("old") Wireless network taxonomy

	single hop	multiple hops
infrastructure (e.g., APs)		
no infrastructure		

("old") Wireless network taxonomy

	single hop	multiple hops
infrastructure (e.g., APs)	host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: *mesh net*
no infrastructure	no base station, no connection to larger Internet (Bluetooth, ad hoc nets)	no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET

Cellular networks vs ad-hoc networks

Table 5.1. Differences between cellular networks and ad hoc wireless networks

Cellular Networks	Ad Hoc Wireless Networks
Fixed infrastructure-based	Infrastructure-less
Single-hop wireless links	Multi-hop wireless links
Guaranteed bandwidth (designed for voice traffic)	Shared radio channel (more suitable for best-effort data traffic)
Centralized routing	Distributed routing
Circuit-switched (evolving toward packet switching)	Packet-switched (evolving toward emulation of circuit switching)
Seamless connectivity (low call drops during handoffs)	Frequent path breaks due to mobility
High cost and time of deployment	Quick and cost-effective deployment
Reuse of frequency spectrum through geographical channel reuse	Dynamic frequency reuse based on carrier sense mechanism
Easier to achieve time synchronization	Time synchronization is difficult and consumes bandwidth
Easier to employ bandwidth reservation	Bandwidth reservation requires complex medium access control protocols
Application domains include mainly civilian and commercial sectors	Application domains include battlefields, emergency search and rescue operations, and collaborative computing
High cost of network maintenance (backup power source, staffing, etc.)	Self-organization and maintenance properties are built into the network
Mobile hosts are of relatively low complexity	Mobile hosts require more intelligence (should have a transceiver as well as routing/switching capability)
Major goals of routing and call admission are to maximize the call acceptance ratio and minimize the call drop ratio	Main aim of routing is to find paths with minimum overhead and also quick reconfiguration of broken paths
Widely deployed and currently in the third generation of evolution	Several issues are to be addressed for successful commercial deployment even though widespread use exists in defense

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Please ignore some ...

Applications of ad-hoc networks

- Military
- Emergency operations
- Collaborative and distributed computing
- Wireless mesh networks
- Wireless sensor networks
- Hybrid wireless networks

Wireless mesh networks, example

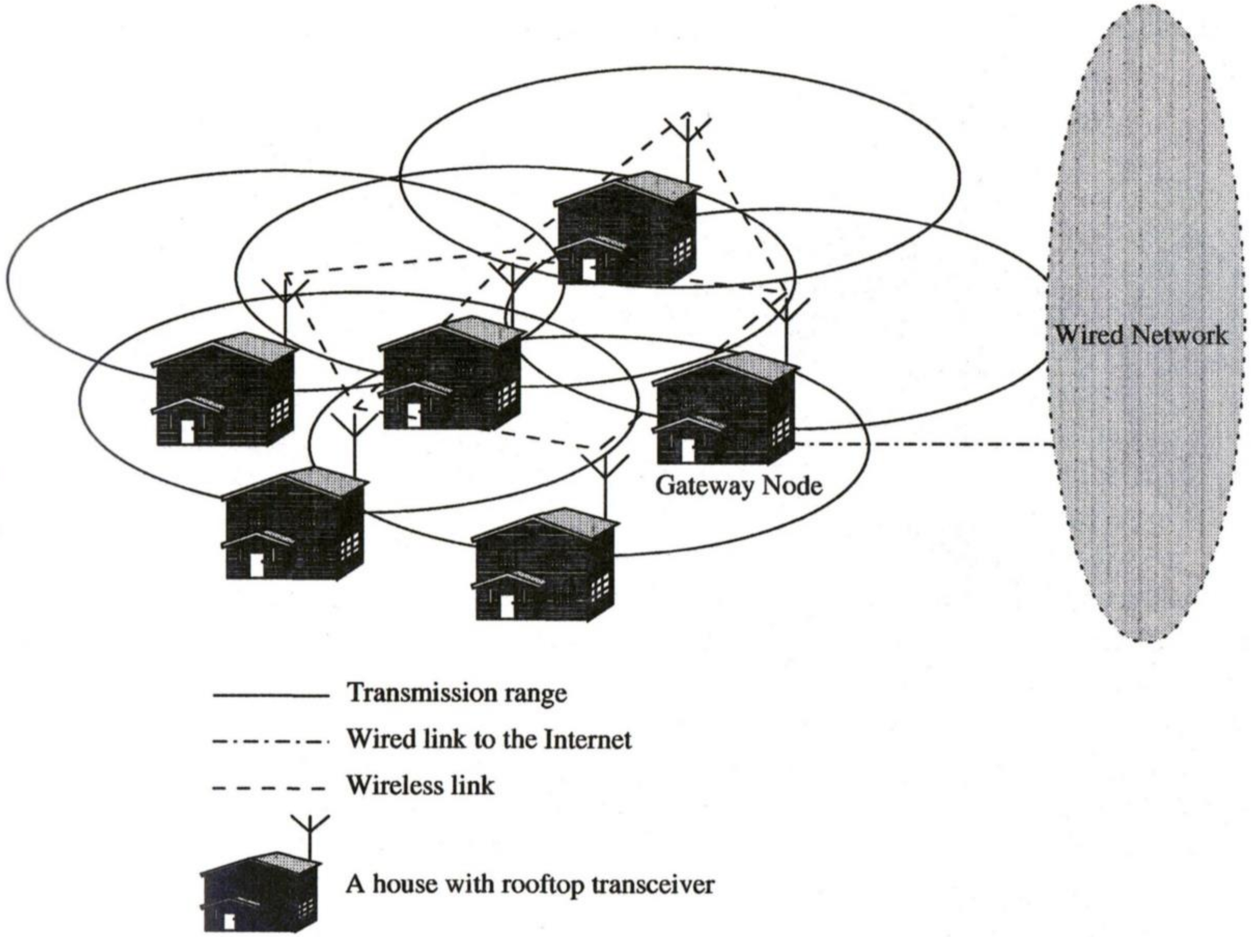


Figure 5.4. Wireless mesh network operating in a residential zone.

Wireless mesh networks, example

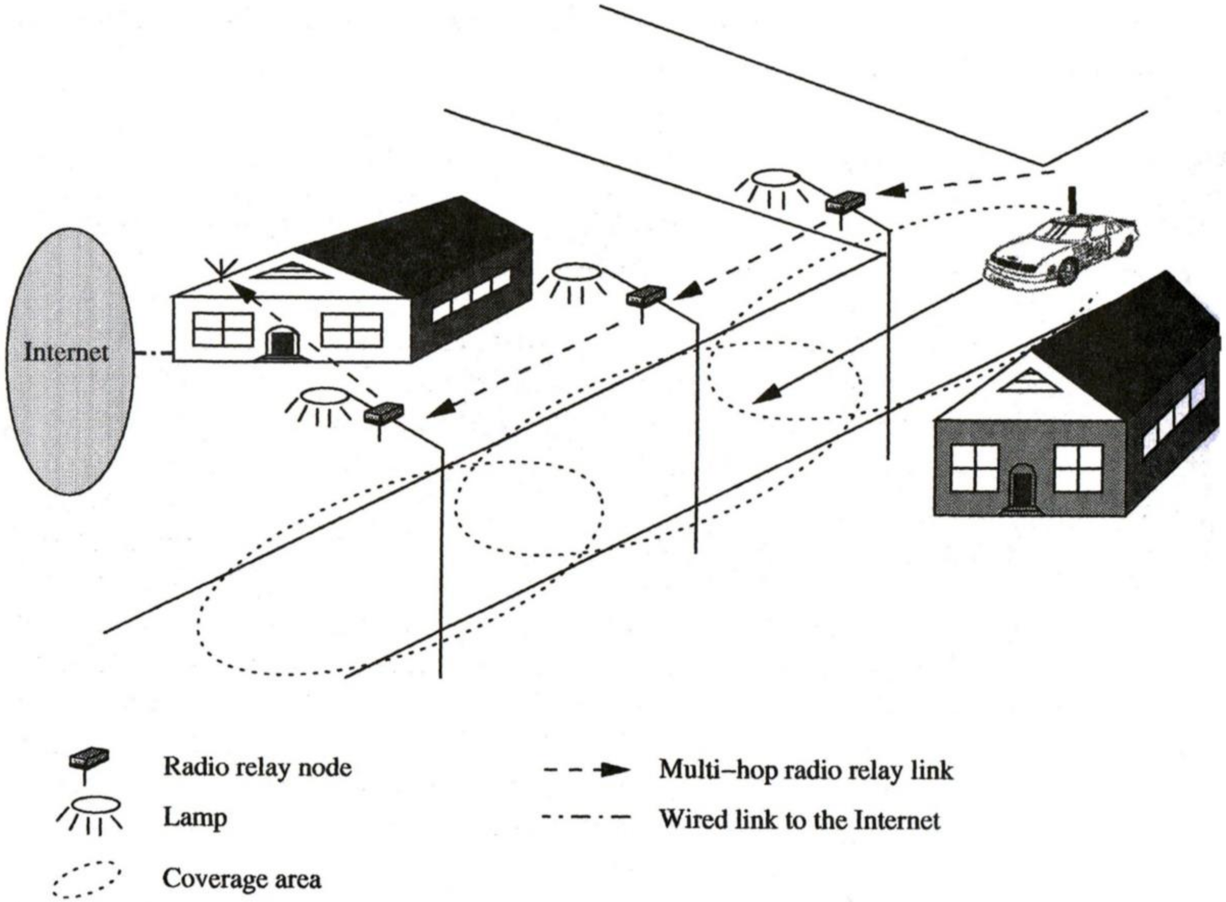


Figure 5.5. Wireless mesh network covering a highway.

Hybrid wireless networks, example

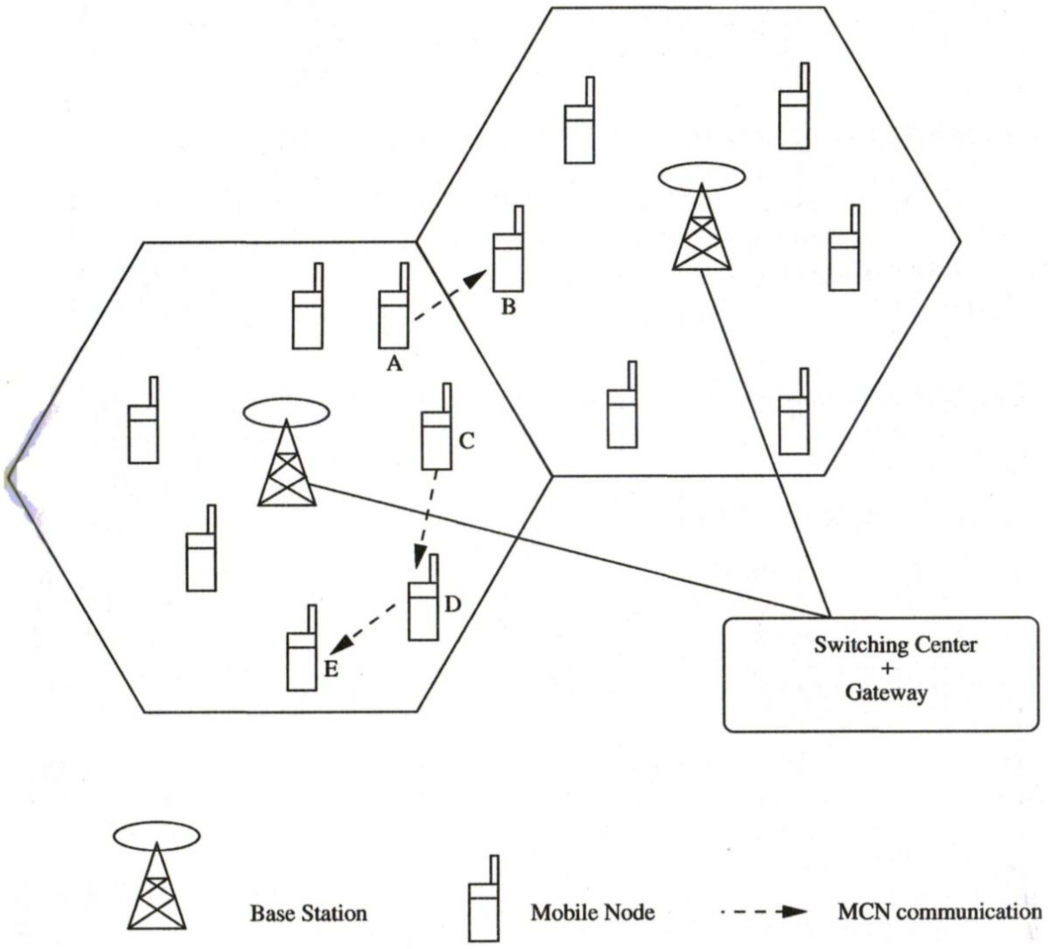


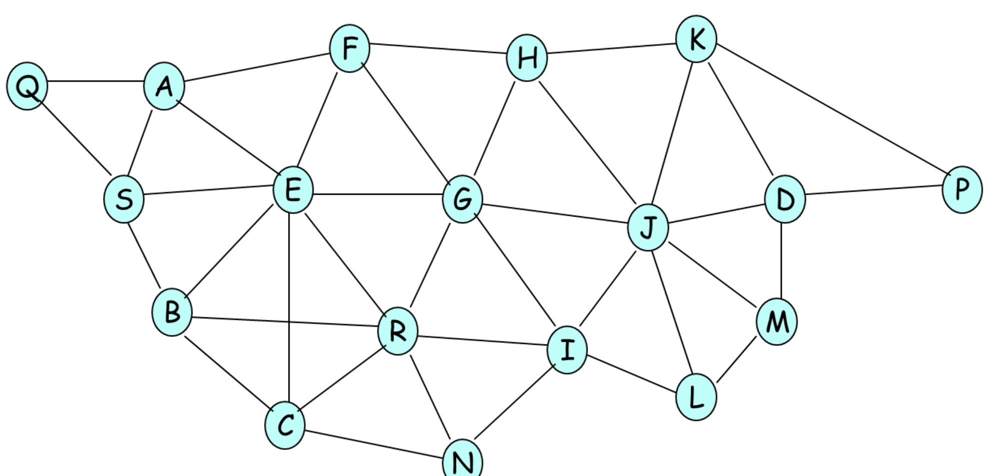
Figure 5.6. MCN architecture.

