Routing in Ad Hoc Wireless Networks

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Outline of Discussion

- Background Concepts
- Example Wireless Routing Protocols
  - DSR
  - Fuzzy Routing
  - AODV
  - ZRP
  - IZR
  - Structured Routing
- Conclusion
- References

Background Concepts

Why not use routing protocols designed for wired networks?

- Mainly design issues:
  - Too dynamic (i.e. mobile nodes)
  - No specific nodes dedicated for control
  - Different link characteristics (e.g. delay, bandwidth)
  - Different node characteristics (e.g. power constraints, multiple access issues)
- [MM04]

Wired Protocol Performance in Wireless Setting: Packet Delivery %

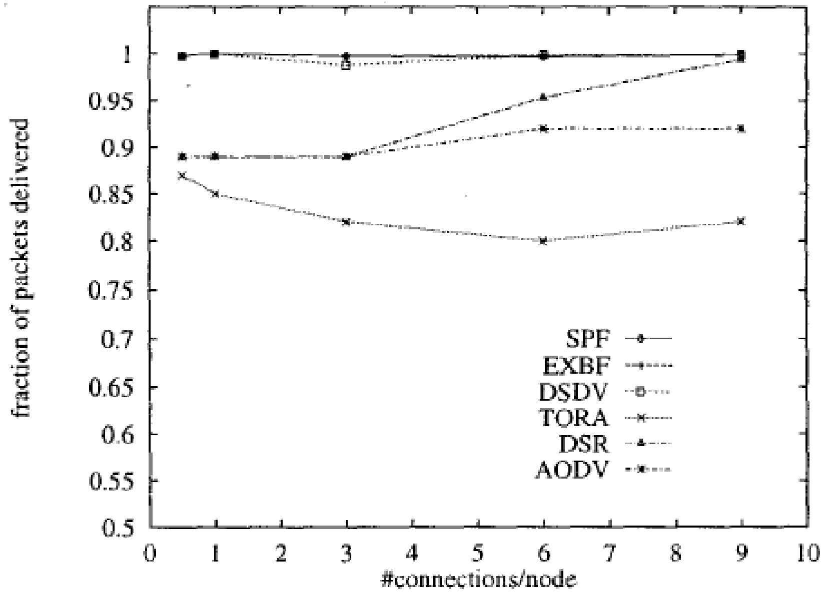


Figure 1. Fraction of packets delivered for all routing protocols for the low mobility case.

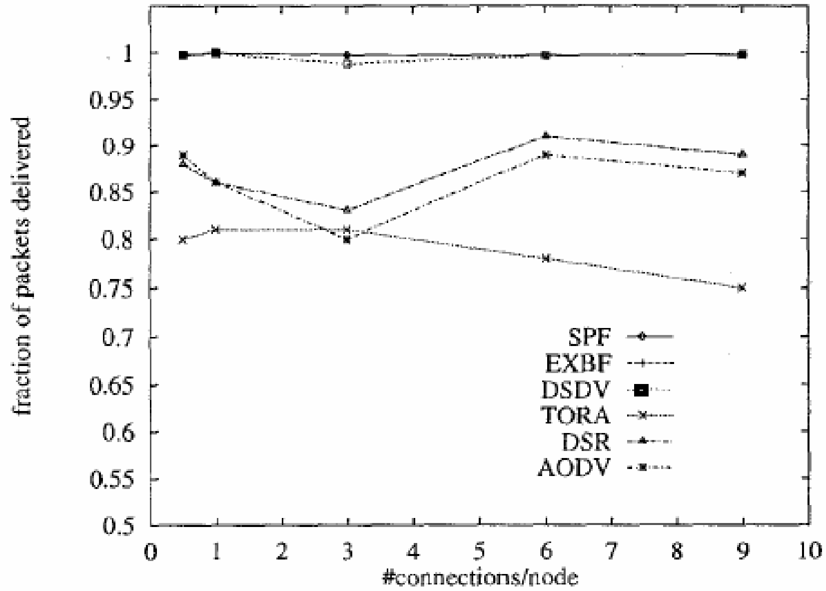


Figure 2. Fraction of packets delivered for all routing protocols for the high mobility case.

Figures from: [DCYS98]

Wired Protocol Performance in Wireless Setting: Delay

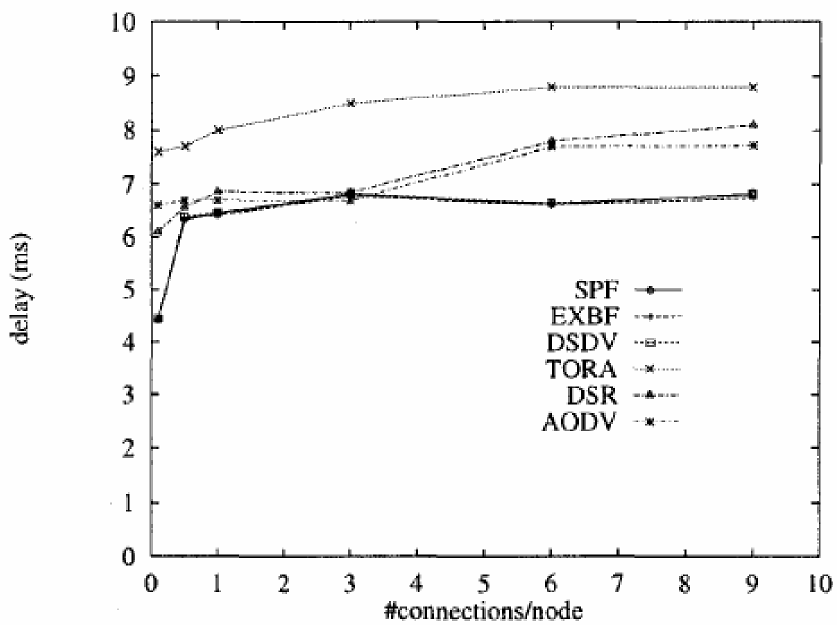


Figure 3. Average end-to-end delay for all routing protocols for the low mobility case.

