This lecture is being recorded

18-452/18-750
Wireless Networks and Applications
Lecture 12: Ad Hoc Networks

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Spring Semester 2022

http://www.cs.cmu.edu/~prs/wirelessS22/

Announcements

- If you have not sent me information on team or topic, please do so as soon as possible
  - About 2/3 of the class have provided information
- I fixed the inconsistency of the due dates:
  - P2 topics and teams: asap
  - Survey topics and teams: next week Monday
  - Midterm: Wed, Mar 2

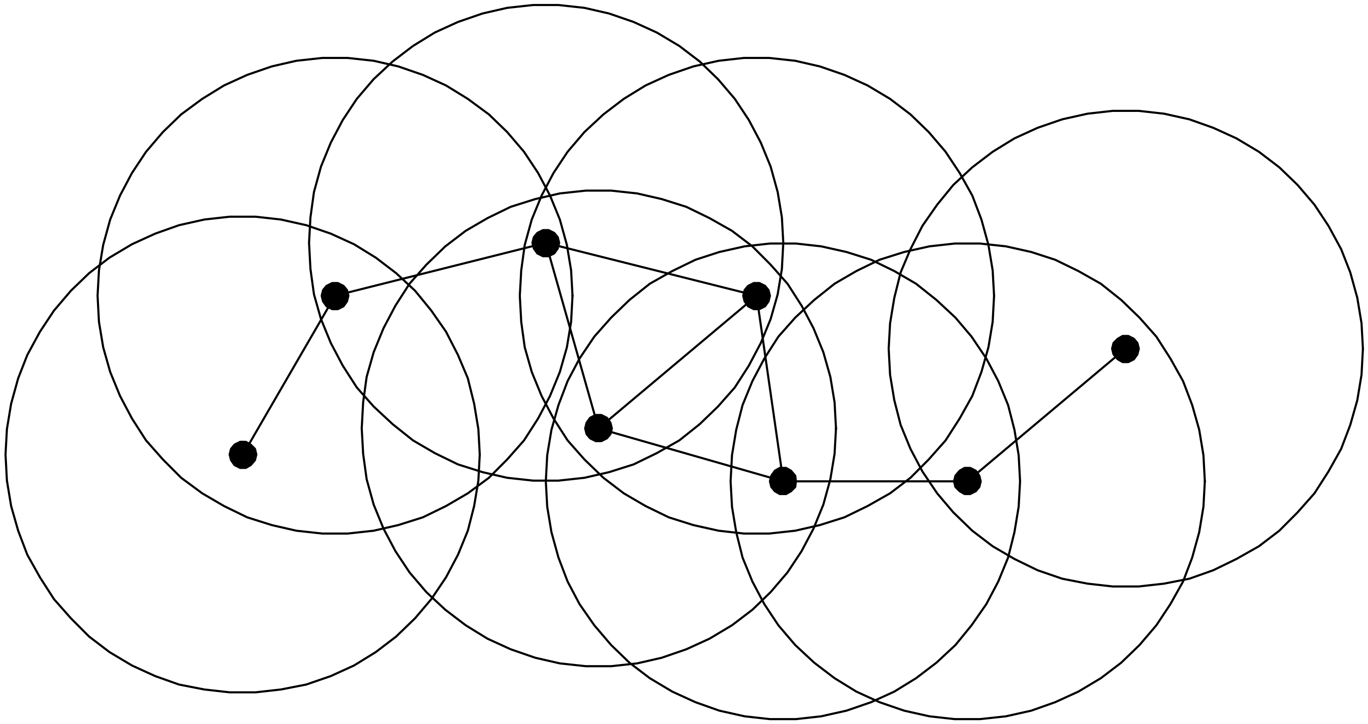
Ad Hoc Routing

- Definition and challenges
- Routing:
  - » Classes: proactive versus reactive routing
  - » Proactive routing with a twist
  - » Reactive routing DSR
  - » Geographic routing: GPSR
- Discussion

