Mobile Ad Hoc Networks

Overview

- Introduction
- A brief look at the following (w.r.t MANETs)
  - Medium Access Control
  - Routing (unicast)
    - Reactive Protocols
    - Proactive Protocols
    - Hybrid Protocols
  - Transport and Security Issues
- Conclusion

Mobile Ad hoc Networks

I. Introduction

Wireless Networks

- Need: Access computing and communication services, on the move
- Infrastructure-based Networks
  - traditional cellular systems (base station infrastructure)
- Wireless LANs
  - typically radio links (802.11, etc), can be Infrared
  - very flexible within the reception area; ad-hoc networks possible
  - lower bandwidth than wired networks (1-54 Mbit/s)
- Ad hoc Networks
  - useful when infrastructure not available, impractical, or expensive
  - originally military applications, rescue, home networking
  - interesting potential for Metro-area networking

Cellular Wireless

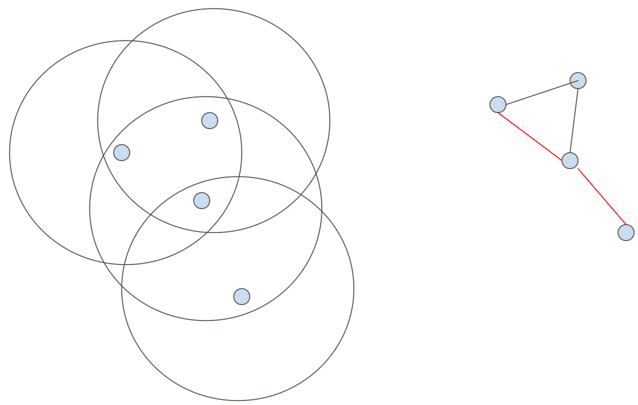
- Single hop wireless connectivity to the wired world
  - Space divided into cells
  - A base station is responsible to communicate with hosts in its cell
  - Mobile hosts can change cells while communicating
  - Hand-off occurs when a mobile host starts communicating via a new base station

Mobile Ad Hoc Networks (MANETs)

- Formed by wireless hosts which may be mobile
- Without (necessarily) using a pre-existing infrastructure
- Routes between nodes may potentially contain multiple hops

Mobile Ad Hoc Networks (MANETs)

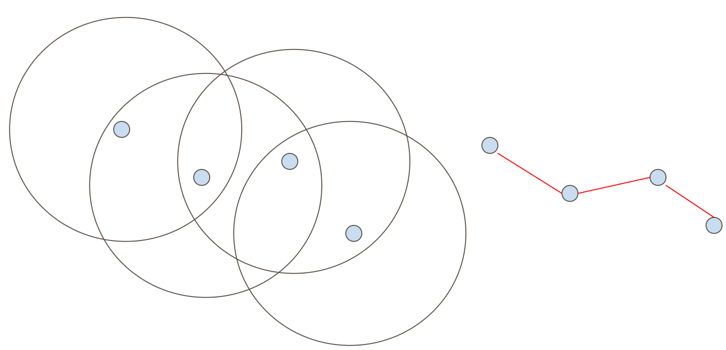
- May need to traverse multiple links to reach destination



7

Mobile Ad Hoc Networks (MANETs)

- Mobility causes route changes



8

Why Ad Hoc Networks ?

- Setting up of fixed access points and backbone infrastructure is not always viable
  - Infrastructure may not be present in a disaster area or war zone
  - Infrastructure may not be practical for short-range radios; Bluetooth (range ~ 10m)
- Ad hoc networks:
  - Do not need backbone infrastructure support
  - Are easy to deploy
  - Self-configure
  - Useful when infrastructure is absent, destroyed or impractical

Many Applications

- Personal area networking
  - cell phone, laptop, ear phone, wrist watch
- Military environments
  - soldiers, tanks, planes
- Civilian environments
  - taxi cab network
  - meeting rooms
  - sports stadiums
  - boats, small aircraft
- Emergency operations
  - search-and-rescue
  - policing and fire fighting

Many Variations

- Fully Symmetric Environment
  - all nodes have identical capabilities and responsibilities
- Asymmetric Capabilities
  - transmission ranges and radios may differ
  - battery life of different nodes may differ
  - processing capacity may be different at different nodes
  - speed of movement
- Asymmetric Responsibilities
  - only some nodes may route packets
  - some nodes may act as leaders of nearby nodes (e.g., cluster head)

11

Many Variations

- Traffic characteristics may differ in different ad hoc networks
  - bit rate
  - timeliness constraints
  - reliability requirements
  - unicast / multicast / geocast
  - host-based addressing / content-based addressing / capability-based addressing
- May co-exist (and co-operate) with an infrastructure-based network

12

Many Variations

- Mobility patterns may be different
  - people sitting at an airport lounge
  - New York taxi cabs
  - kids playing
  - military movements
  - personal area network
- Mobility characteristics
  - speed
  - predictability
    - direction of movement
    - pattern of movement
  - uniformity (or lack thereof) of mobility characteristics among different nodes

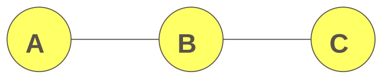
13

Challenges in Design & Operation of MANETs

- Lack of a centralized entity
- ALL communications is carried over the wireless medium
  - Limited wireless transmission range
  - Broadcast nature of the wireless medium
    - Hidden terminal problem (see next slide)
    - Exposed terminal problem
    - Ease of snooping on wireless transmissions (security hazard)
- Packet losses due to transmission errors
- Mobility-induced route changes
- Mobility-induced packet losses
- Battery constraints
- Potentially frequent network partitions

14

Hidden Terminal Problem



Nodes A and C cannot hear each other

Transmissions by nodes A and C can collide at node B

Nodes A and C are hidden from each other

15

Challenges in Design & Operation of MANETs

- Given all these challenges, the design of ad-hoc should allow for a high degree of
  - Reliability
  - Survivability
  - Availability
  - Manageability of the network

16

Mobile Ad hoc Networks

II. Medium Access Control Protocols

Motivation

- Can we apply media access methods from fixed networks?
- Example CSMA/CD
  - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - Send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3)
- Medium access problems in wireless networks
  - Signal strength decreases proportional to the square of the distance
  - Sender would apply CS and CD, but the collisions happen at the receiver
  - Sender may not "hear" the collision, i.e., CD does not work
  - CS might not work, e.g. if a terminal is "hidden"

Multiple Access with Collision Avoidance (MACA) [Kar90]

- MACA uses signaling packets for collision avoidance
  - RTS (request to send)
    - sender request the right to send from a receiver with a short RTS packet before it sends a data packet
  - CTS (clear to send)
    - receiver grants the right to send as soon as it is ready to receive
- Signaling packets contain
  - sender address
  - receiver address
  - packet size
- Variants of this method are used in IEEE 802.11

19

Multiple Access with Collision Avoidance (MACA) [Kar90]

- MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - C waits after receiving CTS from B
- MACA avoids the problem of exposed terminals
  - B wants to send to A, C to another terminal
  - now C does not have to wait, as it cannot receive CTS from A

20

MACAW Scheme [Bha94]

- Suggested use of RTS-CTS-DS-DATA- ACK message exchange for a data packet transmission
  - Two new control packets were added to the packet train: DS and ACK packets
- A new back-off algorithm, the Multiple Increase and Linear Decrease (MILD) algorithm, was also proposed
  - Address the unfairness problem in accessing the shared channel
- The drawback of the MACAW scheme is inherited from the MACA scheme: the RTS/CTS packet collisions in a network with hidden terminals degrade its performance

21

Floor Acquisition Multiple Access (FAMA) Scheme [Ful94]

- Each ready node has to acquire the channel (the “floor") before it can transmit its data packets
- Uses both CS and RTS/CTS dialogue to ensure the acquisition of the "floor" and the successful transmission of the data packets
- Was extended to FAMA-NPS (FAMA Non- persistent Packet Sensing) and FAMA-NCS (FAMA Non-persistent Carrier Sensing) [Ful97]
- FAMA-NCS uses carrier sensing to keep neighbor nodes from transmitting while the channel is being used for data packet transmission
- FAMA-NCS out-performs non-persistent CSMA and previous FAMA schemes in multi-hop networks

22

Dual Busy Tone Multiple Access (DBTMA) Scheme [Haa02]

- In addition to the use of an RTS packet, two out-of-band busy tones are used
  - Transmit Busy Tone + RTS packet
  - Receive Busy Tone
- *DBTMA* scheme completely solves the *hidden terminal* and the *exposed terminal* problems.
  - forbids the hidden terminals to send any packet on the channel while the receiver is receiving the data packet
  - allows the exposed terminals to initiate transmission by sending out the RTS packets
  - allows the hidden terminals to reply RTS packets by setting up the Receive Busy Tone and initiate data packet reception

23

Mobile Ad hoc Networks

III. Routing Protocols

Unicast Routing Protocols

- Many protocols have been proposed
- Some specifically invented for MANET
- Others adapted from protocols for wired networks
- No single protocol works well in all environments
  - some attempts made to develop adaptive/hybrid protocols
- Standardization efforts in IETF
  - MANET, MobileIP working groups
  - **http://www.ietf.org**

25

Unicast Routing Protocols

- Proactive Protocols
  - Traditional distributed shortest-path protocols
  - Maintain routes between every host pair at all times
  - Based on periodic updates; High routing overhead
  - Example: DSDV (destination sequenced distance vector)
- Reactive Protocols
  - Determine route if and when needed
  - Source initiates route discovery
  - Example: DSR (dynamic source routing)
- Hybrid Protocols
  - Adaptive; Combination of proactive and reactive
  - Example : ZRP (zone routing protocol)

26

Protocol Trade-offs

- Proactive Protocols
  - Always maintain routes
  - Little or no delay for route determination
  - Consume bandwidth to keep routes up-to-date
  - Maintain routes which may never be used
- Reactive Protocols
  - Lower overhead since routes are determined on demand
  - Significant delay in route determination
  - Employ flooding (global search)
  - Control traffic may be bursty
- Which approach achieves a better trade-off depends on the traffic and mobility patterns