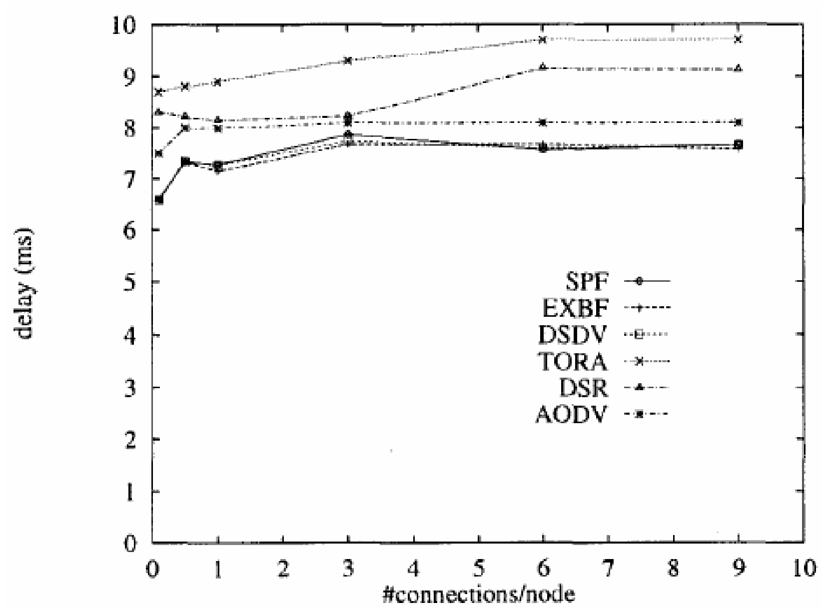


Figure 4. Average end-to-end delay for all routing protocols for the high mobility case.

Figures from: [DCYS98]

Wired Protocol Performance in Wireless Setting: Routing Load

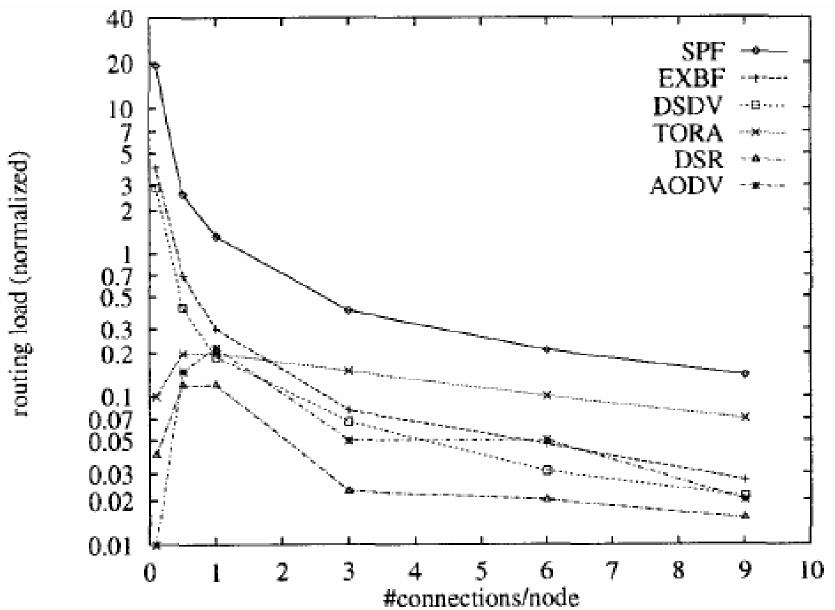


Figure 5. Normalized routing load for all routing protocols for the low mobility case.

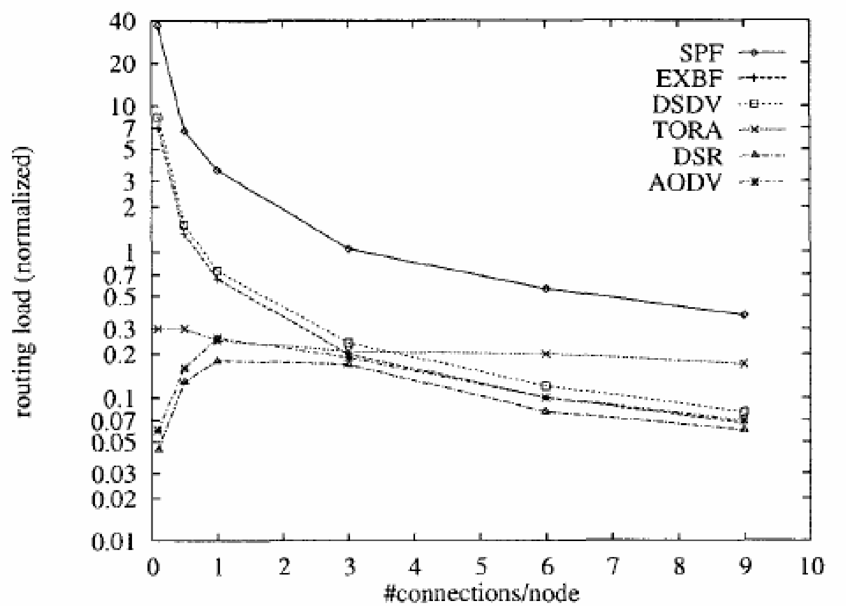


Figure 6. Normalized routing load for all routing protocols for the high mobility case.