- Structured as a survey
  - » But a bit longer since it covers more material

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**

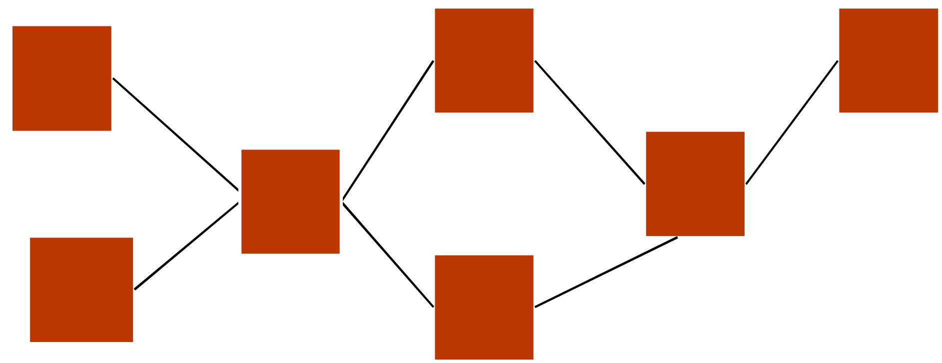


Ad Hoc Networking Challenging

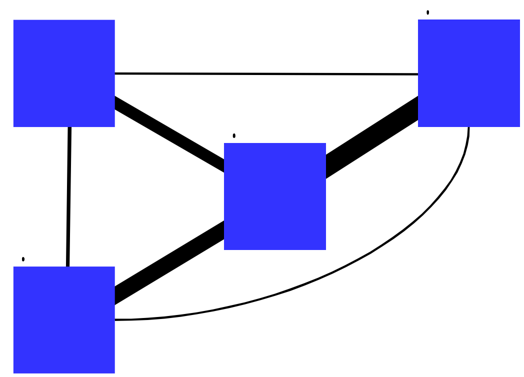
- All the challenges of wireless, and more:
  - » Decentralized: nobody is in charge – no planning!
  - » No fixed infrastructure, random network design
  - » Generic ad hoc can be arbitrarily bad: limited batteries, malicious nodes, high mobility, low density, ..
- Precise challenges depend on the application domain, e.g., vehicular networks versus first-responder networks versus sensor networks
  - » Domain focus simplifies the problem and makes it more interesting …
  - » Most research papers address the complex general case
- The big challenge: Routing

Traditional Routing vs Ad Hoc

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



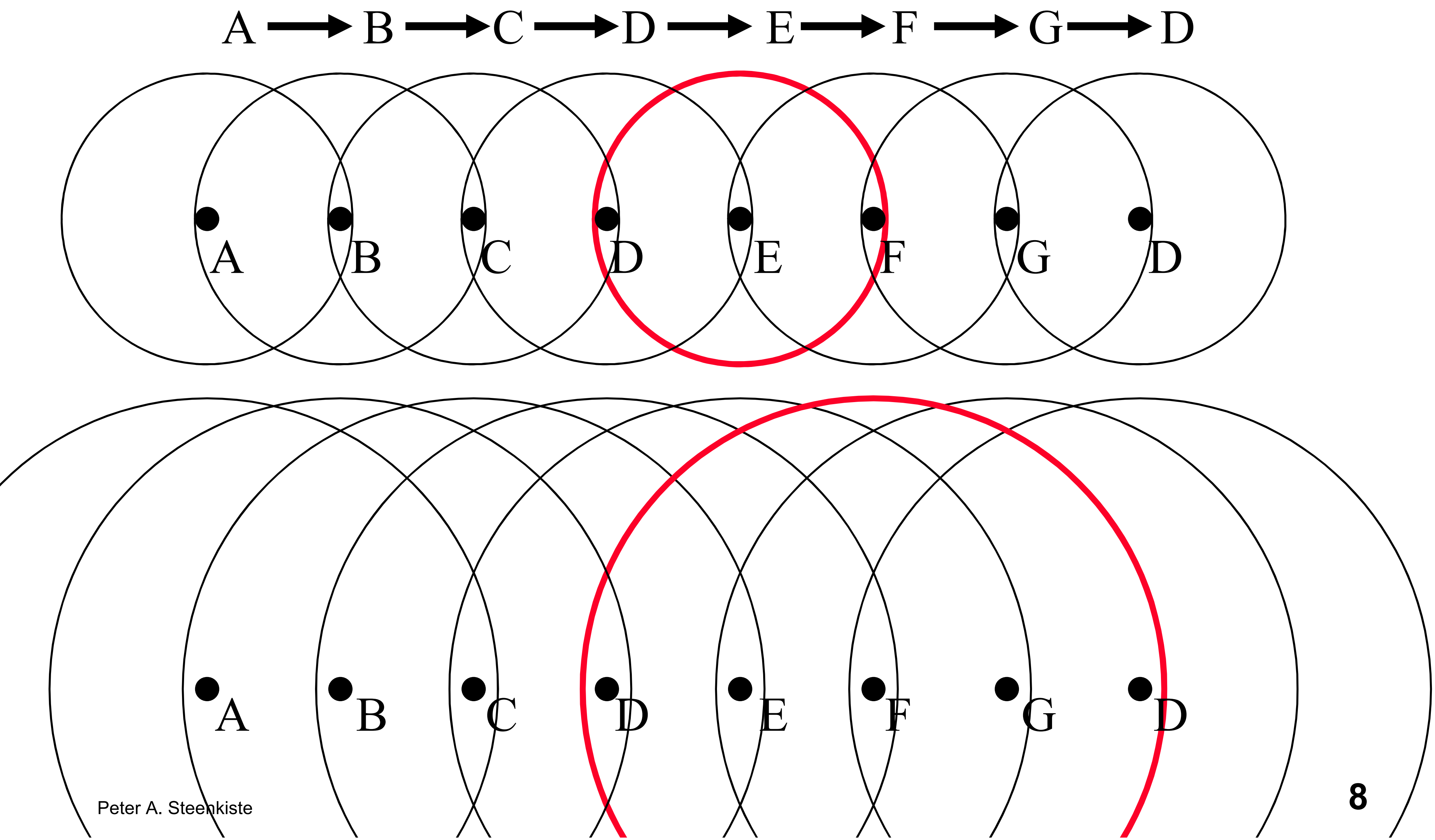
- **Ad Hoc wireless network**
  - » N^2 links - but many stink!
  - » Topology may be really weird
  - » Links interfere with each other
  - » Dynamic link conditions means that link quality is unpredictable
    - – So the topology also changes constantly!



