18-452/18-750
Wireless Networks and Applications
Lecture 11:
Mesh and Ad Hoc Networks

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http://www.cs.cmu.edu/~prs/wirelessS17/

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1

Overview

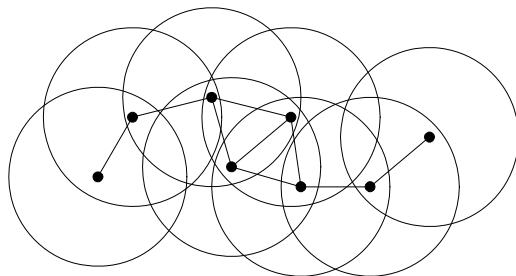**Context: ad hoc routing course project**

- **Ad hoc networking concept**
- **Proactive versus reactive routing**
- **Proactive, table based routing: DSDV**
- **Reactive routing DSR**
- **Geographic routing: GPSR**
- **Other routing solutions**
- **Wireless link metrics**

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2

Ad Hoc Networking

- **Goal: Communication between wireless nodes**
  - » **No infrastructure – network must be self-configuring**
  - » **It may require multiple hops to reach a destination**

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3

Ad Hoc Networking Challenging

- **All the challenges of wireless, plus some of:**
  - » **No fixed infrastructure**
  - » **Mobility and multi-hop!**
  - » **Ad hoc – no rational "network design" – random!**
  - » **Decentralized – nobody is in charge!**
  - » **Can be arbitrarily bad: limited batteries, malicious nodes, high mobility, low density, ..**
- **Precise challenges depend on the application domain, e.g., vehicular networks versus first-responder networks versus sensor networks**
- **Nodes are traffic sources, sinks and forwarders**
- **The big challenge: Routing**

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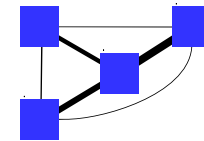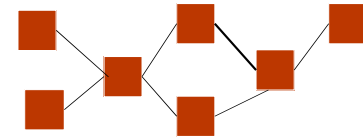
4

Ad Hoc Routing Requirements

- **Find multi-hop paths through the network**
- **Low resource consumption**
  - » **Bandwidth, memory, CPU cycles, ..**
- **Adapt to new routes in response to movement and environment changes**
- **Deal with interference**
  - » **Many co-located wireless nodes**
- **Scale well with the number of nodes**
  - » **Localize effects of link changes**

5

Traditional Routing vs Ad Hoc

- **Traditional network:**
  - » **Well-structured**
  - » **~O(N) nodes & links**
  - » **All links work ~= well**
  - » **Sensible topology**
- **Ad Hoc network**
  - » **N^2 links - but many stink!**
  - » **Topology may be really weird**
  - » **Reflections, multi-path and interference affect link quality unpredictably**
    - – **May affect both link throughput and topology**

6

Forwarding Packets is expensive

- **Assume link throughput is X**
  - » **X depends on the WiFi version**
  - » **Distance, obstacles and fading reduce capacity**
- **What is throughput of a chain?**
  - » **A -> B -> C   ?**
  - » **A -> B -> C -> D   ?**
  - » **Assume minimum power for radios.**
  - » **Now assume a dense network, i.e., all radios can hear each other**

- **Routing metric should take this into account**

7

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- **Vehicular networks**
- **Wireless link metrics**

8

Proactive or Table-based Protocols

- **Proactive: routers maintain routes independently of the need for communication**
  - » Similar to wired networking – uses forwarding table
- **Update messages are sent periodically or when network topology changes**
- **Low latency – forwarding information is always readily available**
- **Bandwidth might get wasted due to periodic updates**
- **Routers maintain O(N) state per node, N = #nodes**

Reactive or On-Demand Routing

- **Routers discover a route only when there is data to be sent**
- **Saves energy and bandwidth during periods of inactivity or low activity**
- **Traffic can be bursty $\rightarrow$ can cause congestion during periods of high activity**
  - » Due to overhead caused by on-demand route discovery
- **Route discovery introduces significant delay for the first packet of a new transfer**
- **Good for light loads, but the network can collapse under high loads**

Many Other Variants

- **Geographic routing: forward packet based on the geographic coordinates of the device**
  - » No route discovery overhead and no network state stored on the device
- **Hybrid approaches: used different algorithms in different parts of the network**
- **Hierarchical approaches: create a hierarchy of clusters**
  - » Improve scalability be reducing routing overhead