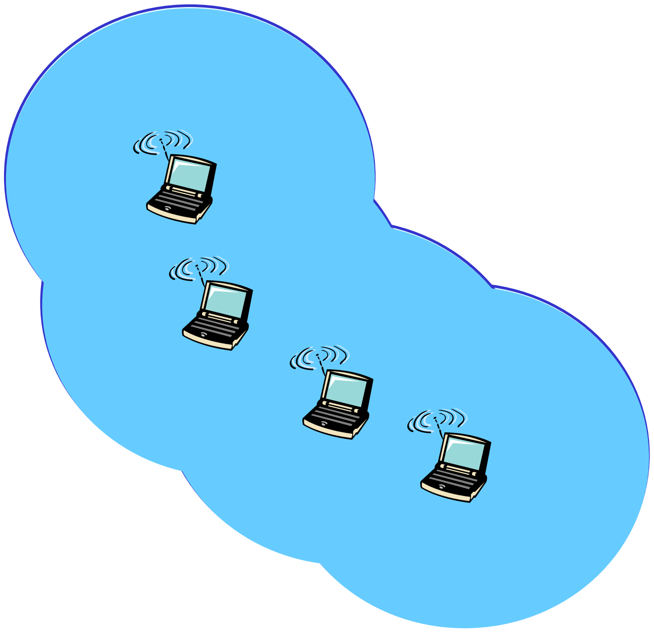
Issues in ad-hoc wireless networks

- Medium access scheme
- Routing
  - Multicasting
- Transport layer protocol
- Pricing scheme
- Quality of service provisioning
- Self-organization
- Energy management
- Addressing and service discovery
- Scalability
- Deployment considerations

Issues: Routing in Ad-hoc Networks

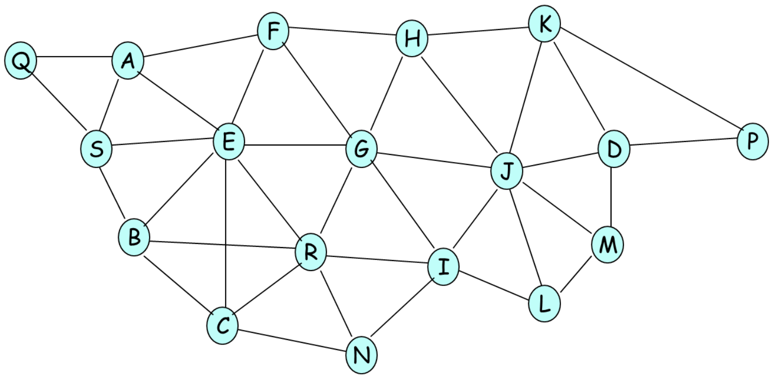
- Mobility
- Bandwidth constraint
- Error-prone and shared channel
- Location-dependent contention
- Other resource constraints





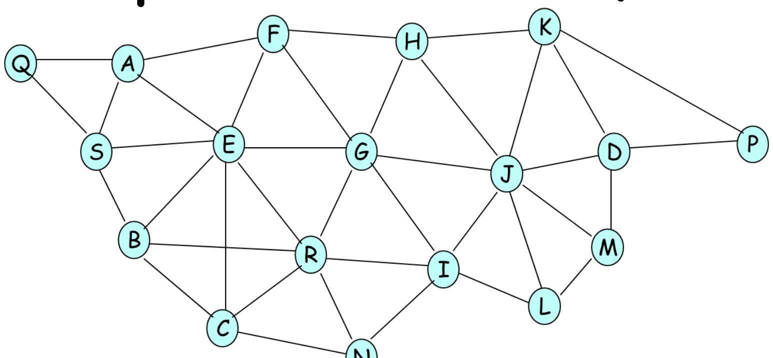
Unicast Routing Protocols

- Many protocols have been proposed
  - Some invented specifically for MANET
  - Others adapted from previously proposed protocols for wired networks
- No single protocol works well in all environments
  - some attempts to develop adaptive protocols



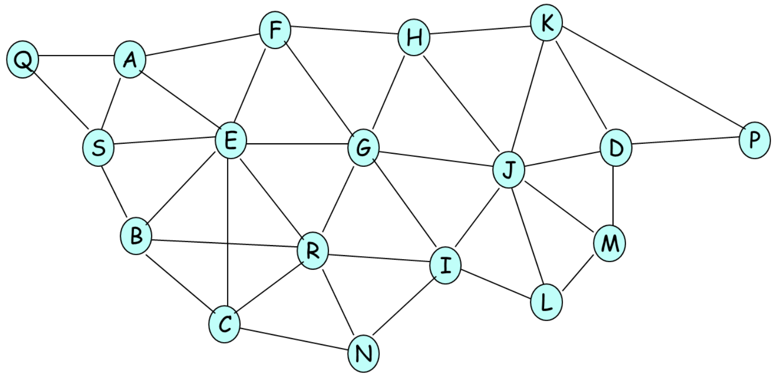
The ideal protocol (p303)

- Distributed
- Localized (and scalable)
- Adaptive
- Minimal maintenance and overhead
- Loop free (and free from stale routes)
- Balance scares resources usage against performance (and/or QoS)

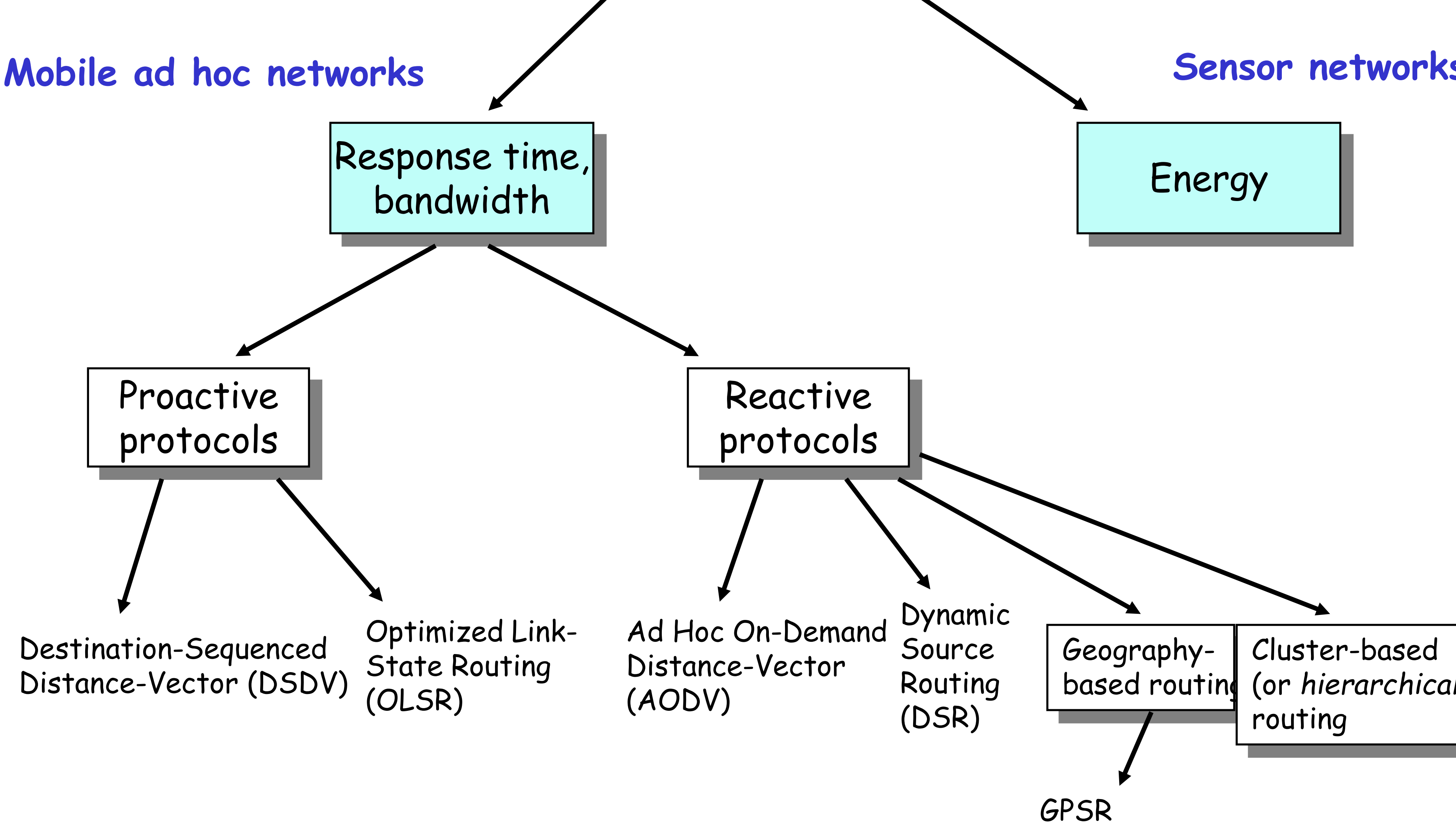


Routing protocol classification

- Route information mechanism
  - Proactive (table-driven)
  - Reactive (demand-driven)
  - Hybrid
- Temporal information
  - Past vs. Future information
- Routing toplogy
  - Flat vs. hierarchical
- Specific resources
  - Geography or Power



Taxonomy: Routing protocols for wireless ad hoc networks



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  - Flat vs. hierarchical
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  - Geography or Power

Route update mechanism

- Proactive (or table-drive) protocols
  - Determine routes independent of traffic pattern
  - Traditional link-state and distance-vector routing protocols
    - Destination Sequenced Distance Vector (DSDV)
    - Optimized Link State Routing (OLSR)
- Reactive (or demand-drive) protocols
  - Route is only determined when actually needed
  - Protocol operates ***on demand***
    - Dynamic Source Routing (DSR)
    - Ad hoc On-demand Distance Vector (AODV)
    - Temporally Ordered Routing Algorithm (TORA)
- Hybrid Protocols
  - Combine these behaviors (e.g., table in limited zone, and demand drive otherwise)
    - Greedy Perimeter Stateless Routing (GPSR)
    - Zone Routing Protocol (ZRP)

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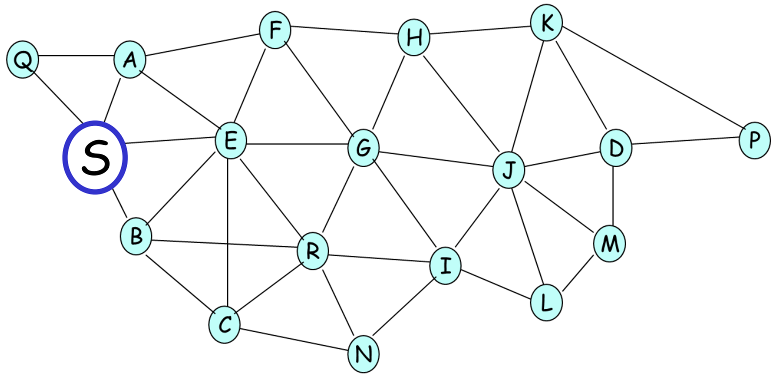
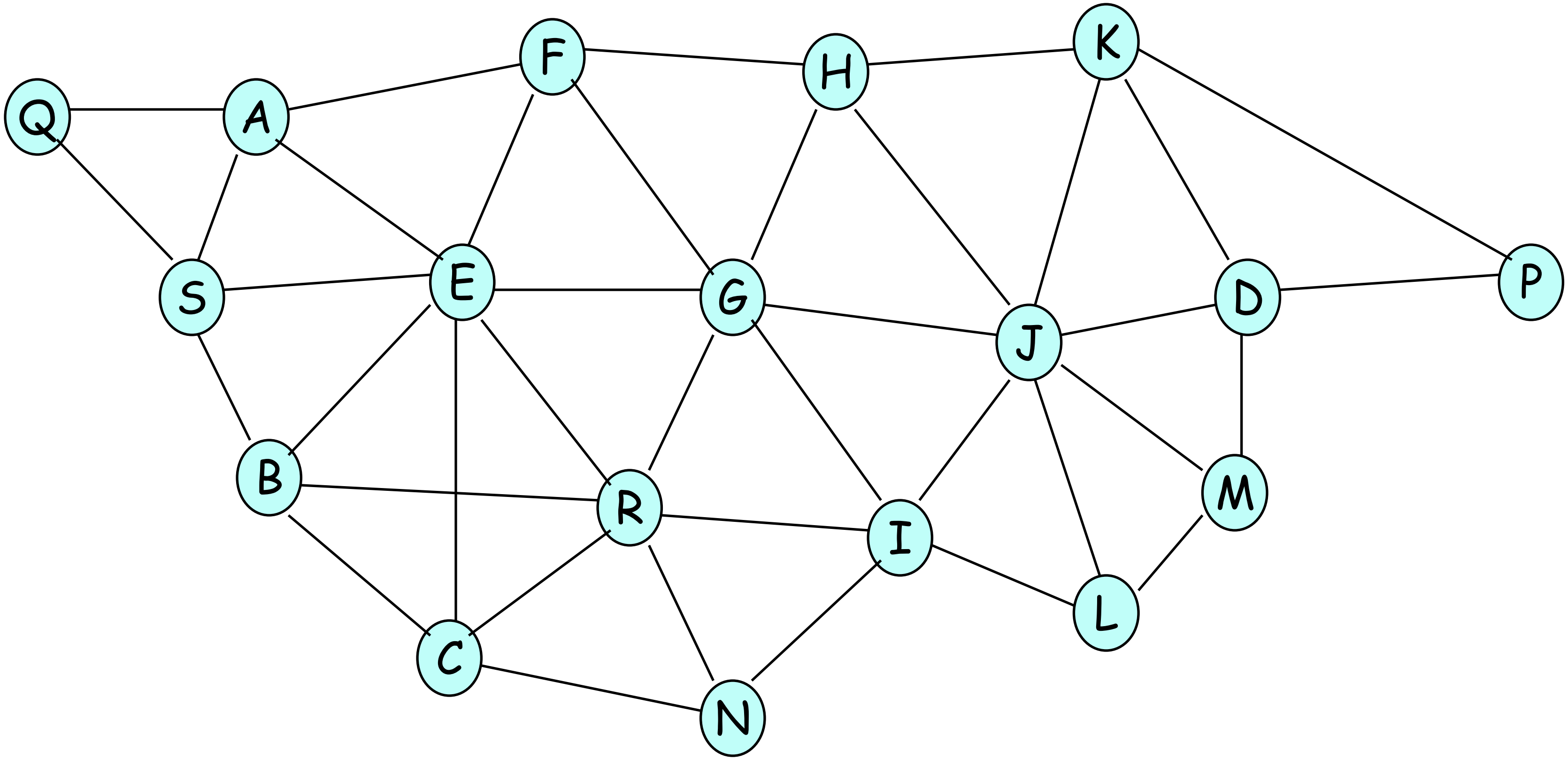
Dynamic Source Routing (DSR) [Johnson96]

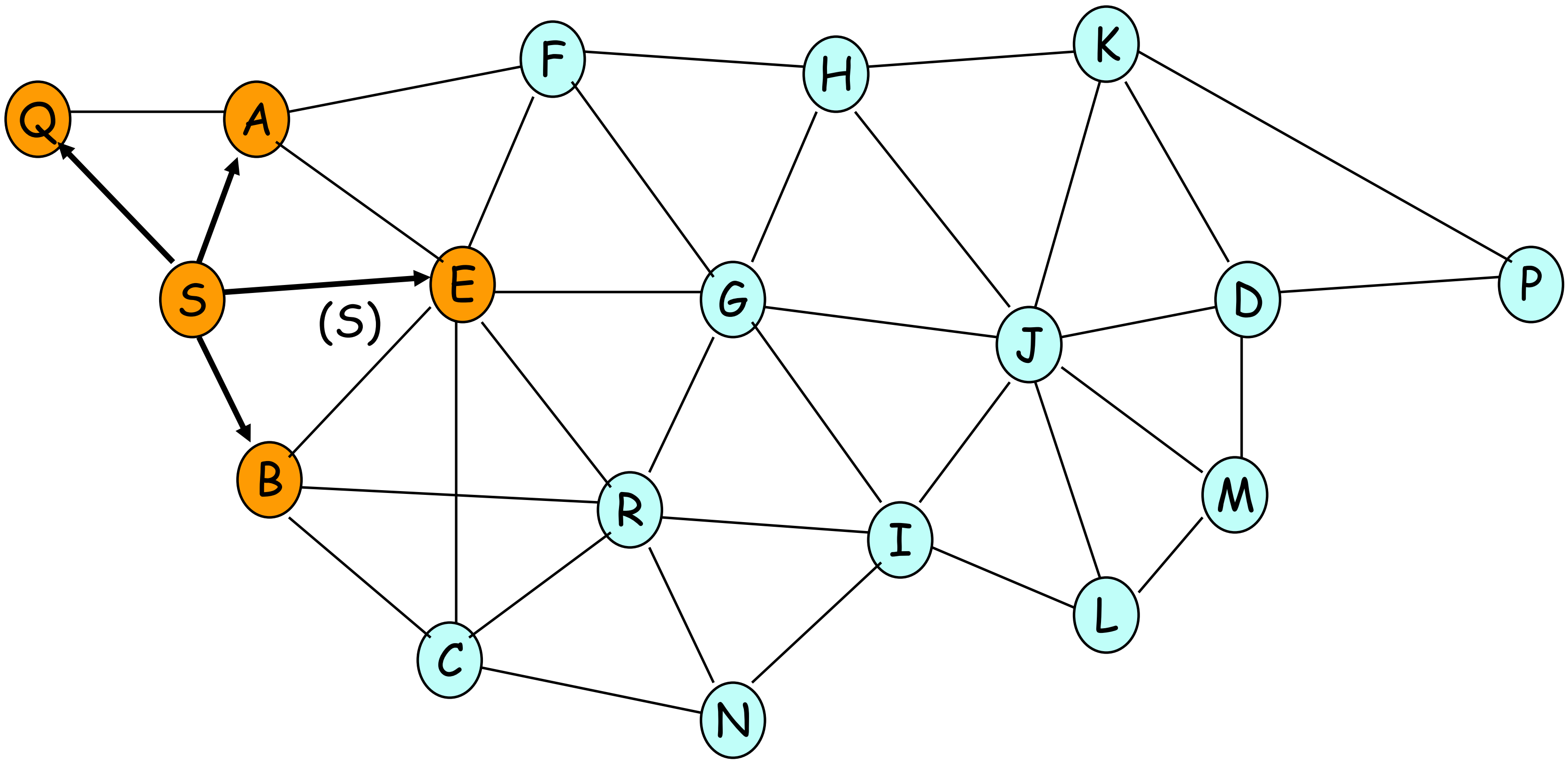
- When node S wants to send a packet to node D, but does not know a route to D, node S initiates a route discovery
- Source node S floods Route Request (RREQ)
- Each node appends own identifier when forwarding RREQ