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
  - » Now assume dynamic link conditions, mobility, ..

2 Simple Examples



Ad Hoc Routing
A Sampling of Solutions

- Proactive routing: each router maintains a forwarding table listing all destinations
  - » Uses routing algorithms similar to those in the Internet
  - » Example: traditional algorithms with wireless metrics
- Reactive routing: only find a path when you need it
  - » Avoids the overhead of periodically executing a routing protocols but can introduce high packet delay
  - » Example: DSR
- Geographic routing: find a path based on geographic coordinates
  - » Does not require any topology information
  - » Does not maintain forwarding tables
  - » Example: GPSR

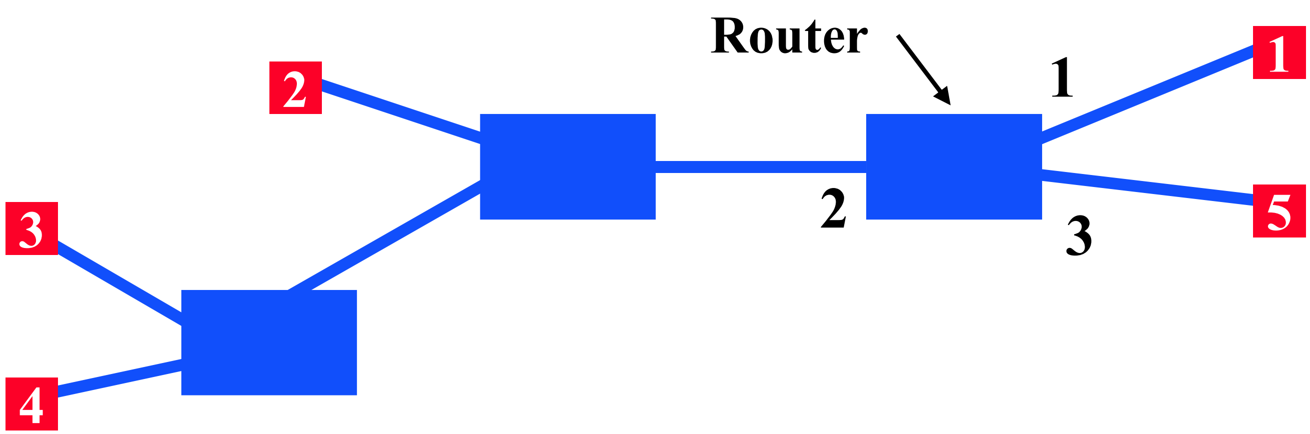
Proactive or Table-based Protocols

- 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
- Routing algorithms use a link metric
  - » Typically simple and static – how about a channel specific metric for wireless?

