Tutorial Notes

C-K. Toh, Ph.D.
Director of Research, TRW USA

Ad Hoc Wireless Networking Course Notes

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Tutorial Notes

AD HOC WIRELESS MOBILE NETWORKING

Course Outline

First Half

- Introduction to Wireless Networks
- Fundamentals of Ad Hoc Wireless Networks
- Ad Hoc Network vs. Bluetooth vs. WAP
- Ad Hoc Media Access Methods
- TCP over Ad Hoc Networks

Second Half

- Service Discovery for Ad Hoc Networks
- Ad Hoc Routing Protocol Design & Implementation
- Ad Hoc Network Implementation (Success)
- Practical Ad Hoc Network Performance outdoors

Tutorial Notes

AD HOC WIRELESS MOBILE NETWORKING

Notice on Course Notes

Written in 2002, the author has decided to release this tutorial notes to the public – for teaching and research purposes only. It should not to be sold or republished elsewhere.

C-K. Toh, Ph.D.
Author of

1997: “Wireless ATM & Ad Hoc Networks”, Kluwer Academic Publishers, ISBN 0-7923-9822-X

2001 : “Ad Hoc Mobile Wireless Networks” Prentice Hall Publishers ISBN 0130078174, 2002

AD HOC WIRELESS MOBILE NETWORKING

Ad Hoc Networks - Intro

From Cellular,
WAP, Bluetooth to

AD HOC MOBILE NETWORKS

AD HOC WIRELESS MOBILE NETWORKING
INTRODUCTION

What is an Ad Hoc Wireless Network?

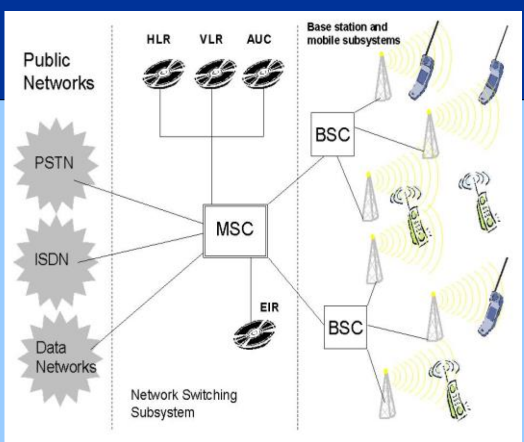
- The next Bluetooth????
- Supports *Anytime & Anywhere* Computing.
- Spontaneous formation & deformation of “all-wireless” networks.
- No wireless base stations required.
- Each mobile host acts as a router.
- Peer-to-peer communications.
- Peer-to-remote communications.
- “Ad Hoc” - can appear / disappear in different forms...

AD HOC WIRELESS MOBILE NETWORKING
INTRODUCTION

Cellular Infrastructured Networks - e.g. GSM

Characteristics

- **Wireless last-hop**
- **Fixed Backbone Network**
- **Radio Base Stations**
- **Wireless Access**
- **Mobility Support**
- **Location Management**
- **Access tied down to place and time**
- **WLANs, CDPD, GSM, etc.,**

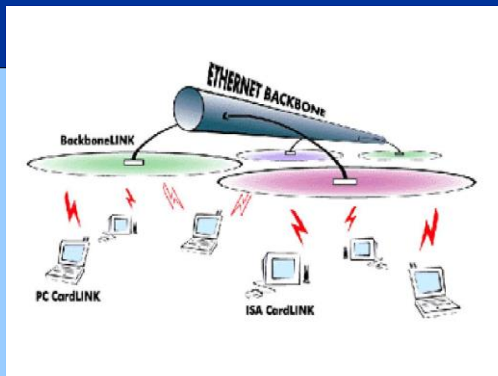


AD HOC WIRELESS MOBILE NETWORKING
INTRODUCTION

Cellular Infrastructured Networks - Wireless LANs

Technology Focus

- Wireless Air Interface (802.11, CSMA, etc)
- Wireless Transceiver Design
- Routing
- Connection Setup
- Client/Server
- Handoff Support (Mobile IP)
- Location Management
- Host Registration

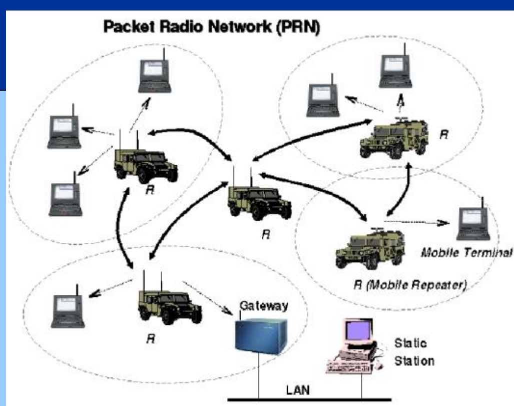


AD HOC WIRELESS MOBILE NETWORKING
INTRODUCTION

The Early Packet Radio Networks

Characteristics

- Presence of mobile repeaters
- Mobile terminals affiliated with repeaters
- Static Station for Routing
- Built in 1970s
- Built for DARPA
- Technology ahead of time
- Not entirely infrastructureless
- Source PR talks to affiliated repeater
- Repeaters exchange info about existence of PRs



AD HOC WIRELESS MOBILE NETWORKING

INTRODUCTION

Routing in Packet Radio Networks

Characteristics

- PRNET features fully distributed network management
- Each PR gathers and maintains network topology
- Each PR can make independent decision on how to route data through network to any destination
- Stored network information include:

  - neighbor table
  - tier table
  - device table

AD HOC WIRELESS MOBILE NETWORKING

INTRODUCTION

Routing in Packet Radio Networks

Characteristics

- For neighboring table, a Packet Radio Organization Packet (PROP) is broadcast every 7.5s, announcing its presence and info about the network topology from its perspective

- For tier table, tier information ripples outward from each packet radio at an average rate of 3.75s

- Goal of table is to maintain “best info” about how to get to dest PR

- Best route = shortest route with good connectivity at each hop

- Ultimately, all PR know all devices and to which PR they are attached.

AD HOC WIRELESS MOBILE NETWORKING
INTRODUCTION

Routing in Packet Radio Networks

Neighboring Table

Neighboring PRs	Link Quality

Tier Table

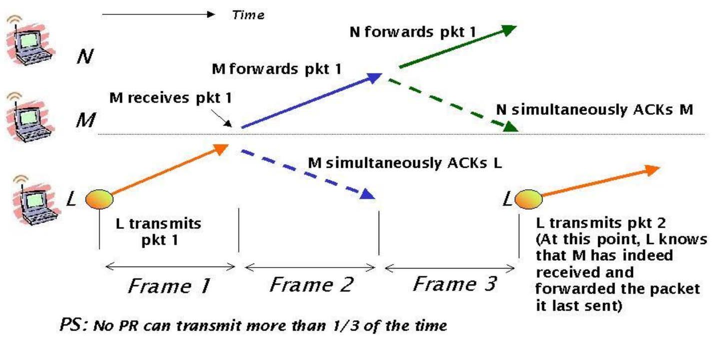
Dest PR	Next PR	Tier

Routing Header Field

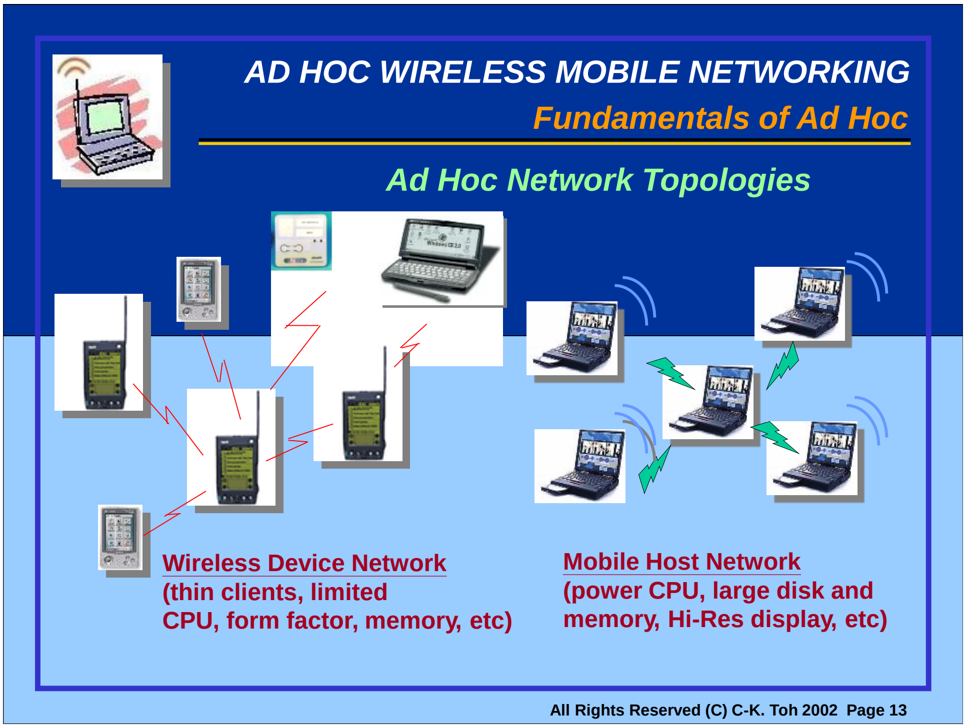
Source PR ID
Previous PR ID
Next PR ID
Destination PR ID

AD HOC WIRELESS MOBILE NETWORKING
INTRODUCTION

3-Frame Packet Forwarding in PRNETs



PS: No PR can transmit more than 1/3 of the time


AD HOC WIRELESS MOBILE NETWORKING
Fundamentals of Ad Hoc
Ad Hoc Network Topologies
Wireless Device Network
(thin clients, limited
CPU, form factor, memory, etc)
Mobile Host Network
(power CPU, large disk and
memory, Hi-Res display, etc)
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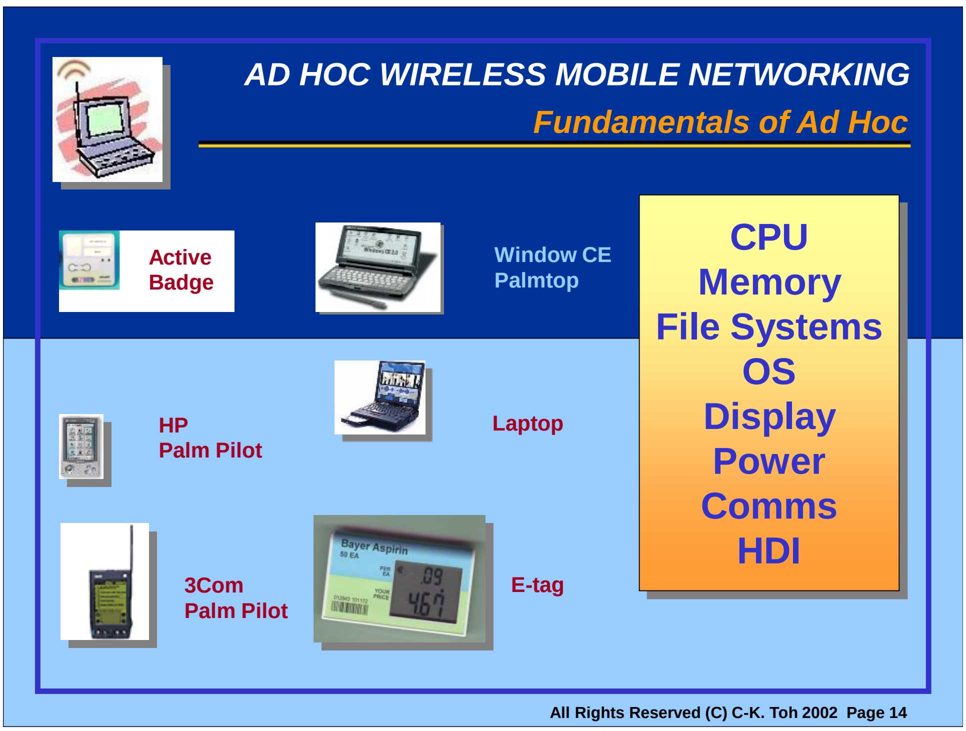
AD HOC WIRELESS MOBILE NETWORKING
Fundamentals of Ad Hoc
Active
Badge
Window CE
Palmtop
HP
Palm Pilot
Laptop
3Com
Palm Pilot
E-tag
CPU
Memory
File Systems
OS
Display
Power
Comms
HDI
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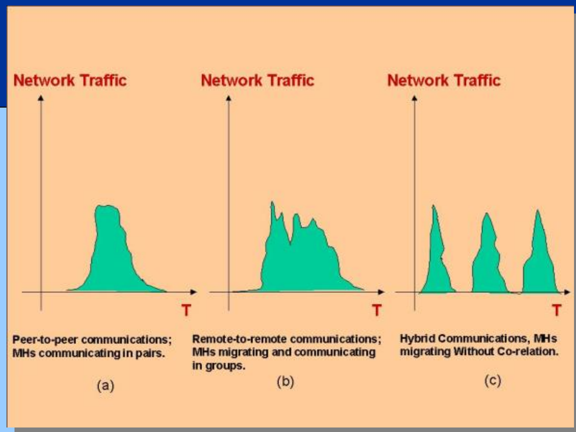
Traffic Characteristics of Ad Hoc Networks

Source and Group Dependent

- Bursty or Constant bit rate
- Peer-to-peer (pairs)
- Peer-to-Remote (group)



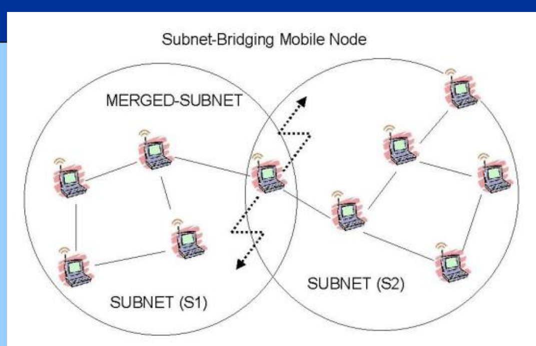
AD HOC WIRELESS MOBILE NETWORKING

Fundamentals of Ad Hoc

Different Mobility Patterns

Co-related or not?