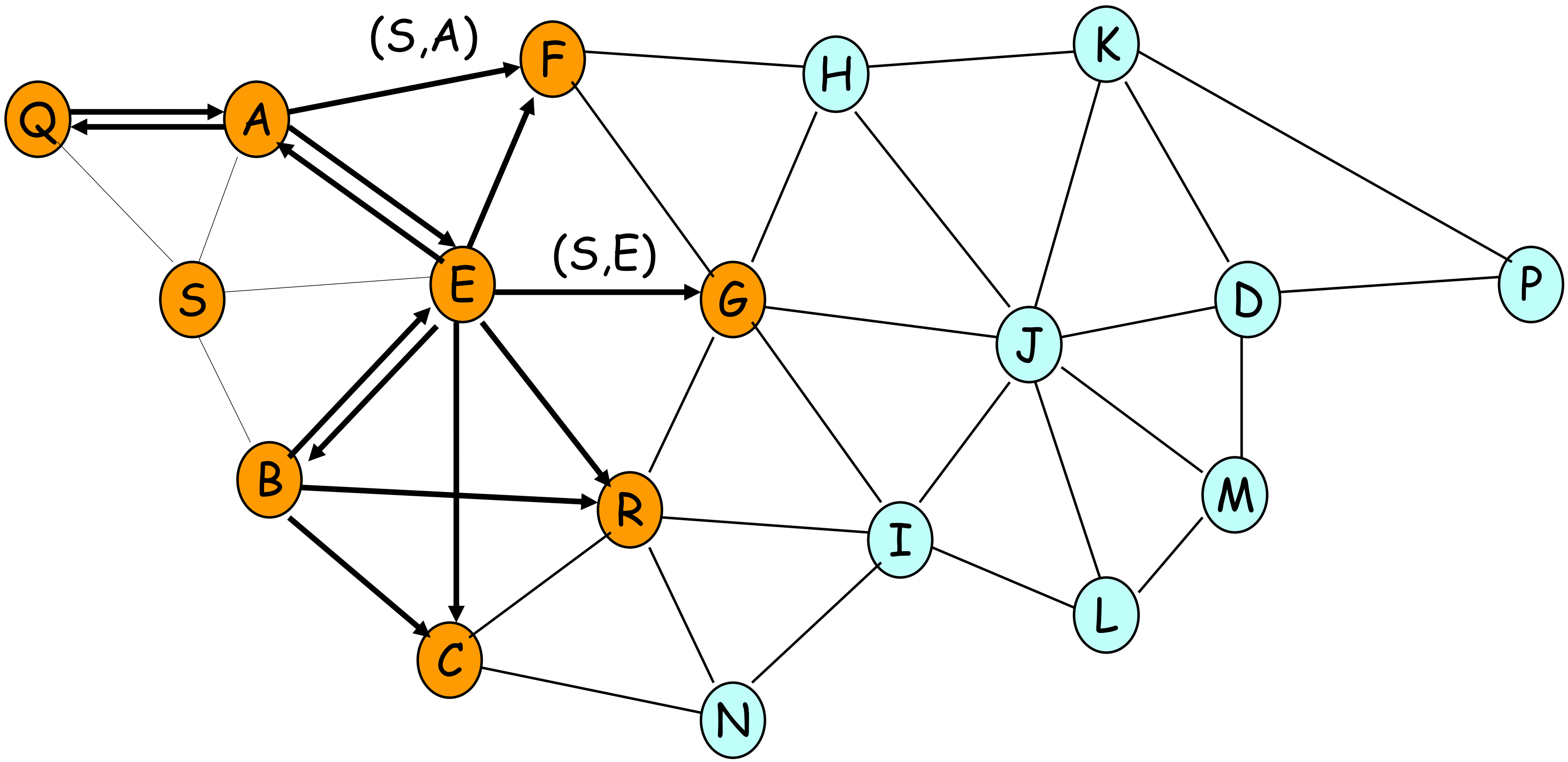
DSR: Route discovery (1)



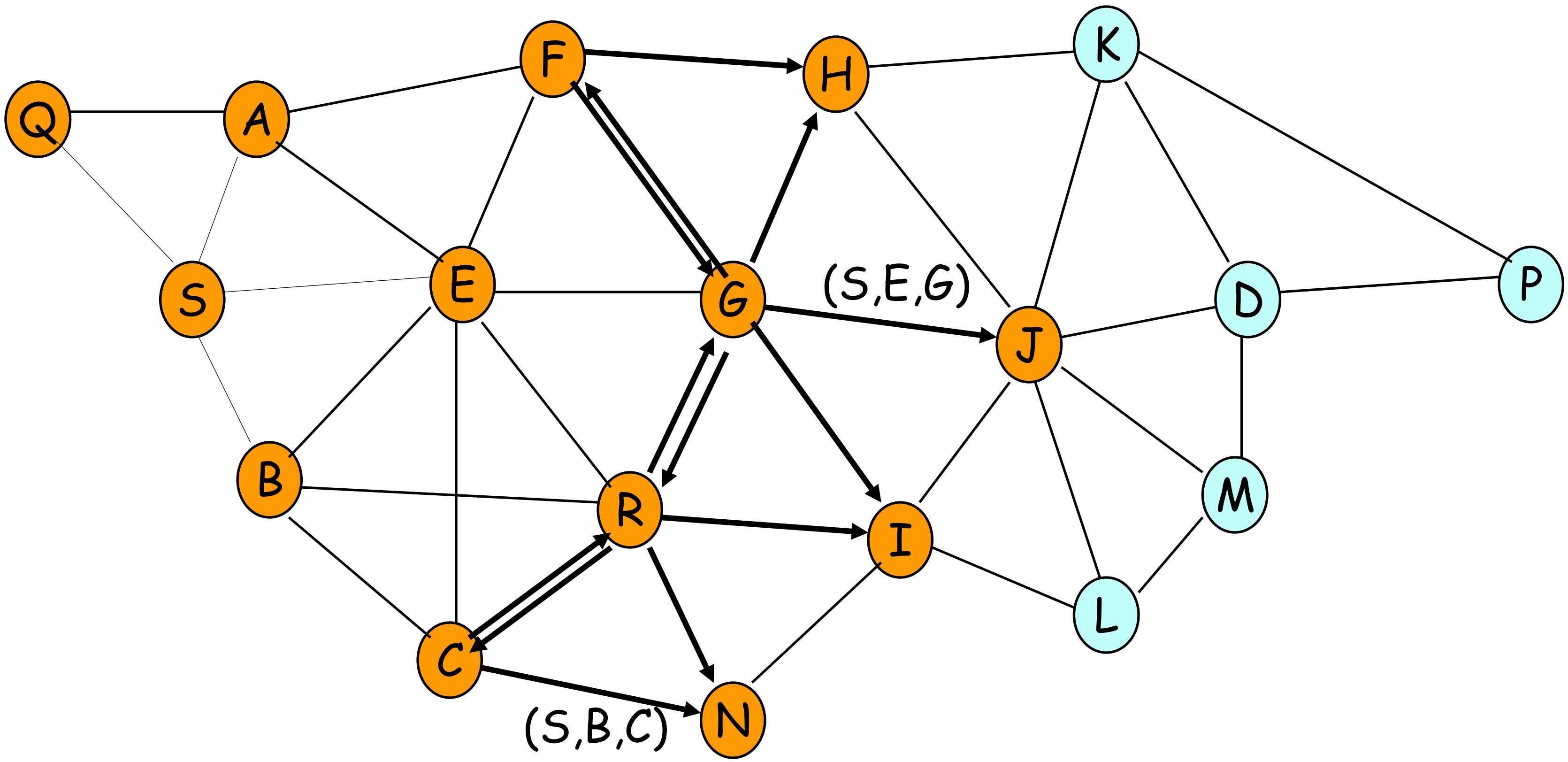
DSR: Route discovery (2)



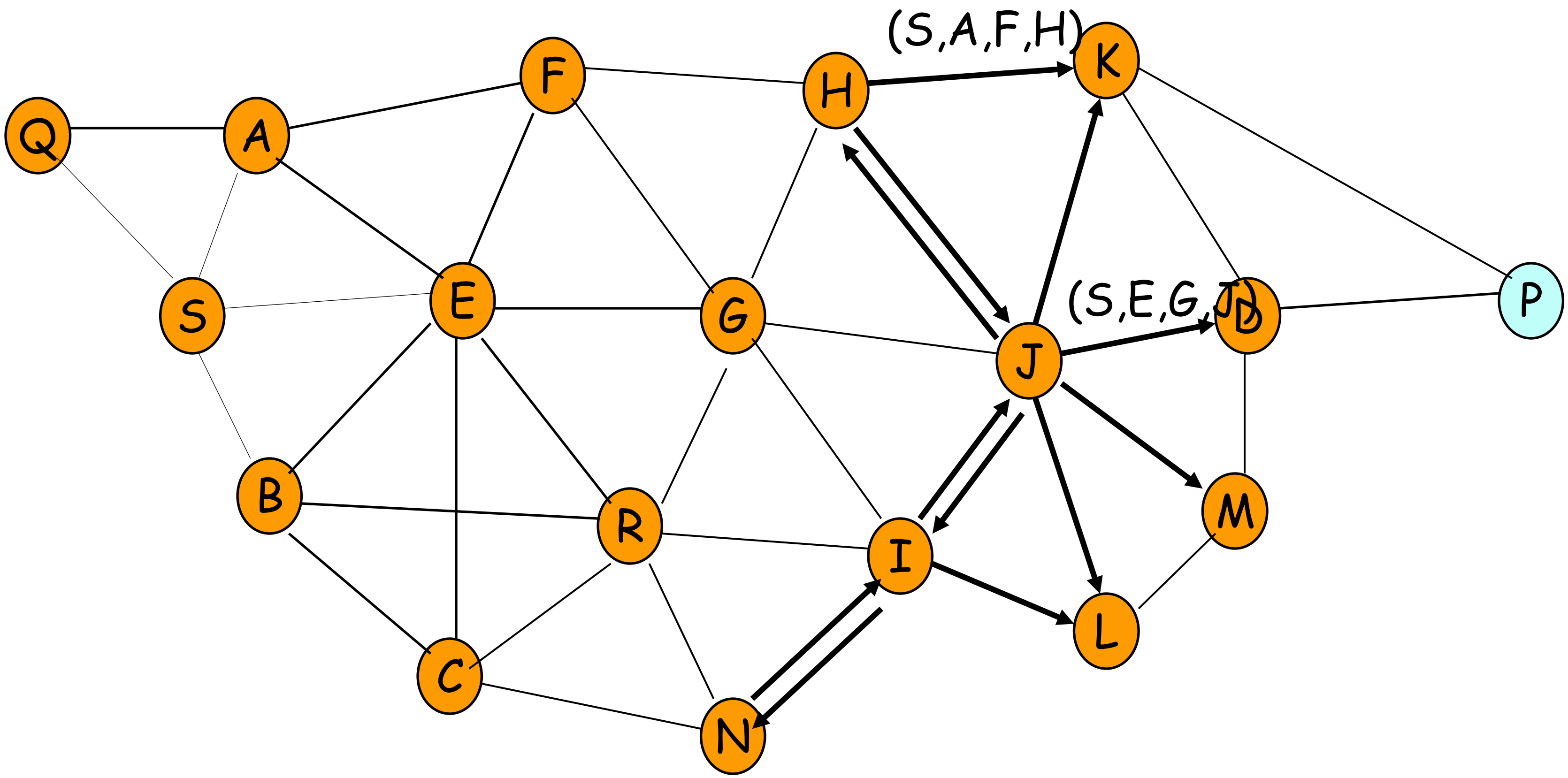
DSR: Route discovery (3)



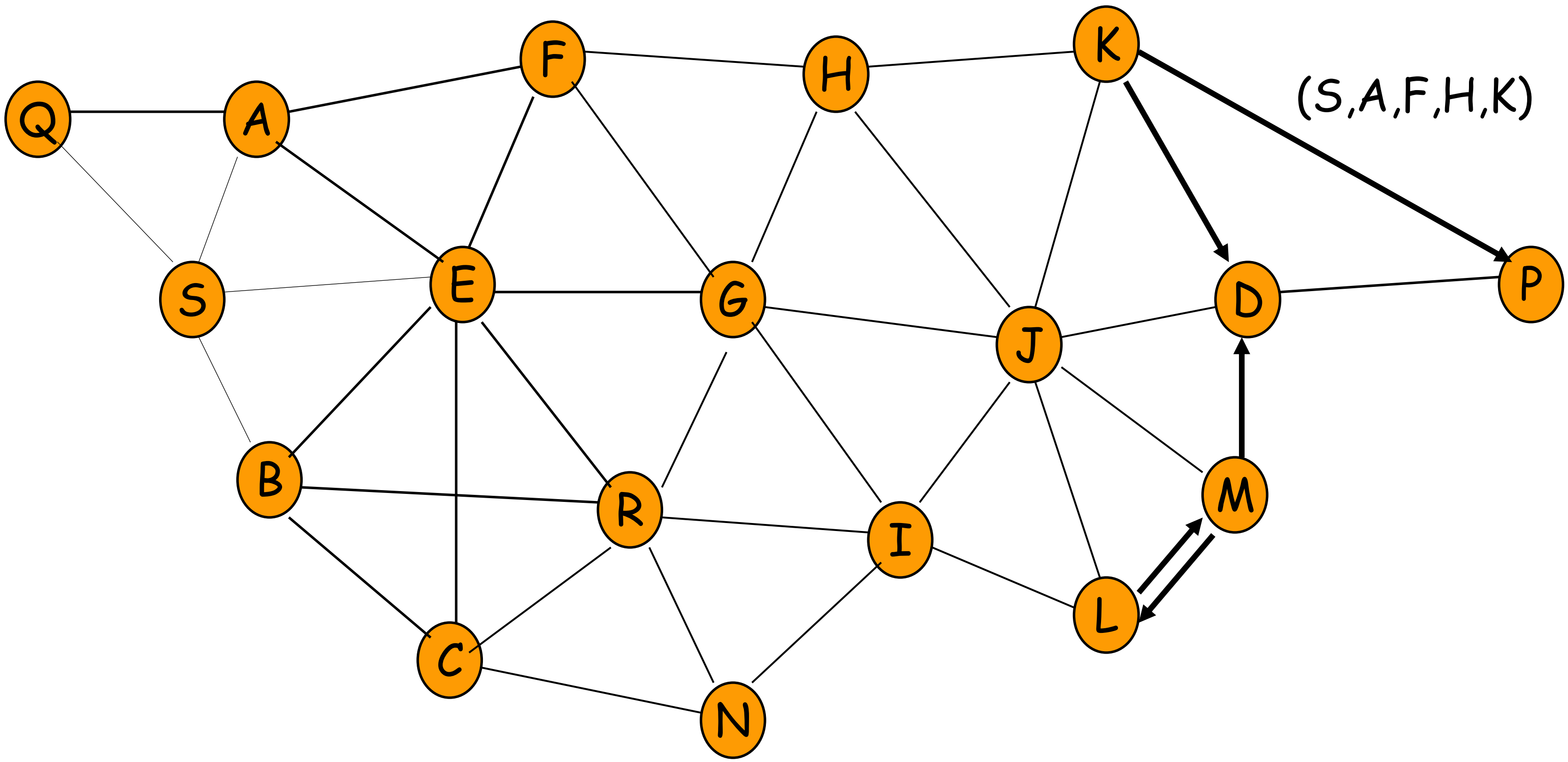
DSR: Route discovery (4)