Figures from: [DCYS98]

Network Environments [V01]

- Fully symmetric
  - Nodes have identical characteristics
  - Nodes are all equally responsible to route
- Asymmetric
  - Any node characteristic can vary
    - transmitter, processor, memory, mobility, etc.
  - Nodes are all still equally responsible to route
- Asymmetric responsibility
  - Only some nodes will route packets

MANET Routing Protocol Requirements [MM04]

1. Fully distributed, no critical nodes
2. Allow for random node events (e.g. entering, leaving, neighbor changes)
3. Minimum delay to determine path (at transmission time)
4. Minimize storage requirements
5. Must remove (or not propagate) invalid paths

MANET Routing Protocol Requirements [MM04]

6. Minimize packet collisions
7. Low convergence time to optimal paths
8. Minimize resource use (e.g. processing time, bandwidth usage, power consumption)
9. Nodes should store local information only
10. Provide a minimum QoS

Routing protocol inputs [MM04]

- Traditional route update
  - Proactive (table-based)
  - Reactive (on-demand)
  - Hybrid
- Temporal information
  - Past information
  - Future information
- Topology
  - Flat topology
  - Hierarchical topology
- Other network resource
  - Power levels
  - Geographical information

Reactive vs. Proactive

- Reactive
  - Routes are established after a transmission request is made
  - Advantages:
    - Allows for more flexible power scenarios
    - Less state needed at each node
  - Disadvantages:
    - Delay before transmission to establish route
    - High short-term overhead needed to establish routes
- Proactive
  - Routes are established initially and already exist before requests are made
  - Advantages:
    - No delay needed to establish route
    - Low short-term overhead needed
  - Disadvantages:
    - High long-term overhead needed to maintain routes
    - Need dedicated memory to store long term routing information

Singlepath vs. Multipath

- Singlepath
  - Use one path from source to destination
  - Similar to wired routes
  - Advantages:
    - Simple to implement
  - Disadvantages:
    - Source must find a new route to destination if old one fails

- Multipath
  - Use more than one path from source to destination
  - Advantages:
    - Load balancing can occur
    - Higher tolerance to link failures
  - Disadvantages:
    - Adds complexity to receiver and sender

Short Hops vs. Long Hops

- Research to date suggests short-hop:
  - Provides lower energy consumption
    - Lower transmission power needed due to shorter distance between nodes
  - Provides higher link capacity
    - Higher received signal strength due to shorter distance between nodes
- Long-hop intuitively should have less total delay due to smaller total processing delay [H04]

Short Hop vs. Long Hop [H04]

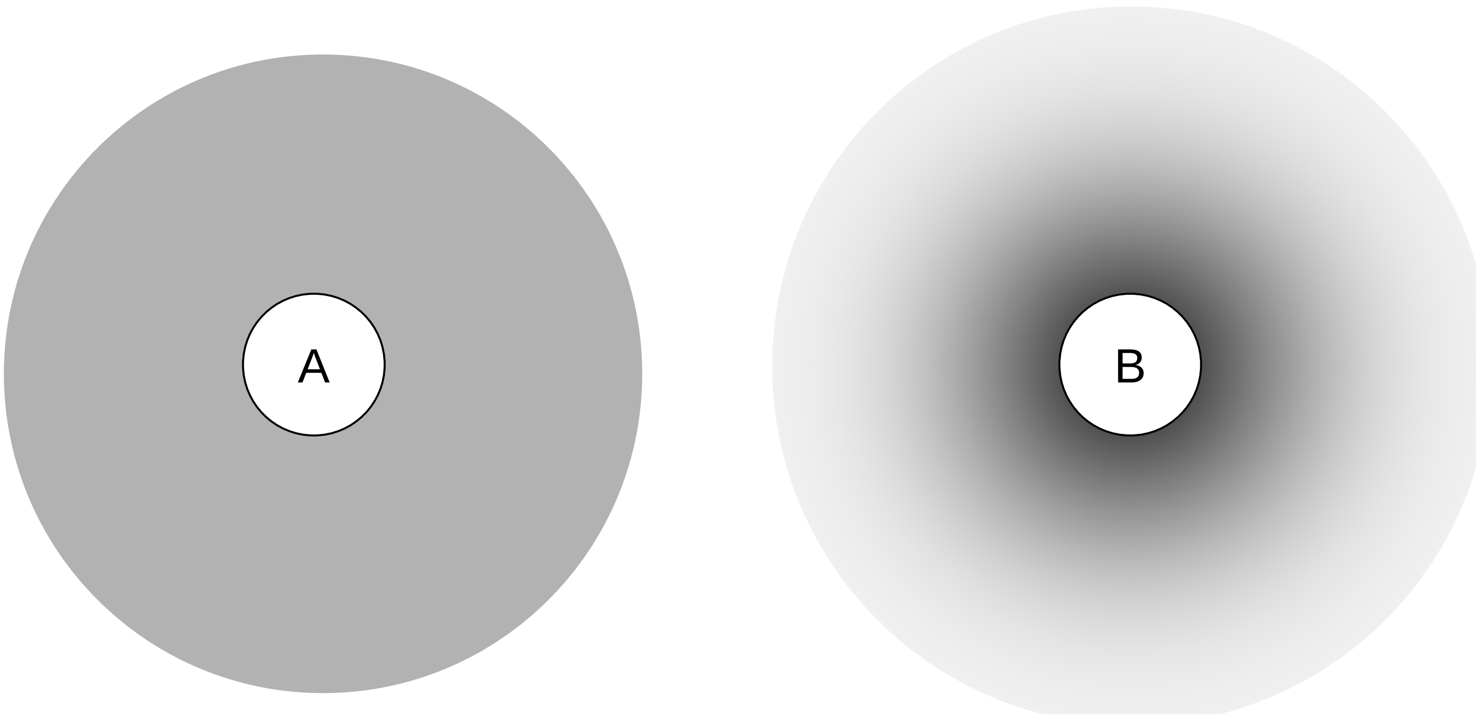
- [H04] disputes the current research
- Qualitatively analyzes characteristics not considered by researchers
- Assumptions:
  - Reception probabilities represented by Rayleigh random variable instead of simply Gaussian noise
  - Uniformly distributed distances between nodes
  - Short-hop and long-hop have same delay constraints