- Mobile user decides where to move
- Presence of Local mobility
- Presence of Group mobility
- Presence of Unpredictability
- Local area mobility
- Wide area mobility



AD HOC WIRELESS MOBILE NETWORKING

Fundamentals of Ad Hoc

Ad Hoc Network Applications

- Traditional applications: Telnet, FTP, WWW, Ping, etc.
- Client/Server applications.
- Collaborative computing (Mobile CSCW)
- Bluetooth applications
- Context/location-aware applications
- Mobile multimedia
- Battlefield Scenarios
- Etc.

AD HOC WIRELESS MOBILE NETWORKING

Fundamentals of Ad Hoc

Challenges in Ad Hoc Mobile Networks

- Host is no longer just an end system

- Also acting as an intermediate system
- Changing network topology over time
- Every node can be mobile
- Limited Power Capacity
- Limited Wireless Bandwidth
- Presence of Varying Channel Quality

AD HOC WIRELESS MOBILE NETWORKING

Fundamentals of Ad Hoc

Challenges in Ad Hoc Mobile Networks

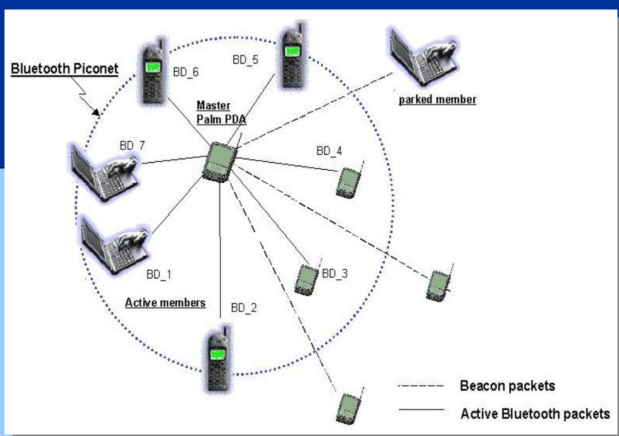
- No centralized entity
- How to support routing?
- How to support channel access?
- How to deal with mobility?
- How to conserve power?
- How to use bandwidth efficiently?
- How do we support addressing??

AD HOC WIRELESS MOBILE NETWORKING

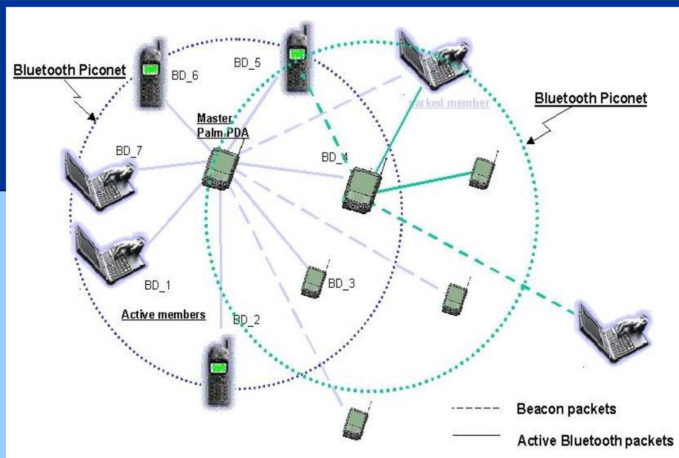
Ad Hoc vs. Bluetooth vs. WAP

Key Features

- Frequency hop spread spectrum (FH/TDD Channel)
- 1 Mbps
- 10m radio cell
- Master and slave behavior
- Synchronous and asynchronous service
- Device communications and networking



AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc vs. Bluetooth vs. WAP



Scatternet

- **Communication beyond a piconet; Multiple Masters**

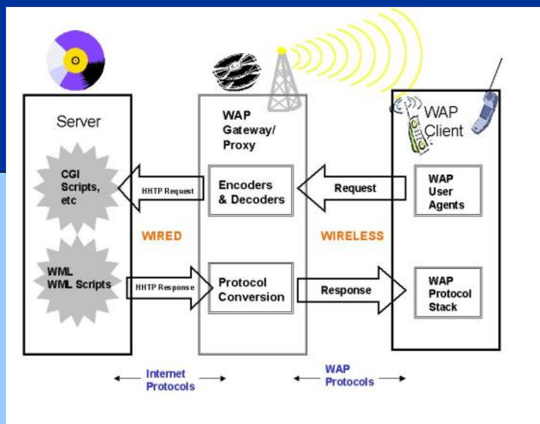
AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc vs. Bluetooth vs. WAP

Bluetooth Scatternet

- **Communications beyond a piconet**

- **A *master* of a piconet can act as a *slave* of another master in another piconet**
- **A device cannot serve as a master for both piconets!**
- **A device within the locality of 2 piconets will have to perform time sharing, I.e., it will spend a few slots on 1 piconet and a few slots on the other.**
- **No deeper clustering other than piconets and scatternets in BT!!!**

AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc vs. Bluetooth vs. WAP



WAP Key Features

- Wireless multimedia messaging
- Internet based news/services
- Server, WAP client, WAP Proxy
- Device to network, not really device-to-device
- WML (Wireless Markup Language) used instead of HTML
- WML optimized for wireless

AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc vs. Bluetooth vs. WAP

Cellular	WAP	Bluetooth	Ad Hoc
Mobile Telephony Last-Hop/ One-Hop Access	Mobile Internet Mobile E-Commerce Last/1-Hop	Mobile Internet, E-Commerce, audio Scatternet	Mobile Internet, E-Commerce, Audio, video Beyond Scatternet

Time →

AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols

Layer 2

Media Access over
AD HOC MOBILE NETWORKS

AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols – Layer 2

An ad hoc route comprises multihop wireless links and hence hop-by-hop wireless Relay & access!!!

General Concepts

CSMA protocols suffer from hidden terminal problem in multi-hop wireless ad hoc networks

- Control Handshakes before transmission have been proposed to overcome the problem.
- Several variations have been developed based on the above concept.
- Protocols can be characterized as Sender- or Receiver-Initiated.

AD HOC WIRELESS MOBILE NETWORKING

Ad Hoc MAC Protocols

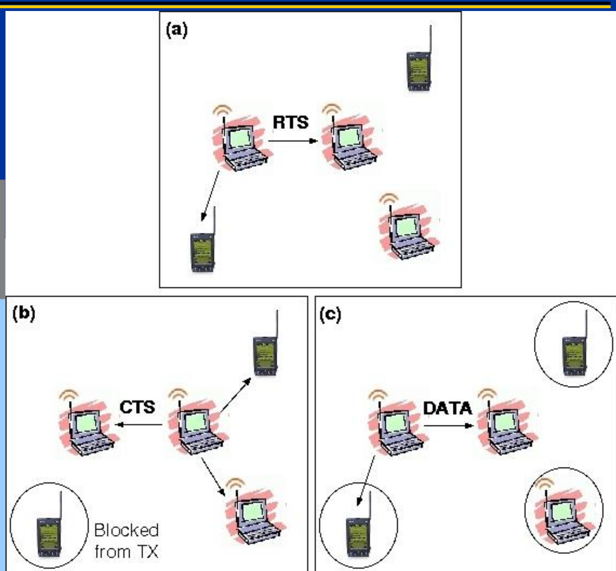
Sender-Initiated MAC Protocols

1. MACA (Multiple Access Collision Avoidance) uses dialog (RTS/CTS) to solve hidden terminal problem
2. MACAW (MACA with ACK) uses more handshaking to avoid packet collision and provides faster recovery.
3. FAMA (Floor Acquisition Multiple Access) adds carrier sensing capability to reduce possibility of collisions.

Ad Hoc MAC Protocols

RTS-CTS-DATA Handshake in MACA

(Multiple Access with Collision Avoidance)



Receiver Initiated MAC

Reduced number of control packets

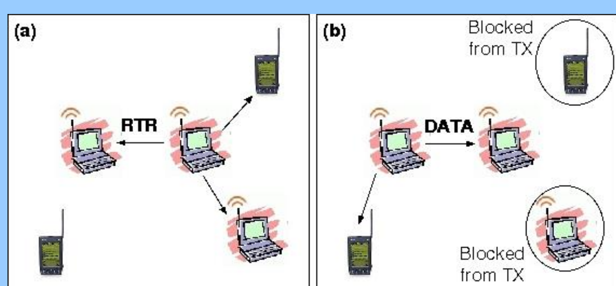
Only one packet, sent by receiver, is required in each handshake.

MACA-BI (MACA By Invitation) assumes that a MH can predict the packet arrival time of its neighbors.

RIMA (Receiver Initiated Multiple Access) requires a new packet arrival prediction method.

RTR-DATA Handshake in MACA-BI

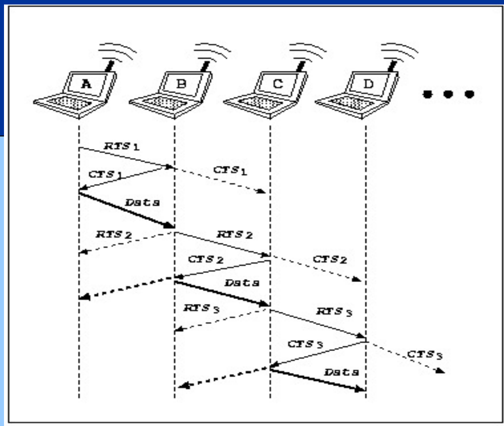
(Multiple Access with Collision Avoidance By Invitation)



AD HOC WIRELESS MOBILE NETWORKING

Ad Hoc MAC Protocols

The bottleneck of RTS/CTS Handshake in Ad Hoc Route Path

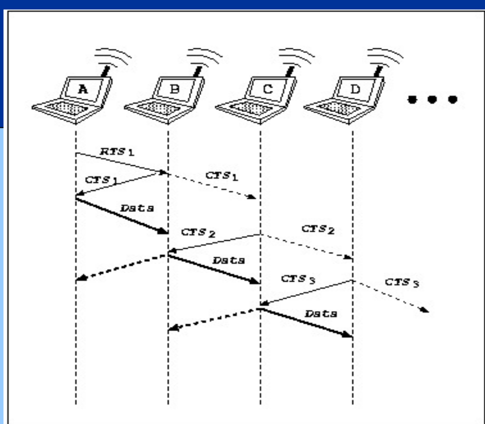


- Each data transmission per hop requires a RTS/ CTS handshake !!
- Overhead grows with number of hops in an ad hoc route
- Limit data throughput performance!!

AD HOC WIRELESS MOBILE NETWORKING

Ad Hoc MAC Protocols

New MARCH Protocol:
Media **A**ccess Control with **R**edu**C**ed **H**andshake

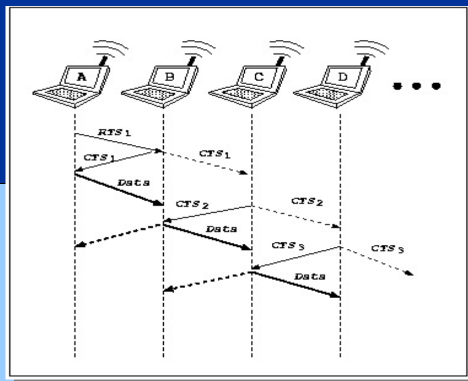


- Only first hop uses RTS-CTS handshake.
- After first hop handshaking, reduces to CTS-only.
- Node C can send CTS2 when available.
- Wait time (Tw) ≅ data transmission time

AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols

Features of MARCH Protocol:

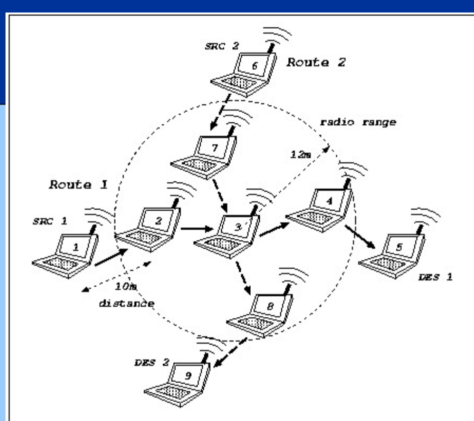
Media **A**ccess Control with **R**edu**C**ed **H**andshake



- Reduces control overhead
- Uses modified RTS/CTS
- Utilizes carrier sensing
- Does not depend on traffic prediction.
- Exploits the broadcast characteristics of omni- directional antennas.
- Can differentiate between routes

AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols

- **Simulation environment**
  - OPNET tool
  - MARCH and MACA



  - 2 overlapping routes.
  - 1 Mbps Channel
  - Lossless channel
  - Radio range 12m
  - Node Distance 10m
  - Nodes hear only first neighbor(s)
  - Control packets: 128 bits
  - Data Packets: 2048 bits
  - Tw = 2ms

AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols

Simulation details

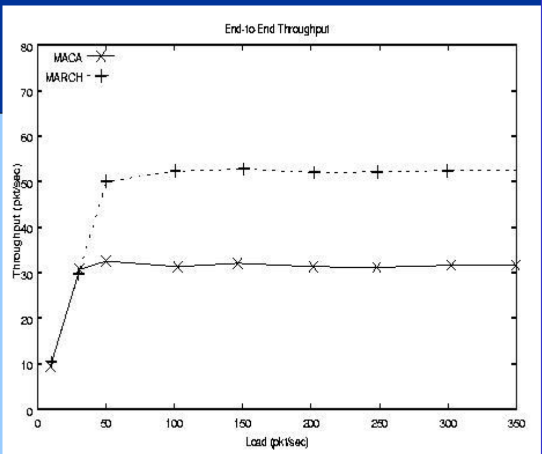
- Pre- Established two routes
- Each route is 4 hops long
- Intersecting at middle node (Node 3)
- Nodes 1 and 6 are the sources of routes 1 & 2 respectively
- Nodes 5 and 9 are the destinations of routes 1 & 2 respectively
- Data packets are generated according to a Poisson process with rates varying from 10pkts/sec to 350 pkts/sec

Parameters of Interest

- End-to-End Throughput
- Control Overhead per link per data packet
- End-to-End Delay

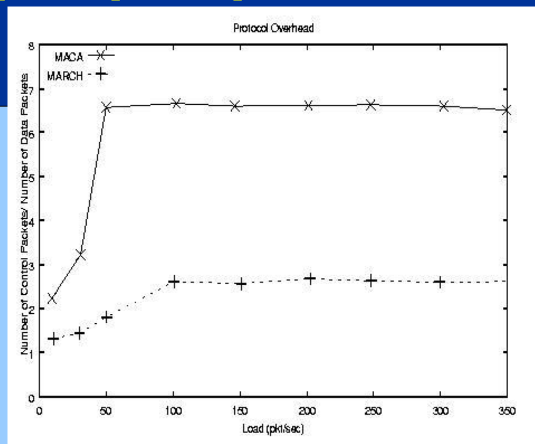
AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols

- End-to-End Throughput
  - More than 60% improvement over MACA
  - Reduced collisions due to less control messages.
  - Less collisions over (bottleneck) crossing node



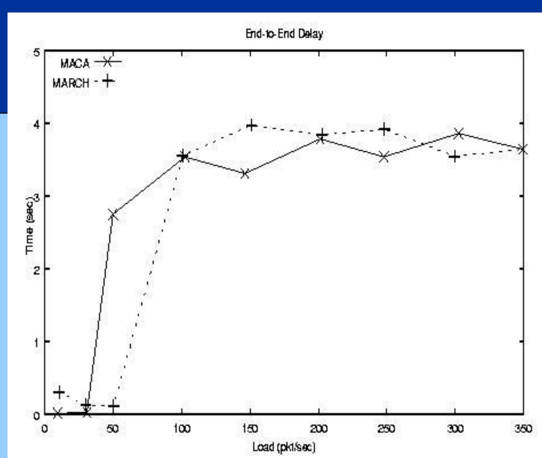
AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols

- **Control Overhead per link per data packet**
  - Initial:
    - MACA = 2
    - MARCH = 1.25
  - After 100pkts/sec load:
    - MACA = 7
    - MARCH = 3
  - MARCH reaches saturation at 100pkts/sec
  - MARCH has less overhead



AD HOC WIRELESS MOBILE NETWORKING
Ad Hoc MAC Protocols

- **End to End Delay**
  - MACA affected by collisions at 50pkts/sec, MARCH at 100pkts/sec
  - Same average delay after that.
  - MARCH delay can be improved by Tw

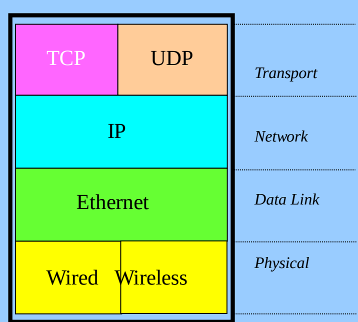


Layer 4

TCP over AD HOC MOBILE NETWORKS

Functions of TCP

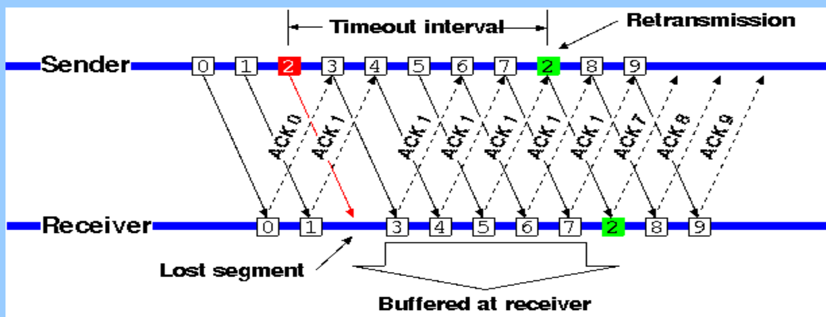
- TCP: Transmission Control Protocol
- Reliable End-to-End communications
- Ensure packets delivered in-order
- Provides ***Flow control***
- Provides ***Congestion control***
- Widely used in TELNET, FTP,...



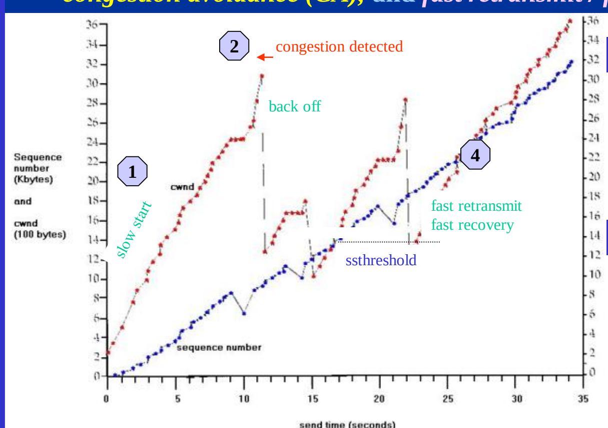
TCP Flow Control Example

- TCP relies on ***sequence numbers*** to keep track of flow of frames
- TCP sender expects an ACK to confirm receipt
- **Retransmit** if a frame is lost or in error

Selective Repeat Mechanism



- TCP congestion control mechanism consists of *slow start (SS), congestion avoidance (CA),* and *fast retransmit / fast recovery*.



Fast Retransmit

- 3 or more duplicated ACKs imples missing segment
- Retx missing segment before timeout

Fast Recovery

- After fast retransmit sender performs congestion avoidance, but not slow start.

Variants of TCP

- TCP [1983]: First release - 4.2 BSD (Go-Back-N)
- TCP Tahoe [1988]: 4.3BSD Tahoe
  - Slow start; Congestion avoidance
- TCP Reno [1990]: 4.3BSD Reno
  - Plus Fast retransmit; Plus Fast recovery
- TCP Vegas [1994 (SIGCOMM94)]
  - An improvement of TCP Reno
  - Uses expected and actual bandwidth to change window
  - >33% throughput improvement than Reno
- TCP SACK [1988, 1996]: RFC1072, RFC2018
  - Selective Acknowledgment
  - An improvement of TCP Reno
  - Receiver can inform SRC of missing segment blocks using SACK fields on the ACK message.

AD HOC WIRELESS MOBILE NETWORKING
TCP over AD HOC

Problems with TCP in Ad Hoc Networks

- TCP originally designed for wired networks with <1% packet errors (Losses due to congestion).
- Ad hoc wireless networks have multi-hop wireless links.
- Communication can break when any node moves.
- This (*route failure*) can affect TCP performance.
- Congestion exists in ad hoc too.
- TCP cannot distinguish between *route failure due to mobility* and route failure due to *network congestion*.
- Erroneous flow and congestion control reduces TCP throughput over ad-hoc!!!

AD HOC WIRELESS MOBILE NETWORKING

TCP over AD HOC

- **FLOW CONTROL:**
  - What if ACK frame was lost?
  - What if ACK frame was delayed for too long?
- **CONGESTION CONTROL:**
  - When should we conclude there is a congestion?
  - TCP has no mechanisms to deal with route failures..
- **=> We need to enhance TCP for ad hoc!!**

AD HOC WIRELESS MOBILE NETWORKING

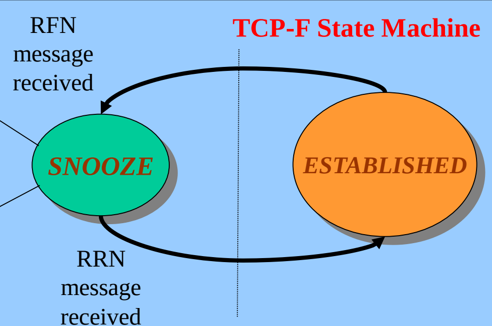
TCP over AD HOC

TCP-F INTRODUCES:

TCP-F

- **TCP *SNOOZE* state:** to avoid time-out
- **Route Failure Notification (RFN):** inform sender of route failure happenning.
- **Route Re-establishment Notification (RRN):** inform sender of successful route reconfiguration.

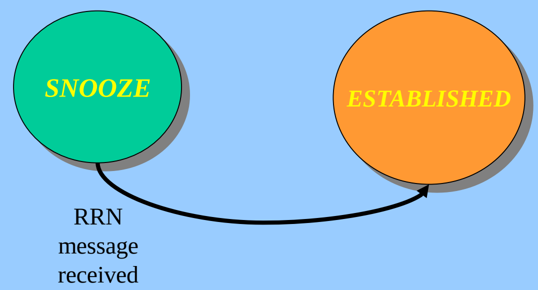
- **Freezes:**
  - all its timers
  - *cwnd* size, ssthreshold, RTT estimate
- **stops further transmission**



AD HOC WIRELESS MOBILE NETWORKING
TCP over AD HOC

- When RRN is received, transmission is resumed.
- All timer and state variable values are restored.

TCP-F State Machine



AD HOC WIRELESS MOBILE NETWORKING
TCP over AD HOC

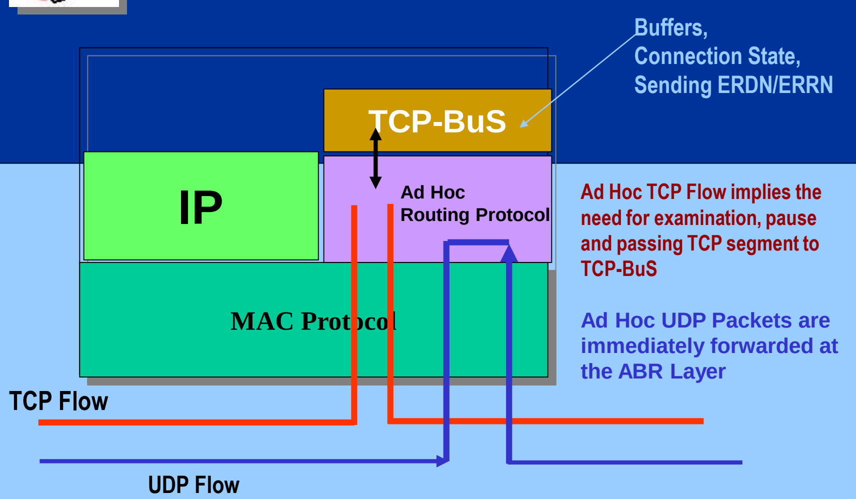
PROBLEMS:

- By resuming from SNOOZE state, retransmission timer is likely to expire.
- Result in retransmission and slow start.
- Also, what if RFN or RRN is lost?

TCP-BuS - Improvement over TCP-F

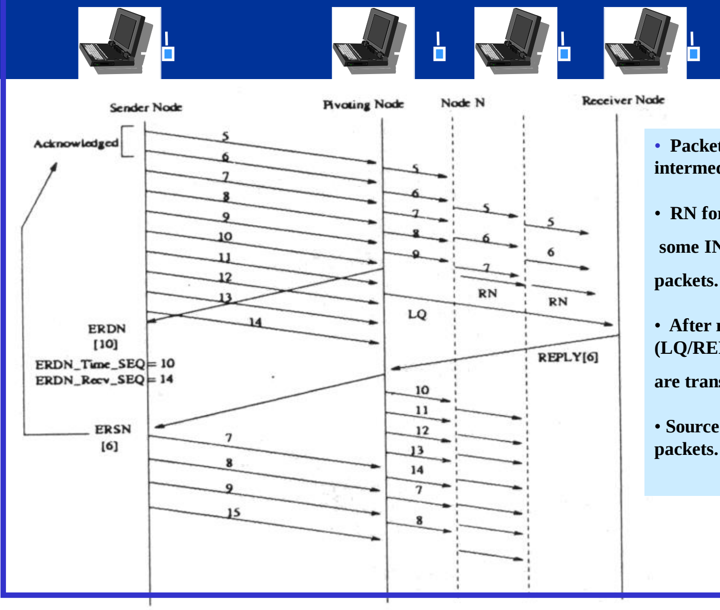
1. Explicit Notification
2. Reliable Transmission of Control Messages
3. Buffering
4. Extension of Timeout Values
5. Selective Fast Retransmission

AD HOC WIRELESS MOBILE NETWORKING
TCP over AD HOC



AD HOC WIRELESS MOBILE NETWORKING

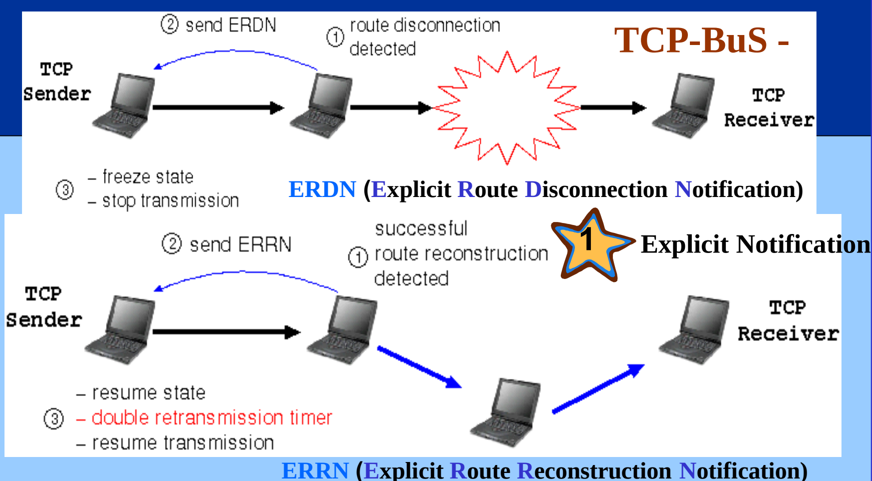
How TCP-BuS Works



- Packets are buffered at intermediate nodes (IN)
- RN for route notify forces some INs to flush buffered packets.
- After route reconstruction (LQ/REPLY) buffered packets are transmitted from IN
- Source only re-sends lost packets.

