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

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Fall Semester 2018

http://www.cs.cmu.edu/~prs/wirelessF18/

Announcements

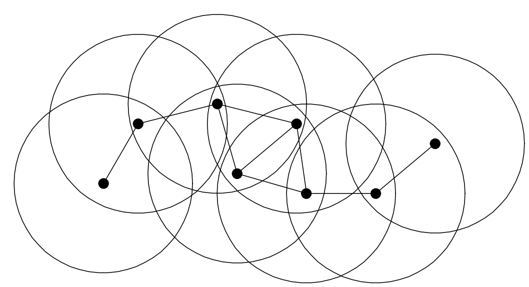
- **Today: Ad Hoc networking overview**
  - » Motivation: possible topic for project
- **P1 update:**
  - » Should be ready by tomorrow
  - » 3 students who are not in team should get back to me
- **P2 deadline is this Friday**
  - » Can use piazza to look for partners, share topics, etc.
  - » Please use tag "project2"
  - » Extra office hours tomorrow 2-3pm
- **OFDM Q&A: will answer questions as part of lecture on 802.11an and 802.11ac (MIMO)**

Overview

Context: ad hoc routing course project
  - » We will get back to WiFi soon
- **Ad hoc networking concept**
- **Proactive versus reactive routing**
- **Proactive, table based routing: DSDV**
- **Reactive routing DSR**
- **Geographic routing: GPSR**
- **Wireless link metrics**
- **Ad hoc networking examples**

Ad Hoc Networking

- **Goal: Communication between wireless nodes**
  - » No infrastructure – network must be self-configuring
- **It may require multiple hops to reach a destination**
  - » Nodes are traffic sources, sinks and forwarders



Ad Hoc Routing Requirements

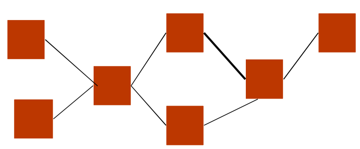
- Find multi-hop paths through the network
- Low resource consumption
  - » Bandwidth, memory, CPU cycles, ..
- Adapt to new routes in response to movement and environment changes
- Deal with interference
  - » Many co-located wireless nodes
  - » Links in the same area interfere with each other
- Scale well with the number of nodes
  - » Localize effects of link changes
  - » Network-wide updates are expensive

Ad Hoc Networking Challenging

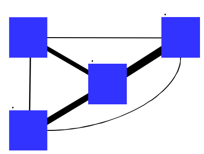
- All the challenges of wireless, and more:
  - » No fixed infrastructure
  - » Decentralized – nobody is in charge!
  - » Ad hoc – no rational "network design" – random!
  - » Mobility and multi-hop!
  - » Generic ad hoc can be arbitrarily bad: limited batteries, malicious nodes, high mobility, low density, ..
- Precise challenges depend on the application domain, e.g., vehicular networks versus first-responder networks versus sensor networks
  - » Domain focus typically simplifies the problem
- The big challenge: Routing

Traditional Routing vs Ad Hoc

- Traditional wired network:
  - » Well-structured
  - » ~O(N) nodes & links
  - » All links work ~= well
  - » Sensible topology
  - » Links are independent



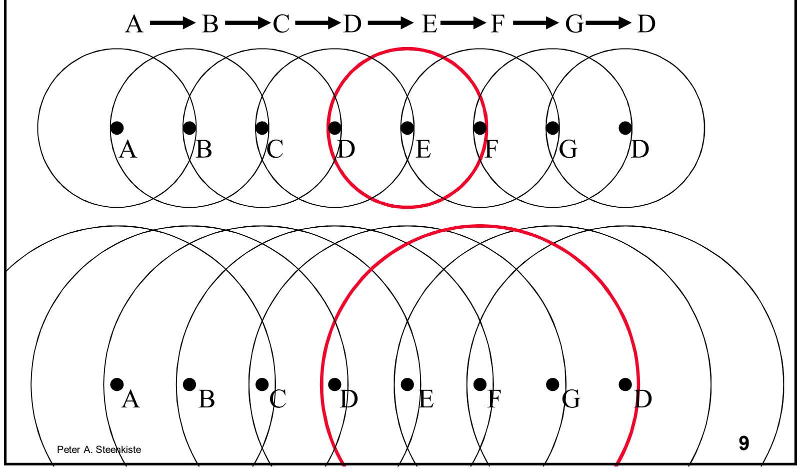
- Ad Hoc wireless network
  - » N^2 links - but many stink!
  - » Topology may be really weird
  - » Reflections, multi-path and interference affect link quality unpredictably
    - – May affect both link throughput and topology