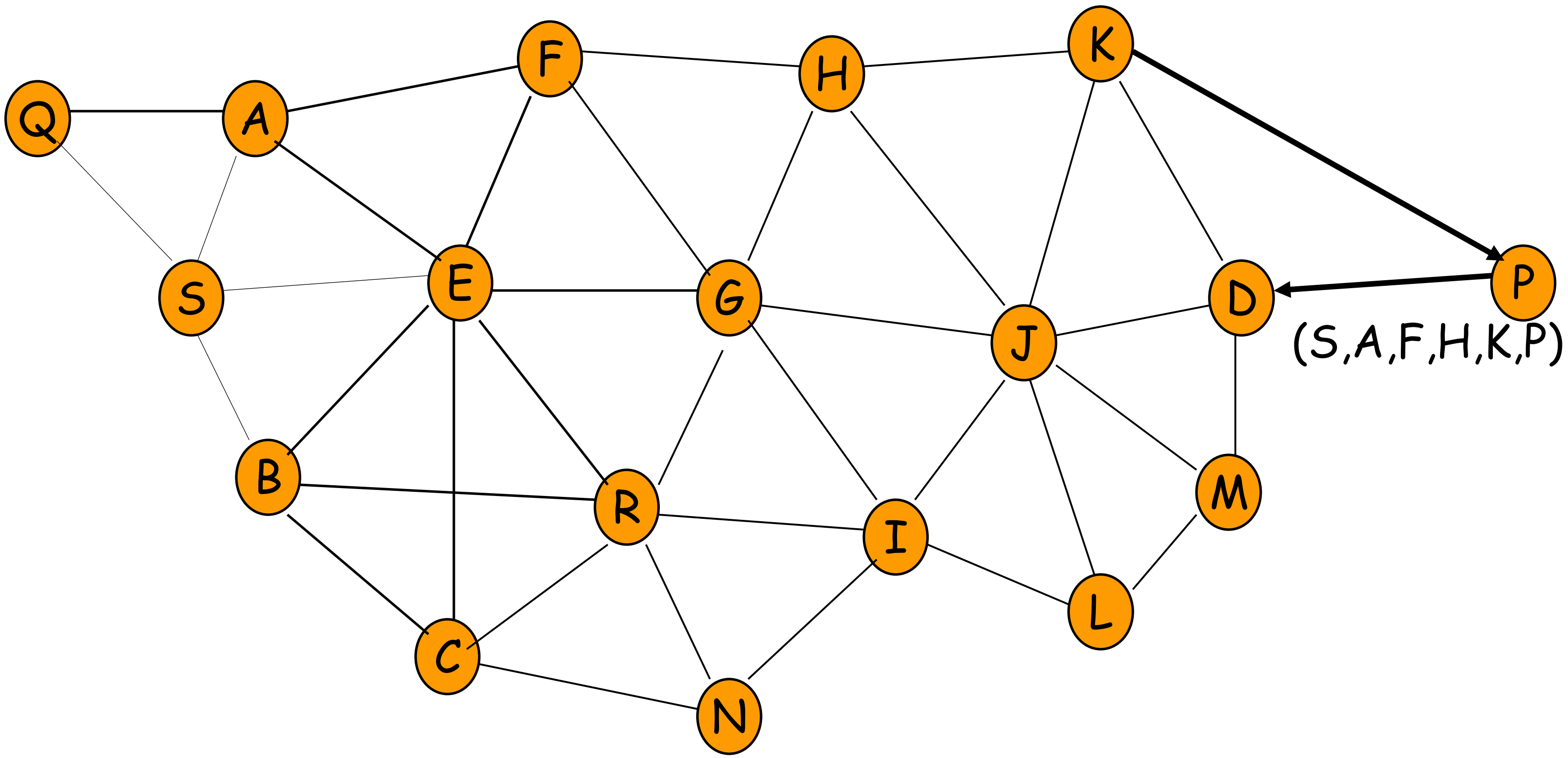
DSR: Route discovery (5)



DSR: Route discovery (6)

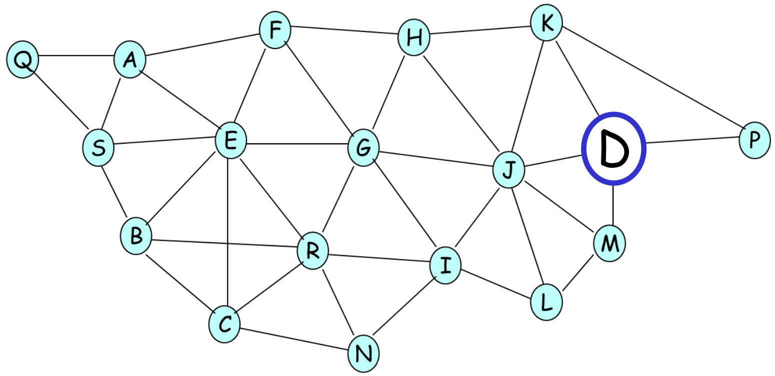


DSR: Route discovery (7)

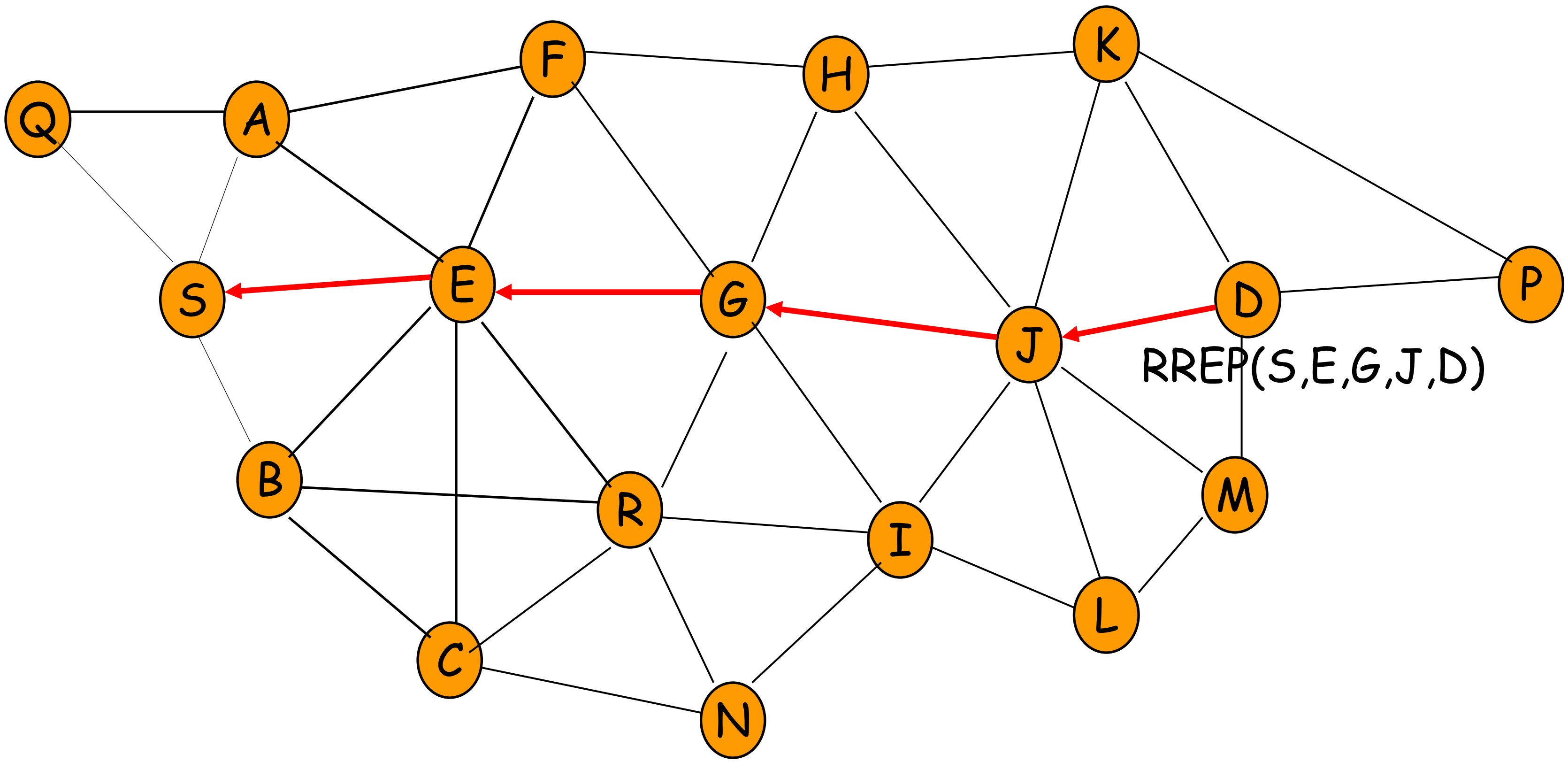


Route Discovery in DSR

- 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

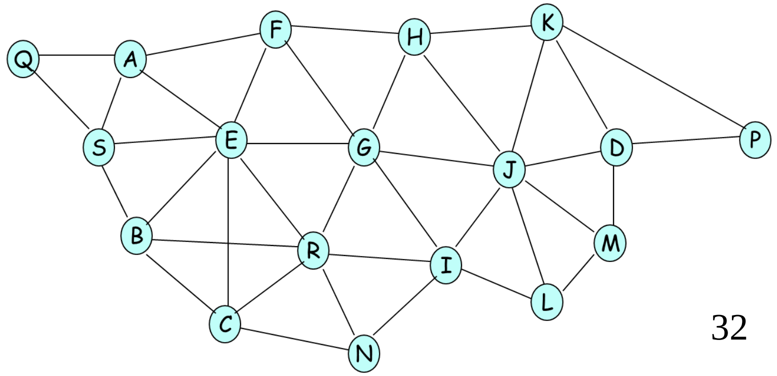


DSR: Route discovery (8)



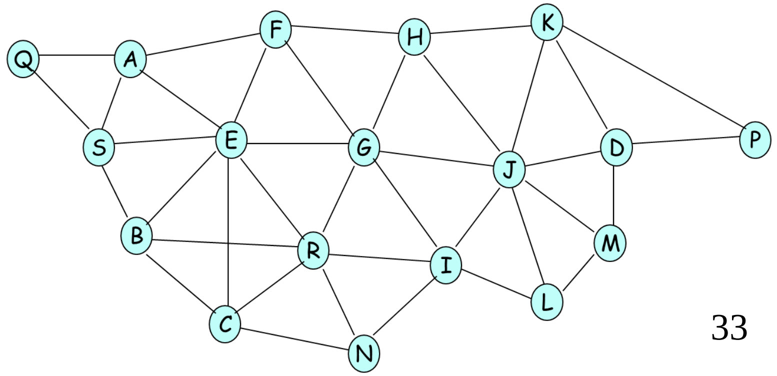
DSR: RREP assumption

- Route reply by reversing the route (as illustrated) works only if all the links are **bidirectional**
- If unidirectional links are allowed, then RREP may need a reverse route discovery from D to S
- **Note:** IEEE 802.11 assumes that links are bidirectional (since ACKs are used)

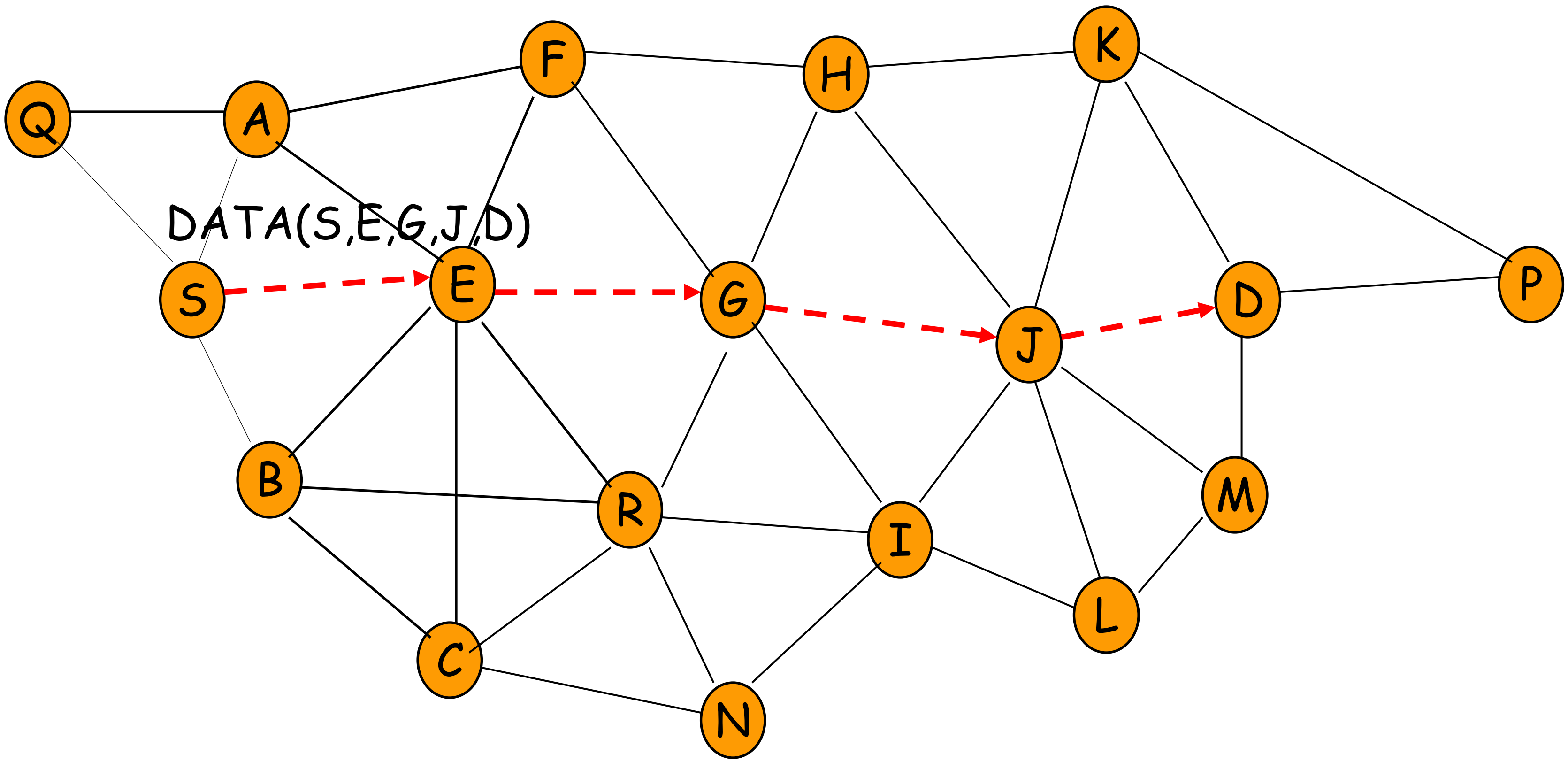


DSR: Caching and "source routing"