AD HOC WIRELESS MOBILE NETWORKING

TCP over AD HOC

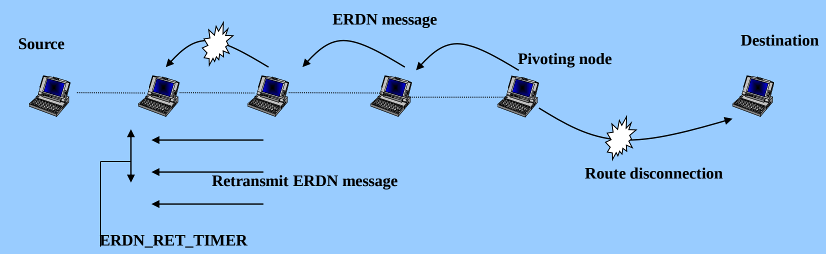


AD HOC WIRELESS MOBILE NETWORKING

TCP over AD HOC

• IN doesn't hear upstream ERDN message and retransmits during ERDN_RET_TIMER.

(a) ERDN loss



2 Reliable Retransmission of Control Messages

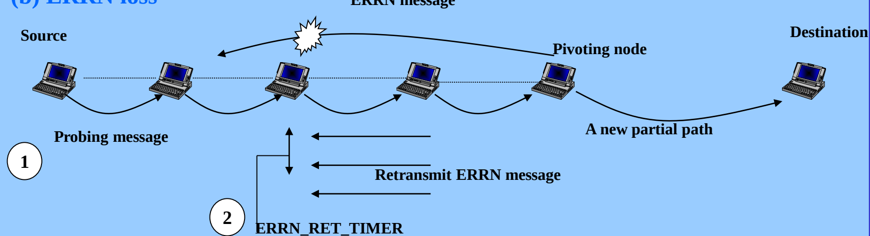
AD HOC WIRELESS MOBILE NETWORKING

TCP over AD HOC

1 - Source Probe: After receiving ERDN, Source sends Probe Msg. to check for successful route reconstruction.

2 - ERRN Retransmission: If after ERRN_RET_Timer there are no data coming from Source, ERRN is retransmitted.

(b) ERRN loss

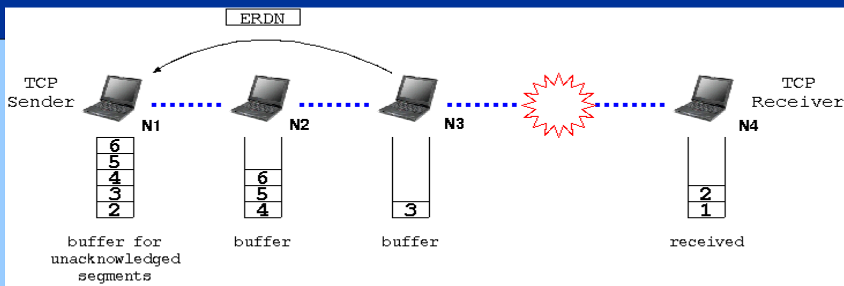


2 Reliable Retransmission of Control Messages

AD HOC WIRELESS MOBILE NETWORKING

TCP over AD HOC

Buffering of TCP Segments

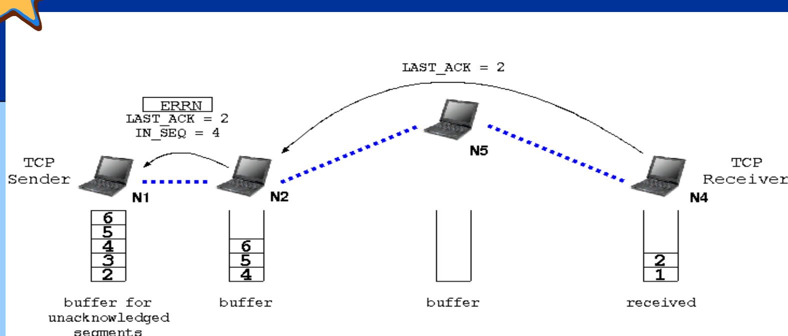


- ERDN is sent to TCP sender when route failure is detected.
- TCP sender stops transmission and freezes internal states.

AD HOC WIRELESS MOBILE NETWORKING

TCP over AD HOC

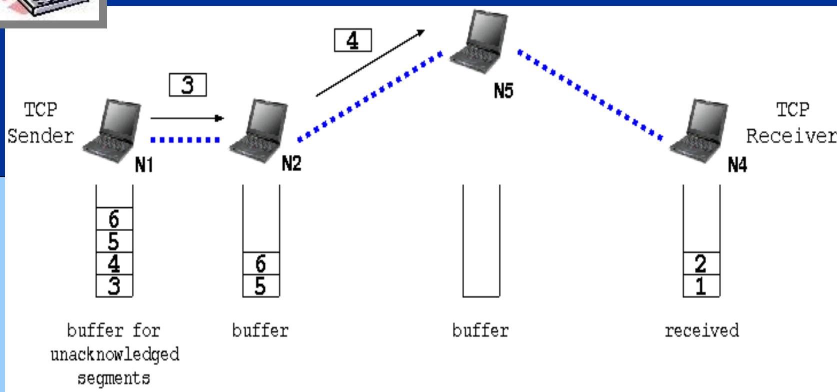
Buffering Example (RRC completed)



- When RRC is completed, TCP sender receives ERRN with buffer status at TCP receiver and IN.

AD HOC WIRELESS MOBILE NETWORKING

TCP over AD HOC



- TCP sender resumes transmission according to the received feedback.
- INs resume transmission from their buffers.

BreakTime!

AD HOC WIRELESS MOBILE NETWORKING

Service Discovery over AD HOC

Layer 5

SERVICE DISCOVERY FOR AD HOC MOBILE NETWORKS

AD HOC WIRELESS MOBILE NETWORKING

Service Discovery over AD HOC

Service discovery in the Internet - Service Location Protocol (RFC 2165)

User Agent - responsible for interrogating service availability. Acts as an agent to search for requested services

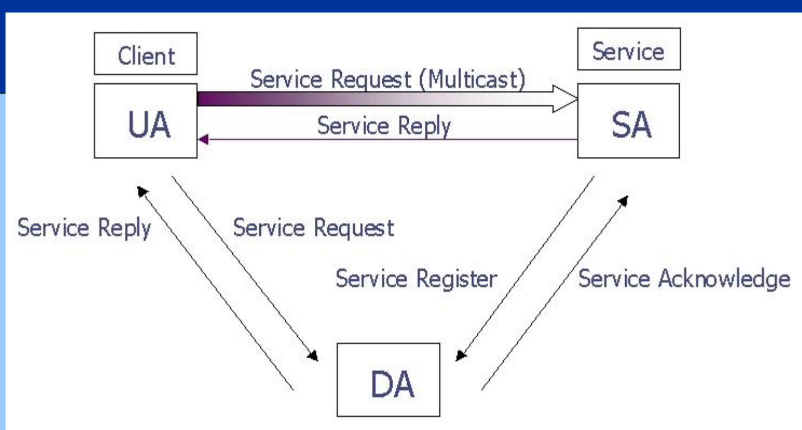
Directory Agent - consolidates all service replies and caches them into a directory. Acts as proxy and reply back to UA.

Service Agent - Advertises available services to UA/DA.

AD HOC WIRELESS MOBILE NETWORKING

Service Discovery over AD HOC

Principle of Service Location Protocol (SLP)



AD HOC WIRELESS MOBILE NETWORKING
Service Discovery over AD HOC

Limitations of Existing SLP Schemes

Presence of mobility of nodes (UA, SA, DA, intermediate nodes in the route)

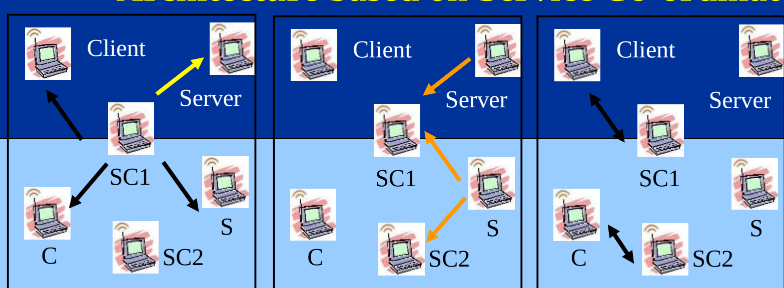
Latency and Packet Loss Issues

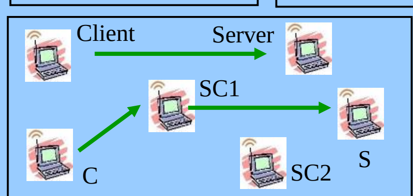
Device Heterogenity

Power Constraints

AD HOC WIRELESS MOBILE NETWORKING
Service Discovery over AD HOC

Architecture based on Service Co-ordinators

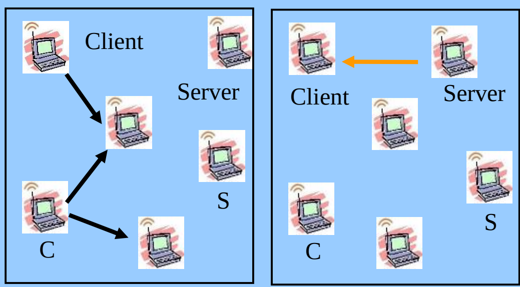




1. SCs advertise themselves
2. Servers register with SCs
3. Clients query SC according to their chosen SC
4. Clients access specific server for services

AD HOC WIRELESS MOBILE NETWORKING
Service Discovery over AD HOC

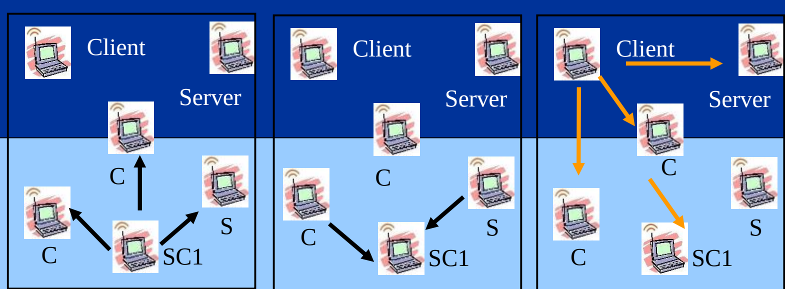
Architecture based on Distributed Query

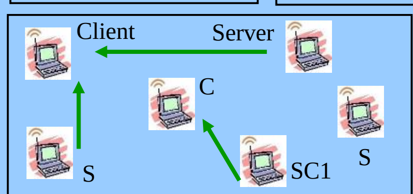


1. **Client broadcast their service queries to neighbors**
2. **An available server responds to the corresponding client**

AD HOC WIRELESS MOBILE NETWORKING
Service Discovery over AD HOC

Architecture based on Hybrid Service Location





1. SCs advertise themselves
2. Servers register with SC
3. Clients query SC or broadcast service query to network
4. SCs or servers respond with service information

Comparisons: SCs or no SCs ?
- parameter: service availability

1. SCs helps queries to scale
2. But how to position and select SCs???
3. Service definition in ad hoc sense. What is it ???
4. Hybrid approach is best, see paper:

Further Reference: Guillermo Guichal, and C-K. Toh - "Service Location Architectures for Mobile Ad Hoc Wireless Networks", Proceedings of IEEE Personal Indoor and Mobile Radio Conference (IEEE PIMRC), San Diego, 2001

Layer 3

ROUTING PROTOCOLS FOR AD HOC MOBILE NETWORKS & WIRELESS AD HOC NETWORK IMPLEMENTATION

- *Inclusion of a video show of ad hoc networking in real action .....*

AD HOC WIRELESS MOBILE NETWORKING
AD HOC Routing Protocol

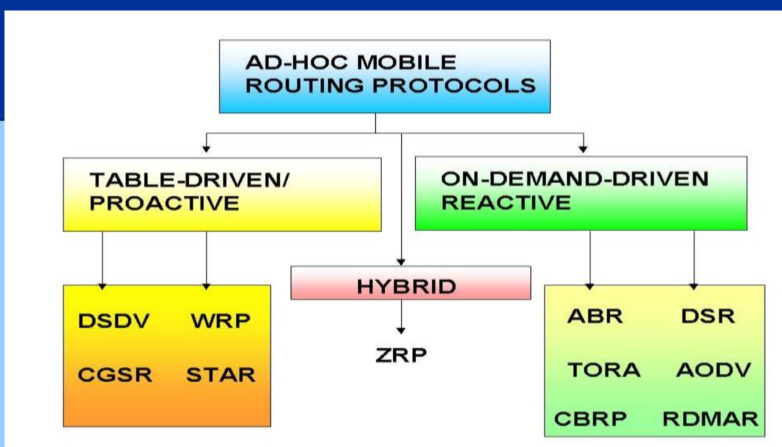
OUTCOME OF USING EXISTING INTERNET ROUTING PROTOCOLS

OSPF (Open Shortest Path First)
- Slow convergence
- Route inconsistency
- Little throughput
- High usage of power
- Periodic broadcast

RIP (Routing Internet Protocol)
- Slow convergence
- Little throughput
- High usage of power
- Periodic broadcast
- Signs of instability

AD HOC WIRELESS MOBILE NETWORKING
AD HOC Routing Protocol

OVERVIEW OF CURRENT APPROACHES



History of Ad Hoc Routing Research

Pioneers:

Toh, Perkins, Johnson

Other followers later on…

Toh uses a new routing metric known as association stability, and successfully implemented a Wi-Fi ad hoc network in 1998.