27

Mobile Ad hoc Networks

III. Routing Protocols

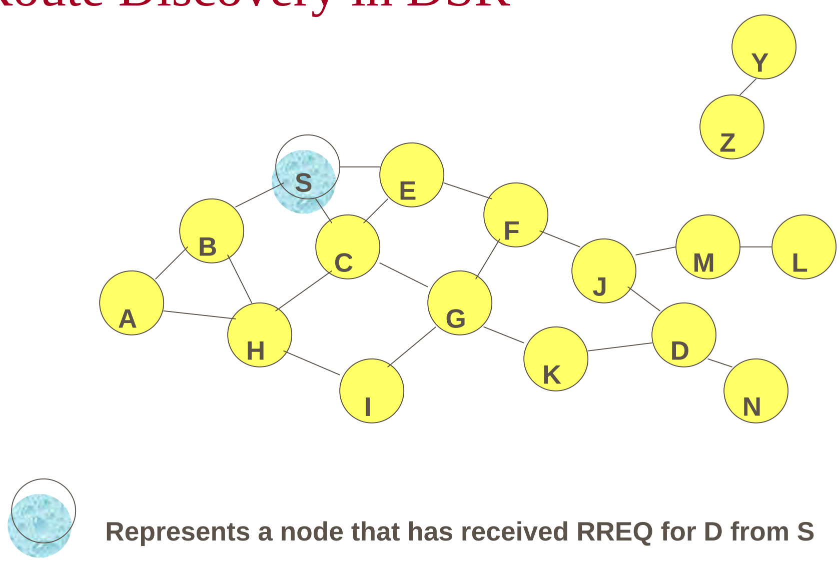
1. Reactive protocols

Dynamic Source Routing (DSR) [Joh96]

- When node S wants to send a packet to node D, but does not know a route to D, node S initiates a route discovery
- Source node S floods Route Request (RREQ)
- Each node appends own identifier when forwarding RREQ

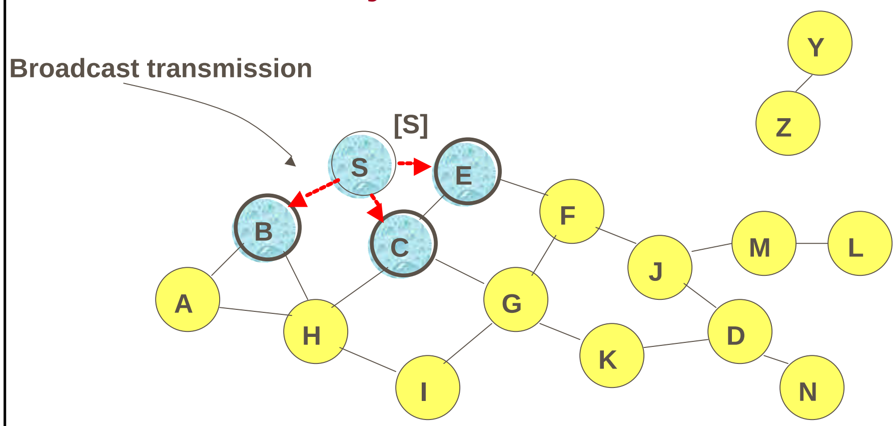
29

Route Discovery in DSR



30

Route Discovery in DSR

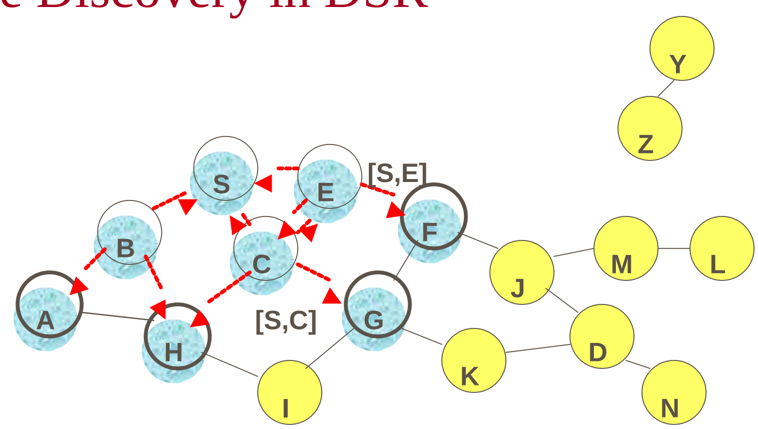


Represents transmission of RREQ

[X,Y] **Represents list of identifiers appended to RREQ**

31

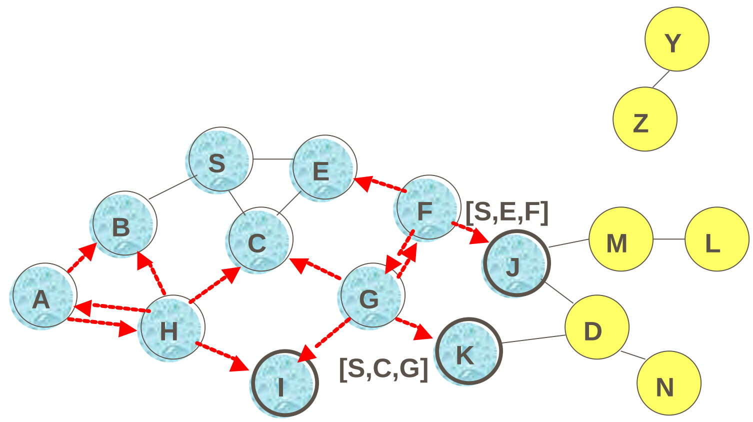
Route Discovery in DSR



- Node H receives packet RREQ from two neighbors: **potential for collision**

32

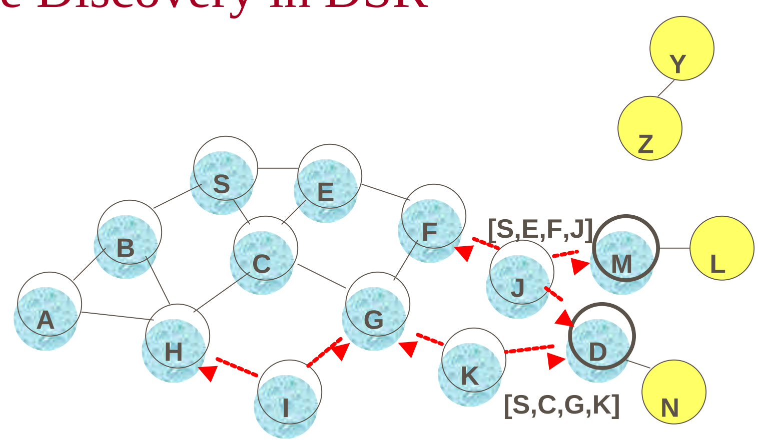
Route Discovery in DSR



• Node C receives RREQ from G and H, but does not forward it again, because node C has **already forwarded RREQ** once

33

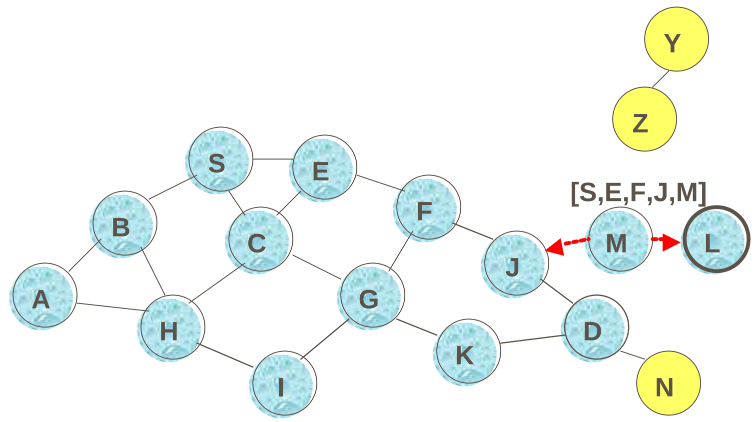
Route Discovery in DSR



• Nodes J and K both broadcast RREQ to node D
• Since nodes J and K are **hidden** from each other, their **transmissions may collide**

34

Route Discovery in DSR



• Node D **does not forward** RREQ, because node D is the **intended target** of the route discovery

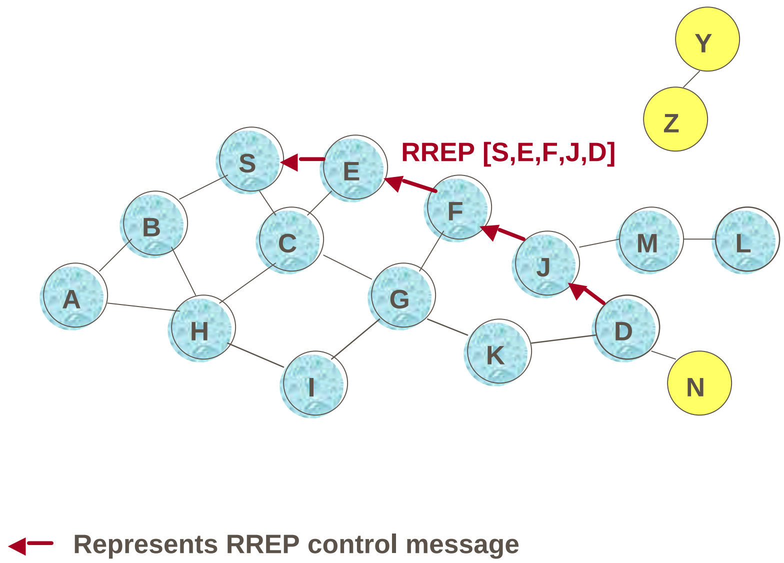
35

Route Discovery in DSR

- Destination D on receiving the first RREQ, sends a Route Reply (RREP)
- RREP is sent on a route obtained by reversing the route appended to received RREQ
- RREP includes the route from S to D on which RREQ was received by node D

