Ad Hoc Wireless Networking
Course Notes

March
2002

Course Outline

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

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...

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**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.,
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

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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
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.
Routing in Packet Radio Networks

### Neighboring Table

<table>
<thead>
<tr>
<th>Neighboring PRs</th>
<th>Link Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Tier Table

<table>
<thead>
<tr>
<th>Dest PR</th>
<th>Next PR</th>
<th>Tier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Routing Header Field

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

---

**3-Frame Packet Forwarding in PRNETs**

- **N** forwards pkt 1
- **M** receives pkt 1
- **M** simultaneously ACKs **L**
- **N** simultaneously ACKs **M**
- **L** transmits pkt 2
  - *(At this point, L knows that M has indeed received and forwarded the packet it last sent)*

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

Active Badge
HP Palm Pilot
3Com Palm Pilot
E-tag

CPU
Memory
File Systems
OS
Display
Power
Comms
HDI

Window CE
Palmtop

Laptop

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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)

Different Mobility Patterns

- 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 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.

### 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
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?

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
Scatternet

- Communication beyond a piconet; Multiple Masters

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!!!
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

<table>
<thead>
<tr>
<th>Cellular</th>
<th>WAP</th>
<th>Bluetooth</th>
<th>Ad Hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile Telephony</td>
<td>Mobile Internet</td>
<td>Mobile Internet, E-Commerce, audio</td>
<td>Mobile Internet, E-Commerce, audio, Audio, video</td>
</tr>
<tr>
<td>Last-Hop/One-Hop Access</td>
<td>Mobile E-Commerce</td>
<td>Scatternet</td>
<td>Beyond Scatternet</td>
</tr>
</tbody>
</table>

Time
Ad Hoc MAC Protocols – Layer 2

Media Access over AD HOC MOBILE NETWORKS

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.

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

(a) RTR (Multiple Access with Collision Avoidance By Invitation)

(b) DATA

Blocked from TX

Blocked from TX

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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!!

New MARCH Protocol: Media Access Control with Reduced Handshake

- Only first hop uses RTS-CTS handshake.
- After first hop handshaking, reduces to CTS-only.
- Node C can send CTS2 when available.
- Wait time ($T_w$) $\cong$ data transmission time
Features of MARCH Protocol:

- 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

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
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 10 pkts/sec to 350 pkts/sec

Parameters of Interest

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

End-to-End Throughput

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

• 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
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.

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

- 3 or more duplicated ACKs implies missing segment.
- Retx missing segment before timeout.
- 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.

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**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!!!
• 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!!

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

TCP-F State Machine

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

- RFN message received
- RRN message received

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

**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
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.
(a) ERDN loss

- **IN doesn’t hear upstream ERDN message and retransmits during ERDN_RET_TIMER.**

(b) ERRN loss

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.
Buffering of TCP Segments

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

Buffering Example (RRC completed)

- When RRC is completed, TCP sender receives ERRN with buffer status at TCP receiver and IN.
- TCP sender resumes transmission according to the received feedback.
- INs resume transmission from their buffers.
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.

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**Principle of Service Location Protocol (SLP)**

![Service Discovery Diagram](image)
### 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

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### 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
Architecture based on Distributed Query

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

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:


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

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

OVERVIEW OF CURRENT APPROACHES

AD-HOC MOBILE ROUTING PROTOCOLS
- TABLE-DRIVEN/PROACTIVE
  - DSDV
  - CGSR
- ON-DEMAND-DRIVEN REACTIVE
  - WRP
  - STAR
  - ZRP
  - ABR
  - DSR
  - TORA
  - AODV
  - CBRP
  - RDMAR
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
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

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

Cell Size of 10m

N0
2m/sec

N1

N2

N3

N4

N5

Associativity Ticks

Threshold 5

Time

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.....”
**Route Discovery**

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

**AD HOC MOBILE NETWORKING**
**AD HOC Routing Protocol**

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

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**KEY CONCEPTS IN ABR ROUTING**

- 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.
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.
ABR Software Protocol Architecture