Johnson extends source routing for ad hoc

Perkins extends distance vector routing for ad hoc

Misconception: Getting a protocol accepted by IETF does not imply that the protocol is the best. Very often, it is chosen due to "other" reasons.

OVERVIEW OF CURRENT APPROACHES

Table-Driven Approach

- Use of periodic route updates
- Can be link-state based
- Can be distance vector based
- Mobility is treated as link changes

On-Demand Driven Approach

- Route discovered upon request by source
- No periodic route updates
- Caching may be used
- Power efficient
- Bandwidth efficient

Time and Event Driven Updates

AD HOC WIRELESS MOBILE NETWORKING
AD HOC Routing Protocol

OVERVIEW OF CURRENT APPROACHES

Pro-active Approach

- Will always react or do something
- Reaction in addition to those for link changes
- Not efficient if little mobility
- Periodic route updates

Reactive Approach

- React specifically to link changes
- React to need by the source
- No periodic route update
- Similar to on-demand protocols

AD HOC MOBILE NETWORKING
AD HOC Routing Protocol

ABR: ASSOCIATIVITY-BASED ROUTING
US PATENT: 5,987,011

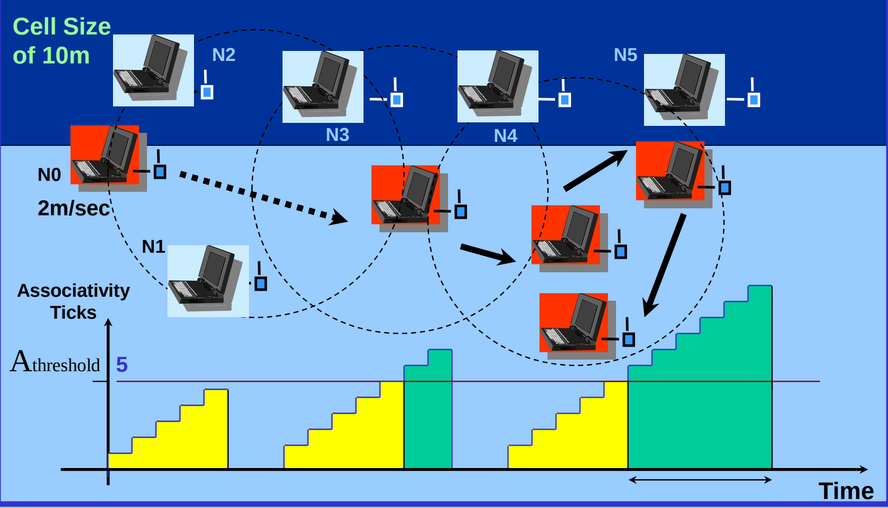
History

- Cambridge University
- Inventor: C-K. Toh
- Dated: 1993
- Patented 1996
- Implemented 1998
- Simulation Performed 1996
- Field Trials 1997,98,99

Key Features

- Concept of Associativity
- New Routing Metrics
  + Longevity of a route
  + Route Relaying Load
  + Link Capacity
- Source-initiated
- No periodic route updates

AD HOC MOBILE NETWORKING
AD HOC Routing Protocol



AD HOC MOBILE NETWORKING
AD HOC Routing Protocol

Fundamentals of Associativity

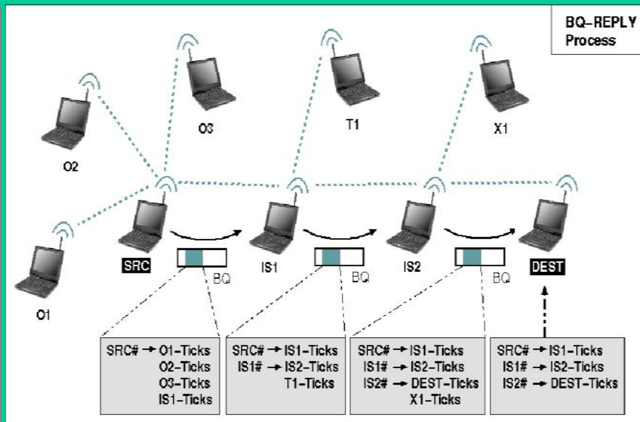
- No point choosing a shortest-hop route if route is going to be invalidated due to nodes mobility

- Each node learns its "association" with surrounding nodes
- **Association can be in terms of: (a) signal strength, (b) power life, (c) period of presence, (d) spatial and temporal characteristics**
- Chose a route that comprises nodes that exhibit high degree of association stability, i.e. "similar to **finding security in an unsecured world**....."

AD HOC MOBILE NETWORKING
AD HOC Routing Protocol

Route Discovery

- Source initiates route search
- Search packet captures stability and route path info
- Destination node selects the most stable route (heuristic here!)



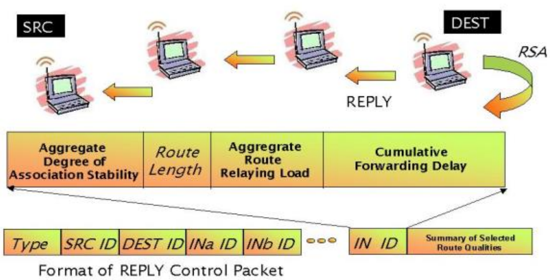
Key: Only discover routes when you need it. Else do nothing.

AD HOC MOBILE NETWORKING
AD HOC Routing Protocol

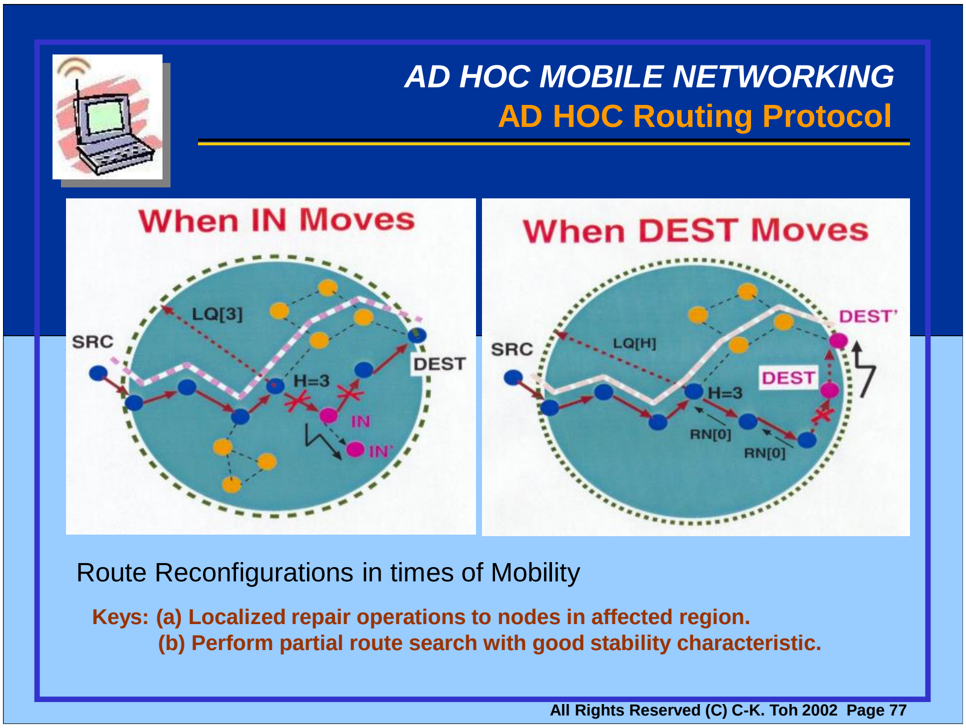
KEY CONCEPTS IN ABR ROUTING

Route Discovery

- Destination sends a REPLY
- "program" nodes in selected route as forwarding nodes
- Source finally informed & can start sending data



Key: Only selected nodes perform data packet relaying.


AD HOC MOBILE NETWORKING
AD HOC Routing Protocol
When IN Moves
SRC
LQ[3]
H=3
DEST
IN
IN'
When DEST Moves
SRC
LQ[H]
H=3
DEST'
DEST
RN[0]
RN[0]
Route Reconfigurations in times of Mobility
Keys: (a) Localized repair operations to nodes in affected region.
(b) Perform partial route search with good stability characteristic.
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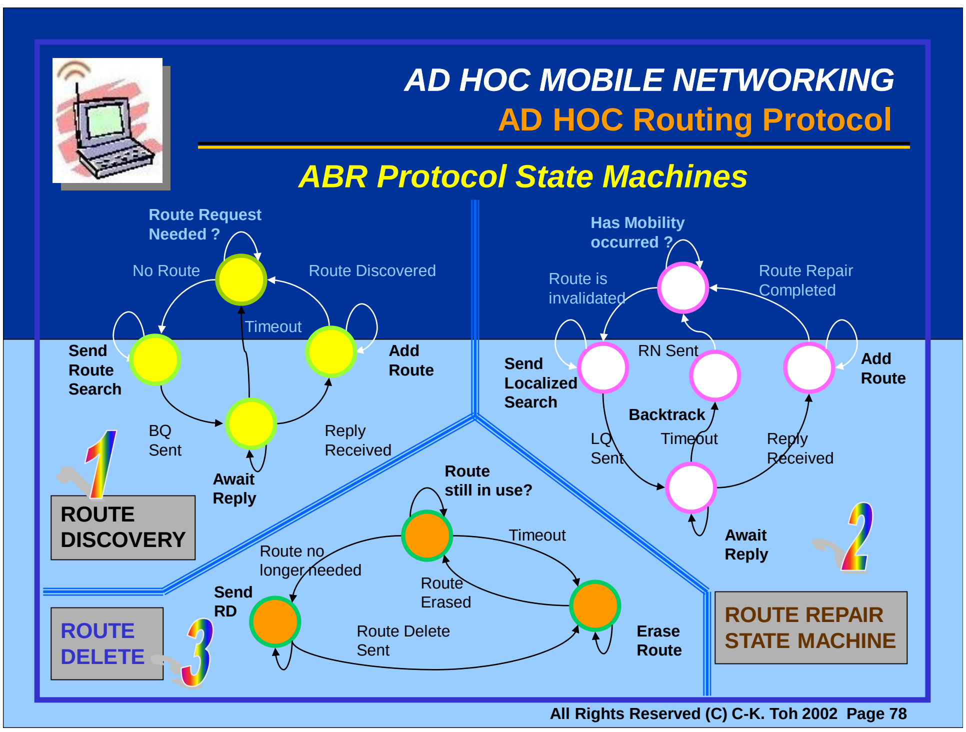
AD HOC MOBILE NETWORKING
AD HOC Routing Protocol
ABR Protocol State Machines
Route Request Needed ?
No Route
Route Discovered
Timeout
Send Route Search
Add Route
BQ Sent
Reply Received
Await Reply
1
ROUTE DISCOVERY
Has Mobility occurred ?
Route is invalidated
Route Repair Completed
RN Sent
Send Localized Search
Add Route
Backtrack
LQ Sent
Timeout
Reply Received
Await Reply
2
ROUTE REPAIR STATE MACHINE
Route still in use?
Timeout
Route no longer needed
Route Erased
Send RD
Route Delete Sent
Erase Route
ROUTE DELETE
3
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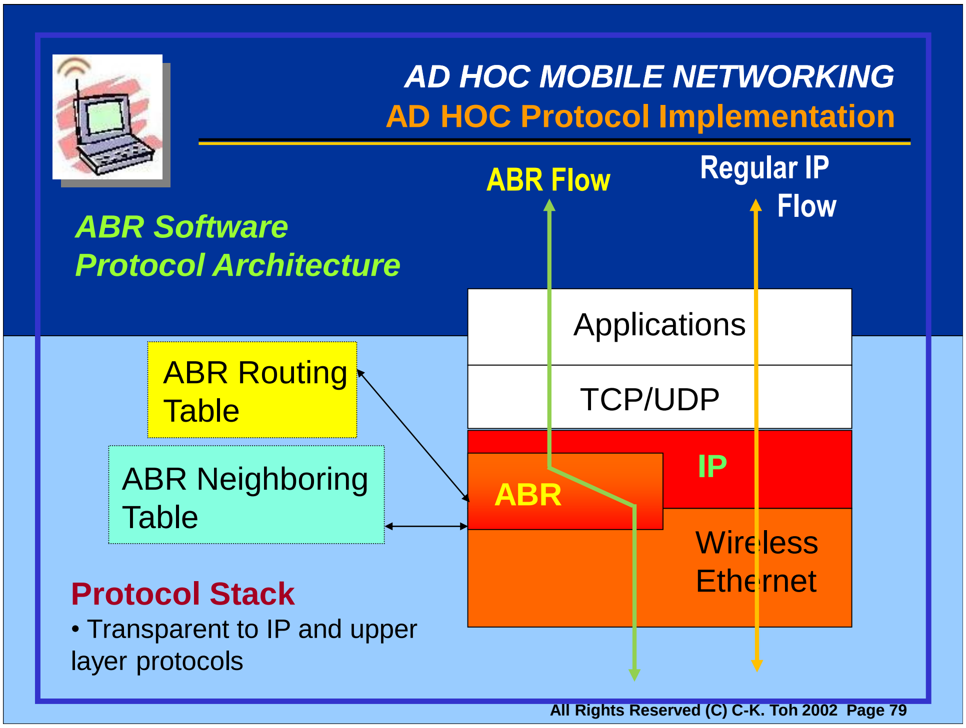
AD HOC MOBILE NETWORKING
AD HOC Protocol Implementation
ABR Software
Protocol Architecture
ABR Flow
Regular IP
Flow
Applications
TCP/UDP
IP
ABR
Wireless
Ethernet
ABR Routing
Table
ABR Neighboring
Table
Protocol Stack
• Transparent to IP and upper layer protocols
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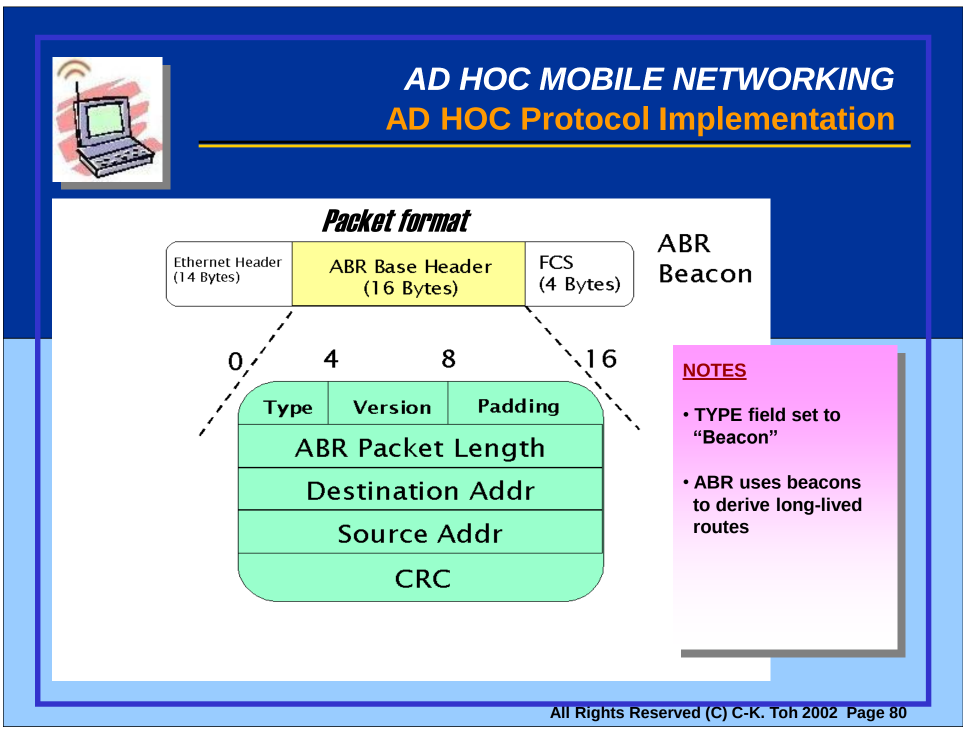
AD HOC MOBILE NETWORKING
AD HOC Protocol Implementation
Packet format
Ethernet Header
(14 Bytes)
ABR Base Header
(16 Bytes)
FCS
(4 Bytes)
ABR
Beacon
0
4
8
16
Type
Version
Padding
ABR Packet Length
Destination Addr
Source Addr
CRC
NOTES
• TYPE field set to "Beacon"
• ABR uses beacons to derive long-lived routes
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AD HOC MOBILE NETWORKING