36

Route Reply in DSR



37

Route Reply in DSR

- Route Reply can be sent by reversing the route in Route Request (RREQ) only if links are guaranteed to be bi-directional
  - To ensure this, RREQ should be forwarded only if it received on a link that is known to be bi-directional
- If unidirectional (asymmetric) links are allowed, then RREP may need a route discovery for S from node D
  - Unless node D already knows a route to node S
  - If a route discovery is initiated by D for a route to S, then the Route Reply is piggybacked on the Route Request from D

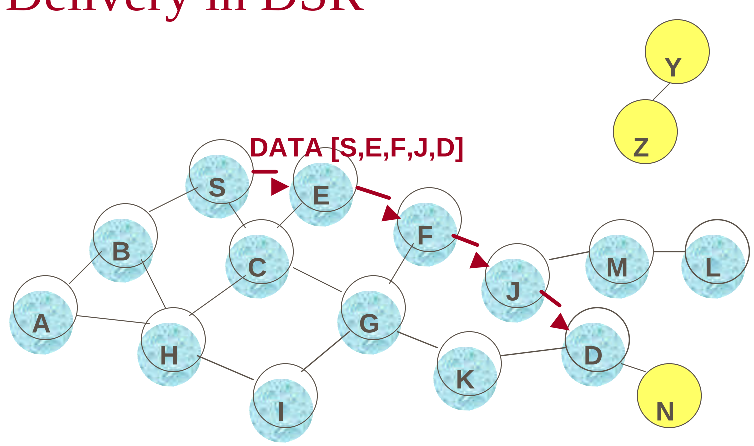
38

Dynamic Source Routing (DSR)

- Node S on receiving RREP, caches the route included in the RREP
- When node S sends a data packet to D, the entire route is included in the packet header
  - hence the name source routing
- Intermediate nodes use the source route included in a packet to determine to whom a packet should be forwarded

39

Data Delivery in DSR



Packet header size grows with route length

40

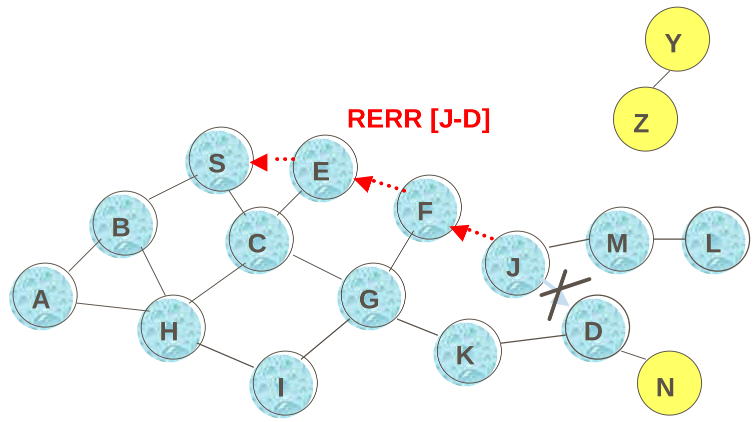
DSR Optimization: Route Caching

- Each node caches a new route it learns by *any means*
- When node S finds route [S,E,F,J,D] to node D, node S also learns route [S,E,F] to node F
- When node K receives Route Request [S,C,G] destined for node D, node K learns route [K,G,C,S] to node S
- When node F forwards Route Reply RREP [S,E,F,J,D], node F learns route [F,J,D] to node D
- When node E forwards Data [S,E,F,J,D] it learns route [E,F,J,D] to node D
- A node may also learn a route when it overhears Data packets

Use of Route Caching

- When node S learns that a route to node D is broken, it uses another route from its local cache, if such a route to D exists in its cache. Otherwise, node S initiates route discovery by sending a route request
- Node X on receiving a Route Request for some node D can send a Route Reply if node X knows a route to node D
- Use of route cache
  - can speed up route discovery
  - can reduce propagation of route requests

Route Error (RERR)



J sends a route error to S along route J-F-E-S when its attempt to forward the data packet S (with route SEFJD) on J-D fails

Nodes hearing RERR update their route cache to remove link J-D

43

Route Caching: Beware!

- Stale caches can adversely affect performance
- With passage of time and host mobility, cached routes may become invalid
- A sender host may try several stale routes (obtained from local cache, or replied from cache by other nodes), before finding a good route

44

Ad Hoc On-Demand Distance Vector (AODV) Routing [Per99]

- DSR includes source routes in packet headers
- Resulting large headers can sometimes degrade performance
  - particularly when data contents of a packet are small
- AODV attempts to improve on DSR by maintaining routing tables at the nodes, so that data packets do not have to contain routes
- AODV retains the desirable feature of DSR that routes are maintained only between nodes which need to communicate

45

AODV

- Route Requests (RREQ) are forwarded in a manner similar to DSR
- When a node re-broadcasts a Route Request, it sets up a reverse path pointing towards the source
  - AODV assumes symmetric (bi-directional) links
- When the intended destination receives a Route Request, it replies by sending a Route Reply
- Route Reply travels along the reverse path set-up when Route Request is forwarded

46

Temporally-Ordered Routing Algorithm (TORA) [Par00]

- In TORA, routes to a destination are defined by a Directional Acyclic Graph (DAG) rooted at the destination
- It is a merger of the proactive link reversal algorithm for destination-oriented Directional-Acyclic-Graph creation proposed in [Gaf81] and the on-demand query-reply mechanism of Lightweight Mobile Routing (LMR) [Cor95]
- TORA also supports a proactive mode

47

Mobile Ad hoc Networks

III. Routing Protocols

2. Proactive protocols

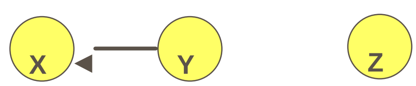
Destination-Sequenced Distance-Vector (DSDV) Routing [Per94]

- Improves over the conventional Bellman-Ford distance-vector protocol
  - It eliminates route looping, increases convergence speed, and reduces control message overhead
- Each node maintains a routing table which stores
  - next hop towards each destination
  - a cost metric for the path to each destination
  - a destination sequence number that is created by the destination itself
  - Sequence numbers used to avoid formation of loops
- Each node periodically forwards the routing table to its neighbors
  - Each node increments and appends its sequence number when sending its local routing table
  - This sequence number will be attached to route entries created for this node

49

Destination-Sequenced Distance-Vector (DSDV)

- Assume that node X receives routing information from Y about a route to node Z

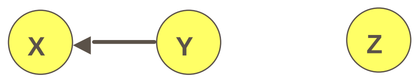


- Let S(X) and S(Y) denote the destination sequence number for node Z as stored at node X, and as sent by node Y with its routing table to node X, respectively

50

Destination-Sequenced Distance-Vector (DSDV)

- Node X takes the following steps:



  - If S(X) > S(Y), then X ignores the routing information received from Y
  - If S(X) = S(Y), and cost of going through Y is smaller than the route known to X, then X sets Y as the next hop to Z
  - If S(X) < S(Y), then X sets Y as the next hop to Z, and S(X) is updated to equal S(Y)

51

Wireless Routing Protocol (WRP) [Mur96]

- Again, improves over the Bellman-Ford distance-vector protocol
  - It reduces amount of route looping, and has a mechanism to ensure reliable exchange of update messages
- Each node maintains a distance-table matrix
  - contains all destination nodes,
  - all neighbors through which the destination node can be reached
  - For each neighbor-destination pair, if a route exists, the route length is recorded
- Each node neighbor broadcasts its current best route to selected destinations on an event driven incremental basis
  - acknowledgments are expected from all neighbor nodes
  - If some acknowledgments are missing, the broadcast will be repeated, with a *message retransmission list* specifying the subset of neighbors that need to respond

52

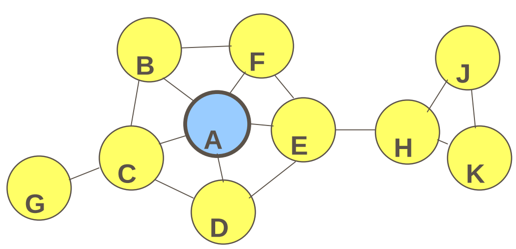
Optimized Link State Routing (OLSR) [Jac00]

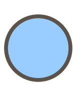
- It's a link-state protocol where the link information is disseminated through an efficient flooding technique
- The overhead of flooding link state information is reduced by requiring fewer nodes to forward the information
- A broadcast from node X is only forwarded by its *multipoint relays*
- Multipoint relays of node X are its neighbors such that each two-hop neighbor of X is a one-hop neighbor of at least one multipoint relay of X
  - Each node transmits its neighbor list in periodic beacons, so that all nodes can know their 2-hop neighbors, in order to choose the multipoint relays

53

Optimized Link State Routing (OLSR)

- Nodes C and E are multipoint relays of node A



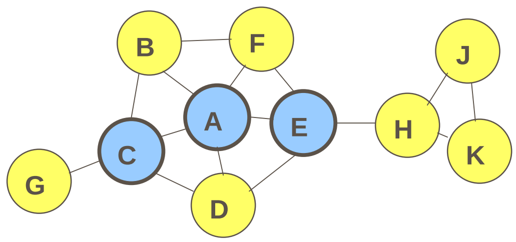


Node that has broadcast state information from A

54

Optimized Link State Routing (OLSR)

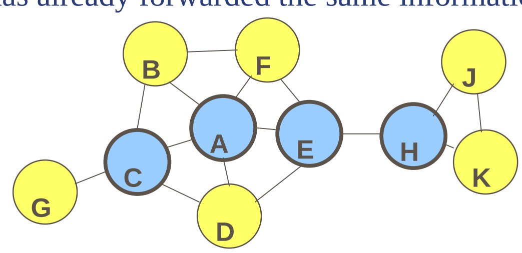
- Nodes C and E forward information received from A



Node that has broadcast state information from A

Optimized Link State Routing (OLSR)

- Nodes E and K are multipoint relays for node H
- Node K forwards information received from H
  - E has already forwarded the same information once



Node that has broadcast state information from A

Optimized Link State Routing (OLSR)