Ad Hoc Routing

- Classes: proactive versus reactive routing
- Proactive, table based routing: DSDV
- Reactive routing DSR
- Geographic routing: GPSR

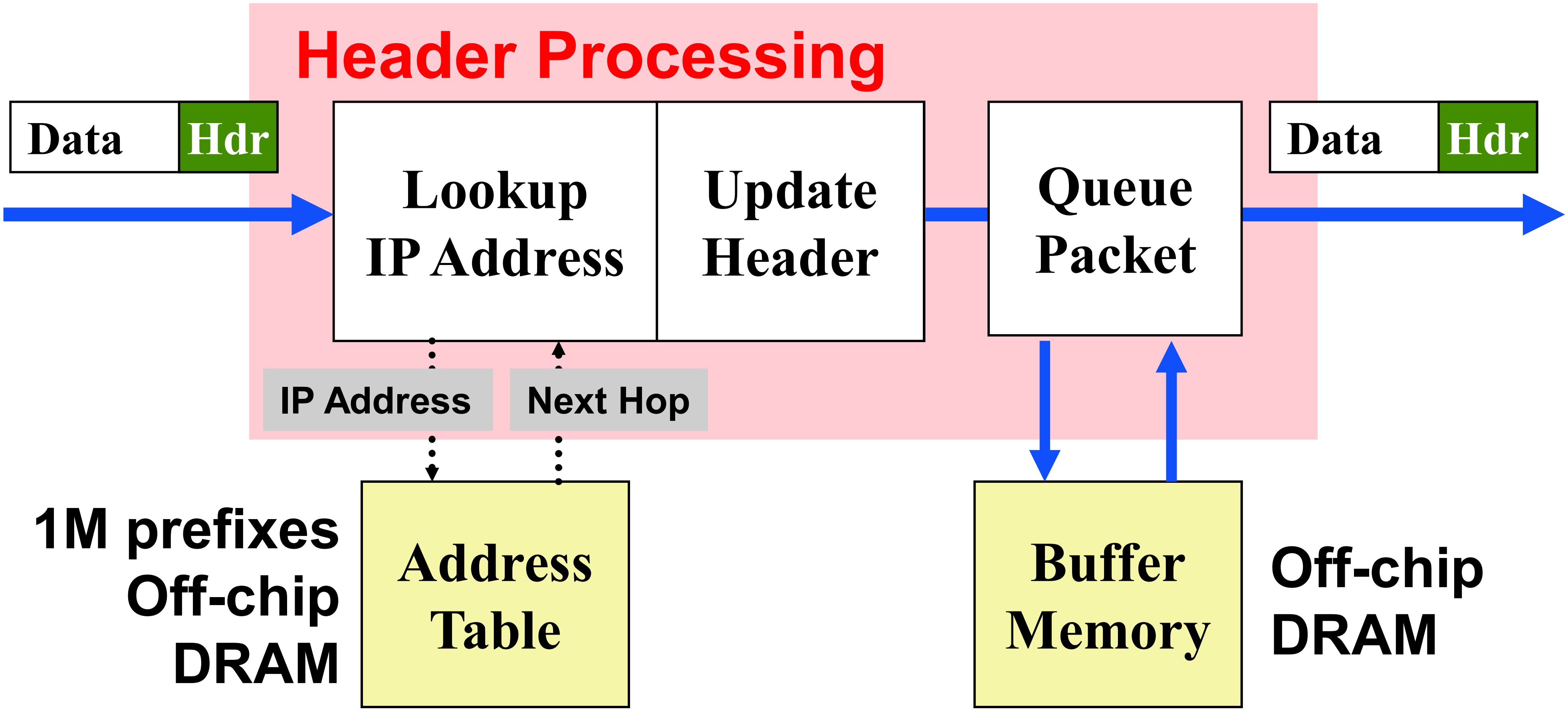
Packet Forwarding versus Routing



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

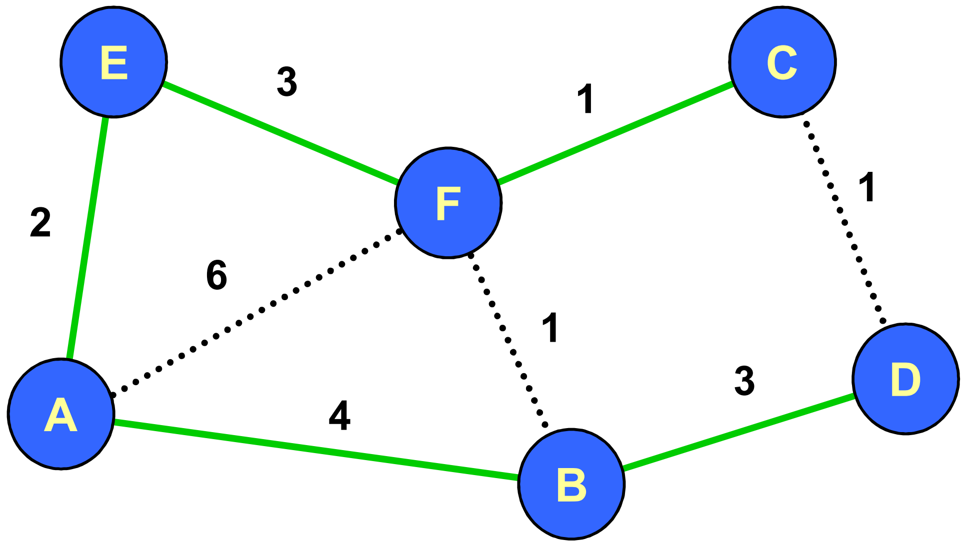
- Routing finds a path between two end-points
- Forwarding receives a packet and decides which egress port to send it out on
- Most networks use a routing protocol to pre-calculate paths between every pair of nodes
  - » Routers put the result in a forwarding table
- Forwarding only requires a lookup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



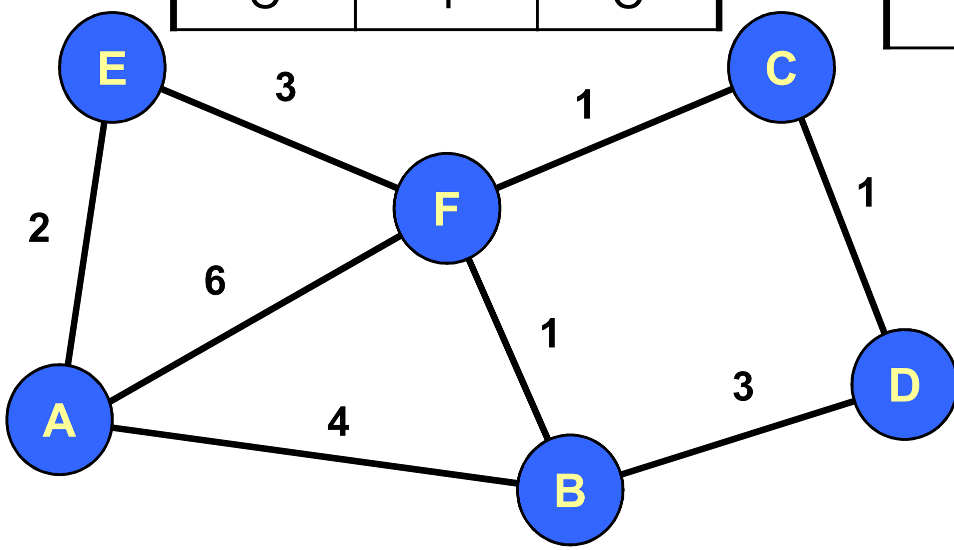
- **Set of shortest paths forms tree**
  - » **Shortest path spanning tree**
- **Solution is not unique**
  - » **E.g., A-E-F-C-D also has cost 7**

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

Routing in Wireless Networks

- Traditional routing metrics tend to be simple
  - » All links have a cost of 1 – shortest path routing
  - » Integer value that reflects the bandwidth of the link – use high value to make low bandwidth link unattractive
- But wireless link capacity is unpredictable and influenced by many factors!