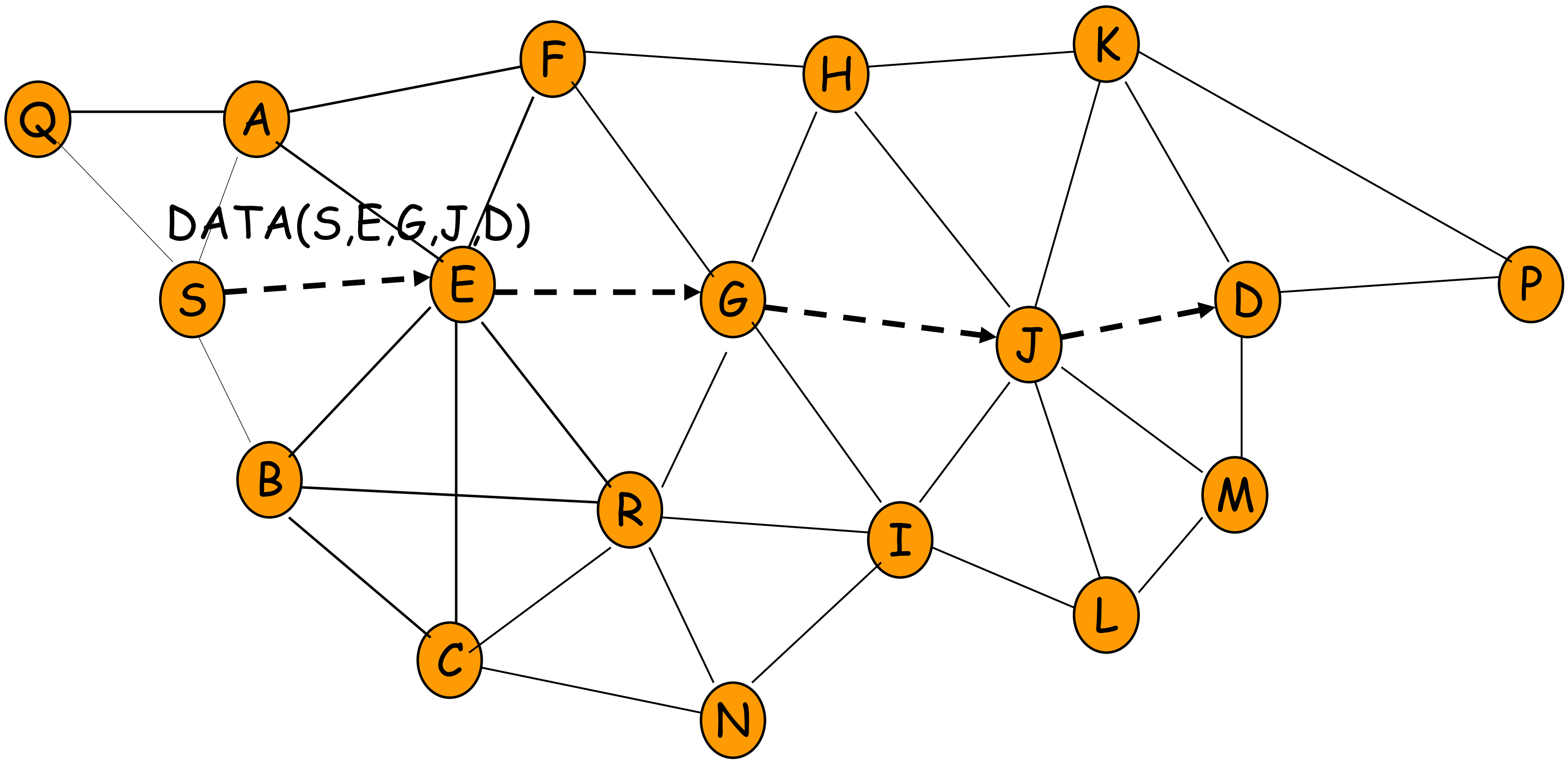
- Node S on receiving RREP, caches the route included in the RREP
- When node S sends a data packet to D, the entire route is included in the packet header
  - hence the name source routing
- Intermediate nodes use the source route included in a packet to determine to whom a packet should be forwarded



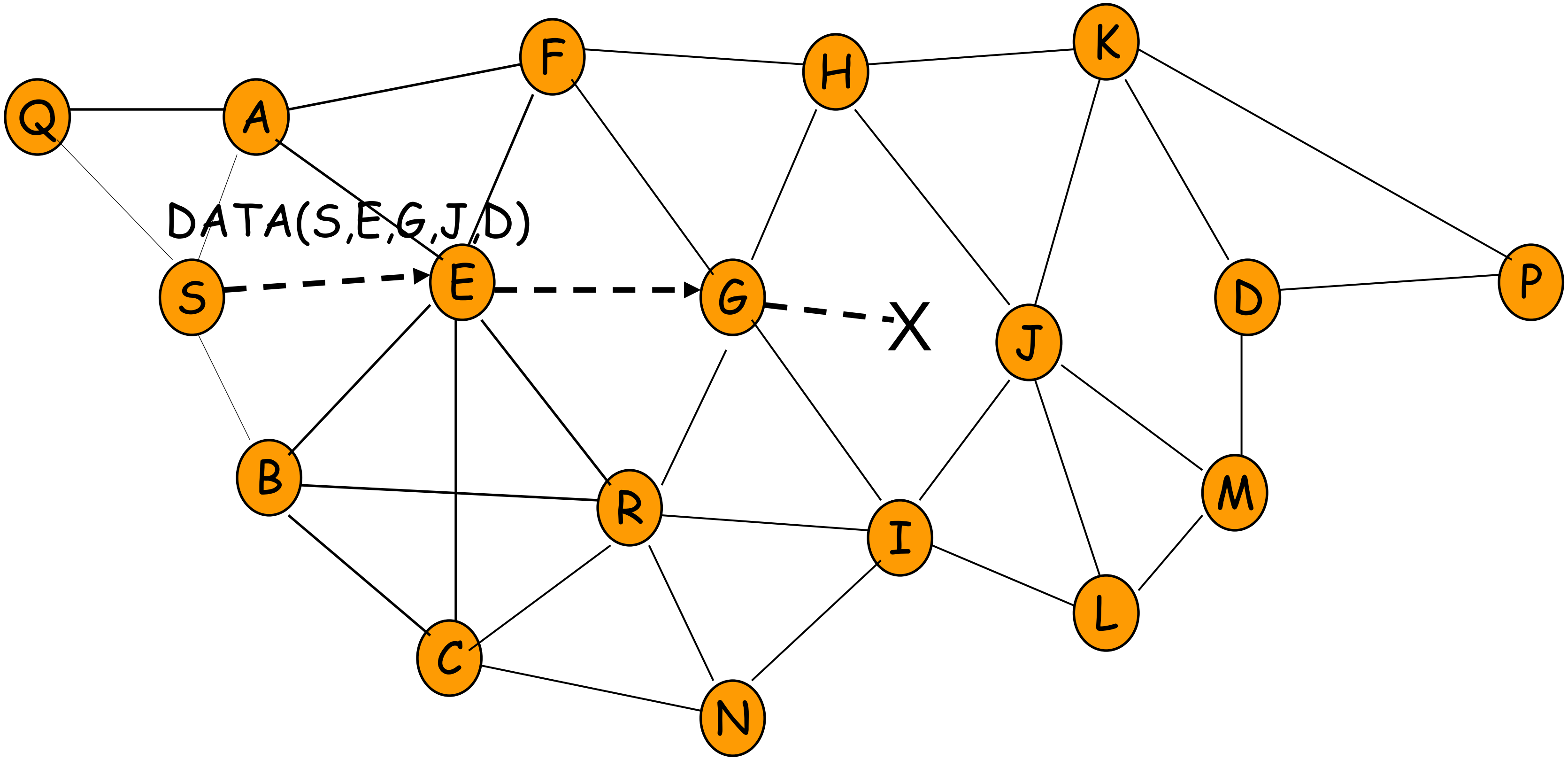
DSR: Data delivery



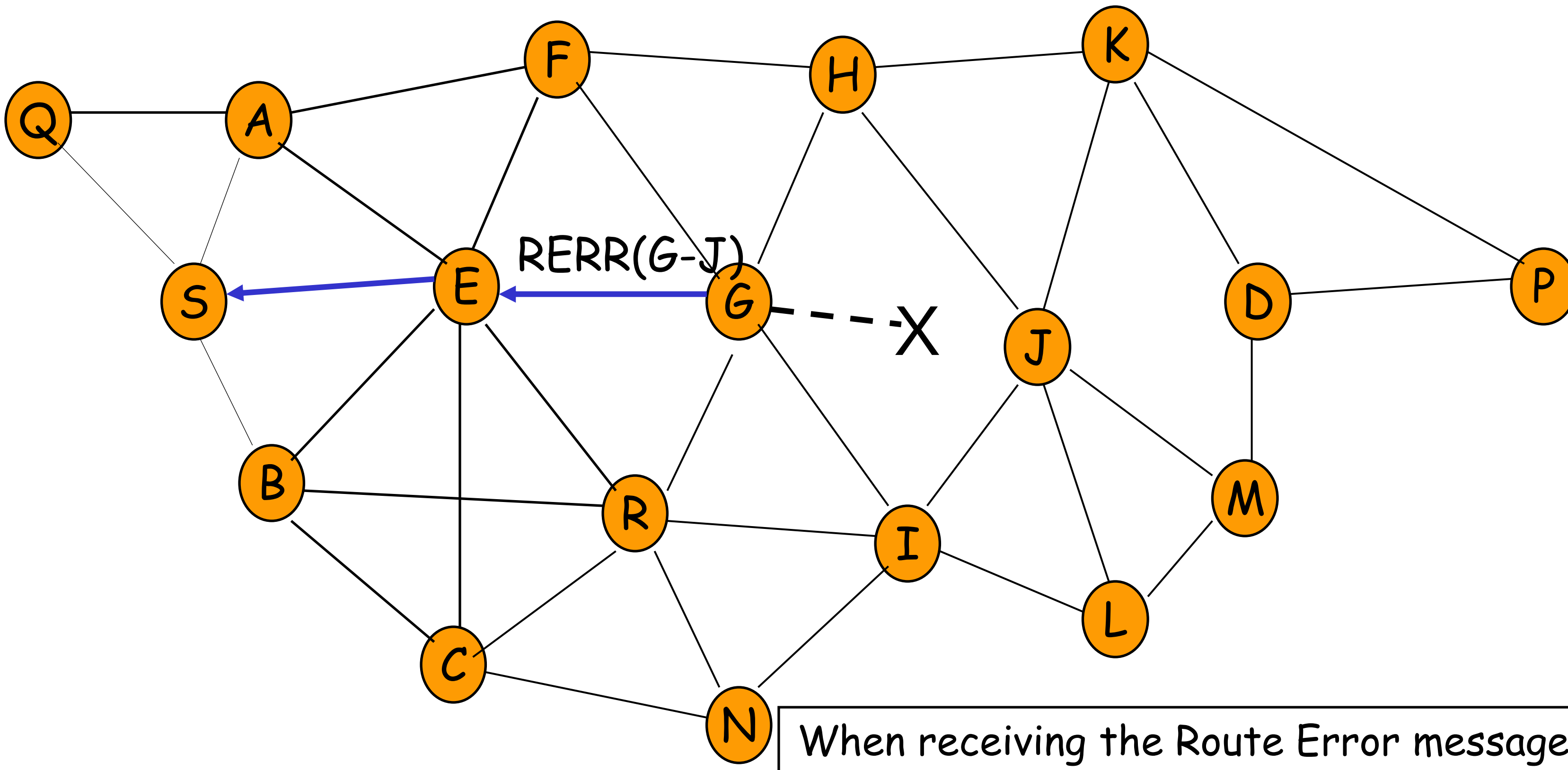
DSR: Data delivery



DSR: Route maintenance (1)



DSR: Route maintenance (2)

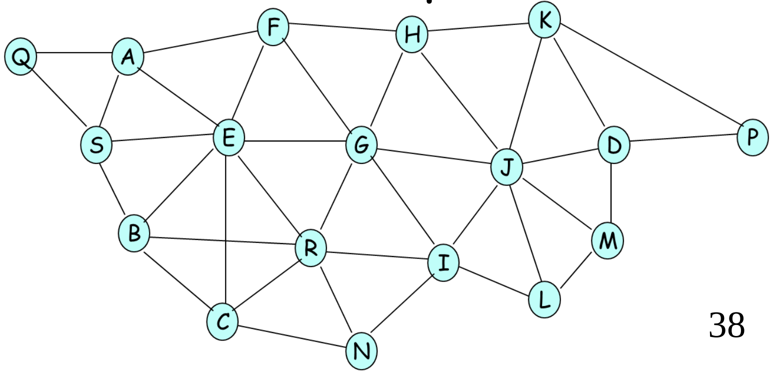


When receiving the Route Error message (RERR), S removes the broken link from its cache.
It then tries another route stored in its cache; if none, it initializes a new route discovery

DSR: Optimization of route discovery: route caching

Principle: Nodes cache new routes learned by any means …

- When node S finds route [S,E,G,J,D] to node D, node S also learns route [S,E,G] to node G
- When node H receives Route Request [S,E,F] destined for node D, node H learns route [H,F,E,S] to node S
- When node G forwards Route Reply RREP [S,E,G,J,D], node G learns route [G,J,D] to node D
- When node E forwards Data [S,E,G,J,D] it learns route [E,G,J,D] to node D
- A node may also learn a route when it **overhears** Data packets ...



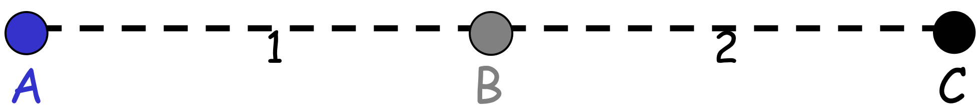
Use of Route Caching

- Use of route cache can
  - speed up route discovery
  - reduce propagation of route requests
- However, route caching has its downside
  - stale caches can severely hamper the performance of the network

Destination Sequenced Distance Vector Algorithm (DSDV)

1. Based on Bellman-Ford Next Hop Routing.
2. Each Node Maintains **Routing Table**, in which the attributes of each destination are :
   A. Next Hop on Path
   B. Distance (in hops) to destination.
   C. Sequence Number (keep current route; originating from destination)
3. Nodes Exchange Updates With Neighbours
   - Full Routing Updates (periodic)
   - Incremental Updates (triggered)

Background: Distance Vector (Tables)

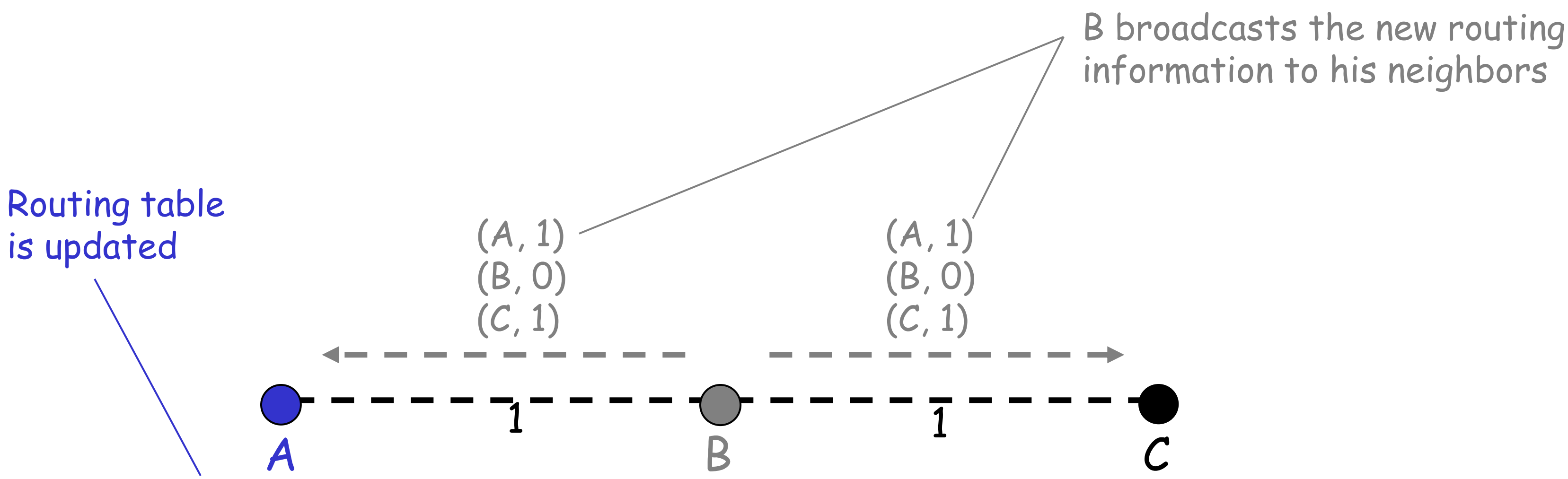


Dest.	Next	Metric	...
A	A	0	
B	B	1	
C	B	3	

Dest.	Next	Metric	...
A	A	1	
B	B	0	
C	C	2	

Dest.	Next	Metric	...
A	B	3	
B	B	2	
C	C	0	

Background: Distance Vector (Update)



Dest.	Next	Metric	...
A	A	0	
B	B	1	
C	B	~~3~~ 2	

Dest.	Next	Metric	...
A	A	1	
B	B	0	
C	C	1	

Dest.	Next	Metric	...
A	B	~~3~~ 2	
B	B	1	
C	C	0	

Distance Vector

- DV not suited for ad-hoc networks!
  - Loops
  - Count to Infinity
- New Solution -> DSDV Protocol

DSDV (Table Entries)

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.

Destination	Next	Metric	Seq. Nr	I
A	A	0	A-550	
B	B	1	B-102	
C	B	3	C-588	
D	B	4	D-212	

DSDV (Route 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 = ∞

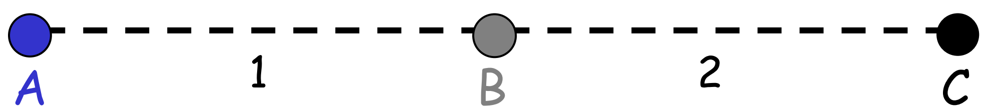
Destination	Next	Metric	Seq. Nr
A	A	0	A-550
B	B	1	B-102
C	B	3	C-588
D	B	4	D-312

DSDV (Route Selection)

Update information is compared to own 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.