- OLSR floods information through the multipoint relays
- The flooded itself is fir links connecting nodes to respective multipoint relays
- Routes used by OLSR only include multipoint relays as intermediate nodes

Mobile Ad hoc Networks

III. Routing Protocols

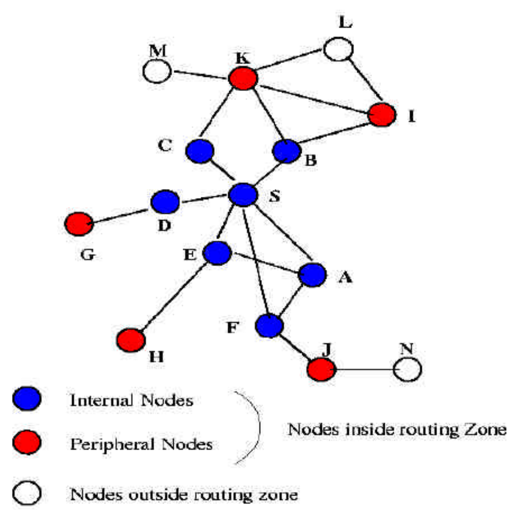
3. Hybrid protocols

Zone Routing Protocol (ZRP) [Pea99]

- ZRP combines proactive and reactive approaches
- All nodes within hop distance at most *d* from a node X are said to be in the routing zone of node X
- All nodes at hop distance exactly *d* are said to be peripheral nodes of node X's routing zone
- Intra-zone routing: Proactively maintain routes to all nodes within the source node's own zone.
- Inter-zone routing: Use an on-demand protocol (similar to DSR or AODV) to determine routes to outside zone.

59

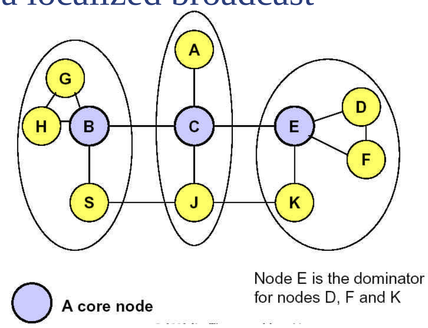
Zone Routing Protocol (ZRP) [Pea99]



60

Core-Extraction Distributed Ad hoc Routing (CEDAR) [Siv99]

- A subset of nodes in the network is identified as the *core*
- Each node in the network must be adjacent to at least one node in the core
- Each core node determines paths to nearby core nodes by means of a localized broadcast



Location-Aided Routing (LAR) [Ko98]

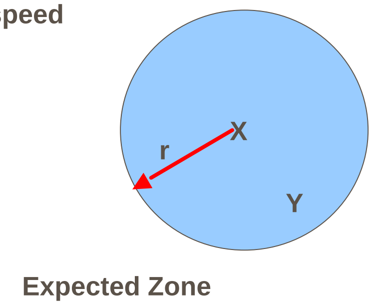
- Exploits location information to limit scope of route request flood
  - Location information may be obtained using GPS
- *Expected Zone* is determined as a region that is expected to hold the current location of the destination
  - Expected region determined based on potentially old location information, and knowledge of the destination's speed
- Route requests limited to a *Request Zone* that contains the Expected Zone and location of the sender node

Expected Zone in LAR

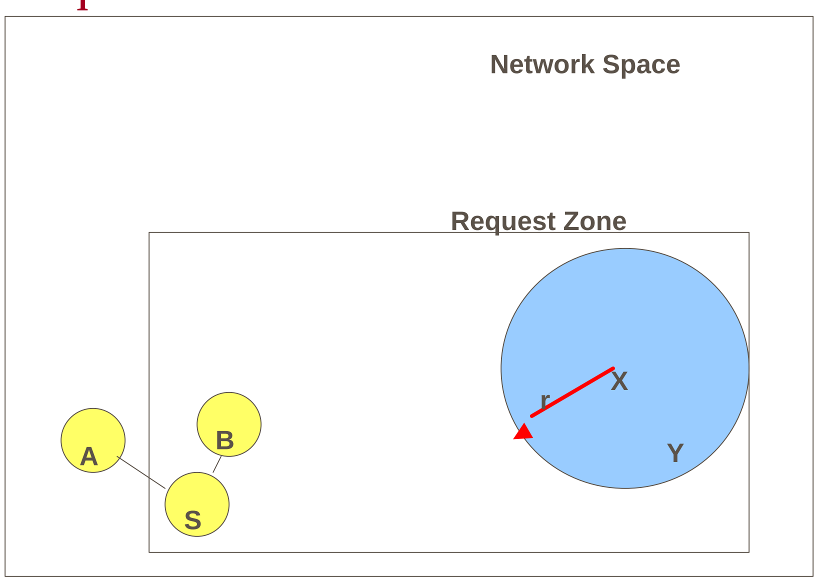
X = last known location of node D, at time t0

Y = location of node D at current time t1, unknown to node S

r = (t1 - t0) * estimate of D’s speed



Request Zone in LAR



LAR

- Only nodes within the request zone forward route requests
  - Node A does not forward RREQ, but node B does (see previous slide)
- Request zone explicitly specified in the route request
- Each node must know its physical location to determine whether it is within the request zone

65

LAR

- Only nodes within the request zone forward route requests
- If route discovery using the smaller request zone fails to find a route, the sender initiates another route discovery (after a timeout) using a larger request zone
  - the larger request zone may be the entire network
- Rest of route discovery protocol similar to DSR

66

Other Routing Protocols

- Plenty of other routing protocols
- Discussion here is far from exhaustive

67

Mobile Ad hoc Networks

IV. Transport Issues

User Datagram Protocol (UDP)

- UDP provides unreliable delivery
- Studies comparing different routing protocols for MANET typically measure UDP performance
- Several performance metrics are often used
  - Routing overhead per data packet
  - Packet loss rate
  - Packet delivery delay

69

UDP Performance

- Several relevant studies [Broch98Mobicom,Das9ic3n,Johansson99Mobicom,Das00Infocom,Jacquet00Inria]
- Results comparing a specific pair of protocols do not always agree, but some general (and intuitive) conclusions can be drawn
  - Reactive protocols may yield lower routing overhead than proactive protocols when communication density is low
  - Reactive protocols tend to loose more packets (assuming than network layer drops packets if a route is not known)
  - Proactive protocols perform better with high mobility and dense communication graph

70

UDP Performance

- Many variables affect performance
  - Traffic characteristics
    - one-to-many, many-to-one, many-to-many
    - small bursts, large file transfers, real-time, non-real-time
  - Mobility characteristics
    - low/high rate of movement
    - do nodes tend to move in groups
  - Node capabilities
    - transmission range (fixed, changeable)
    - battery constraints
  - Performance metrics
    - delay
    - throughput
    - latency
    - routing overhead
  - Static or dynamic system characteristics (listed above)

71

UDP Performance

- Difficult to identify a single scheme that will perform well in all environments
- Holy Grail: Routing protocol that dynamically adapts to all environments so as to optimize "performance"
  - Performance metrics may differ in different environments

72

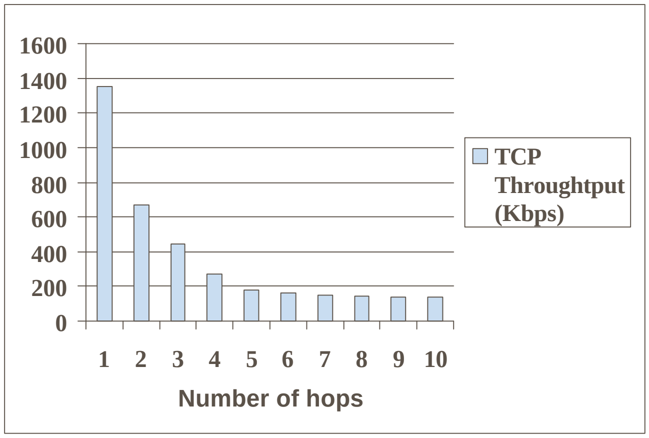
Transmission Control Protocol (TCP)

- Reliable ordered delivery
- Implements congestion avoidance and control
- Reliability achieved by means of retransmissions if necessary

Throughput over Multi-Hop Wireless Paths [Gerla99]

- Connections over multiple hops are at a disadvantage compared to shorter connections, because they have to contend for wireless access at each hop

Impact of Multi-Hop Wireless Paths [Holland99]



TCP Throughput using 2 Mbps 802.11 MAC

75

Throughput Degradations with Increasing Number of Hops

- Packet transmission can occur on at most one hop among three consecutive hops
  - Increasing the number of hops from 1 to 2, 3 results in increased delay, and decreased throughput
- Increasing number of hops beyond 3 allows simultaneous transmissions on more than one link, however, degradation continues due to contention between TCP Data and Acks traveling in opposite directions
- When number of hops is large enough, the throughput stabilizes due to *effective pipelining*

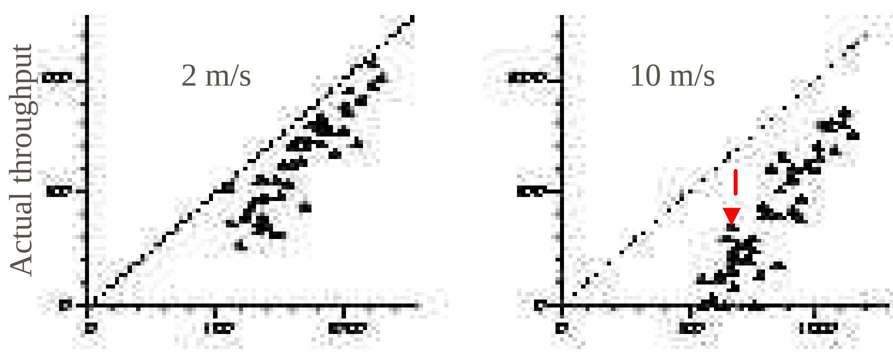
76

Ideal Throughput

- *f(i)* = fraction of time for which shortest path length between sender and destination is *I*
- *T(i)* = Throughput when path length is *I*
  - From previous figure
- Ideal throughput = Σ *f(i)* * *T(i)*