Short Hop vs. Long Hop [H04]

- Results:
  - Interference: long hop does not create more interference
  - End-to-end Reliability: long hop has higher reliability if assumptions hold
  - Energy Consumption: short hop has no advantages in low power environments
  - Path Efficiency: long hop is more efficient due to less total hops
  - Multicast: long hop is more efficient for multicast
- Bottom line: Mathematics are great, but real results are needed to prove these concepts

A New Network Model

- [H04] suggests using a Rayleigh fading model to represent reception probabilities



Disk Model Rayleigh Fading Model

Rayleigh Fading Model

- Disk model: the probability of correctly receiving the data is the same regardless of location within the transmission radius
  - Easier to work with and use in mathematical relations
- Rayleigh fading model: the probability of correctly receiving the data changes with the distance from the transmitter
  - More realistic and allows for more complex schemes

Some Existing Wireless Routing Protocols

- DSDV
- WRP
- CGSR
- STAR
- OLSR
- FSR
- HSR
- GSR
- DSR
- AODV
- ABR
- SSA
- FORP
- PLBR
- CEDAR
- ZRP
- ZHLS
- RABR
- LBR
- COSR
- PAR
- LAR
- OLSB

Example Wireless Routing Protocols

Dynamic Source Routing (DSR)

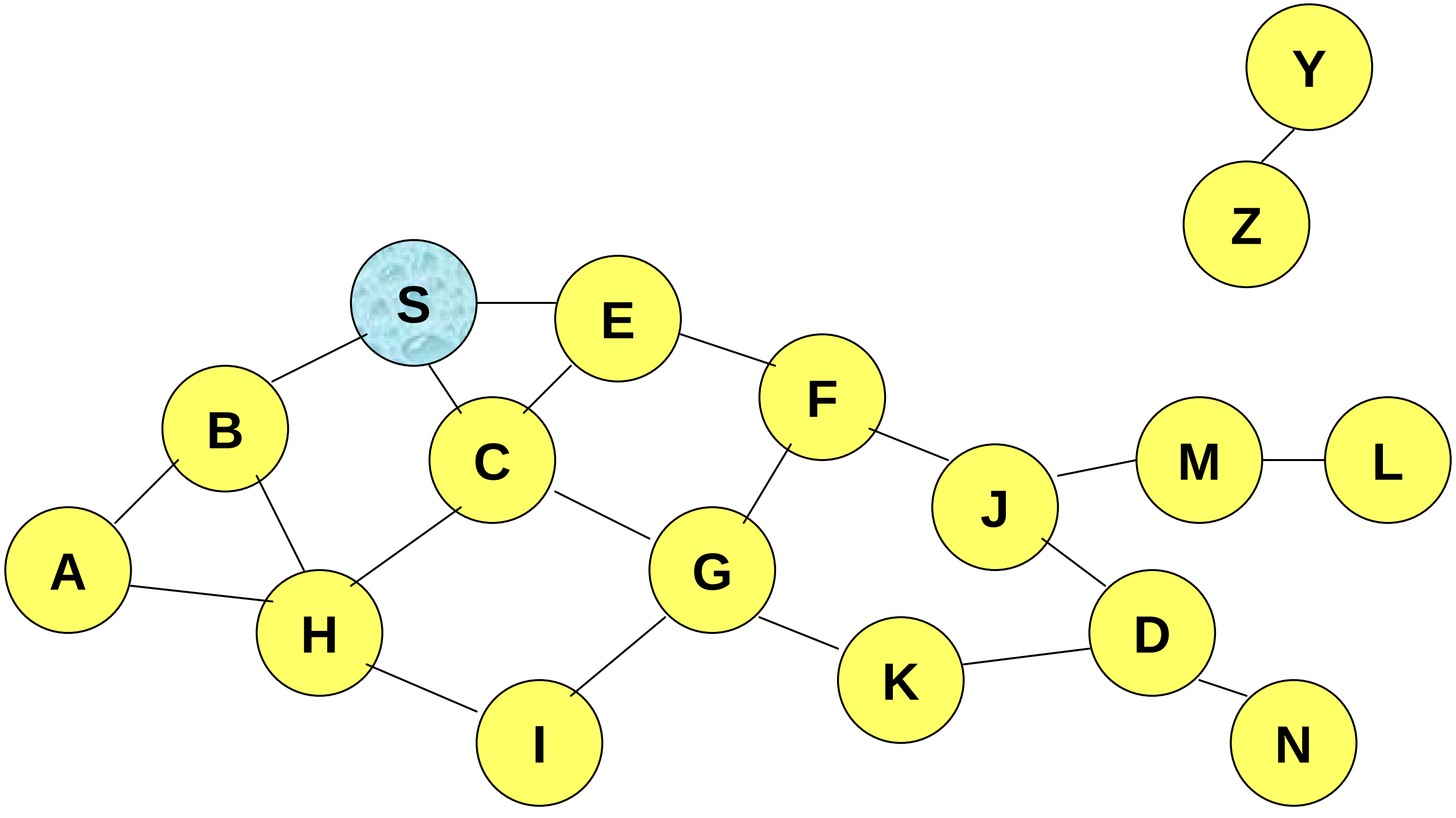
- Reactive, source-based
- To determine the route to a destination:

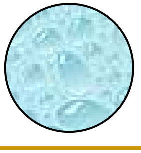
1. Source floods RouteRequest messages to its neighbors
2. Each neighbor will flood RouteRequest messages, storing the path in the header
3. When the destination responds with a RouteReply message containing the path

DSR

- Sequence numbers are used to prevent loops
  - A node can only flood the RouteRequest packet if it has not already flooded it
- On link failure:
  - Adjacent node sends a RouteError message to the source
  - The source will remove the route from its route entry list

Route Discovery in DSR

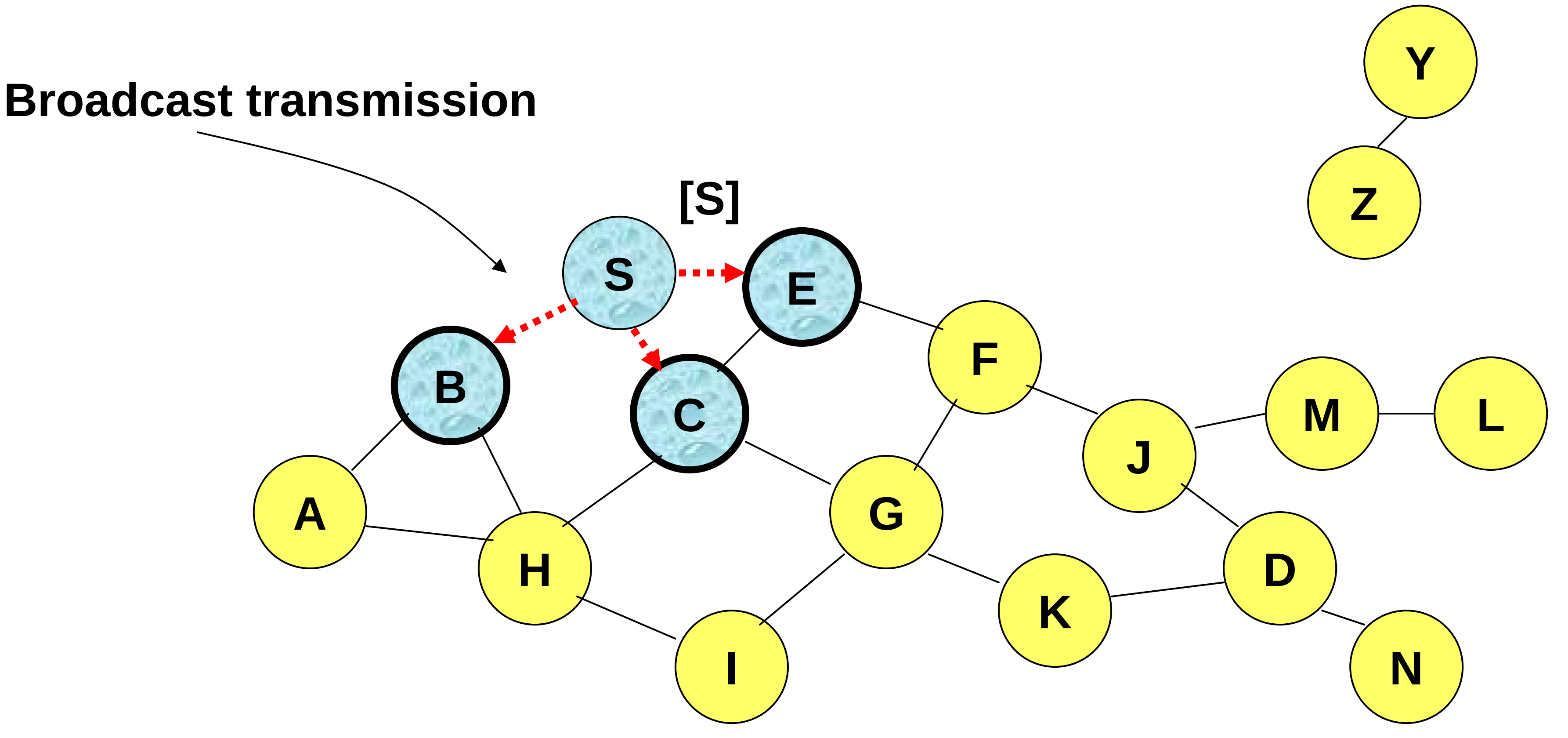




Represents a node that has received RREQ for D from S

Slide used with permission from: [V01]