- **Best solutions is highly context dependent: density, traffic load, degree of mobility, …**
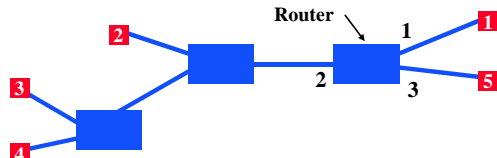
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Packet Forwarding versus Routing

Router

2

3
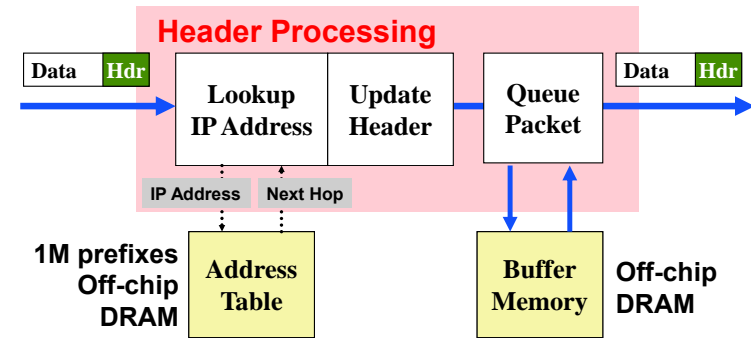
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1

3

1

5

Destination
Address Port

IP1	1
IP2	2
IP3	2
IP4	2
IP5	3

- Routing finds a path between two end-points
- Forwarding receives a packet and decides which egress port to send it out on
- Most networks use a routing protocol to pre-calculate paths between every pair of nodes
  » The result is put in a forwarding table in every router
- Forwarding only requires a lookup in the forwarding table – fast!
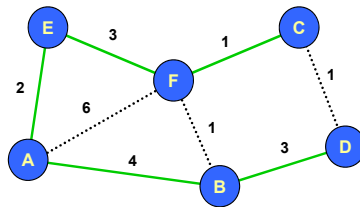
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13

Generic Router Architecture

Header Processing

Data Hdr

Lookup IP Address	Update Header

Queue Packet

Data Hdr

IP Address Next Hop

1M prefixes Off-chip DRAM

Address Table

Buffer Memory

Off-chip DRAM

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14

14

Routes from Node A

Forwarding Table for A		
Dest	Cost	Next Hop
A	0	A
B	4	B
C	6	E
D	7	B
E	2	E
F	5	E

E 3 C
    1
2   F
  6   1
A 4 B 3 D

- **Set of shortest paths forms tree**
  » **Shortest path spanning tree**
- **Solution is not unique**
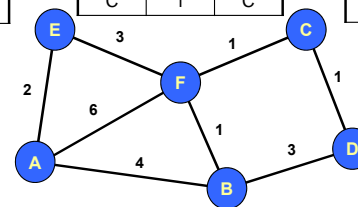 » **E.g., A-E-F-C-D also has cost 7**

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15

Different View: How to Get to Node C

Forwarding Table for E		
Dest	Cost	Next Hop
C	4	F

Forwarding Table for F		
Dest	Cost	Next Hop
C	1	C

Forwarding Table for C		
Dest	Cost	Next Hop
C	-	-

E 3 C
2   F   1
  6   1
A 4 B 3 D

Forwarding Table for A		
Dest	Cost	Next Hop
C	6	E

Forwarding Table for B		
Dest	Cost	Next Hop
C	2	F

Forwarding Table for D		
Dest	Cost	Next Hop
C	1	C

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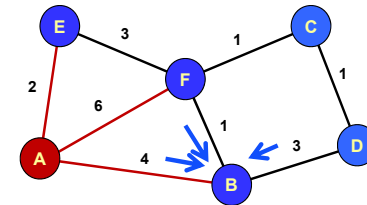
16

Traditional Routing Solutions

- **Link state routing**
  - » Each router obtains a full topology of the network by having nodes periodically flood connectivity information
  - » Each router then uses Dijkstra's algorithm to locally calculate its forwarding table
  - » Bad fit for ad hoc: LS flooding creates a lot of traffic and relies on all routers having a consistent view of network
- **Distance vector**
  - » Each router tells its neighbors its shortest path to each destination
  - » Routers then use the "best" option provided to them
  - » Based on the Bellman-Ford algorithm
  - » More promising for ad hoc: has lower routing overhead
  - » Challenge is how to avoid routing loops (details omitted)

Distance-Vector Method

Initial Table for A		
Dest	Cost	Next Hop
A	0	A
B	4	B
C	∞	–
D	∞	–
E	2	E
F	6	F

- **Each router periodically exchanges tables with its neighbors**
  - » **Contains the cost/next hop of best known path to all destination**
- **Routers pick the best of the candidates paths**
  - » **May be the path it is currently using already**