77

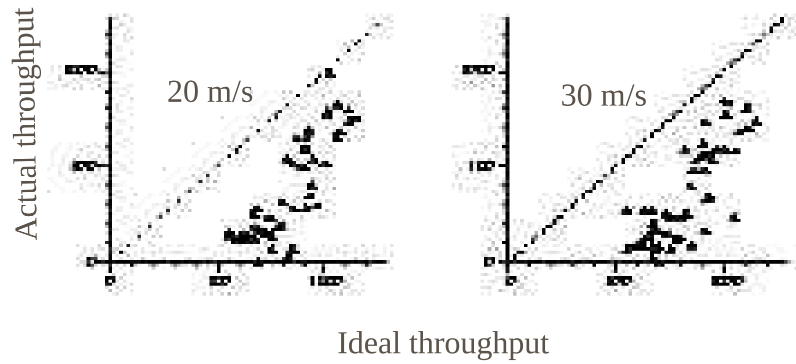
Impact of Mobility
TCP Throughput



Ideal throughput (Kbps)

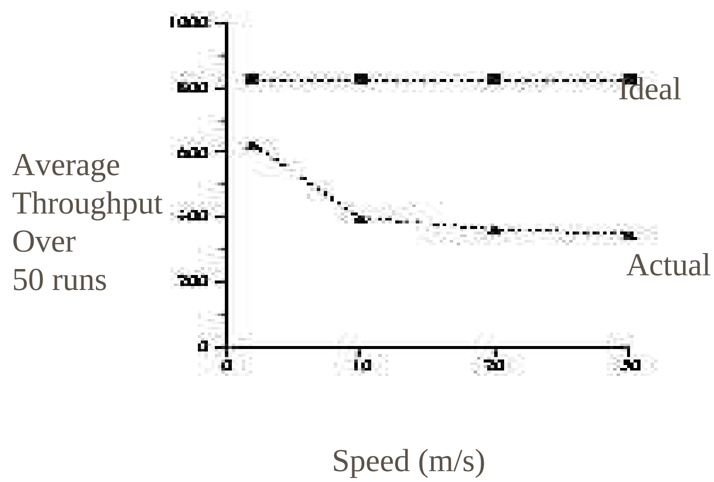
78

Impact of Mobility



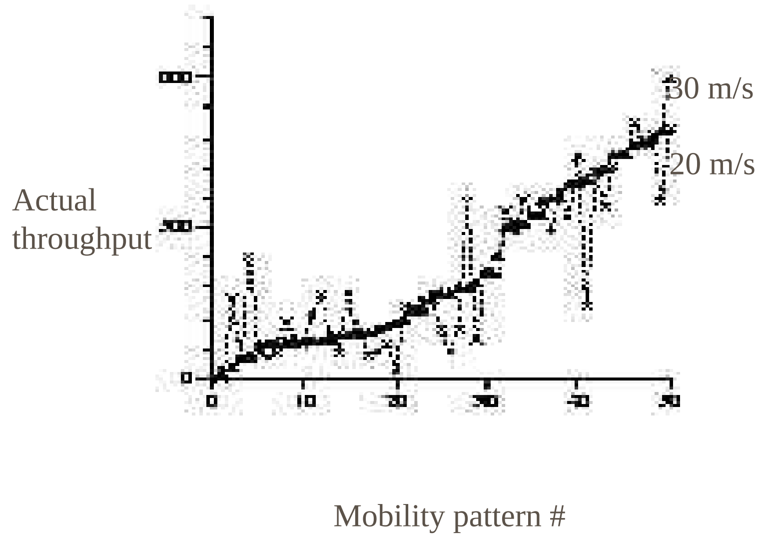
79

Throughput generally degrades with increasing speed …



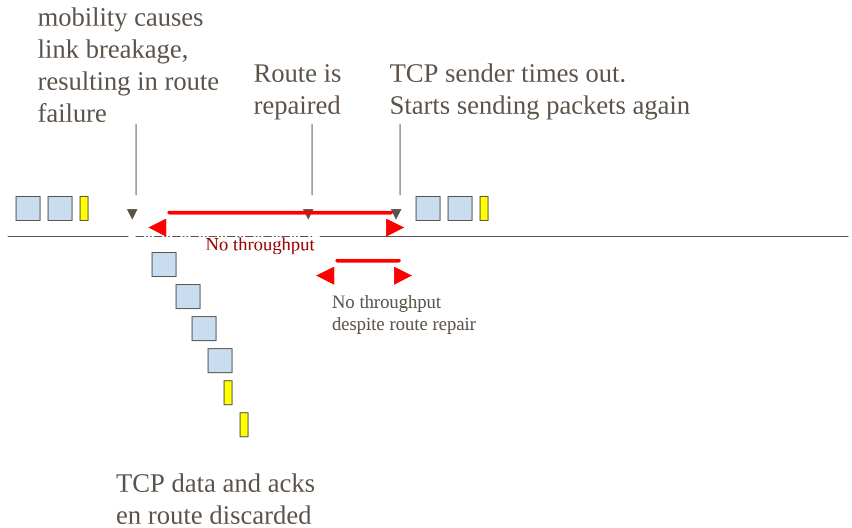
80

But not always …



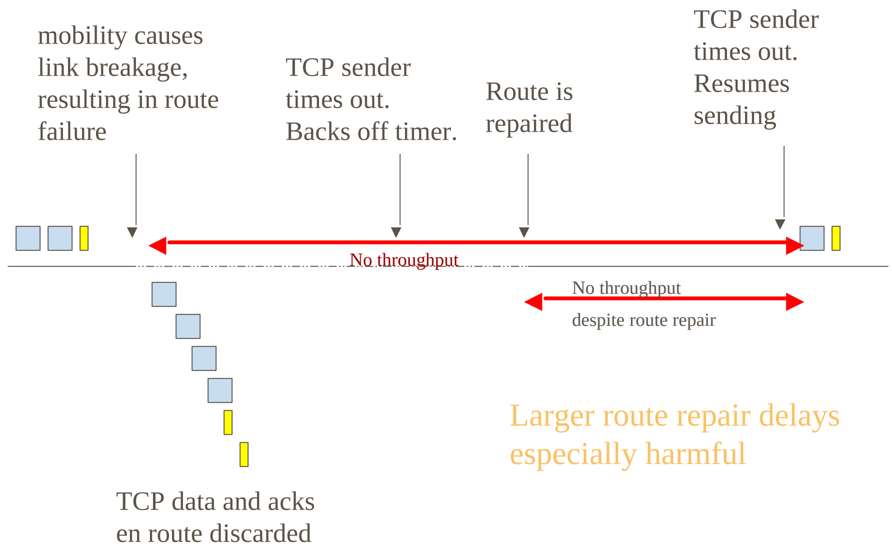
81

Why Does Throughput Degrade?



82

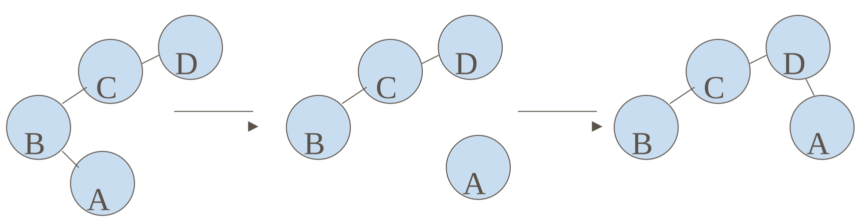
Why Does Throughput Degrade?



Larger route repair delays especially harmful

83

Why Does Throughput Improve? Low Speed Scenario



1.5 second route failure

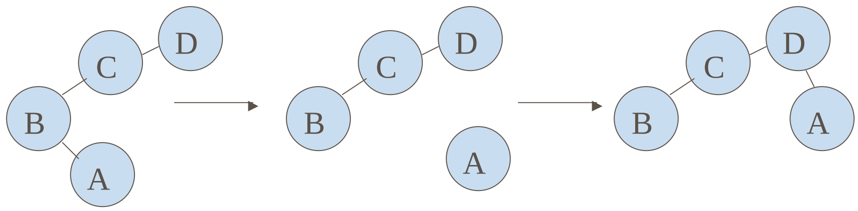
Route from A to D is broken for ~1.5 second.

When TCP sender times after 1 second, route still broken.

TCP times out after another 2 seconds, and only then resumes.

84

Why Does Throughput Improve? Higher (double) Speed Scenario



0.75 second route failure

Route from A to D is broken for ~ 0.75 second.

When TCP sender times after 1 second, route is repaired.