DSDV (Tables)



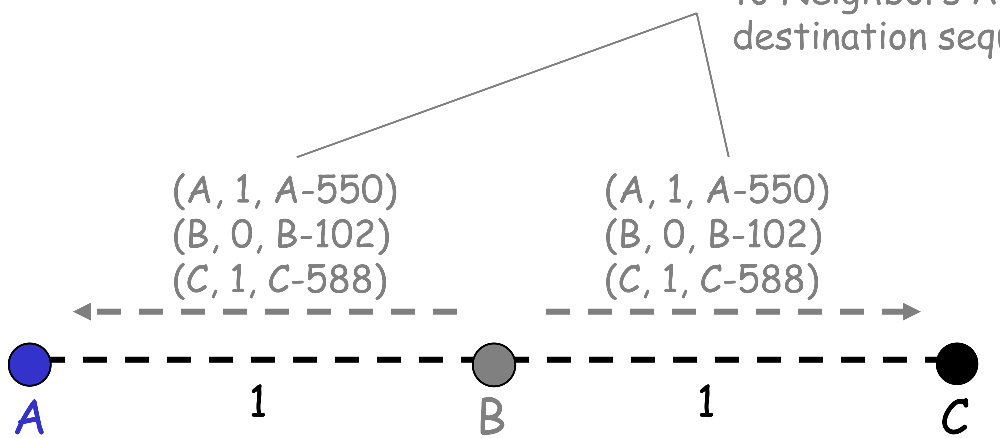
Dest.	Next	Metric	Seq
A	A	0	A-550
B	B	1	B-100
C	B	3	C-586

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

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

DSDV (Route Advertisement)

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



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

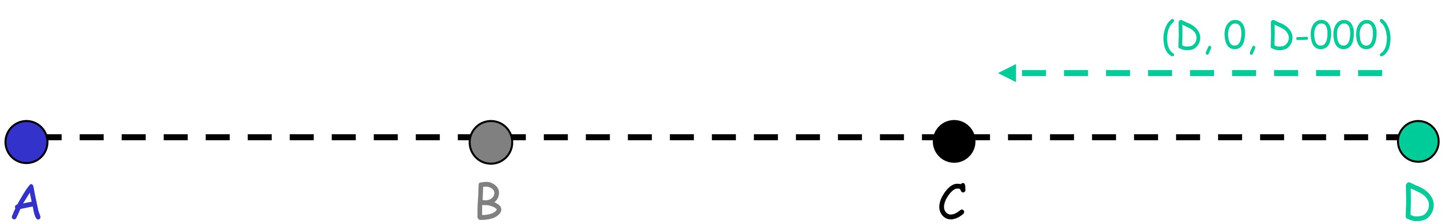
Dest.	Next	Metric	Seq.
A	B	2	A-550
B	B	1	B-102
C	C	0	C-588

DSDV (Respond to 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)

DSDV (New Node)

1. D broadcast for first time
Send Sequence number D-000

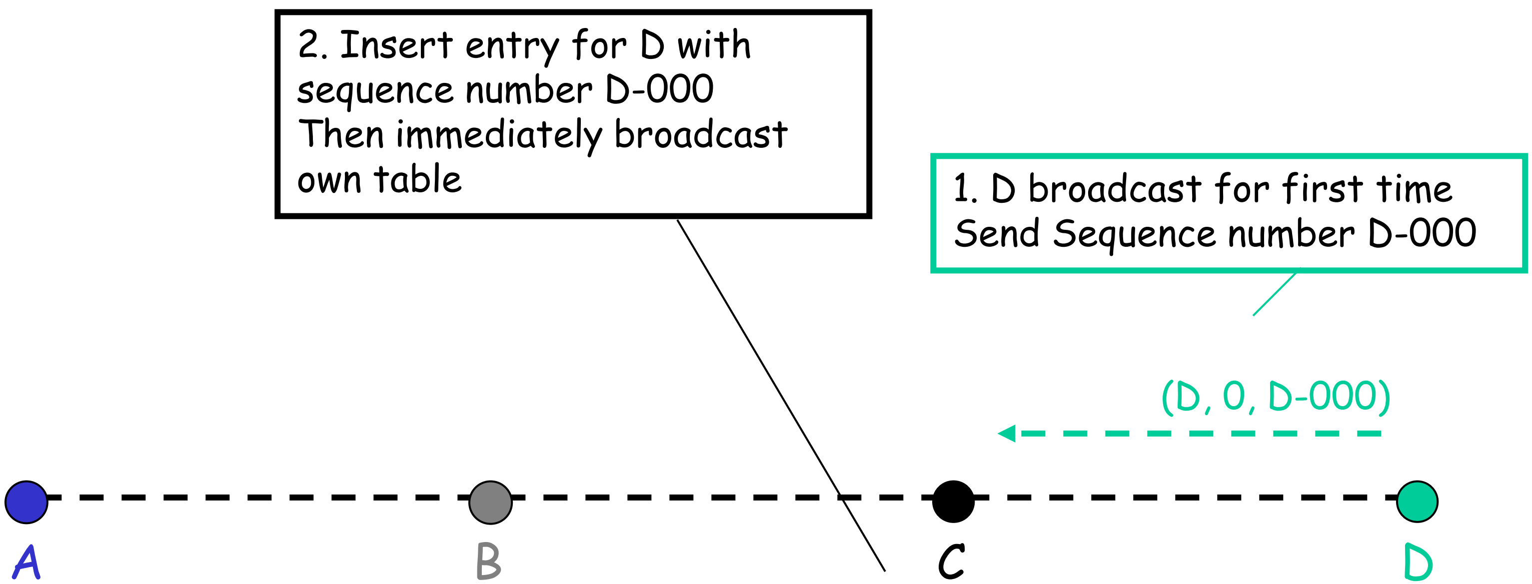


Dest.	Next	Metric	Seq.
A	A	0	A-550
B	B	1	B-104
C	B	2	C-590

Dest.	Next	Metric	Seq.
A	A	1	A-550
B	B	0	B-104
C	C	1	C-590

Dest.	Next	Metric	Seq.
A	B	2	A-550
B	B	1	B-104
C	C	0	C-590

DSDV (New Node)

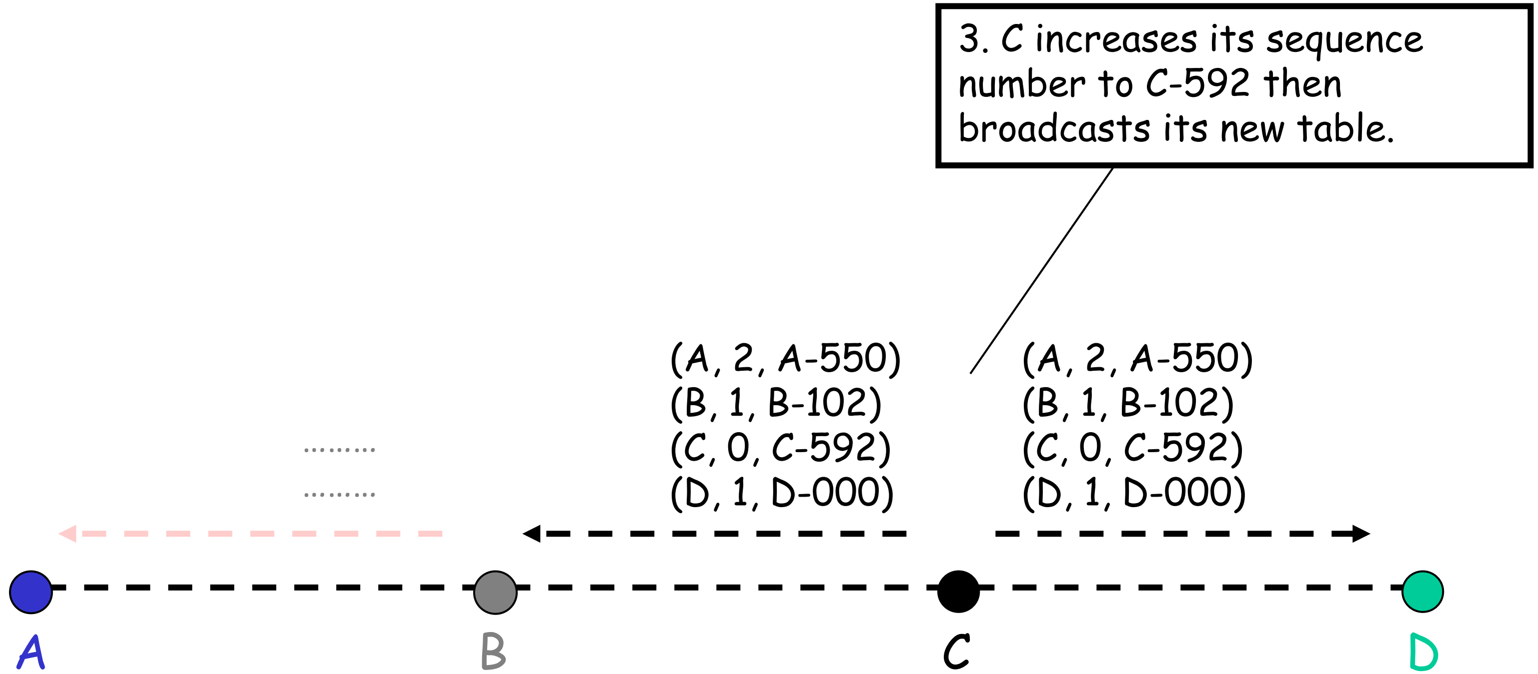


Dest.	Next	Metric	Seq.
A	A	0	A-550
B	B	1	B-104
C	B	2	C-590

Dest.	Next	Metric	Seq.
A	A	1	A-550
B	B	0	B-104
C	C	1	C-590

Dest.	Next	Metric	Seq.
A	B	2	A-550
B	B	1	B-104
C	C	0	C-590
D	D	1	D-000

DSDV (New Node cont.)

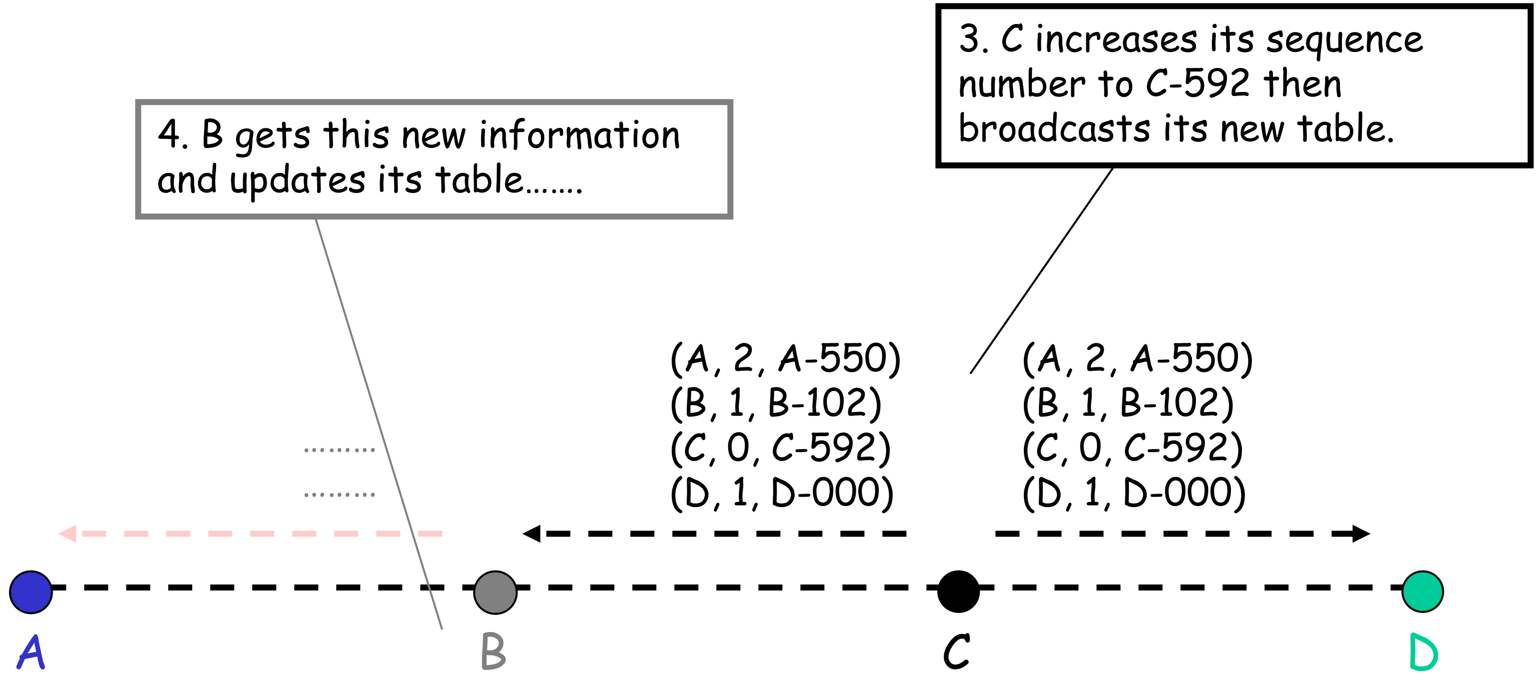


Dest.	Next	Metric	Seq.
A	A	0	A-550
B	B	1	B-104
C	B	2	C-590

Dest.	Next	Metric	Seq.
A	A	1	A-550
B	B	0	B-102
C	C	1	C-592

Dest.	Next	Metric	Seq.
A	B	2	A-550
B	B	1	B-102
C	C	0	C-592
D	D	1	D-000

DSDV (New Node cont.)



Dest.	Next	Metric	Seq.
A	A	0	A-550
B	B	1	B-104
C	B	2	C-590

Dest.	Next	Metric	Seq.
A	A	1	A-550
B	B	0	B-102
C	C	1	C-592
D	C	2	D-000

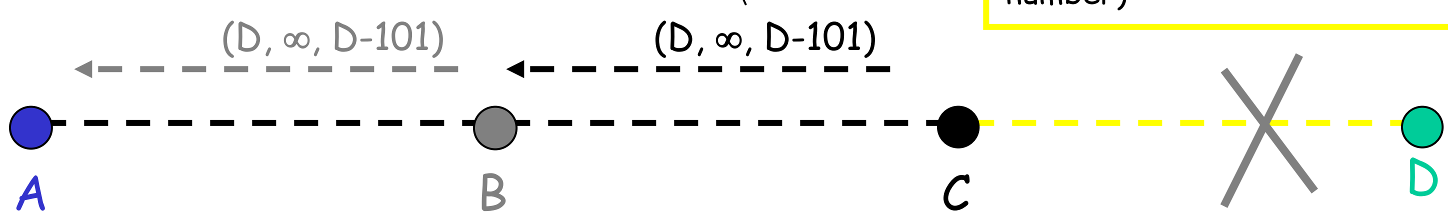
Dest.	Next	Metric	Seq.
A	B	2	A-550
B	B	1	B-102
C	C	0	C-592
D	D	1	D-000

DSDV (Immediate Advertisement)

3. Immediate propagation B to A:
(update information has higher Seq. Nr. -> replace table entry)

2. Immediate propagation C to B:
(update information has higher Seq. Nr. -> replace table entry)

1. Node C detects broken Link:
-> Increase Seq. Nr. by 1
(only case where not the destination sets the sequence number -> odd number)



A:

Dest.	Next	Metric	Seq.
...	...	...	...
~~D~~	~~B~~	~~3~~	~~D-100~~
D	B	∞	D-101

B:

Dest.c	Next	Metric	Seq.
...	...	...	...
~~D~~	~~C~~	~~2~~	~~D-100~~
D	C	∞	D-101

C:

Dest.	Next	Metric	Seq.
...	...	...	
~~D~~	~~D~~	~~1~~	~~D-100~~
D	D	∞	D-101

Some general trade-offs

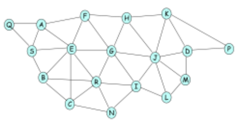
- Latency of route discovery
  -
- Overhead of route discovery/maintenance

Some general trade-offs

- Latency of route discovery

Destination	Next	Metric	Seq. Nr
A	A	0	A-550
B	B	1	B-102
C	B	3	C-588
D	B	4	D-312

  - Proactive protocols may have lower latency
    - Routes are maintained at all times