- Idea: pick a link metric that reflects how expensive to send a packet over a link
- Must account for many factors:
  - » Losses/retransmission of data packets and ACKs
  - » Channel effects such as attenuation, fading, …
  - » Interference from neighboring links, etc.

Example Metrics

- **Expected Transmission Count – ETX**
  - » **Number transmissions needed to successfully deliver a packet over the link – includes retransmissions**
  - » **1 / (d_f x d_r) with d_f and d_r representing forward/revers delivery link delivery rates**
  - » **What does NOT account for?**
- **Expected Transmission Time – ETT**
  - » **Considers both the impact of retransmissions (ETX) and of the link bandwidth**
  - » **Link bandwidth considers channel quality (bit rate) and the impact interference from neighboring links**

http://pdos.csail.mit.edu/papers/grid:mobicom03/paper.pdf

http://www.cs.jhu.edu/~cs647/class-papers/Routing/p114-draves.pdf

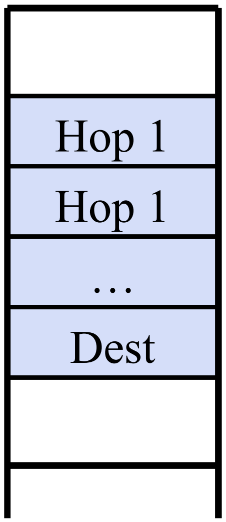
Overview

- 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

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
- Route discovery introduces significant delay for the first packet of a new transfer
- Bad if many nodes send packets to many destinations at random times or in unstable networks

