BS(0) [$ns_ node 1.0.0]
$BS(0) random-motion 0
$BS(0) set X_ 1.0
$BS(0) set Y_ 2.0

# create mobilenodes in the same domain as BS(0)
$ns_ node-config -wiredRouting OFF
set node_(0) [ $ns_ node 1.0.1]
$node_(0) base-station [AddrParams addr2id [$BS(0) node-addr]]

#create and attach Agents – TCP/UDP/CBR
  :
  :
#include movement..
$ns_at 10.0 "$node(0)  setdest 200.0 150.0 15.0
  :
  :
  :
```

Ad hoc nets

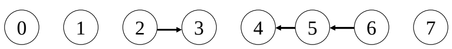


- Military scenarios
- Cooperating robots
- Discovery and self organization
- End nodes have to act as routers
- Nodes can be partitioned
- Transport implications:
  - Route failures may cause blackouts ➔ need longer retransmit timeout
  - Frequent rerouting causes packet loss, reordering, RTT variations
    - Need link layer notifications
    - Fast recovery or non-congestive models (TCPW)
  - For extended periods of partitioning may need connectionless protocols and a lot of application smarts

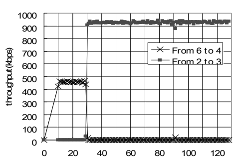
Ad hoc nets and TCP

- **802.11 Binary Exp Backoff (BEB) scheme: when multiple TCP connections share a common bottleneck, the interaction of 802.11 BEB and TCP causes unfairness**
- **Unfairness observed even with no mobility**
- **Unfairness can be extreme in certain ad hoc network scenarios: some TCP connections practically shut off while others achieve full throughput (ie, the latter capture the channel); aggregate throughput across connections remains constant**
- **Result: unfairness and capture lead to uneven, unpredictable performance of TCP flows – untenable in the battlefield and emergency recovery nets**

ns-2 example of TCP "capture" with 802.11

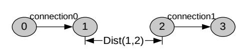


- String topology, each node can only reach its neighbors
- First TCP session starts at time =10.0s from 6 to 4
- Second TCP session starts at 30.0s from node 2 to 3
- At 30.0s, the throughput of first session drops to zero: session (2,3) has captured the channel!



What causes unfairness/capture?

- Hidden and exposed terminal problems (explained earlier)
- Large Interference range (usually larger than transmission range)
- Binary Exponential Backoff (BEB) of 802.11 tends to favor the last successful node
- TCP's timeout and backoff worsen the unfairness
- Lack of "cooperation" between TCP and MAC
- Simulation topology

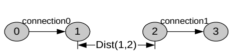


Trans. range = 376m
Dist(0,1) = Dist(2,3) = 300m

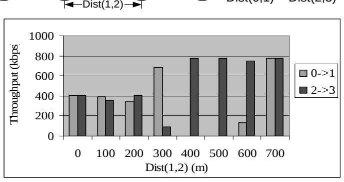
Hidden node: node 2 is hidden from node 0; but, it can interfere with the reception at node 1
Exposed node: node 1 is exposed to transmissions from 2 to 3; thus node 1 cannot transmit to node 0 while 2 transmits to 3

Experiement: vary the distance Dist (1,2). Thus, different pairs of nodes are hidden and/or exposed to each other in different runs

Unfairness in simple TCP test case



Trans. range = 376m
Dist(0,1) = Dist(2,3) = 300m

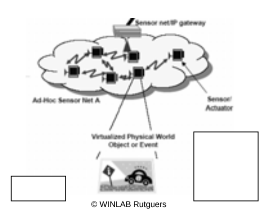


Throughput of FTP/TCP connections for variable Dist(1,2)
TCP Window = 1pkt

- **D < 300m; almost fair**
- **D = 300m; connection (0,1) dominates**
- **300 < D < 600, connection (2,3) dominates**
- **Solution (UCI): new backoff scheme, antennae**

Sensor nets

- Tiny devices for sensing environment, actuators for reacting
  - Habitat monitoring, burglar alarms, medical monitors, battlefield management
  - Highway sensors, automobile sensor actuators (traffic control)
- Constraints
  - Low power
  - Small memory
  - Intermittent connectivity
  - High loss rates (2% to 30%)
  - Ad hoc routing
- Network issues
  - Focus on link layer (RPL)
    - Hop-by-hop reliability (ARQ)
  - Usually custom transports
    - Gateway isolates sensors
    - Compression
    - TCP too heavy?



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Personal area nets (PAN)

- Bluetooth – wireless "cable"
  - Short range and low power
  - Ad hoc network
- IEEE 802.15
  - Frequency-hopping spread spectrum
  - ARQ, CRC, FEC
  - Piconet with a Master that controls who can send
  - 751 kbs in 625 us time slots
- Transport implications
  - Varying RTT
  - Non-congestive loss
  - adaptive MSS?
  - Usual noncongestive TCP tricks
    - Split, snoop, TCPW
  - Custom transports

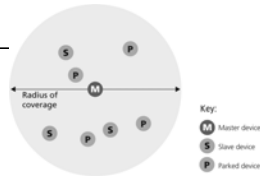
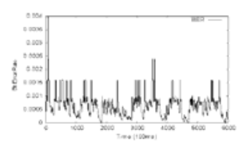
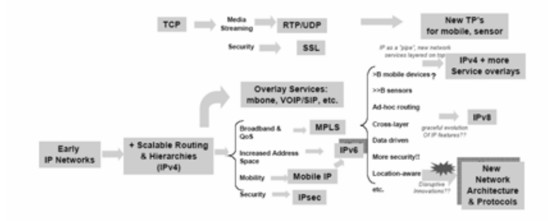


Figure 6.14 ♦ An 802.15 piconet © Kurose



Measured BER of bluetooth with nearby to 802.11 device causing interference

TCP/IP wireless future



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Next time …

- Kernel implementations