Forwarding Packets is expensive

- Assume link throughput is X
  - » X depends on the WiFi version, distance, fading, …
- What is the throughput of a chain?
  - » Basic: A → B → C
  - » Or: A → B → C → D
  - » Or: A → B → C → D → E …
- Considering:
  - » Wired versus wireless
  - » 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

2 Simple Examples



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Proactive or Table-based Protocols

- Proactive: routers maintain routes independently of the need for communication
  - » Similar to wired networking – uses forwarding table
- Route 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, where 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 → 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
  - » Based on coordinates – no routing, so no routing overhead
- Hierarchical approaches: a hierarchy of clusters
  - » Improve scalability by reducing routing overhead
- Hybrid approaches mix different solutions
  - » Proactive routing for nearby nodes for reactive for far nodes
- Domain specific solutions
  - » Vehicular networks, stationary/mesh networks, last mile, …
- Best solutions is highly context dependent: density, traffic load, degree of mobility, …

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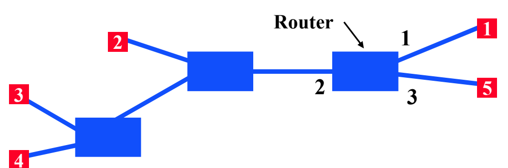
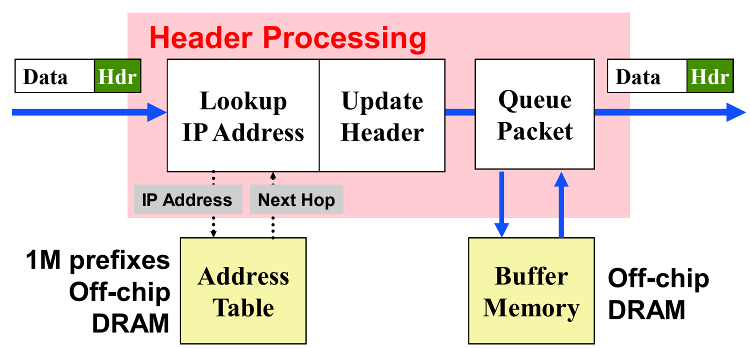
Packet Forwarding versus Routing



Destination Address	Port
IP1	1
IP2	2
IP3	2
IP4	2
IP5	3

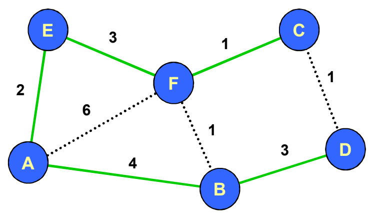
- Routing finds a path between two end-points
- Forwarding receives a packet and decides which egress port to send it out on
- Most networks use a routing protocol to pre-calculate paths between every pair of nodes
  - » The result is put in a forwarding table in every router
- Forwarding only requires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

Generic Router Architecture



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



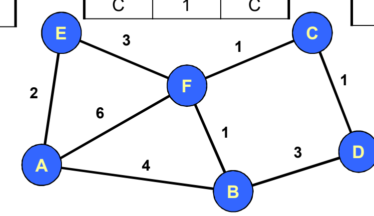
- Set of shortest paths forms tree
  - » Shortest path spanning tree
- Solution is not unique
  - » E.g., A-E-F-C-D also has cost 7

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	-	-



Forwarding Table for A		
Dest	Cost	Next Hop
C	6	E

Forwarding Table for B		
Dest	Cost	Next Hop
C	2	F

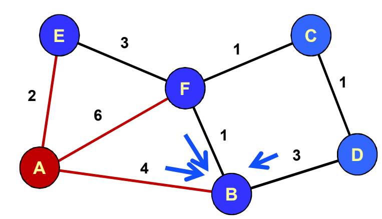
Forwarding Table for D		
Dest	Cost	Next Hop
C	1	C

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, plus the 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
- Novel way of flushing stale information from the network
  - » E.g., limit disruptions of link failures by quickly removing any routes that use the failed link
- 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

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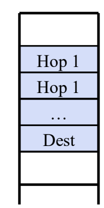
Dynamic Source Routing (DSR) Key Features