WIRELESS AD HOC NETWORK Implementation

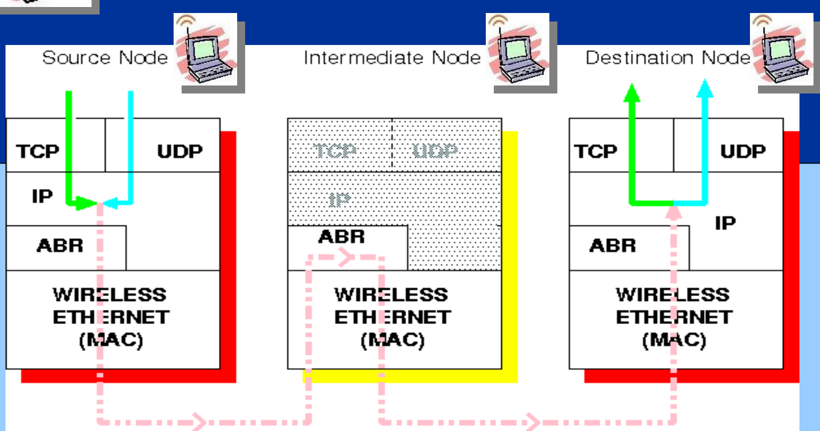
HARDWARE SETUP

Mobile Computers:
- 2 IBM ThinkPad 600
- 3 Compaq Pressario 1240
- 2 Dell Latitude CPi

Radio Device
- Lucent Tech. WaveLAN/PCMCIA
  - Frequency: 2.4GHz
  - Coverage: 200m (open); 50m (semi); 25m(closed)
  - Power : 0.175W (sleep); 1.575W (rx); 1.825W (tx)
  - Media Access : CSMA/CA
  - Data Rate : 2Mbps

AD HOC MOBILE NETWORKING

WIRELESS AD HOC NETWORK Implementation

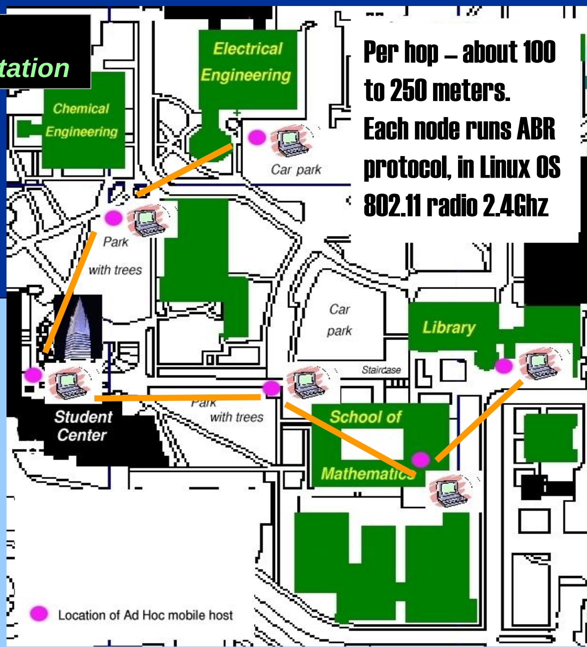


Multi-hop Packet Forwarding & Routing

WIRELESS AD HOC NETWORK Implementation

Implementation Success & Field Trials in Atlanta

- Since Winter 1998
- Laptops with:
  - ABR routing software
  - Lucent WiFi Radio
- Multihop Ad Hoc Network
  - Up to 6 nodes (laptops)
  - Perform a series of tx/rx/mobility experiments
    - Ping, TELENT, FTP,
    - RLOGIN, HTTP web,
    - Video and audio



AD HOC MOBILE NETWORKING

AD HOC Wireless Network Implementation

PING EXPERIMENTS - Sending Packets

(delay includes RRT round trip time & printk – kernel printf)

```
[root@beeslap4 /root]# ./loadif
[root@beeslap4 /root]# ping beeslap3.ee.gatech.edu
PING beeslap3 (199.77.145.15): 56 data bytes
64 bytes from 199.77.145.15: icmp_seq=0 ttl=64 time=20.0 ms
64 bytes from 199.77.145.15: icmp_seq=1 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=2 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=3 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=4 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=5 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=6 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=7 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=8 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=9 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=10 ttl=64 time=7.5 ms
64 bytes from 199.77.145.15: icmp_seq=11 ttl=64 time=7.5 ms

--- beeslap3 ping statistics ---
12 packets transmitted, 12 packets received, 0% packet loss
round-trip min/avg/max = 7.5/8.5/20.0 ms
[root@beeslap4 /root]# []
```

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Implementation

Beaconing Checks

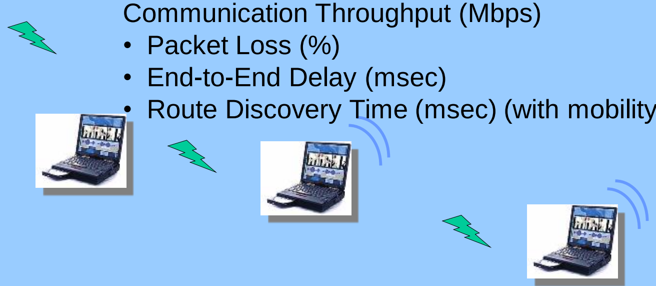
```
[root@beeslap4 /root]# netstat -i -c
Kernel Interface table
Iface   MTU Met  RX-OK RX-ERR RX-DRP RX-OVR  TX-OK TX-ERR TX-DRP TX-OVR Flags
lo     3584   0      0      0      0      0      0      0      0      0 BLRU
eth0   1500   0    164      0      0      0    203      0      0      0 BRU
Kernel Interface table
Iface   MTU Met  RX-OK RX-ERR RX-DRP RX-OVR  TX-OK TX-ERR TX-DRP TX-OVR Flags
lo     3584   0      0      0      0      0      0      0      0      0 BLRU
eth0   1500   0    165      0      0      0    204      0      0      0 BRU
Kernel Interface table
Iface   MTU Met  RX-OK RX-ERR RX-DRP RX-OVR  TX-OK TX-ERR TX-DRP TX-OVR Flags
lo     3584   0      0      0      0      0      0      0      0      0 BLRU
eth0   1500   0    166      0      0      0    205      0      0      0 BRU
Kernel Interface table
Iface   MTU Met  RX-OK RX-ERR RX-DRP RX-OVR  TX-OK TX-ERR TX-DRP TX-OVR Flags
lo     3584   0      0      0      0      0      0      0      0      0 BLRU
eth0   1500   0    167      0      0      0    206      0      0      0 BRU
Kernel Interface table
Iface   MTU Met  RX-OK RX-ERR RX-DRP RX-OVR  TX-OK TX-ERR TX-DRP TX-OVR Flags
lo     3584   0      0      0      0      0      0      0      0      0 BLRU
eth0   1500   0    168      0      0      0    207      0      0      0 BRU

[root@beeslap4 /root]# []
```


AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed - Results

NETWORK COMMUNICATION PERFORMANCE MEASURED ON THE FIELD, OVER THE WORKING AD HOC WIRELESS NETWORK

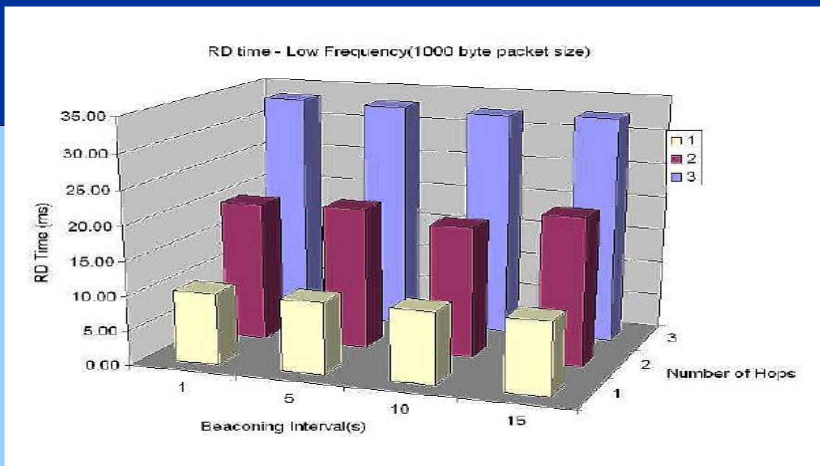
Communication Throughput (Mbps)
- Packet Loss (%)
- End-to-End Delay (msec)
- Route Discovery Time (msec) (with mobility)



AD HOC MOBILE NETWORKING

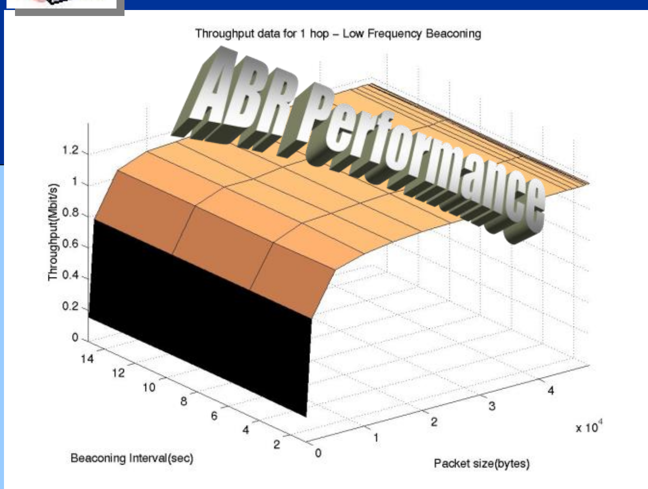
AD HOC Wireless Network Testbed Results

RD Time: Time needed for the source node to discover a route to the destination



AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

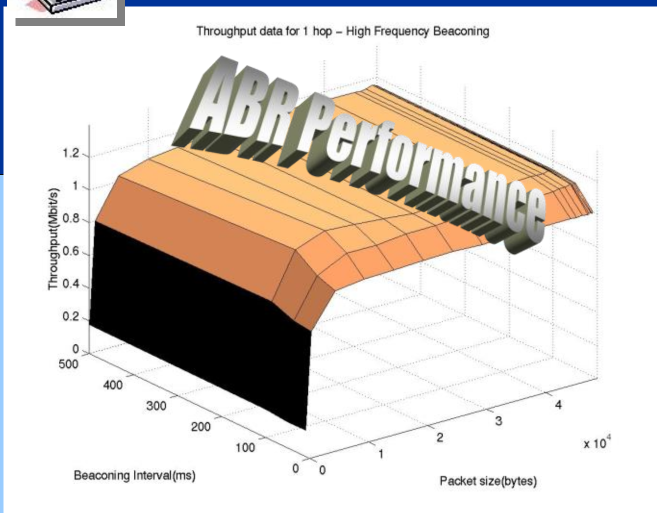


Throughput Performance 1-hop

- *1.18Mbps*
- *Increases with Packet Size*
- *Low Freq Beaconing*
- *Independent of beaconing interval*