85

Why Does Throughput Improve? General Principle

- The previous two slides show a plausible cause for improved throughput
- TCP timeout interval somewhat (not entirely) independent of speed
- Network state at higher speed, when timeout occurs, may be more favorable than at lower speed
- Network state
  - Link/route status
  - Route caches
  - Congestion

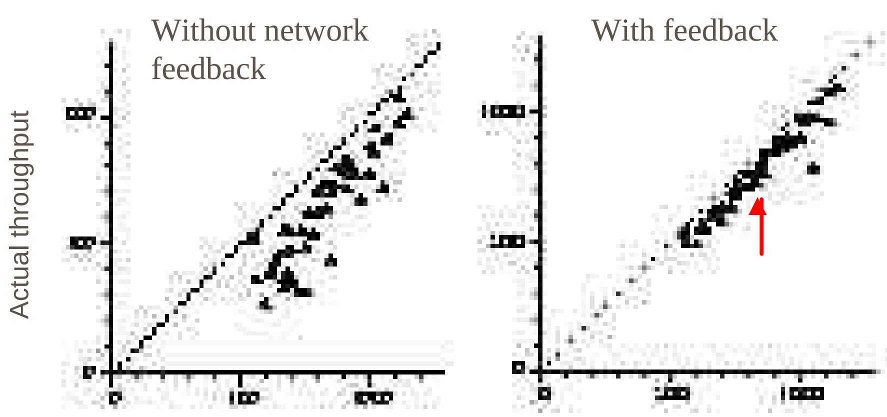
86

How to Improve Throughput (Bring Closer to Ideal)

- Network feedback
- Inform TCP of route failure by explicit message
- Let TCP know when route is repaired
  - Probing
  - Explicit notification
- Reduces repeated TCP timeouts and backoff

87

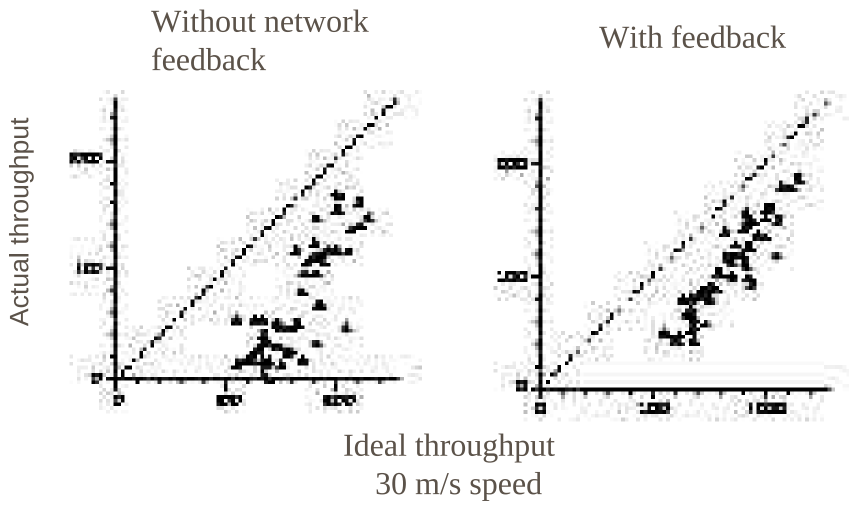
Performance Improvement



Ideal throughput
2 m/s speed

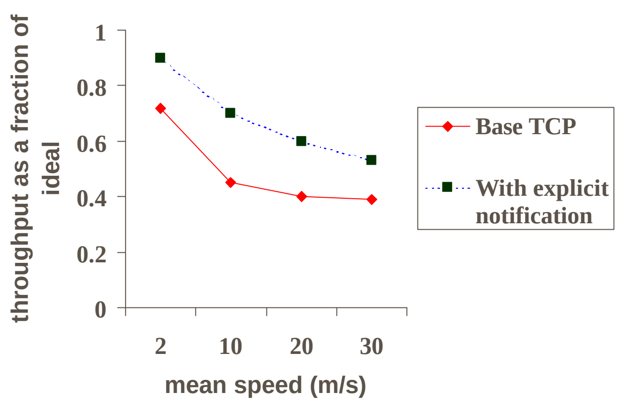
88

Performance Improvement



89

Performance with Explicit Notification

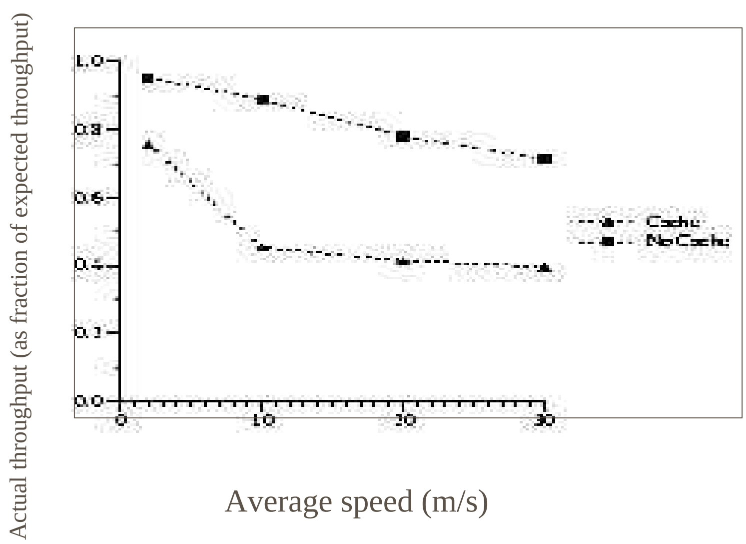


90

Impact of Caching

- Route caching has been suggested as a mechanism to reduce route discovery overhead [Broch98]
- Each node may cache one or more routes to a given destination
- When a route from S to D is detected as broken, node S may:
  - Use another cached route from local cache, or
  - Obtain a new route using cached route at another node

To Cache or Not to Cache



Why Performance Degrades With Caching

- When a route is broken, route discovery returns a cached route from local cache or from a nearby node
- After a time-out, TCP sender transmits a packet on the new route.

  However, the cached route has also broken after it was cached

timeout due to route failure | **timeout, cached route is broken** | **timeout, second cached route also broken**

- Another route discovery, and TCP time-out interval
- Process repeats until a good route is found

93

Issues
To Cache or Not to Cache

- Caching can result in faster route “repair”
- Faster does not necessarily mean correct
- If incorrect repairs occur often enough, caching performs poorly
- Need mechanisms for determining when cached routes are stale

94

Caching and TCP performance

- Caching can reduce overhead of route discovery even if cache accuracy is not very high
- But if cache accuracy is not high enough, gains in routing overhead may be offset by loss of TCP performance due to multiple time-outs

TCP Performance

Two factors result in degraded throughput in presence of mobility:

- Loss of throughput that occurs while waiting for TCP sender to timeout (as seen earlier)
  - This factor can be mitigated by using explicit notifications and better route caching mechanisms
- Poor choice of congestion window and RTO values after a new route has been found
  - How to choose *cwnd* and *RTO* after a route change?

Issues
Window Size After Route Repair

- Same as before route break: may be too optimistic
- Same as startup: may be too conservative
- Better be conservative than overly optimistic
  - Reset window to small value after route repair
  - Let TCP figure out the suitable window size
  - Impact low on paths with small delay-bw product

Issues
RTO After Route Repair

- Same as before route break
  - If new route long, this RTO may be too small, leading to timeouts
- Same as TCP start-up (6 second)
  - May be too large
  - May result in slow response to next packet loss
- Another plausible approach: new RTO = function of old RTO, old route length, and new route length
  - Example: new RTO = old RTO * new route length / old route length
  - Not evaluated yet
  - Pitfall: RTT is not just a function of route length

Mobile Ad hoc Networks

V. Security Issues

Security Issues in Mobile Ad Hoc Networks

- Not much work in this area as yet
- Many of the security issues are same as those in traditional wired networks and cellular wireless
- What's new ?

100

What's New ?

- Wireless medium is easy to snoop on
- Due to ad hoc connectivity and mobility, it is hard to guarantee access to any particular node (for instance, to obtain a secret key)
- Easier for trouble-makers to insert themselves into a mobile ad hoc network (as compared to a wired network)

101

Resurrecting Duckling

- Battery exhaustion threat: A malicious node may interact with a mobile node often with the goal of draining the mobile node's battery
- Authenticity: Who can a node talk to safely?
  - Resurrecting duckling: Analogy based on a duckling and its mother. Apparently, a duckling assumes that the first object it hears is the mother
  - A mobile device will trust first device which sends a secret key

102

Secure Routing

- Attackers may inject erroneous routing information
- By doing so, an attacker may be able to divert network traffic, or make routing inefficient
- Suggests use of digital signatures to protect routing information and data both
- Such schemes need a Certification Authority to manage the private-public keys

103

Secure Routing

- Establishing a Certification Authority (CA) difficult in a mobile ad hoc network, since the authority may not be reachable from all nodes at all times
- Suggests distributing the CA function over multiple nodes

104

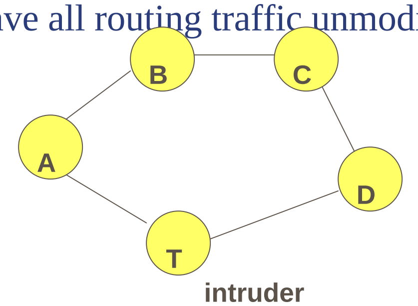
MANET Authentication Architecture

- Digital signatures to authenticate a message
- Key distribution via certificates
- Need access to a certification authority
- Specifies message formats to be used to carry signature, etc.

105

Techniques for Intrusion-Resistant Ad Hoc Routing Algorithms (TIARA)

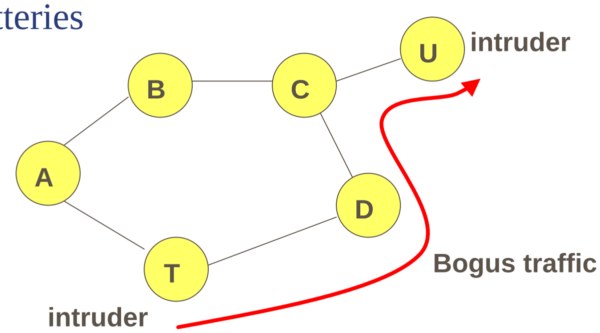
- Flow disruption attack: Intruder (or compromised) node T may delay/drop/corrupt all data passing through, but leave all routing traffic unmodified



106

Techniques for Intrusion-Resistant Ad Hoc Routing Algorithms (TIARA)

- Resource Depletion Attack: Intruders may send data with the objective of congesting a network or depleting batteries



107

Intrusion Detection

- Detection of abnormal routing table updates
  - Uses “training” data to determine characteristics of normal routing table updates (such as rate of change of routing info)
  - Efficacy of this approach is not evaluated, and is debatable
- Similar abnormal behavior may be detected at other protocol layers
  - For instance, at the MAC layer, *normal* behavior may be characterized for access patterns by various hosts
  - Abnormal behavior may indicate intrusion
- Solutions proposed in [Zhang00Mobicom] are preliminary, not enough detail provided

108

Mobile Ad hoc Networks

VI. Conclusion

In Conclusion

- Issues other than routing have received much less attention
- **Other interesting problems:**
  - Applications for MANET
  - Address assignment
  - QoS issues
  - Improving interaction between protocol layers