Route Discovery in DSR

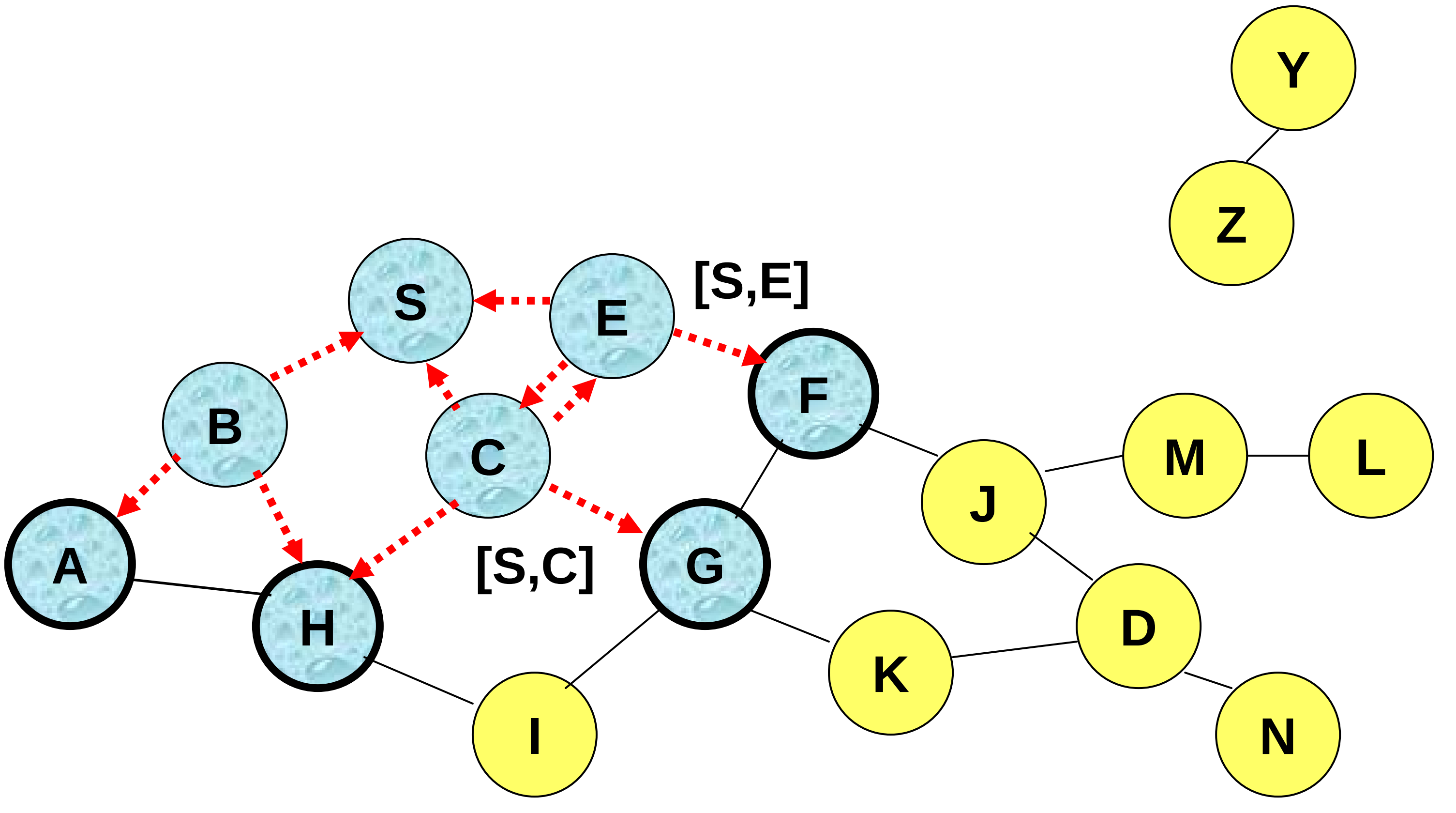


Represents transmission of RREQ

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

Slide used with permission from: [V01]