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

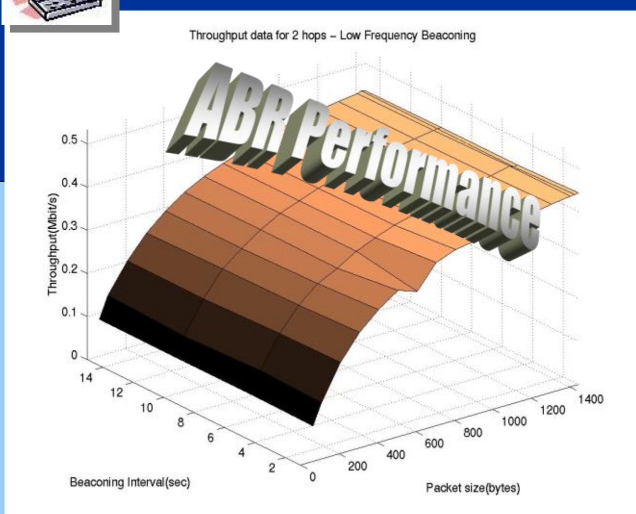


Throughput Performance 1-hop

- ***1.18Mbps***
- ***Packet Size***
- ***Drops to 1 Mbps at High Freq Beaconing***
- ***Curve downwards***

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

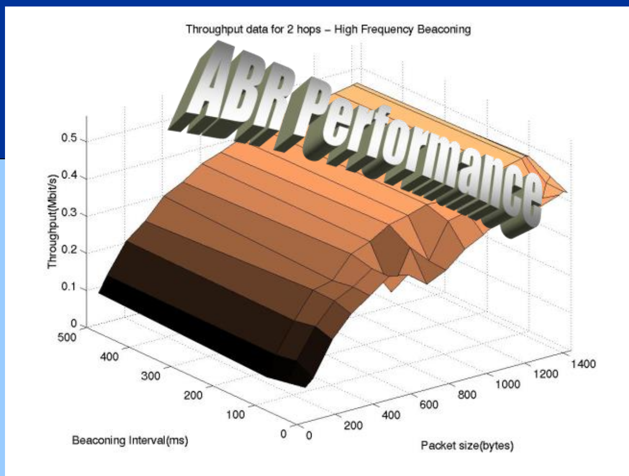


Throughput Performance 2-hops

- ***450Kbps***
- ***Increases with Packet Size***
- ***Low Freq Beaconing***
- ***Route Length of 2 hops***

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

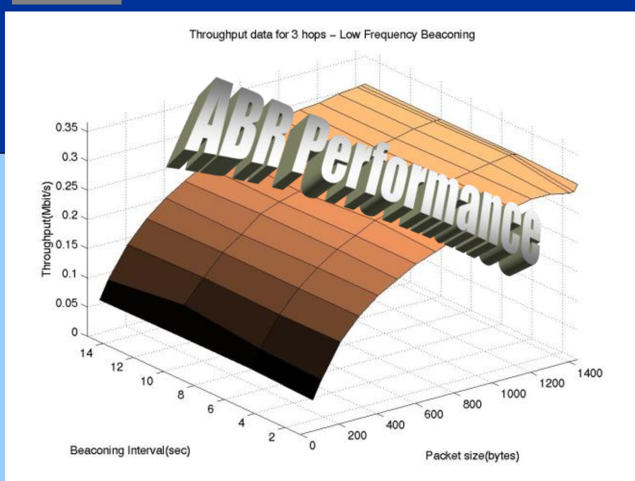


Throughput Performance 2-hops

- ***450Kbps***
- ***Packet Size***
- ***High Freq Beaconing***
- ***Curve downwards, drops to 420Kbps***

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

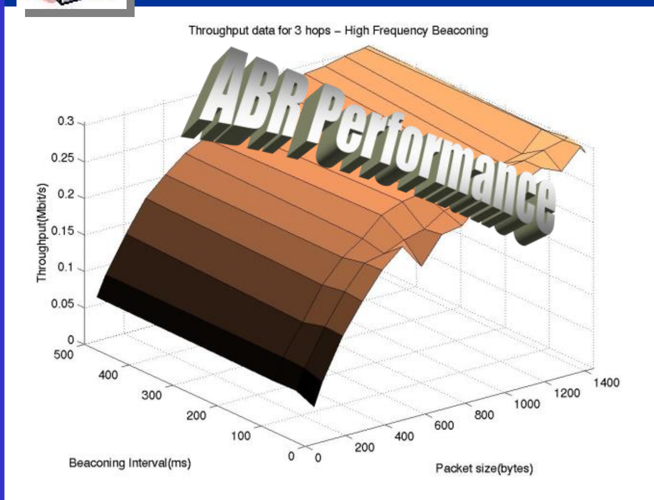


Throughput Performance 3-hops

- ***300Kbps***
- ***Increases with Packet Size***
- ***Low Freq Beaconing***
- ***Route Length of 3 hops***

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

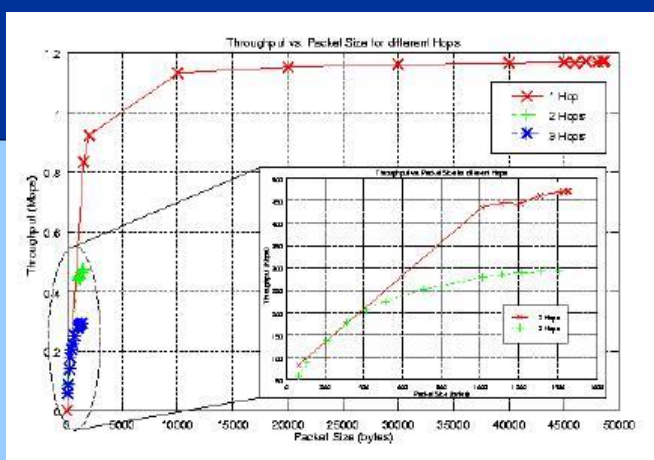


Throughput Performance

- 300Kbps for 3 hops
- Packet Size
- High Freq Beaconing
- Throughput falls with very fast beaconing

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results



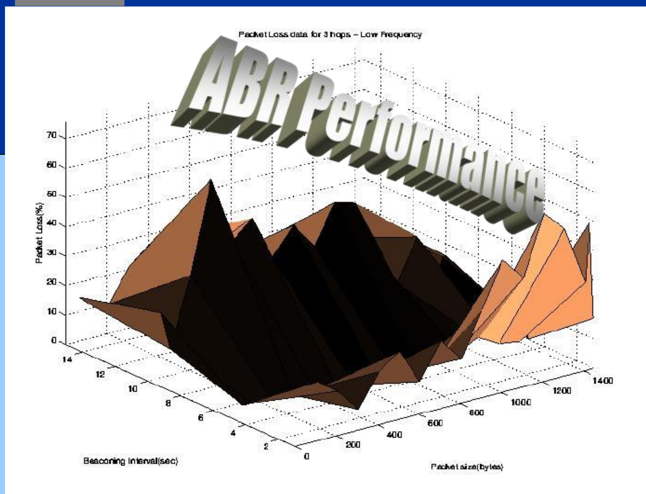
Throughput Performance 3,2,1 hop/s 1sec beacon

- 1 hops = 1.18Mbps
- 2 hops = 450Kbps
- 3 hops = 300Kbps

Bottleneck lies in shared single channel

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

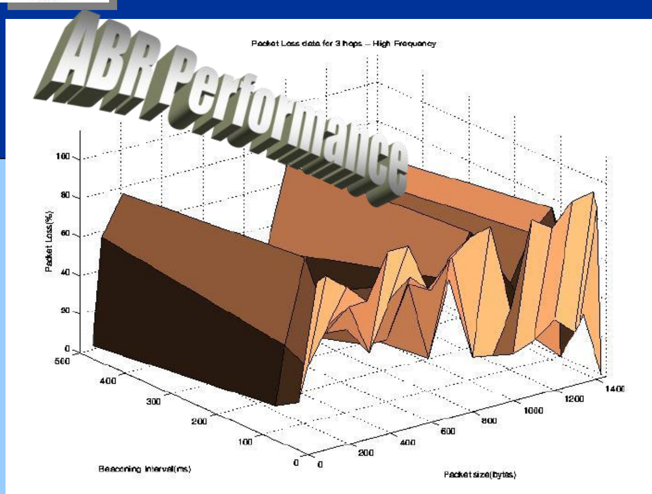


Packet Loss Performance (3hop)

- Packet loss is less affected by low frequency beaconing
- Packet loss worsens as packet size increases...

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

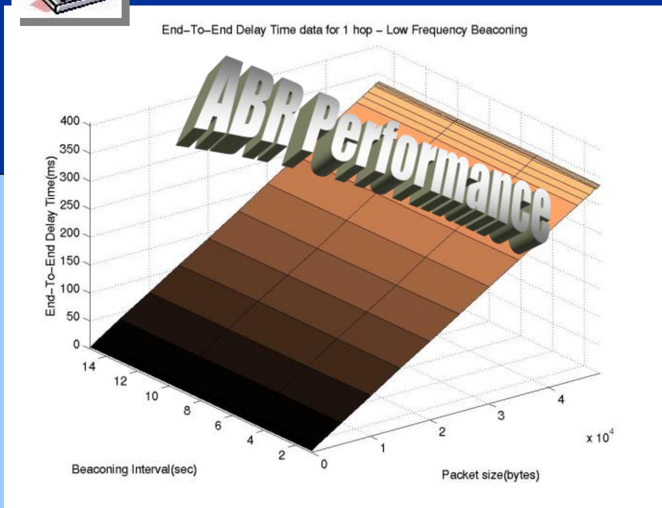


Packet Loss Performance (3hop)

- Worse if packet size is large
- Worse of route length increases
- Worse at extreme high beaconing frequency

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

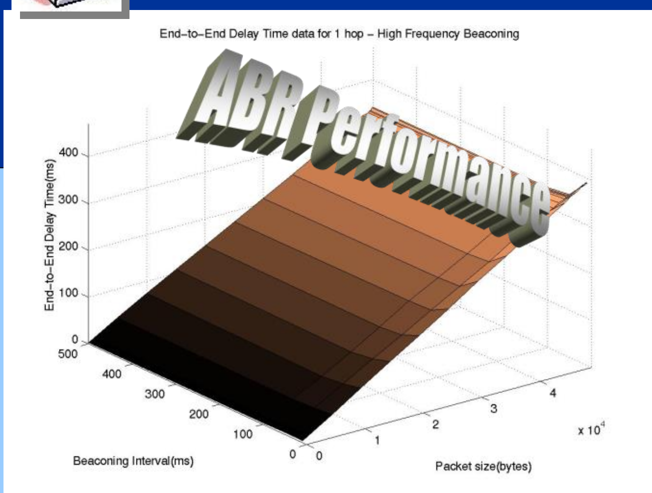


End-to-End Delay (1hop) Performance

- Worse if packet size is large
- Worse of route length increases
- Worse at extreme high beaconing frequency

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

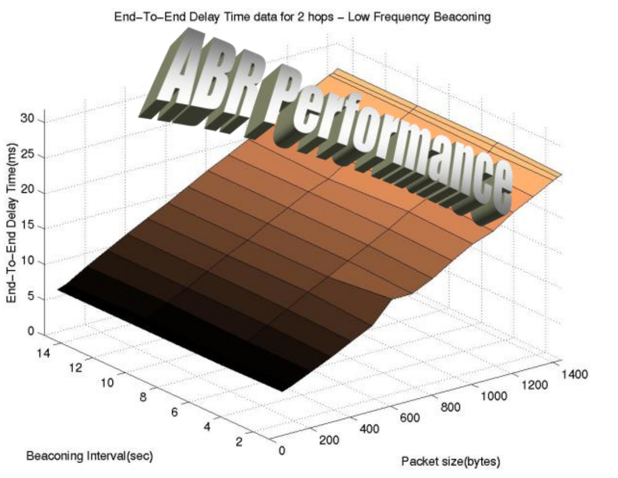


End-to-End Delay (1hop) Performance

- Worse if packet size is large
- Worse of route length increases
- Worse at extreme high beaconing frequency

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

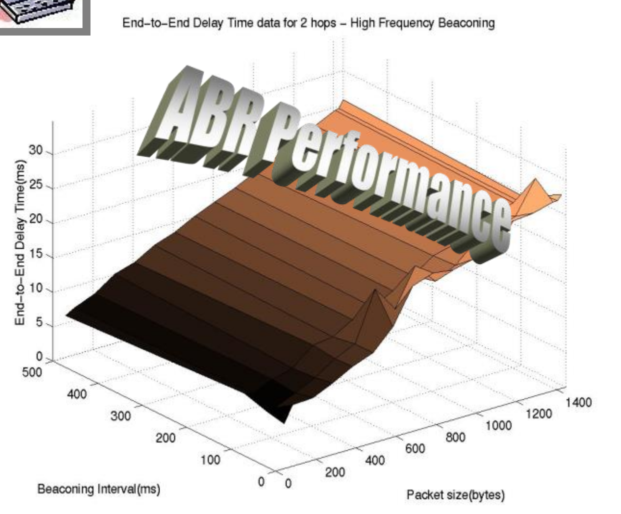


End-to-End Delay (2hop) Performance

- **Worse if packet size is large**
- **Worse of route length increases**
- **27ms at 1400 *bytes***