Dynamic Source Routing (DSR) Key Features

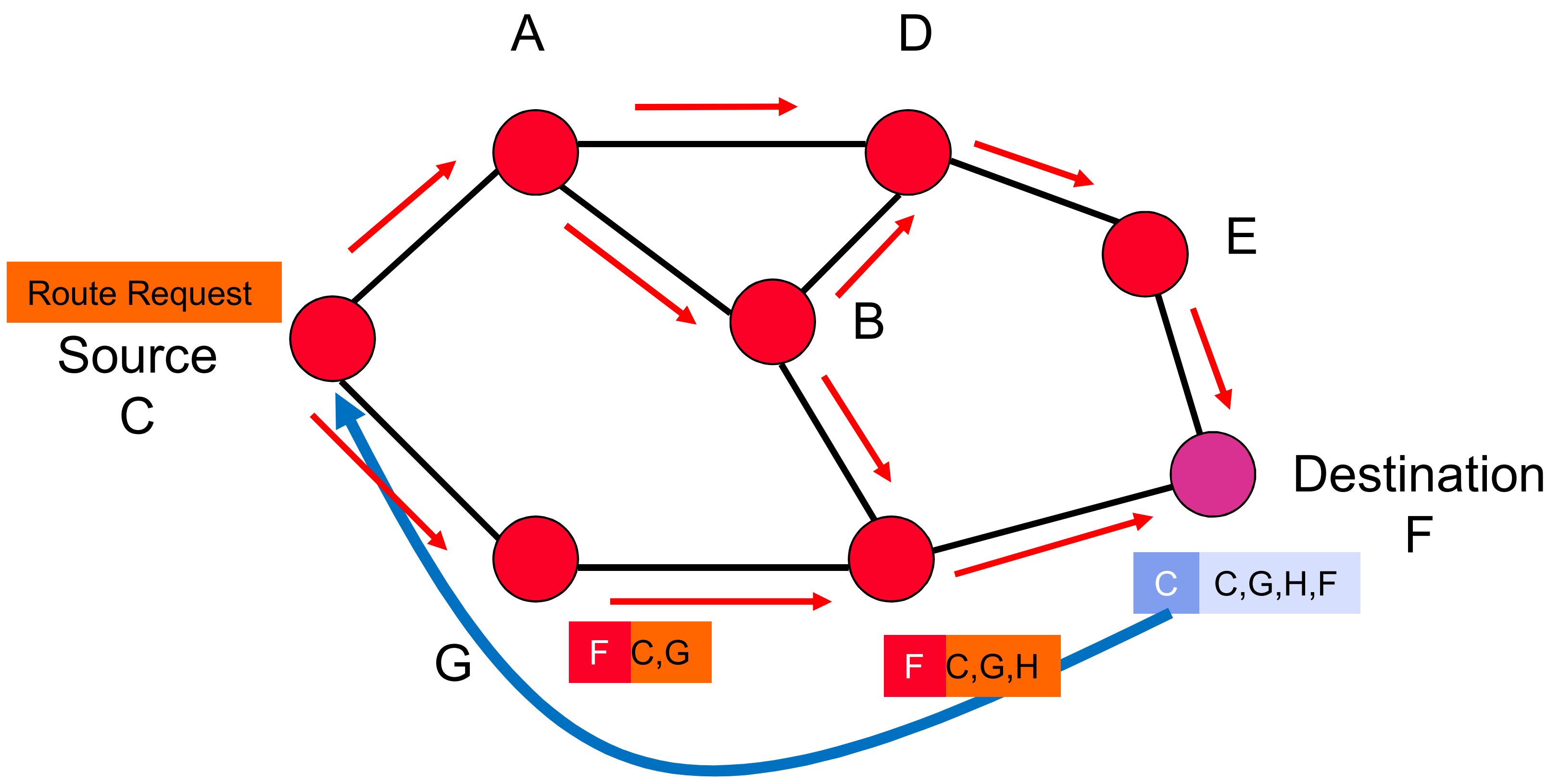


- On-demand route discovery finds route only when it is needed
  - » Avoid overhead of periodic route advertisements
- Uses source routing: path information is stored in the packet header
- DSR control functions:
  - » Route discovery: senders obtain route to destination
  - » Route maintenance: detect 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