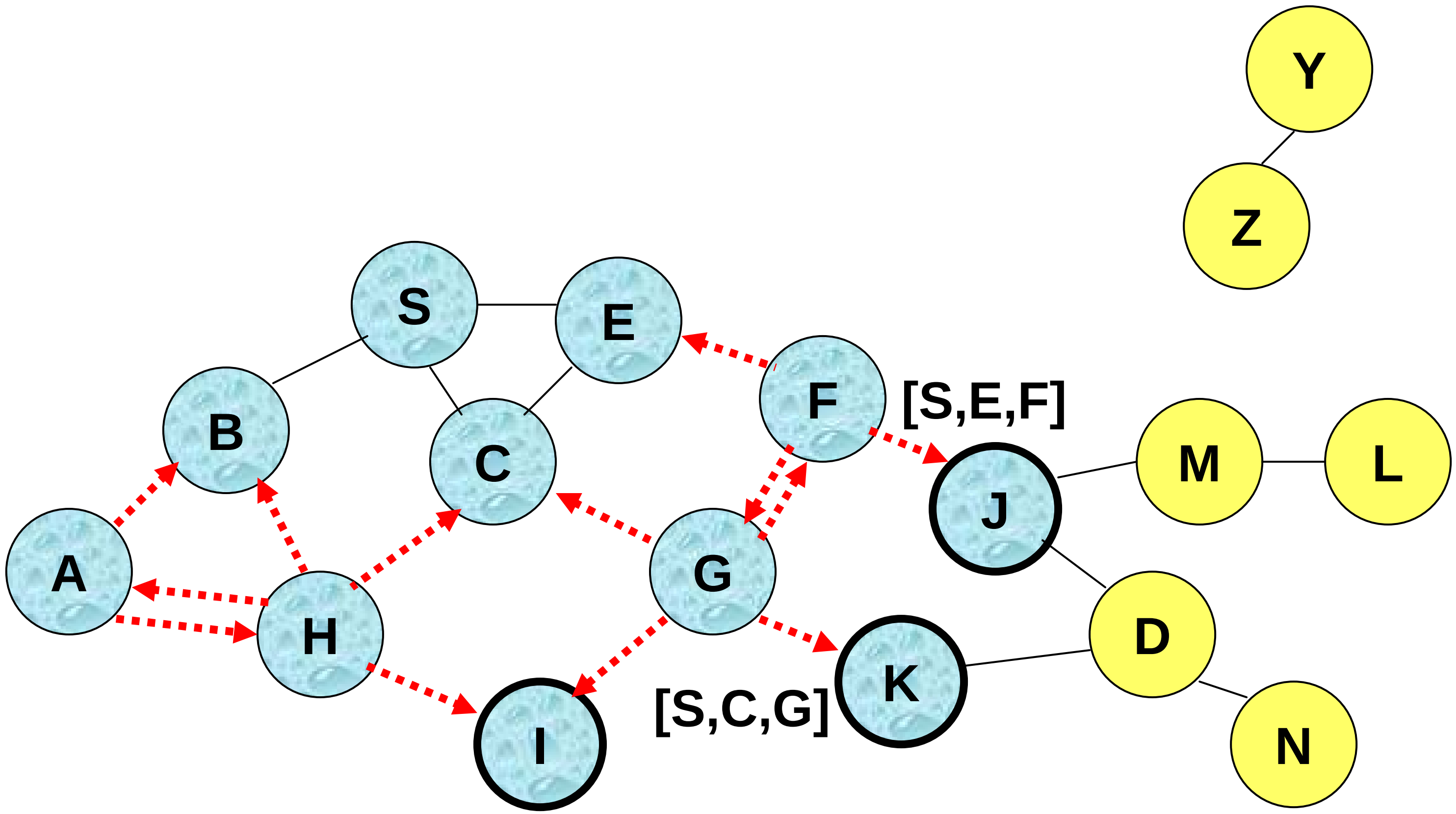
Route Discovery in DSR



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

Slide used with permission from: [V01]