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

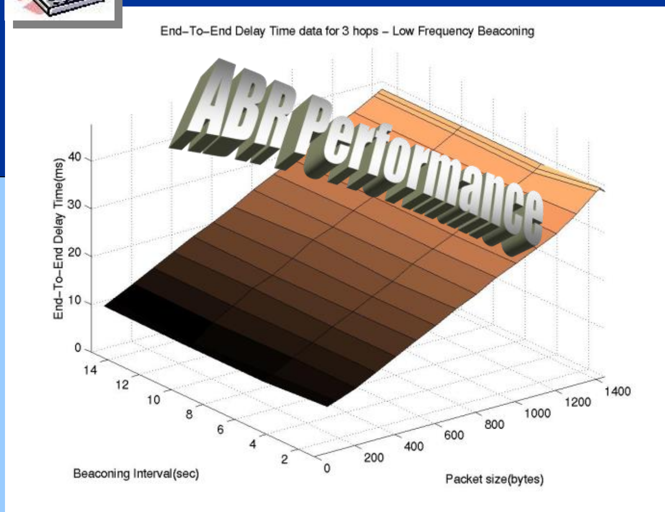


End-to-End Delay (2hop) Performance

- **Worse if packet size is large**
- **Worse of route length increases**
- **30ms at HF beacon at 1300bytes**

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

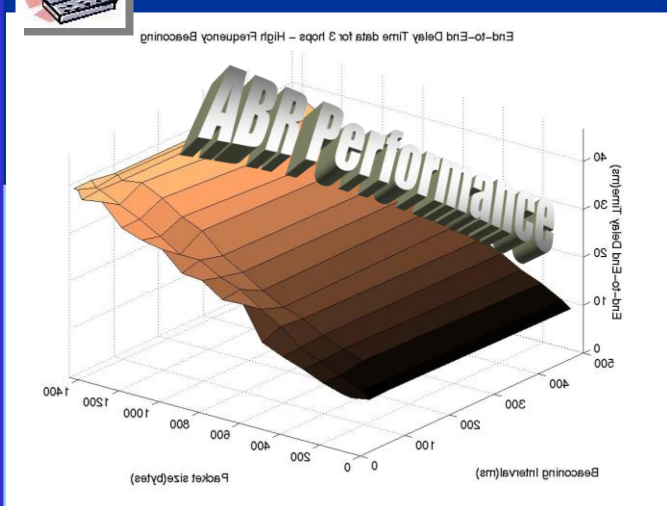


End-to-End Delay (3hop) Performance

- Worse if packet size is large
- Worse if route length increases
- 40ms max for 3 hops

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results



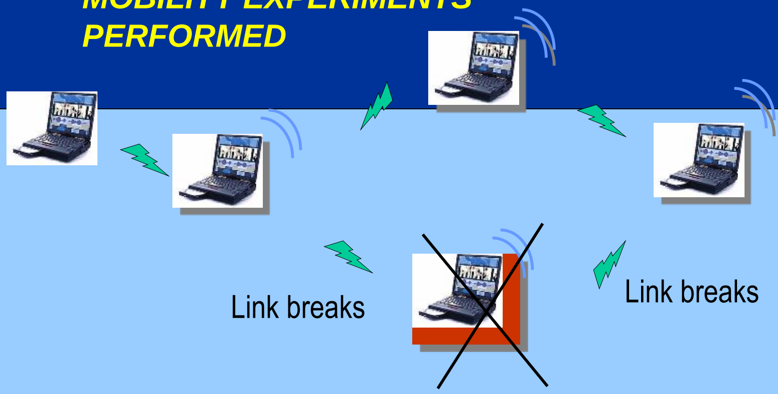
End-to-End Delay (3hop) Performance

- Worse if packet size is large
- Worse of route length increases
- Worse at extreme high beaconing frequency

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Testbed Results

MOBILITY EXPERIMENTS PERFORMED



(C) C-K. Toh, 1999

AD HOC MOBILE NETWORKING

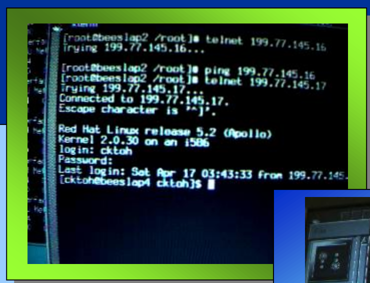
AD HOC Wireless Network Testbed Results

Average Route Reconstruction Time for 50 RRCs (3-hop Route)	Standard Deviation
20.93 ms	0.05

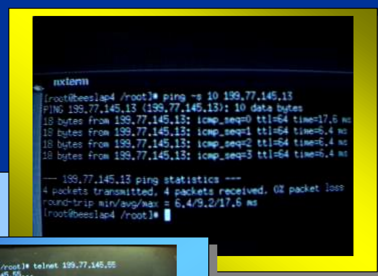
Broken link is successfully and automatically repaired by the routing Protocol.

AD HOC MOBILE NETWORKING

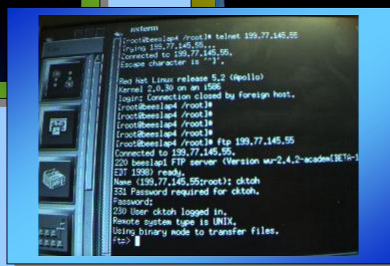
AD HOC Wireless Network: Tested Applications



TELNET works!



PING Works!



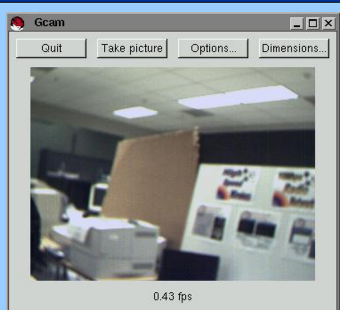
FTP works!

AD HOC MOBILE NETWORKING

AD HOC Wireless Network: Tested Multimedia

Successfully sent multi-hop Audio (64K ADPCM) and live Video (MPEG)

Ref: "Transporting audio over wireless ad hoc networks", Proceedings of IEEE PIMRC conference, 2003.



Sending video via Gcam

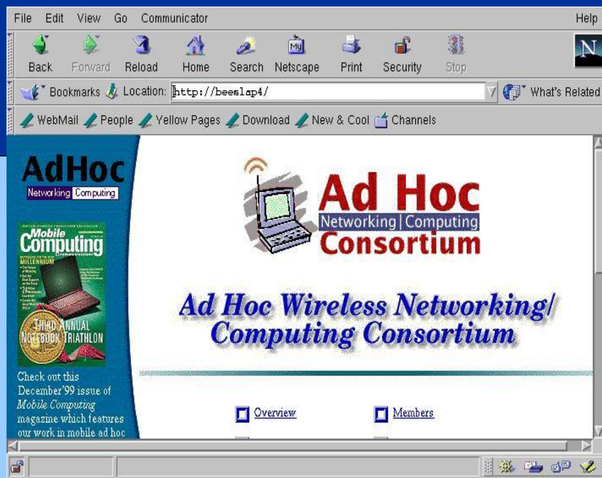
Sending video over ad hoc

AD HOC MOBILE NETWORKING

Web Server-Client Access works over Ad Hoc Wireless Networks (1998)

Web-Based HTTP Access over wireless ad hoc network successful !!

- Ad Hoc Hosts
  - One as web server
  - Another as web client
- Ad Hoc Web Access
  - No problem
  - HTTP over ad hoc works!!!



AD HOC MOBILE NETWORKING

AD HOC Wireless NW: Other Applications

AT THEATER
- *buy tickets online*
- *current show time*
- *today's programs*

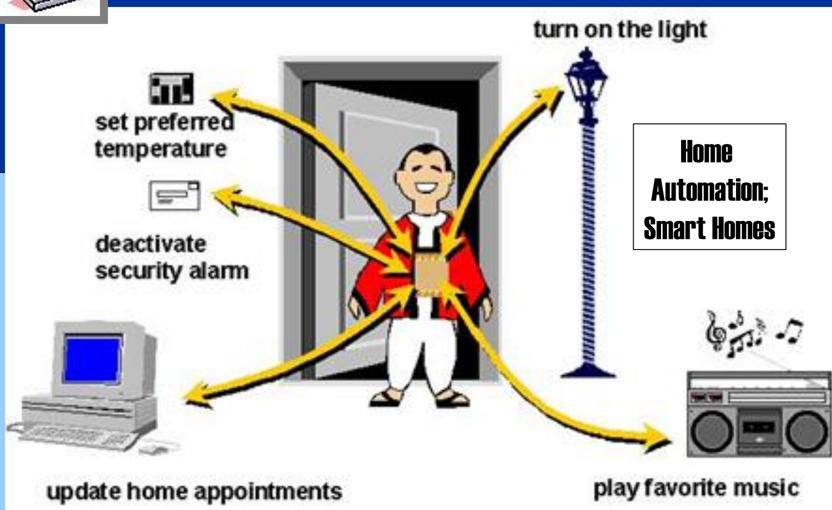
AT SHOPPING MALL
- *online catalog*
- *price comparisons*
- *buy online*

(Location & Context aware Applications)

AT MUSEUM
- *information*
- *automatic guided tour*

AD HOC MOBILE NETWORKING

AD HOC Wireless NW: Other Applications



AD HOC MOBILE NETWORKING

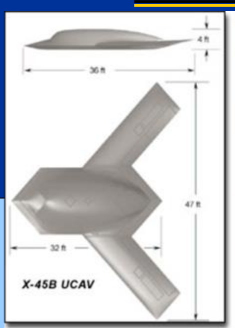
AD HOC Wireless NW: Other Applications

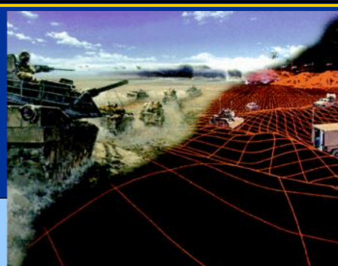
AD HOC MOBILE NETWORKING

AD HOC Wireless NW: Other Applications

AD HOC MOBILE NETWORKING

AD HOC Wireless NW: Defense Applications





Unnamed Combat Air Vehicle (UCAV) –
Not toys..

Operational USAF/Boeing UCAV

Ad hoc Comms in Higher Altitudes..

AD HOC MOBILE NETWORKING

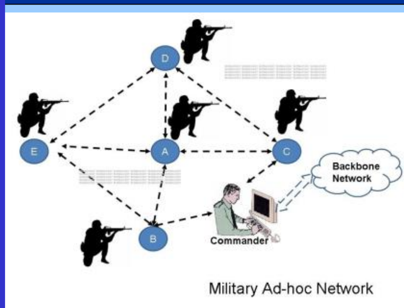
AD HOC Wireless NW: Defense Applications

Using ad hoc technology in the battlefield ……….

AD HOC MOBILE NETWORKING

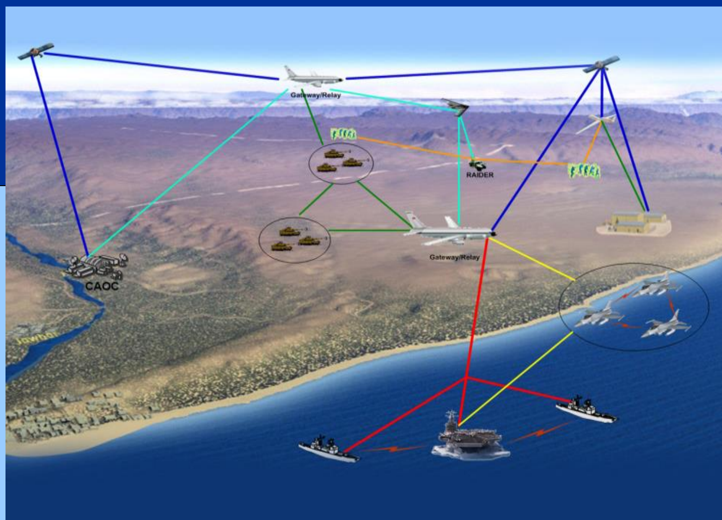
AD HOC Wireless NW: Defense Applications

- Soldiers tactical ad hoc mobile radios create a spontaneous ad hoc network in the battlefield, empowering them with communication capability
- Mobile ad hoc networks extend connectivity to command posts and vehicles



AD HOC MOBILE NETWORKING

AD HOC Wireless NW: Defense Applications



Land,
Air,
Sea
Mobile
Ad Hoc
Networks

- Multi-Dimensions
- Different Altitudes
- Working together

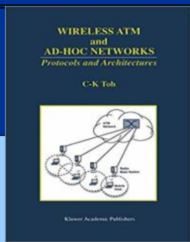
AD HOC MOBILE NETWORKING

TUTORIAL NOTES

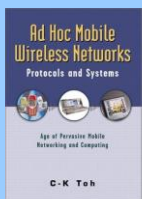
Conclusions

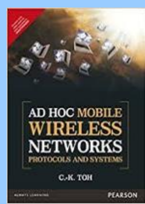
- Wireless ad hoc networks proven to be realizable and practical (1998 implementation)
- It is no longer a myth or hype!
- Today - Computers rule the world.
- Tomorrow - Devices shall rule the world!!!
- Future device will become more and more intelligent…
- Computing and networking will become pervasive
- Ad hoc mobile applications: neighbor-aware; location-aware; connectivity-aware; and context-aware.

Additional References - Books



- **First book on Wireless Ad Hoc Networks (dated 1997)**
- Kluwer Academic Press.
- ISBN 0-7923-9822-X 313 page.





- Covers MAC, Routing, Multicast, TCP, Service Discovery, Power routing, power management, packet radio, protocol implementation, communication performance, ad hoc mobile applications, and more!
- Prentice Hall Publishers (also translated and published in Japan) (also in paperback for India)
- 2002. ISBN 0130078174 302 pages

END