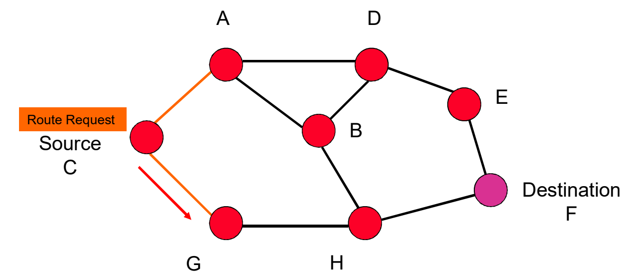
- On-demand route discovery finds route only when it is needed
  - » Avoid overhead of periodic route advertisements
- Uses source routing: path information is stored in the packet header
- DSR control functions:
  - » Route discovery: senders obtain route to destination
  - » Route maintenance: detect changes in topology and update routes that are affected
  - » Route caching: nodes cache route information to avoid route discovery for every packet
    - – Caching can be done on sender and intermediate routers
    - – Flush broken routes from cache



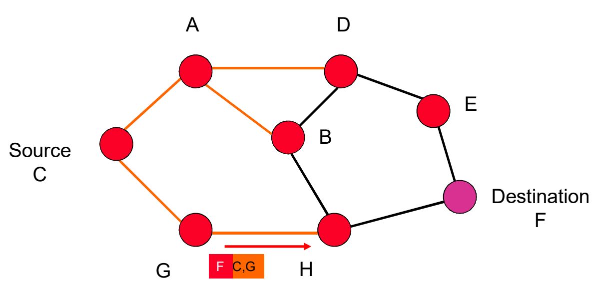
DSR Route Discovery

- 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

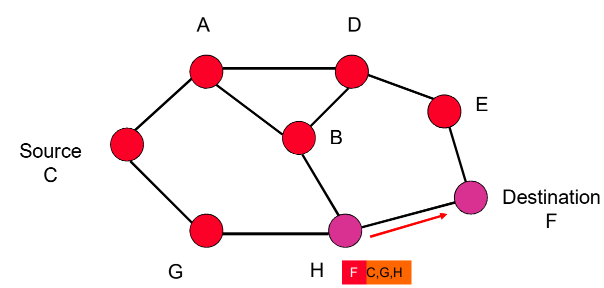
C Broadcasts Route Request to F



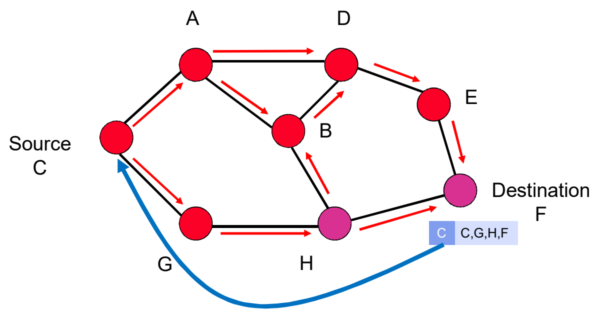
G Rebroadcasts Route Request



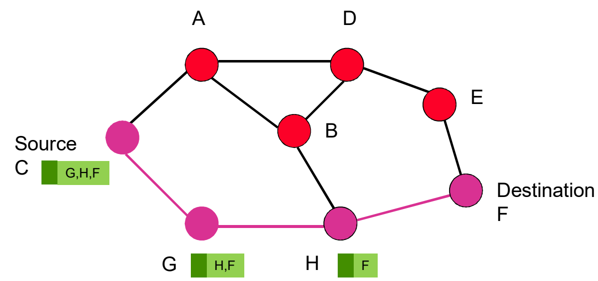
H Rebroadcasts Route Request



F Responds to Route Request



C Transmits a Packet to F



Forwarding Route Requests

- A request is forwarded by a node 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 selected route into a Route-reply packet and sends it back to Source
  - » I.e., route reply uses reverse path of the route selected by the destination
  - » Destination can choose one of the paths, e.g., first path (with shortest delay)

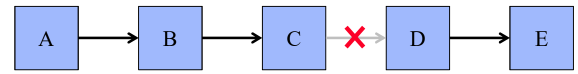
Route Cache

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



- When forwarding a packet, 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 and/or a small number of sender-receiver pairs
  - » Networks with limited mobility
- Periodic messages avoided
- Significant delay for the first packet to a destination
  - » Also, need to buffer packets

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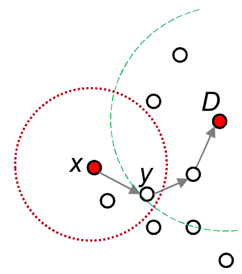
Greedy Perimeter Stateless Routing (GPSR)