Thank You

References

- [Bal97] A. Ballardie, "Core Based Trees (CBT Version 2) Multicast Routing – Protocol Specification," *RFC-2189,* September 1997
- [Bas98] S. Basagni, I. Chlamtac, V.R. Syrotiuk, and B.A. Woodward, "A Distance Routing Effect Algorithm for Mobility (DREAM)," *ACMIEEE MobiCom,* Dallas, Texas, 1998
- [Bel92] S.M. Bellovin and M. Merritt, “Encrypted Key Exchange: Password-based Protocols secure against dictionary attacks,” *IEEE SympSecurity and Privacy,* May 1992
- [Bel99] B. Bellur and R.G. Ogier, "A Reliable, Efficient Topology Broadcast Protocol for Dynamic Networks," *IEEE INFOCOM*, New York, March 1999
- [Ber92] D. Bertsekas and R. Gallager, *Data Networks,* Second Edition, Prentice Hall, Inc., 1992
- [Bha94] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A media access protocol for wireless LAN's," in Proc*. ACM SIGCOMM'94*, pp.212-225, 1994
- [Bia00] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," in *IEEE J.S.A.C.*, vol.18, no.3, pp.535-547, Mar.2000
- [Bla99] M. Blaze, J. Feigenbaum, J. Ioannidis, A.D. Keromytis, “The KeyNote Trust-Management System,” RFC 2074, *IETF,* September 1999
- [Bom98] Bommaiah, McAuley, Talpade, and Liu. AMRoute: Ad hoc multicast routing protocol, Internet-Draft, *IETF,* August 1998
- [Bri00] L. Briesemeister and G. Hommel, "Role-Based Multicast in Highly Mobile but sparsely Connected Ad Hoc Networks", *2000 First Annual Workshop on Mobile and Ad Hoc Networking and Computing,* 2000, pp. 45-50

References

- [Bro98] J. Broch, D.A. Maltz, D.B. Johnson, Y.-CH, J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," *ACM/IEEE MobiCom*, pp85-97, 1998
- [But00] L. Buttyan and J.P. Hubaux, "Enforcing Service Availability in Mobile Ad Hoc WANs,"*1st MobiHoc,* Boston, Massachusetts, August 2000
- [Che89] C. Cheng, R. Reley, S.P.R. Kumar and J.J. Garcia-Luna-Aceves, "A Loop-Free Extended Bellman-Ford Routing Protocol without Bouncing Effect," *ACM Computer Communications Review,* vol. 19, no. 4, 1989, pp. 224-236
- [Che98] T.-W. Chen and M. Gerla, "Global State Routing: A New Routing Scheme for Ad-hoc Wireless Networks," *IEEE ICC,* pp171-175, June 1998
- [Chi97a] C.-C. Chiang, H.-K. Wu, W. Liu, M. Gerla, "Routing in Clustered Multihop, Mobile Wireless Networks with Fading Channel,*" IEEE Singapore International Conference on Networks*, 1997
- [Chi97b] C. Chiang, M. Gerla, and L. Zhang, "Shared tree wireless network multicast", *IEEE International Conference on Computer Communications and Networks (ICCCN'97),* September 1997
- [Cho91] C.-H. Chow, "On multicast path finding algorithms," Proceedings of the *IEEE INFOCOM '91,* pp. 1274-1283, 1991
- [Com00] G. D. Kondylis, S. V. Krishnamurthy, S. K. Dao and G. J. Pottie, "Multicasting Sustained CBR and VBR Traffic in Wireless Ad Hoc Networks", *International Conference on Communications*, 2000. pp 543-549

113

References

- [Cor95] M.S. Corson and A. Ephremides, "A Distributed Routing Algorithm for Mobile Wireless Networks," *ACM/Baltzer Wireless Networks*, vol.1, no.1, pp.61-81, February 1995
- [Das00] S.R. Das, C.E. Perkins, and E.M. Royer, "Performance comparison of two on-demand routing protocols for ad hoc networks," *IEEE INFOCOM*, vol.1, pp.3-12, March 2000
- [Dee96] S. E. Deering, D. Estrin, D. Farinacci, V. Jacobson, C-G Liu and L. Wei, "An Architecture for Wide-Area Multicast Routing," *IEEE/ACM Transactions on Networking*, Vol. 4, No. 2, pp. 153-162, April 1996
- [Dro97] R. Droms, "Dynamic Host Configuration Protocol," IETF RFC 2131, Mar. 1997.
- [Dub97] R. Dube, C.D. Rais, K.-Y. Wang, S.K. Tripathi, "Signal stability-based adaptive routing (SSA) for ad hoc mobile networks," *IEEE Personal Communications*, vol.4, no.1, pp.36-45, February 1997
- [Eph87] A. Ephremeides, J.E. Wieselthier, and D.J. Baker, "A Design Concept for Reliable Mobile Radio Networks with Frequency Hopping Signaling," *Proceedings of the IEEE*, vol.75, no.1, January 1987
- [Fee01] L.M. Feeney, B. Ahlgren, A. Westerlund, "Spontaneous Networking: An Application-Oriented Approach to Ad Hoc Networking," *IEEE Communications Magazine*, vol.39,no.6, pp.176-181, June 2001
- [Ful94] C.L. Fullmer, J.J. Garcia-Luna-Aceves, "Floor acquisition multiple access (FAMA) for packet-radio networks," in Proc. *ACM SIGCOMM'95*, pp.262-273, 1995
- [Ful97] C.L. Fullmer, J.J. Garcia-Luna-Aceves, "Solutions to hidden terminal problems in wireless networks," in Proc. *ACM SIGCOMM'97*, pp.39-49, 1997
- [Gaf81] E. Gafni and D. Bertsekas, "Distributed Algorithms for Generating Loop-Free Routes in Networks with Frequently Changing Topology," *IEEE Transactions on Communications*, vol.29, no.1, pp.11-15, January 1981

114

References

- [Gar93] J.J. Garcia-Luna-Aceves, “Loop-Free Routing Using Diffusing Computations,” *IEEE/ACM Transactions on Networking,* vol. 1, no. 1, February 1993, pp. 130-141
- [Gar98] J.J. Garcia-Luna-Aceves, and E.L. Madruga, "The Core-assisted mesh protocol," *IEEE Journal on Selected Areas in Communications, Special Issue on Ad-Hoc Networks*, vol.17, no.8, August 1998
- [Ger95] M. Gerla and T.C. Tsai, "Multiuser, mobile multimedia radio network," *ACM/Balzer Journal of Wireless Networks*, 1995
- [Ger99] M. Gerla, K. Tang and R. Bagrodia, "TCP Performance in Wireless Multi-hop Networks," in *Mobile Computing Systems and Applications*, pp.41-50, 25-26 Feb.1999
- [Gla99] J.J. Garcia-Luna-Aceves and M. Spohn, "Source-Tree Routing in Wireless Networks,",*IEEE ICNP 99: 7th International Conference on Network Protocols*, Toronto, Canada,October 1999
- [Glo99] *http://www.scienceforum.com/glomo/*
- [Gue01] M. Guerrero, “Secure AODV”, Internet draft sent to manet@itd.nrl.navy.mil mailing list, Aug. 2001
- [Haa01a] Z.J. Haas, M. Perlman, P. Samar, “The Interzone Routing Protocol (IERP) for Ad Hoc Networks,” draft-ietf-manet-zone-ierp-01.txt, IETF MANET Working Group, June 1st, 2001.
- [Haa01b] Z. J. Haas, M. Perlman, “The Performance of Query Control Schemes of the Zone Routing Protocol” IEEE/ACM Transactions on Networking, vol. 9, no. 4, pp. 427-438, Aug. 2001
- [Haa02] Z.J. Haas and J. Deng, "Dual Busy Tone Multiple Access (DBTMA): A Multiple Access Control Scheme for Ad Hoc Networks," *IEEE Transactions of Communications,* to Appear [Hat01] M. Hattig, Editor, “Zero-conf IP Host Requirements,” draft-ietf-zeroconf-reqts-09.txt, IETF MANET Working Group, Aug. 31st, 2001.

115

References

- [IEE99] IEEE Std 802.11, “Wireless LAN Media Access Control (MAC) and Physical Layer (PHY) Specifications,” *IEEE,* 1999
- [Iwa99] A. Iwata, C.-C. Chiang, G. Pei, M. Gerla, and T.-W. Chen, "Scalable Routing Strategies for Ad Hoc Wireless Networks," *IEEE Journal on Selected Areas in Communications, Special Issue on Wireless Ad Hoc Networks,* vol.17, no.8, pp.1369-1379, August 1999
- [Jac98] P. Jacquet, P. Muhlethaler, and A. Qayyum, "Optimized Link State Routing Protocol,” *IETF MANET*, Internet Draft, Nov. 1998
- [Jac00] P. Jacquet, P. Muhlethaler, A. Qayyum, A. Lanouiti, L. Viennot, and T. Clausen, *IETF MANET Internet Draft "draft-ietf-MANET-olsr-02.txt,"* July 2000.
- [Jia99] M. Jiang, J. Li, and Y.C. Tay, *IETF MANET Internet Draft "draft-ietf-MANET-cbrp-spec-01.txt,"* August 1999
- [Joa99] M. Joa-Ng and I.-T. Lu, "A Peer-to-Peer Zone-Based Two-Level Link State Routing for Mobile Ad Hoc Networks," *IEEE Journal on Selected Areas in Communications, Special Issue on Wireless Ad Hoc Networks,* vol.17, no.8, pp.1415-1425, August 1999
- [Joh96] D.B. Johnson and D.A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks," in Mobile Computing, edited by T. Imielinski and H. Korth, chapter 5, pp.153-181, Kluwer Academic Publishers, 1996
- [Joh99] P. Johansson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark, "Scenariobased performance analysis of routing protocols for mobile ad-hoc networks,"*ACM/IEEE MobiCom,* pp.195-206, August 1999.
- [Jub87] J. Jubin and J.D. Tornow, " The DARPA packet radio network protocols,*" Proceedings of IEEE (Special Issue on Packet Radio Networks)*, vol.75, pp.21-32, January 1987