Destination-Sequenced Distance Vector (DSDV)

- **By Perkins and Bhagvat**
- **DV protocol specifically designed for wireless**
  - » **Exchange of routing tables**
  - » **Routing table: the way to the destination, cost**
- **Each node advertises its presence and tables**
  - » **Maintains fresh routes by periodically sending updates to neighbors**
  - » **Update for each destination: hop count, sequence number**
- **Uses sequence number to avoid loops**
  - » **Destinations include sequence number that is incremented for each update**
  - » **Is used to flush old information from the network**

DSDV Properties

- **Keep the simplicity of Distance Vector**
- **Guarantee Loop Freeness**
  - » **New Table Entry for Destination Sequence Number**
- **Allow fast reaction to topology changes**
  - » **Make immediate route advertisement on significant changes in routing table**
  - » **but wait with advertising of unstable routes (damping fluctuations)**

Based on: cone.informatik.uni-freiburg.de/teaching/vorlesung/manet-s07/exercises/DSDV.ppt

DSDV Table Format

Destination	Next	Metric	Seq. Nr	Install Time	Stable Data
A	A	0	A-550	001000	Ptr_A
B	B	1	B-102	001200	Ptr_B
C	B	3	C-588	001200	Ptr_C
D	B	4	D-312	001200	Ptr_D

- **Sequence number originated from destination**
  - » **Ensures loop freeness**
- **Install Time when entry was made**
  - » **Used to delete stale entries from table**
- **Stable Data Pointer to a table holding information on how stable a route is**
  - » **Used to damp fluctuations in network**

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21

DSDV Advertisements

- **Advertise to each neighbor own routing information**
  - » **Destination Address**
  - » **Metric = Number of Hops to Destination**
  - » **Destination Sequence Number**
- **Rules to set sequence number information**
  - » **On each advertisement increase own destination sequence number (use only even numbers)**
  - » **If a node is no more reachable (timeout) increase sequence number of this node by 1 (odd sequence number) and set metric = ∞**
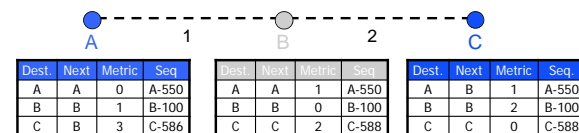
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22

DSDV Route Selection

- **Information in advertisements is compared to content of routing table**
  1. **Select route with higher destination sequence number (This ensure to use always newest information from destination)**
  2. **Select the route with better metric when sequence numbers are equal.**
     - – **Routing metrics can be path length in hops, or metrics that capture link quality**
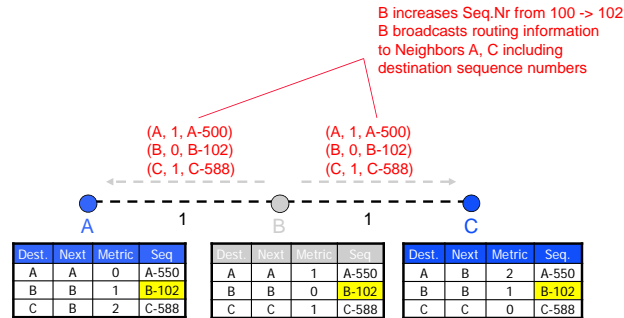
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23

DSDV Example

A table (A):

Dest.	Next	Metric	Seq
A	A	0	A-550
B	B	1	B-100
C	B	3	C-586

B table:

Dest.	Next	Metric	Seq.
A	A	1	A-550
B	B	0	B-100
C	C	2	C-588

C table:

Dest.	Next	Metric	Seq.
A	B	1	A-550
B	B	2	B-100
C	C	0	C-588

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24

DSDV Advertisement

B increases Seq.Nr from 100 -> 102
B broadcasts routing information
to Neighbors A, C including
destination sequence numbers

(A, 1, A-500)   (A, 1, A-500)
(B, 0, B-102)   (B, 0, B-102)
(C, 1, C-588)   (C, 1, C-588)

A   1   B   1   C

Dest.	Next	Metric	Seq.
A	A	0	A-550
B	B	1	B-102
C	B	2	C-588

Dest.	Next	Metric	Seq.
A	A	1	A-550
B	B	0	B-102
C	C	1	C-588

Dest.	Next	Metric	Seq.
A	B	2	A-550
B	B	1	B-102
C	C	0	C-588

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25

DSDV
Dealing with Topology Changes

- **Immediate advertisements**
  - » **Information on new Routes, broken Links, metric change is immediately propagated to neighbors.**