- Use *positions* of neighboring nodes and packet destination to forward packets
  - No connectivity or global topology is assumed – no forwarding or path information anywhere!
  - Nodes are assumed to know their location
  - Need a mechanism for address-to-location look up
- Two forwarding techniques is used
  - *Greedy forwarding*, if possible
  - *Perimeter forwarding*, otherwise

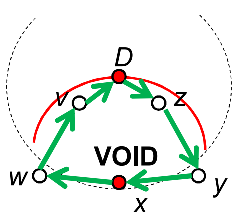
GPSR – Greedy forwarding

- A sender/forwarder *x* chooses to forward to a neighbor *y* such that $\{d_{xy} + d_{yD}\}$ is minimum



GPSR – Perimeter forwarding

- What happens if a node does not have a neighbor that is closer to the destination?
- Right Hand Rule: you forward the packet to your first neighbor clockwise around yourself
  - Traverse an interior region in *clockwise* edge order
  - Guaranteed to reach a (reachable) destination for planar graph



These sequence of edges traversed is called a *PERIMETER*

Many Other Variants

- Hybrid approaches mix different solutions
  - » Use proactive routing for nearby nodes for reactive routing for far nodes
  - » Combine source routing with distance vector (AODV)
- Hierarchical: create a hierarchy of clusters
  - » Improve scalability be reducing routing overhead
  - » Can use different protocols for intra and inter cluster
- Many proposals for optimizations
  - » Links use different frequencies, multiple radios, etc.
  - » Link metrics that consider interference level, …
- Best solutions is highly context dependent: density, traffic load, degree of mobility, …

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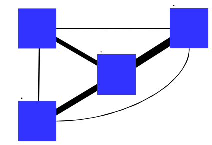
Link Metric

- Routing protocols for wired networks tend to use very simple link metrics
  - » Hop count (all links have cost of 1) or simple integers
  - » Performance of wired links is predictable!
- Wireless links can be very different and their performance can change unpredictably
  - » Hop count is a bad idea – why?
- Some links are so bad they are not really links
- Solution: Require a minimum PDR to qualify as a link
  - » PDR = Packet Delivery Rate
- Is that a sufficient solution?



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Factors Influencing "Link Quality"

- Signal strength and quality: affects the bit rate used for packets
  - » Bit rate affects the transmit time of packets
- Number of retransmissions needed to deliver packets
  - » Retransmissions delay packets and use up more bandwidth
- Interference from nearby nodes
  - » Interference limits the transmission opportunities a node has, i.e., it can take longer to get channel access
  - » Some links may also face more hidden and exposed terminal problems

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ETX: Minimize Number of Transmissions

- Measure each link's packet delivery probability with broadcast probes
  - » Must also measure the reverse link – ACKs must be received too for a transmission to be successful!

  $P(delivery) = P_{packet} * P_{ACK}$
- The link ETX is the average number of transmissions needed to deliver a packet

  $Link\ ETX = 1 / P(delivery) = 1 / (P_{packet} * P_{ACK})$
- Route ETX = sum of link ETX
  - » Pessimistic: not all links interfere with each other
- ETX only considers some factors: bit rate, short probes under-estimate loss rate, traffic load, hidden terminals, …

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ETX: Sanity Checks

- ETX of perfect 1-hop path: 1
- ETX of 50% delivery 1-hop path: 2
- ETX of perfect 3-hop path: 3
- So, e.g., a 50% loss path is better than a perfect 3-hop path!
  - » A PDR threshold would probably fail here …
- But this ignores many real world factors!
  - » Examples?

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ETT: Expected Transmission Time

- The bit rate used for transmission can have a very big impact on performance
  - » E.g., 802.11a rates range from 6 to 54 Mbps
  - » Bit range even much larger for more recent standards (but ad hoc only standardized up to
- ETT – expected *transmission time*

  ETT = ETX / Link rate

  = 1 / (P(delivery) * Bit Rate)
- Accounts for all major factors
  - » Traffic load and competition for transmission time by nearby links is still not accounted for
  - » Must update metric periodically

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Summary

- Ad hoc networks face many challenges
  - » Bad links, interference, mobility, …
  - » Makes routing very challenging
  - » Limited support: hardware and driver limitations
- Many proposals!
  - » Proactive routing: variants of "wired" routing protocols
  - » Reactive routing: only establish a path when it is needed
  - » Geographic routing: use destination location info only
  - » Many variants and extensions
- Specific challenges depend on the application domains
  - » Mesh versus vehicular
  - » Active area of research

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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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