116

References

- [Kad83] B. Kadaba and J. M. Jaffe. "Routing to multiple Destinations in Computer Networks,“ *IEEE Transactions on Communications*, vol. com-31, no. 3, pp. 343-351, March 1983
- [Kar90] P. Karn, "MACA - A new channel access method for packet radio," in *ARRL/CRRL Amateur Radio 9th Computer Networking Conference,* pp.134-140, 1990
- [Ker74] A. Kershenbaum and W. Chou, "A Unified Algorithm for Designing Multidrop Teleprocessing Networks," *IEEE Transactions on Communications,* vol. COM-22, pp.1762-1772, Nov. 1974
- [Ko98] Y.-B. Ko and N.H. Vaidya, "Location-Aided Routing (LAR) in Mobile Ad Hoc Networks," *ACM/IEEE MobiCom,* Dallas, Texas, 1998
- [Kom93] V. P. Kompella, J. C. Pasquale, and G. C. Polyzos, "Multicast routing for multimedia communication," *IEEE/ACM Transactions on Networking,* Vol. 1, No. 3, pp. 286-292,June 1993
- [Kon00] G.D. Kondylis, S.V. Krishnamurthy, S.K. Dao, and G.J. Pottie, "Multicasting Sustained CBR and VBR Traffic in Wireless Ad Hoc Networks", *International Conference on Communications,* 2000, pp.543-549
- [Lam81] L. Lamport, “Password Authentication with Insecure Communication,” *Communications of the ACM, 24 (11),* pp.770-772, November 1981
- [Lee00] S. Lee and C. Kim, "Neighbor Supporting Ad Hoc Multicast Routing Protocol", *2000 First Annual Workshop on Mobile and Ad Hoc Networking and Computing,* 2000, pp. 37-44
- [Lee99] S.-J. Lee, M. Gerla, and C.-C. Chiang, "On-Demand Multicast Routing Protocol", *IEEE WCNC'99*, New Orleans, LA, September 1999, pp.1298-1304
- [Mar00] S. Marti, T.J. Giuli, K. Lai, M. Baker, “Mitigating Routing Misbehavior in Mobile Ad Hoc Networks,” *6th MobiCom,* Boston, Massachusetts, August 2000

117

References

- [Mur95] S Murthy and J.J. Garcia-Luna-Aceves, “A Routing Protocol for Packet Radio Networks,” Proc. of ACM Mobile Computing and Networking Conference, *MOBICOM’95,* Nov. 14-15, 1995
- [Mur96] S. Murthy and J.J. Garcia-Luna-Aceves, "An Efficient Routing Protocol for Wireless Networks," *ACM Mobile Networks and Applications Journal, Special Issue on Routing in Mobile Communication Networks,* October 1996
- [Nik00] N. Nikaein, H. Labiod, and C. Bonnet, "DDR-Distributed Dynamic Routing Algorithm for Mobile Ad hoc Networks," *First Annual Workshop on Mobile and Ad Hoc Networking and Computing (MobiHOC),* August 2000
- [NIS93] FedInfProcStandards, “Secure Hash Standard,” Pub180, *NIST,* May 1993
- [Pap02a] P. Papadimitratos and Z.J. Haas, “Secure Message Transmission in Mobile Ad Hoc Networks,” submitted for publication.
- [Pap02b] P. Papadimitratos and Z.J. Haas, “Secure Routing for Mobile Ad Hoc Networks,” *SCS Communication Networks and Distributed Systems Modeling and Simulation Conference (CNDS 2002),* San Antonio, TX, January 27-31, 2002.
- [Par97] V.D. Park and M.S. Corson, “A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks,” *IEEE INFOCOM ’97*, Kobe, Japan, 1997
- [Par00] V. Park and M.S. Corson, *IETF MANET Internet Draft "draft-ietf-MANET-tora-spec-03.txt,"* November 2000
- [Pau98] S. Paul, Multicasting on the Internet and its Applications, Kluwer Academic Publishers, 1998
- [Pea99] M.R. Pearlman and Z.J. Haas, "Determining the Optimal Configuration for the Zone Routing Protocol," *IEEE Journal on Selected Areas in Communications, Special Issueon Wireless Ad Hoc Networks,* vol.17, no.8, pp.1395-1414, August 1999
- [Pei00] G. Pei, M. Gerla and X. Hong, "LANMAR: Landmark Routing for Large Scale Wireless

118

References

- Ad Hoc Networks with Group Mobility," *First Annual Workshop on Mobile and Ad Hoc Networking and Computing (MobiHOC),* August 2000
- [Per01] Ad Hoc Networking, C.E. Perkins, editor, Addison-Wesley Longman, 2001
- [Per94] C.E. Perkins and P. Bhagwat, "Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers," *ACM SIGCOMM: Computer Communications Review,* vol.24, no.4, pp.234-244, October 1994
- [Per96] C. Perkins, "IP Mobility Support," RFC 2002, *IETF,* October 1996
- [Per99] C.E. Perkins and E.M. Royer, "Ad-hoc On-Demand Distance Vector Routing," *Second IEEE Workshop on Mobile Computing Systems and Applications,* pp.90-100, February 1999
- [Pos81] J. Postel, "Internet Control Message Protocol," RFC 792, *IETF,* September 1981
- [Ram98] R. Ramanathan and M. Steenstrup, "Hierarchically-organized, multihop mobile wireless networks for quality-of-service support," *ACM/Baltzer Mobile Networks and Applications*, vol.3, no.1, pp.101-119, 1998
- [Riv78] R. Rivest, A. Shamir, L. Adleman, "A method for obtaining Digital Signatures and Public Key Cryptosystems," Comm. of ACM, 21 (2), pp. 120-126, Feb. 1978.
- [Roy99a] E.M. Royer and C.-K. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," *IEEE Personal Communications,* April 1999
- [Roy99b] E. Royer and C.E. Perkins "Multicast operation of ad-hoc, on-demand distance vector routing protocol," *ACM/IEEE MobiCom ' 99*, August 1999
- [Rup97] R. Ruppe and S. Griswald, "Near Term Digital Radio (NTDR) System," *IEEE MILCOM,* vol.3, pp.1282-1287, November 1997
- [San00] C. Santivanez, "Asymptotic Behavior of Mobile Ad Hoc Routing Protocols with Respect to Traffic, Mobility and Size," Technical Report TR-CDSP0052, *Department of Electrical and Computer Engineering,* Northeastern University, Boston, MA

References

- [San98] C. Sankaran and A. Ephremides, "Multicasting with Multiuser detection in Ad-Hoc Wireless Networks", *Conference on Information Sciences and Systems(CISS),* 1998, pp.47-54
- [Sha87] N. Shacham and J. Westcott, "Future directions in packet radio architectures and protocols," *Proceedings of IEEE (Special Issue on Packet Radio Networks),* vol.75, pp.83-99, January 1987
- [Sha96] J. Sharony, "An Architecture for Mobile Radio Networks with Dynamically Changing Topology Using Virtual Subnets," *ACM Mobile Networks and Applications,* vol.1, no.1, pp.75-86, 1996
- [Sin99] P. Sinha, R. Sivakumar and V. Bharghavan, "MCEDAR: Multicast Core-Extraction Distributed Ad hoc Routing", *Wireless Communications and Networking Conference,* 1999, pp.1313-1318
- [Siv99] R. Sivakumar, P. Sinha, and V. Bharghavan, "CEDAR: A Core-Extraction Distributed Ad Hoc Routing Algorithm," *IEEE Journal on Selected Areas in Communications, Special Issue on Wireless Ad Hoc Networks,* vol.17, no.8, pp.1454-1465, August 1999
- [Sta99] F. Stajano and R. Anderson, "The Resurrecting Duckling: Security Issues for Ad Hoc Wireless Networks," Security Protocols, *7th International Workshop,* LNCS, Springer-Verlag, 1999
- [Tob75] F.A. Tobagi and L. Kleinrock, "Packet switching in radio channels: part II - The hidden terminal problem in carrier multiple-access and the busy-tone solution," *IEEE Transactions on Communications,* vol. COM-23, no.12, pp.1417-1433, December 1975
- [Toh97] C.K. Toh, "Associativity-Based Routing for Ad-Hoc Mobile Networks, " Wireless Personal Communications, Vol. 4, No. 2, pp. 1-36, Mar. 1997.
- [Tsu88] P.F.Tsuchiya, "The Landmark Hierarchy: a new hierarchy for routing in very large networks," *Computer Communication Review*, vol.18, no.4, August 1988, pp.35-42

References

- [Wax93] B. M. Waxman, "Performance Evaluation of Multipoint Routing Algorithms,“ Proceedings of *IEEE INFOCOM '93,* pp. 980-986, 1993
- [Wie99] J.E. Wieselthier, G.D. Nguyen, and A. Ephremides, "Algorithms for Energy-Efficient Multicasting in Ad Hoc Wireless Networks", *IEEE Military Communications Conference (MILCOM),* 1999, pp.1414-1418
- [Wu87] C. Wu and V.O.K. Li, "Receiver-initiated busy-tone multiple access in packet radio networks," in Proc*. ACM SIGCOMM'87*, pp.336-342, 1987
- [Wu99] C.W. Wu and Y.C. Tay, "AMRIS: A Multicast Protocol for Ad hoc Wireless Networks,“ *IEEE MILCOM '99,* Atlantic City, NJ, November 1999
- [Xu01] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks?" *IEEE Communi.Magazine,* pp.130-137, June 2001
- [Yi01] S. Yi, P. Naldurg, R. Kravets, “Security-Aware Ad-Hoc Routing for Wireless Networks,” UIUCDCS-R-2001-2241 Technical Report, Aug. 2001
- [Zho00] H. Zhou and S. Singh, "Content Based Multicast in Ad Hoc Networks", *2000 First Annual Workshop on Mobile and Ad Hoc Networking and Computing,* 2000, pp.51-60
- [Zho99] L. Zhou and Z.J. Haas, “Securing Ad Hoc Networks,” *IEEE Network Magazine*, vol,13, no.6, November/December 1999