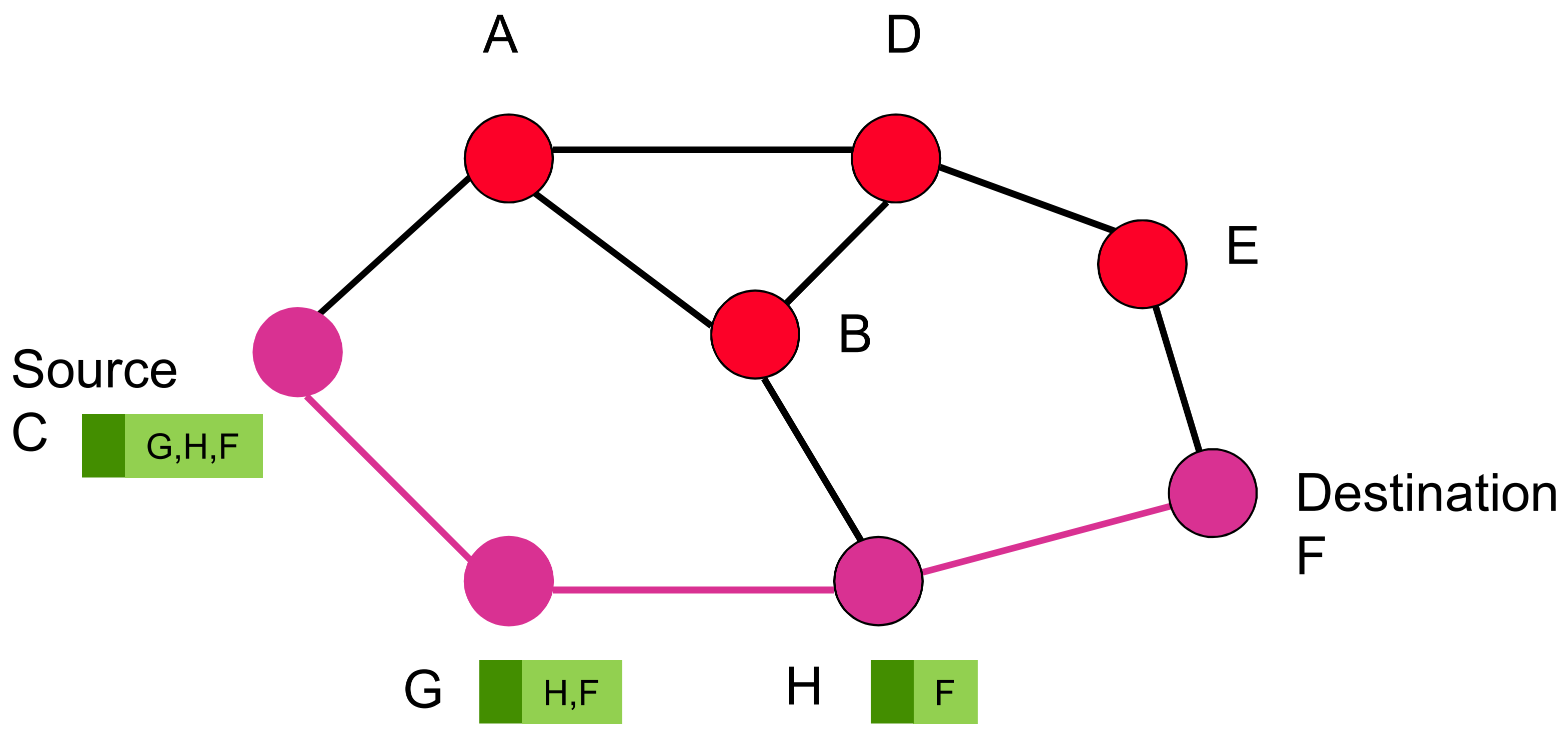
DSR Route Discovery

- 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

Route Request is Re-Broadcasted until Destination is Reached



C Transmits a Packet to F



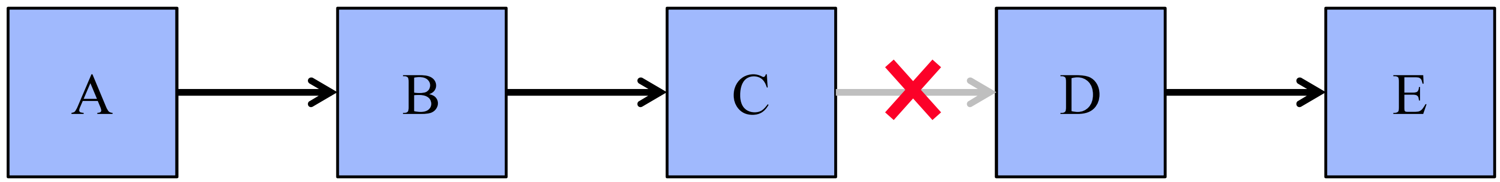
Forwarding Route Requests

- 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 a Route Cache
  - Routes are learned by overhearing route requests/responses
  - Reduces cost of route discovery
- If an intermediate node receives a route request for a destination and has an entry for the destination in its route cache, it
  - Responds to the request using the cached information
  - Does not propagate the request any further
- Nodes use their local route cache when asked to send a data packet
  - If route is missing, they initiate a route request

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 removes the route from its route cache and ..
  - » Intermediate nodes also remove any cached entries to E
- 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

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
  - Stable network topologies, e.g., with limited mobility