  - Reactive protocols may have higher latency
    - Route from X to Y will be found only when X attempts to send to Y
- Overhead of route discovery/maintenance

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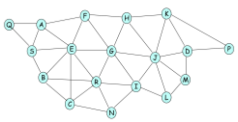

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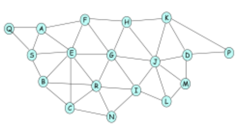
  - Proactive protocols can (but not necessarily) result in higher overhead due to continuous route updating



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    - Routes are determined only if needed

Some general trade-offs

- Latency of route discovery

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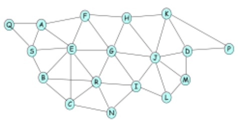

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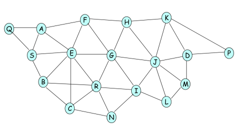


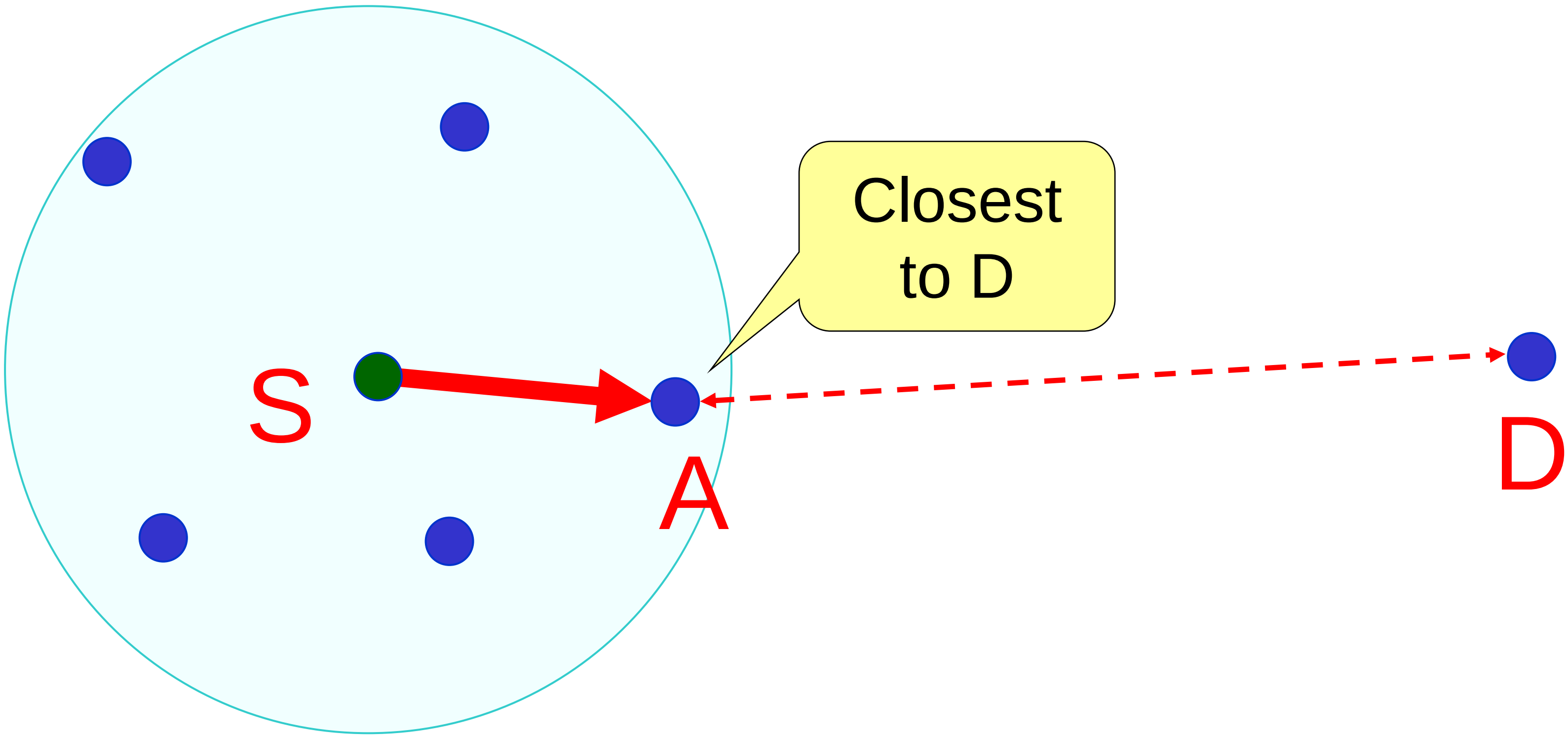
  - Reactive protocols may have lower overhead
    - Routes are determined only if needed
- Which approach achieves a better trade-off depends on the traffic and mobility patterns

GPSR: Greedy Perimeter Stateless Routing for Wireless Networks

B. Karp, H. T. Kung

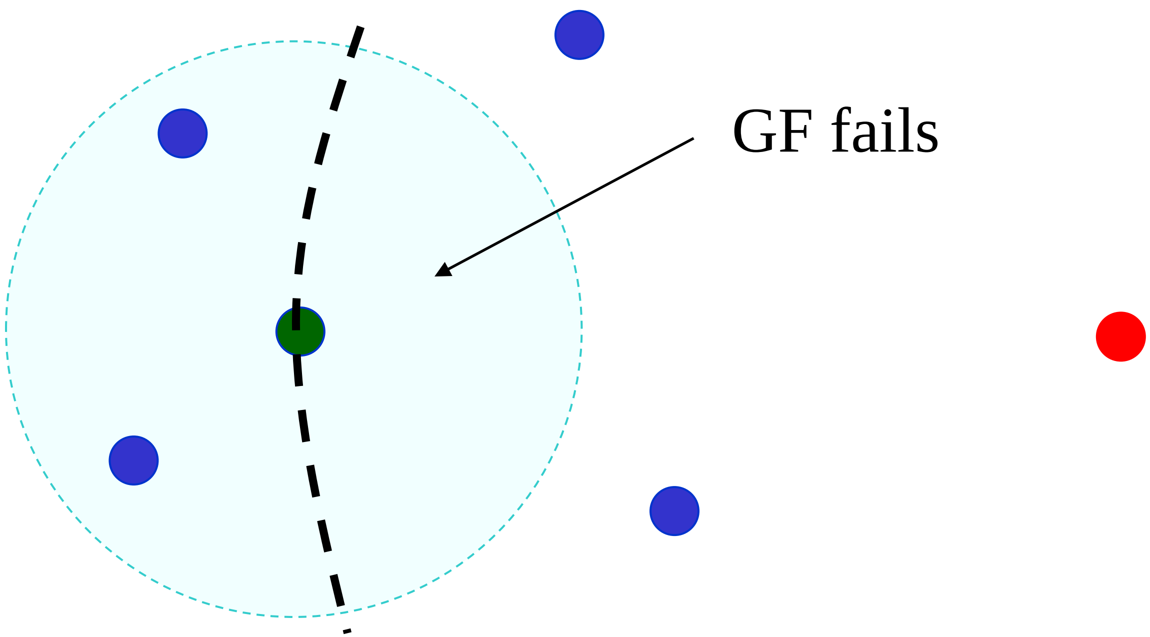
Borrowed slides from Richard Yang

Geographic Routing: Greedy Routing



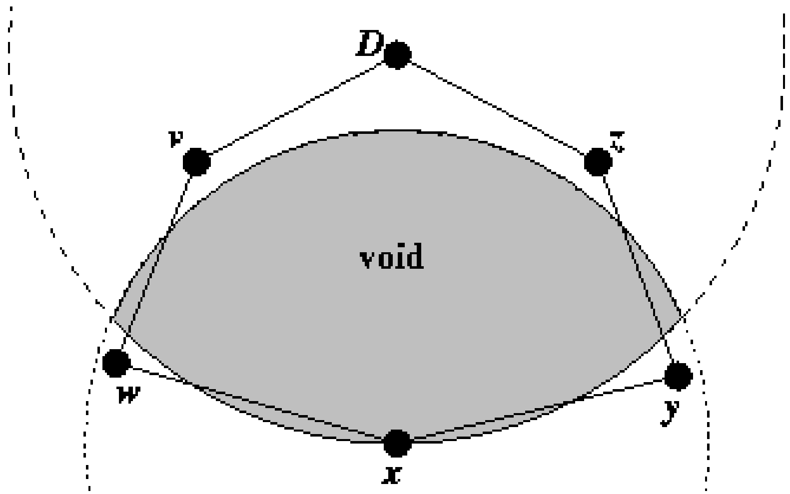
- Find neighbors who are the closer to the destination
- Forward the packet to the neighbor closest to the destination

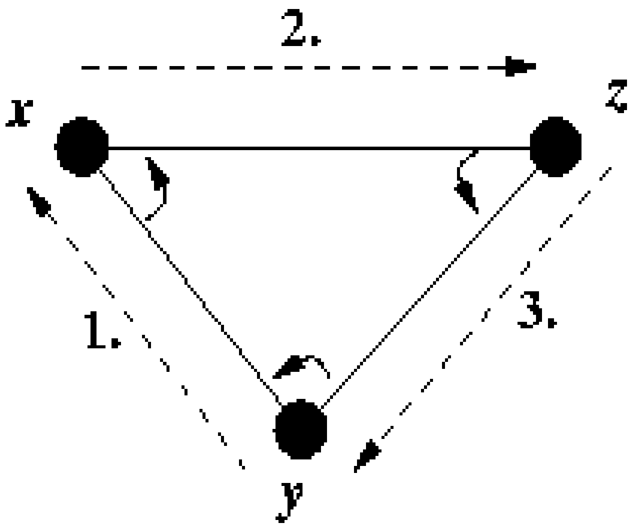
Greedy Forwarding does NOT always work



If the network is dense enough that each interior node has a neighbor closer to all destinations (or in every $2\Pi/3$ angular sector), GF will always succeed

Dealing with Void: Right-Hand Rule

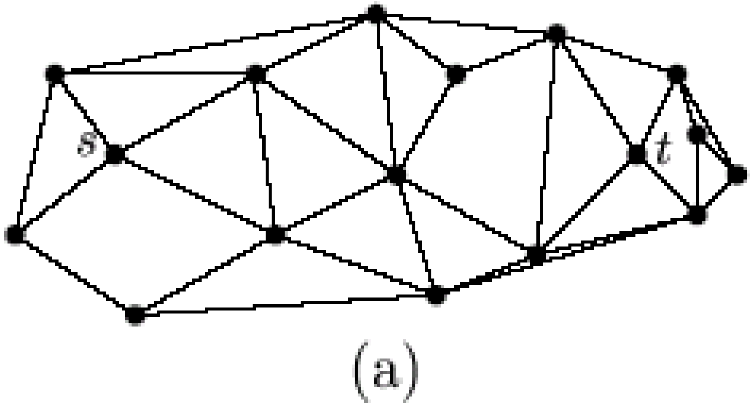




Apply the right-hand rule to traverse the edges of a void

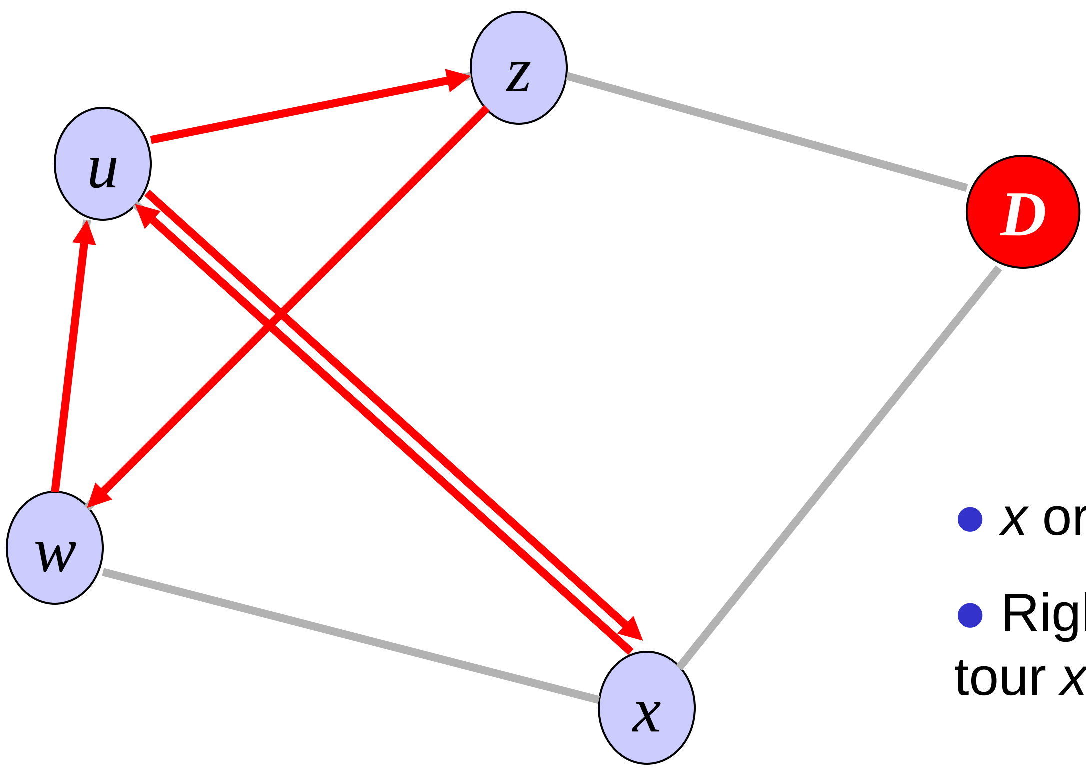
- Pick the next anticlockwise edge
- Traditionally used to get out of a maze

Right Hand Rule on Convex Subdivision



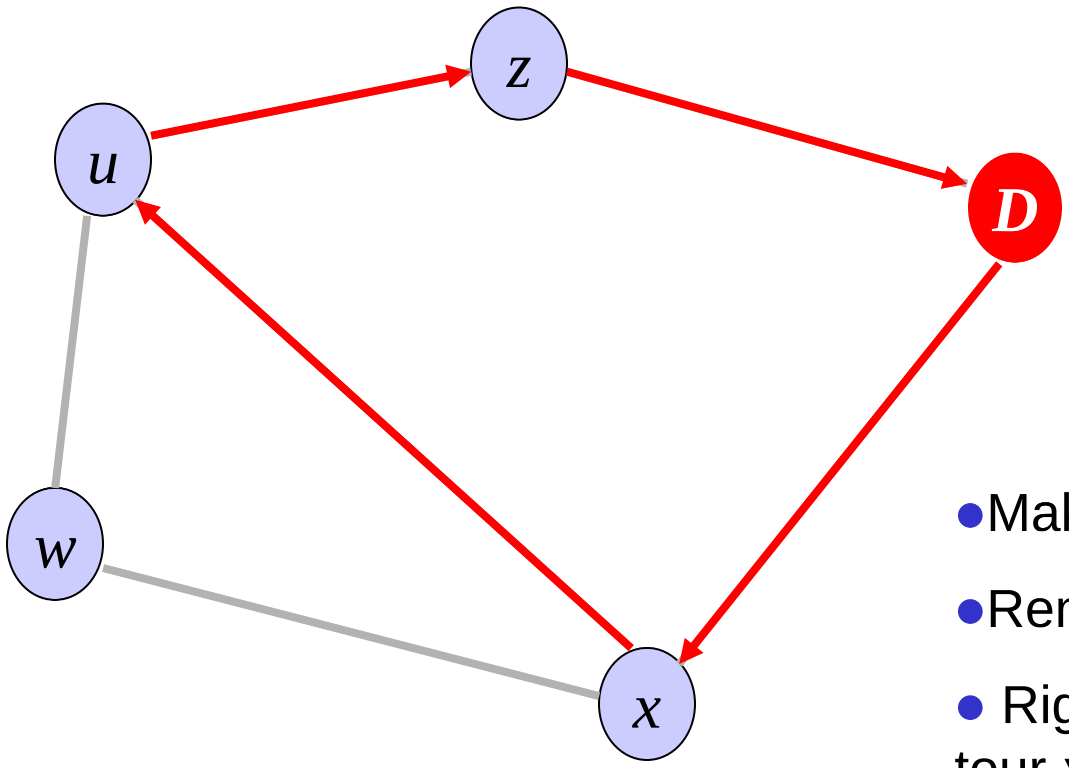
For convex subdivision, right hand rule is equivalent to traversing the face with the crossing edges removed.