Protocol Stack
- Transparent to IP and upper layer protocols

Packet format
- Ethernet Header (14 bytes)
- ABR Base Header (16 bytes)
- FCS (4 bytes)

NOTES
- TYPE field set to “Beacon”
- ABR uses beacons to derive long-lived routes
Mobile Computers:
- 2 IBM ThinkPad 600
- 3 Compaq Presario 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

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, TELNET, FTP,
    - RLOGIN, HTTP web,
    - Video and audio

Per hop – about 100 to 250 meters.
Each node runs ABR protocol, in Linux OS 802.11 radio 2.4Ghz

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# ./sendf
root@beeslap4 /root# ping beeslap3@ee.gatech.edu
PING beeslap3 (199.77.145.150) 36 data bytes
64 bytes from 199.77.145.150: icmp_seq=0 ttl=64 time=29.0 ms
64 bytes from 199.77.145.150: icmp_seq=1 ttl=64 time=23.5 ms
64 bytes from 199.77.145.150: icmp_seq=2 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=3 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=4 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=5 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=6 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=7 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=8 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=9 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=10 ttl=64 time=7.5 ms
64 bytes from 199.77.145.150: icmp_seq=11 ttl=64 time=7.5 ms
```

--- beeslap2 ping statistics ---
12 packets transmitted, 12 packets received, 0% packet loss
round-trip: min/avg/max = 7.5/7.5/7.5 ms
```
Beaconing Checks

```
[root@beeslap4 /root3# netstat -i -c
Kernel Interface Table
    Iface   MTU      RX-OK    RX-ERR    RX-DRP    RX-OVR    TX-OK    TX-ERR    TX-IPF    TX-OVR    Flags
    echo 1500   184      0       0       0       0       0       0       0       0       BRU
Kernel Interface Table
    Iface   MTU      RX-OK    RX-ERR    RX-DRP    RX-OVR    TX-OK    TX-ERR    TX-IPF    TX-OVR    Flags
    echo 1500   166      0       0       0       0       0       0       0       0       BRU
```

AD HOC MOBILE NETWORKING

AD HOC Wireless Network Implementation

Beaconing Checks

```
[root@beeslap4 /root3# netstat -i -c
Kernel Interface Table
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    echo 1500   166      0       0       0       0       0       0       0       0       BRU
```

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

Throughput Performance 1-hop

- 1.18Mbps
- Increases with Packet Size
- Low Freq Beaconsing
- 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

**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

### Throughput Performance 3-hops
- 300Kbps
- Increases with Packet Size
- Low Freq Beaconing
- Route Length of 3 hops
Throughput Performance

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

Bottleneck lies in shared single channel
Packet Loss Performance (3hop)

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

Packet Loss Performance (3hop)

• Worse if packet size is large
• Worse if 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 if 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

- 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
- Worse at extreme high beaconing frequency

End-to-End Delay (3hop) Performance

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

Link breaks

Link breaks

(C) C-K. Toh, 1999

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 Applications

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


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!!!

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**AD HOC MOBILE NETWORKING**

AD HOC Wireless NW: Other Applications

- **AT SHOPPING MALL**
  - online catalog
  - price comparisons
  - buy online
  (Location & Context aware Applications)

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

- **AT MUSEUM**
  - information
  - automatic guided tour
AD HOC MOBILE NETWORKING
AD HOC Wireless NW: Other Applications

- set preferred temperature
- deactivate security alarm
- update home appointments
- play favorite music
- turn on the light

Home Automation; Smart Homes

AD HOC MOBILE NETWORKING
AD HOC Wireless NW: Other Applications

Automatic flight check-in, no wait-in-line
**AD HOC MOBILE NETWORKING**

**AD HOC Wireless NW: Other Applications**

Download E-mails, update schedules, etc.

**AD HOC MOBILE NETWORKING**

**AD HOC Wireless NW: Defense Applications**

Unmanned Combat Air Vehicle (UCAV) - Not toys!

Ad hoc Comms in Higher Altitudes.
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.
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)

- 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)