- Periodic messages are avoided
- Significant delay for the first packet to a destination
  - Also, need to buffer packets

Overview

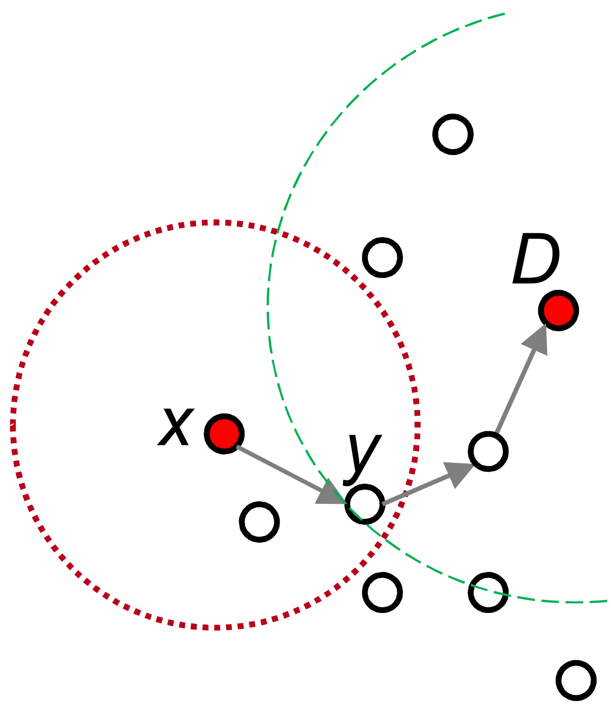
- Ad hoc networking concept
- Proactive versus reactive routing
- Proactive, table based routing: DSDV
- Reactive routing DSR
- Geographic routing: GPSR
- Wireless link metrics
- Ad hoc networking examples

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

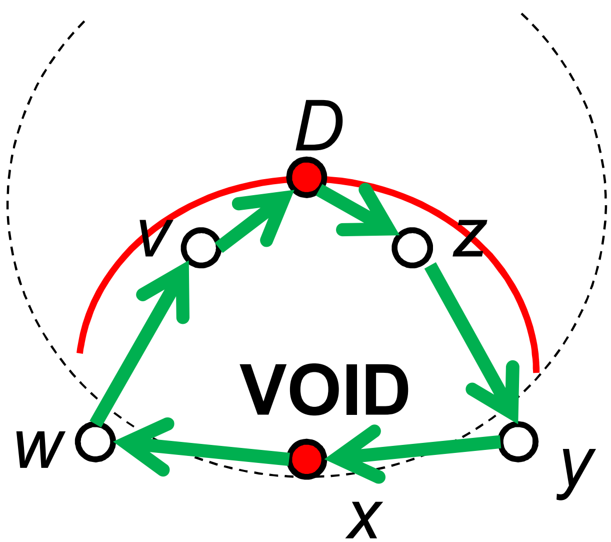
GPSR – Greedy forwarding

- 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**



This sequence of edges traversed is called a *PERIMETER*

Discussion

- **Many variants:**
  - » Hybrid approaches mix different solutions
  - » Hierarchical: create a hierarchy of clusters
- **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, …**
- **Practical applications are rare by exist:**
  - » Mesh networking: wireless, last mile Internet access
  - » Challenging conditions: first responders, military, ..
  - » In the future maybe vehicular, drones, …

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

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