Right-Hand Rule Does Not Work with Cross Edges



- *x* originates a packet to *u*
- Right-hand rule results in the tour *x*-*u*-*z*-*w*-*u*-*x*

Remove Crossing Edge



- Make the graph planar
- Remove (*w*,*z*) from the graph
- Right-hand rule results in the tour *x*-*u*-*z*-v-*x*

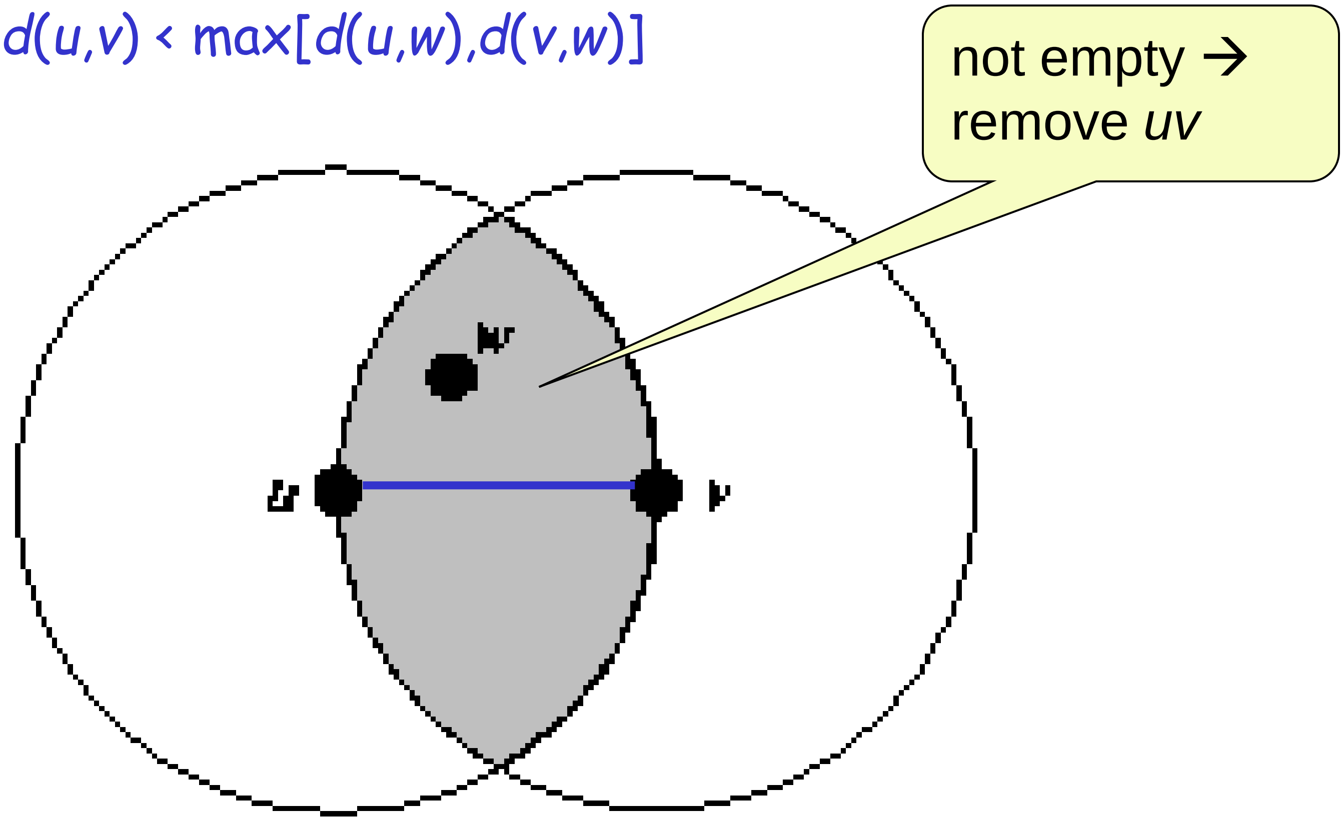
Make a Graph Planar

- Convert a connectivity graph to planar non-crossing graph by removing “bad” edges
  - Ensure the original graph will not be disconnected
  - Two types of planar graphs:
    - Relative Neighborhood Graph (RNG)
    - Gabriel Graph (GG)

Relative Neighborhood Graph

Connection *uv* can exist if

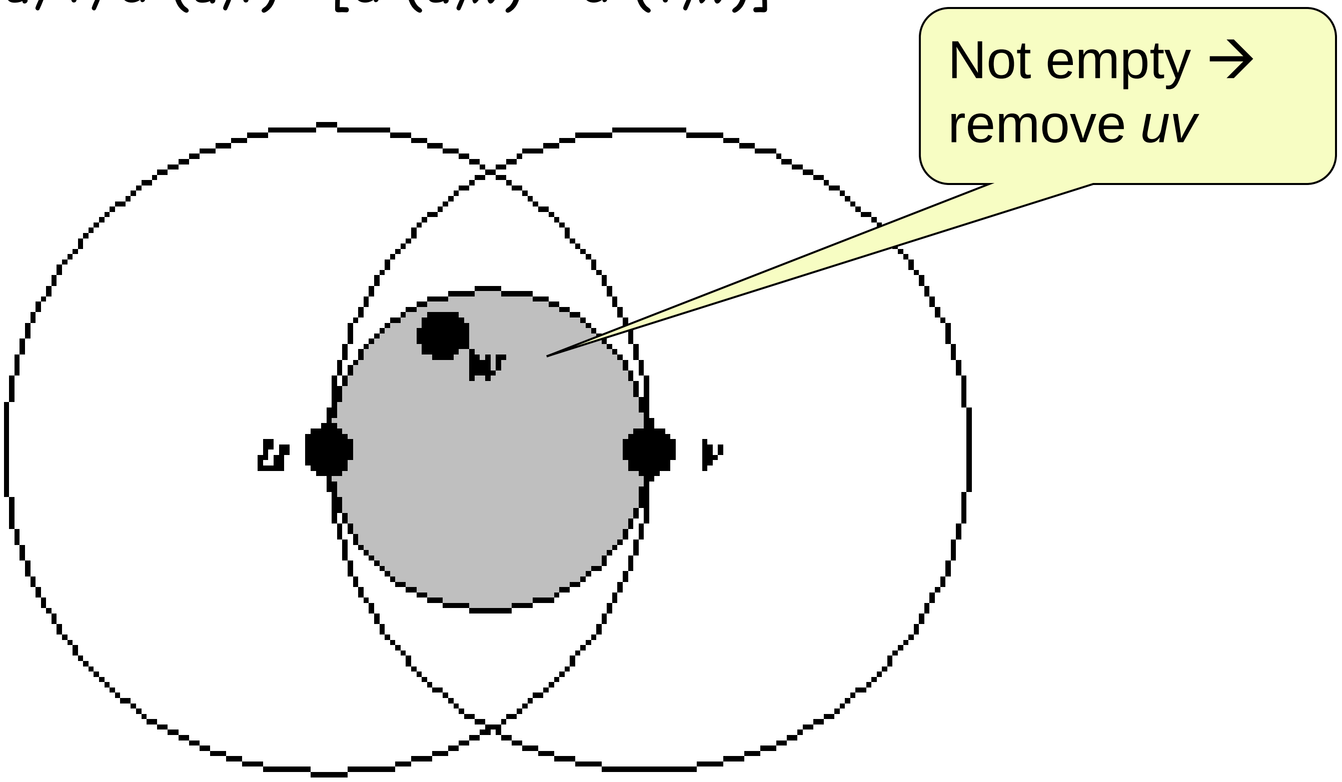
$\forall w \neq u, v, d(u,v) < \max[d(u,w),d(v,w)]$



Gabriel Graph

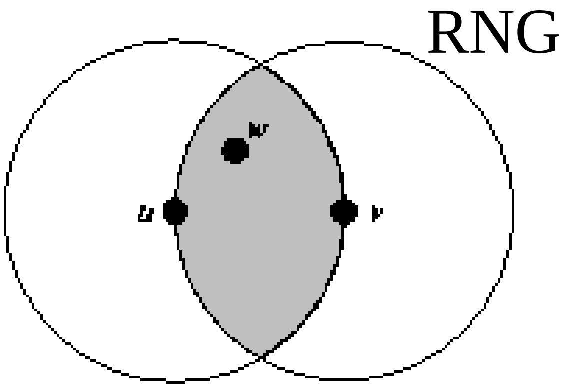
An edge (*u*,*v*) exists between vertices *u* and *v* if no other vertex *w* is present within the circle whose diameter is uv.

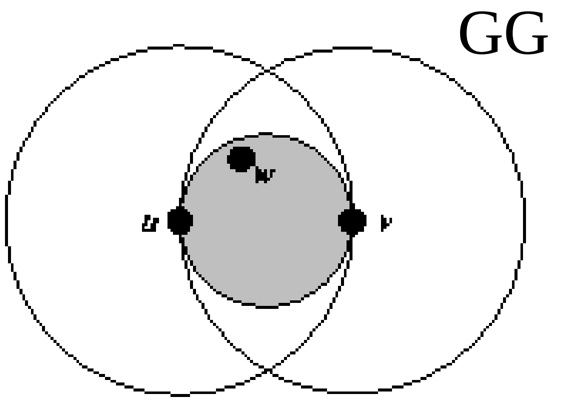
$$\forall w \neq u, v, \; d^2(u,v) < [d^2(u,w) + d^2(v,w)]$$



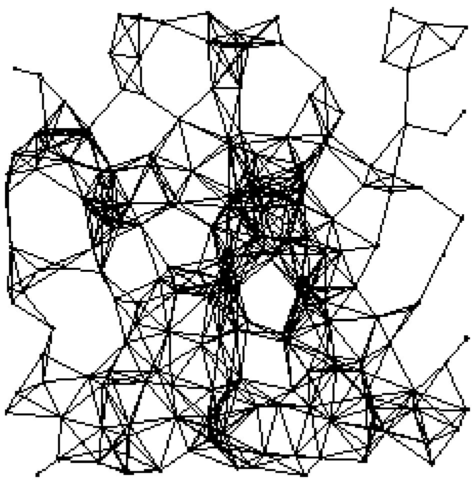
Properties of GG and RNG

- RNG is a sub-graph of GG
  - Because RNG removes more edges
- If the original graph is connected, RNG is also connected

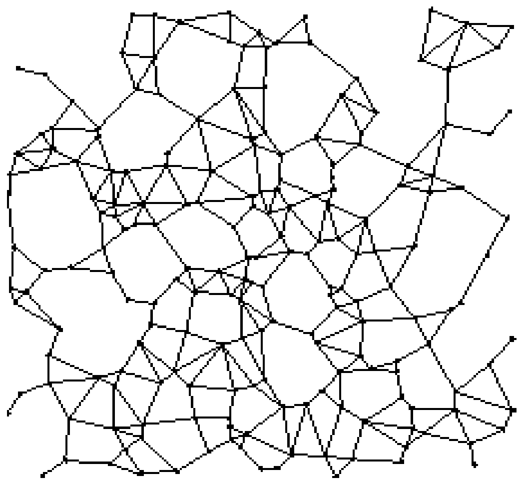




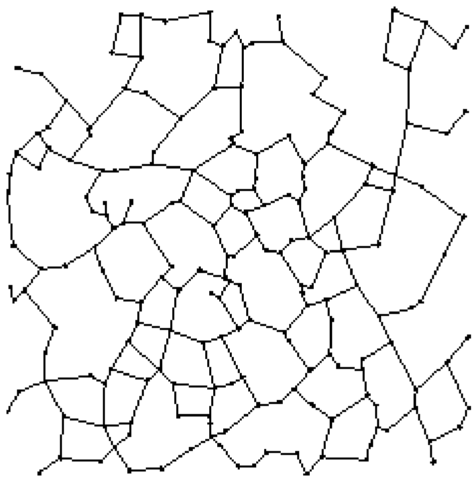
Examples



Full graph



GG subset



RNG subset

- 200 nodes
- randomly placed on a 2000 x 2000 meter region
- radio range of 250 m
- Bonus: remove redundant, competing path → less collision

Greedy Perimeter Stateless Routing (GPSR)

Maintenance

- all nodes maintain a single-hop neighbor table
- Use RNG or GG to make the graph planar

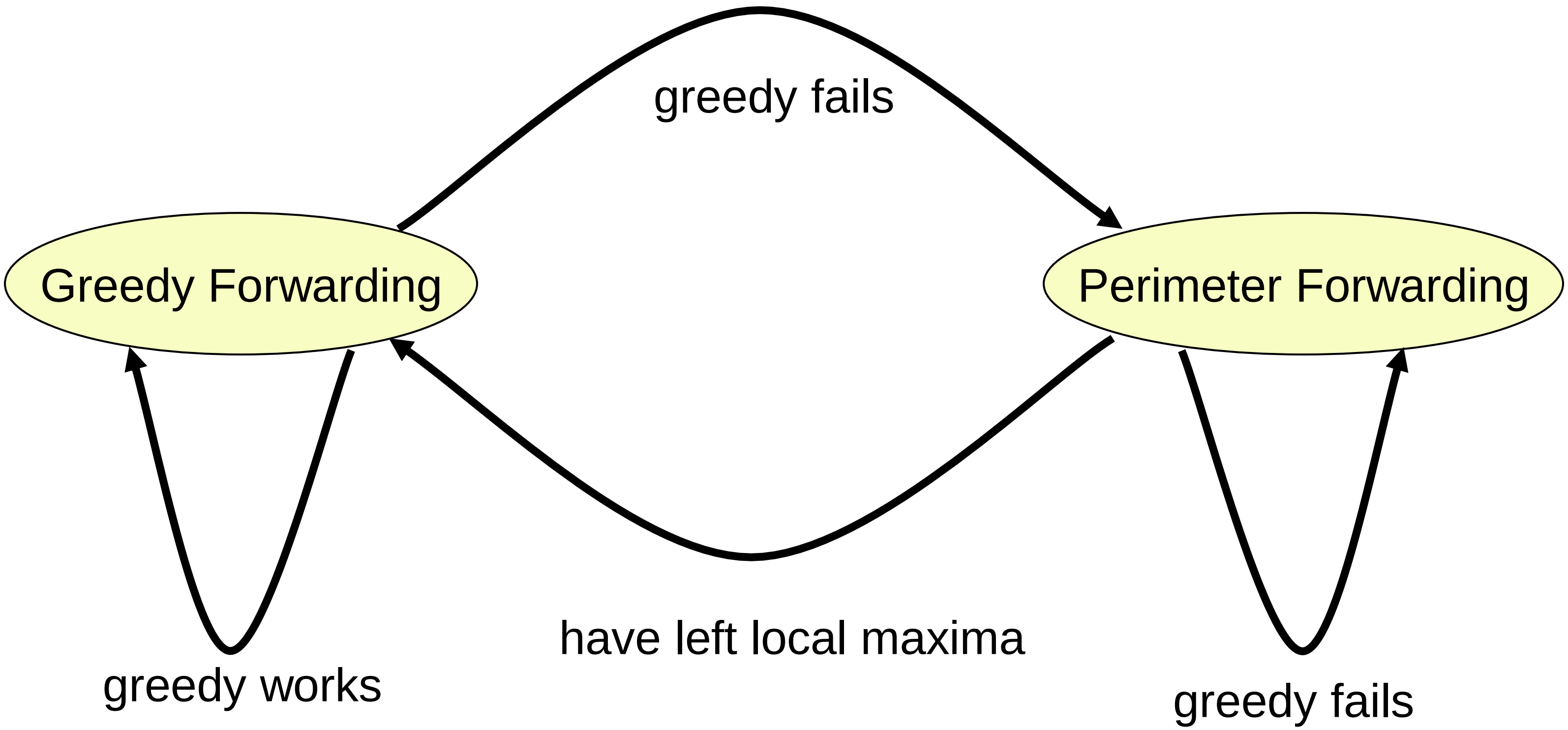
At source:

mode = greedy

Intermediate node:

```
if (mode == greedy) {
    greedy forwarding;
    if (fail) mode = perimeter;
  }
  if (mode == perimeter) {
    if (have left local maxima) mode = greedy;
    else (right-hand rule);
  }
```

GPSR



greedy fails
Greedy Forwarding
Perimeter Forwarding
greedy works
have left local maxima
greedy fails