- **Full/Incremental Update:**
  - » **Full Update: Send all routing information from own table.**
  - » **Incremental Update: Send only entries that has changed. (Make it fit into one single packet)**

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26

Other DSDV Features

- **Sequence number is used to recover from failures quickly and to avoid loops**
  - » **When a link failure is detected, increment sequence number by one and advertise**
  - » **This effectively "poisons" all stale routing entries**
  - » **New even sequence number used for new routes**
- **Stability information can be used to avoid rapid fluctuations in routing tables**
  - » **E.g., oscillating between two paths of similar quaility**
  - » **Give preference to the more stable path**

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27

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28

DSR

- **On-demand route discovery**
  - » Only discover a route when you need it
  - » Avoid the overhead of periodic route advertisements
- **Source routing: path information is stored in the packet header by the sender**
  - » Intermediate nodes can have out of date information

Hop 1
Hop 1
…
Dest

DSR Components

- **Route discovery**
  - » The mechanism by which a sending node obtains a route to destination
- **Route maintenance**
  - » The mechanism by which a sending node detects that the network topology has changed and its route to destination is no longer valid

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DSR Route Discovery

- **Source broadcasts a route-request towards the destination**
  - » The request includes a (partial) path from source to destination
- **Each node forwards the request by adding own address to the path and re-broadcasting**
- **Requests propagate outward until:**
  - » The destination is found, or
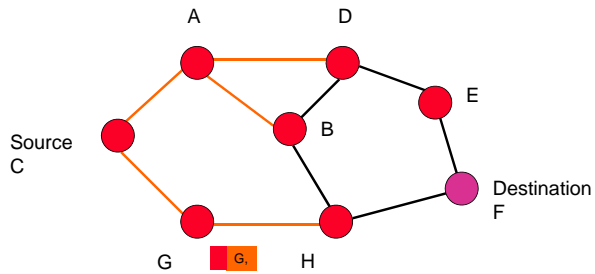 - » A node that has a route to the destination is found

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C Broadcasts Route Request to F

Page 8

G Rebroadcasts Route Request

33

H Responds to Route Request

34

C Transmits a Packet to F

35

Forwarding Route Requests

- **A request is forwarded if:**
  - » **Node is not the destination**
  - » **Node not already listed in recorded source route**
  - » **Node has not seen request with same sequence number**
  - » **IP TTL field may be used to limit scope**
- **Destination copies route into a Route-reply packet and sends it back to Source**

36

Route Cache

- **All source routes learned by a node are kept in Route Cache**
  - » **Reduces cost of route discovery**
- **If an intermediate node receives RR for a destination and has an entry for the destination in its route cache, it responds to RR and does not propagate RR further**
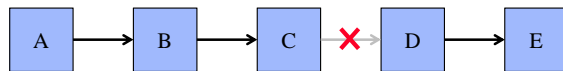- **Nodes overhearing RR/RP may insert routes in their cache**

Sending Data

- **Check cache for route to destination**
- **If route exists then**
  - » **If reachable in one hop, send packet**
  - » **Else insert a routing header to the destination and send**
- **If no route exists, buffer the packet and initiate route discovery**

Basic Route Maintenance

- **Each sender must get an acknowledgement from the next hop**
  - » **Will retransmit the packet up to a limit if needed**
- **If no ACK is received it drops the packet and notifies the sender A of the broken link**
- **A will remove the route from its route cache and ..**
- **Will do a new route discovery when it sends another packet to E**
  - » **It is left up to TCP to recover from the packet loss**
  - » **If A has alternative paths in its route cache, it can use those instead**

Discussion

- **Source routing is good for certain types of networks and traffic loads**
  - » **For example, stable traffic flows or networks with limited mobility**
- **Route discovery protocol used to obtain routes on demand**
  - » **Caching used to minimize use of discovery**
- **Periodic messages avoided**
- **But need to buffer packets**
- **How do you decide between candidate paths?**

Some References

- **DSR:**
  - » www.cs.rice.edu/~dbj/pubs/aw-dsr.pdf
- **DSDV:**
  - » www.cs.jhu.edu/~cs647/class-papers/Routing/p234-perkins.pdf
- **GPSR:**
  - » www.eecs.harvard.edu/~htk/publication/2000-mobi-karp-kung.pdf

- **ETX:**
  - » pdos.csail.mit.edu/papers/grid:mobicom03/paper.pdf
- **ETT**
  - » http://www.cs.jhu.edu/~cs647/class-papers/Routing/p114-draves.pdf

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41