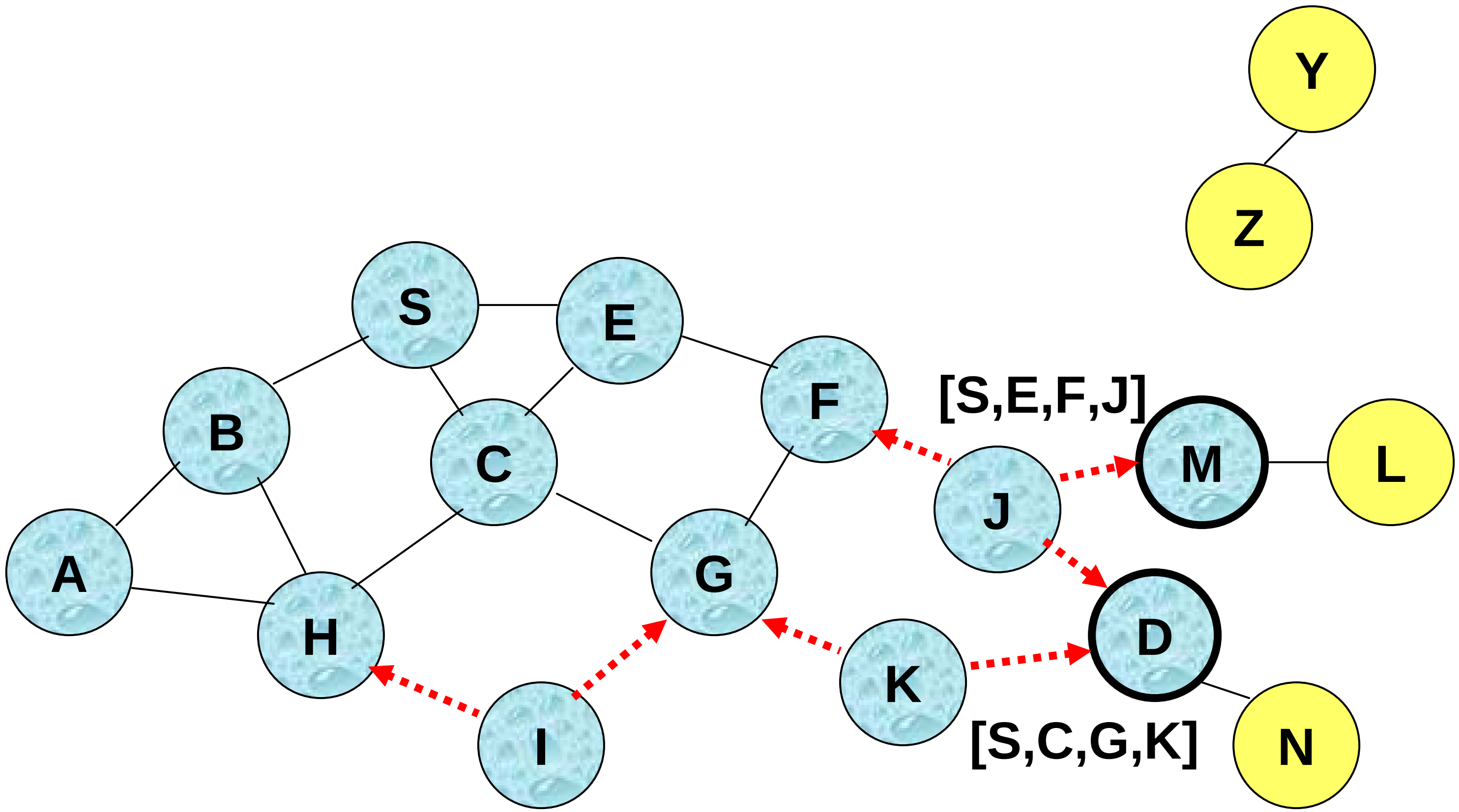
Route Discovery in DSR



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

Slide used with permission from: [V01]

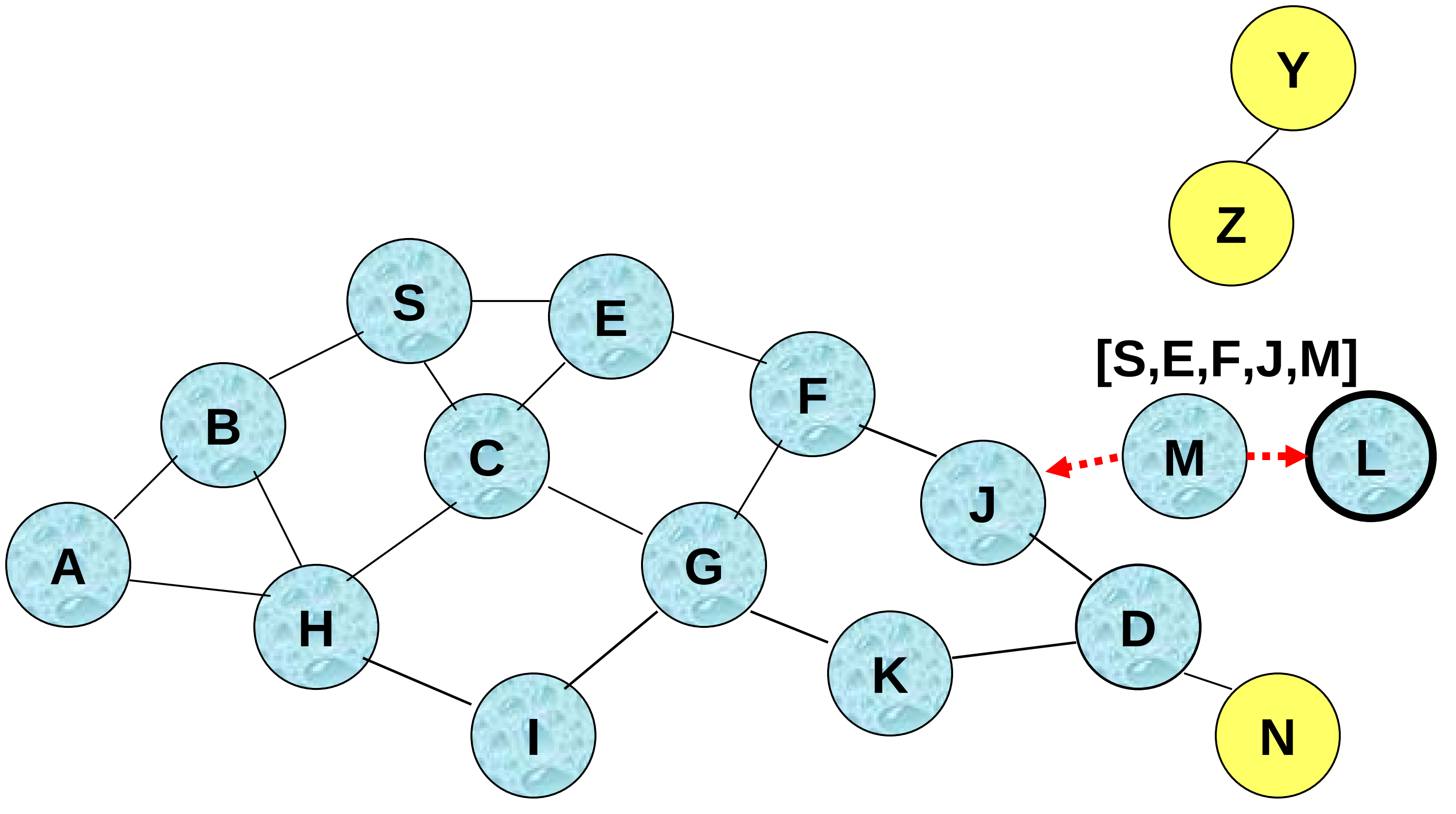
Route Discovery in DSR



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

Slide used with permission from: [V01]

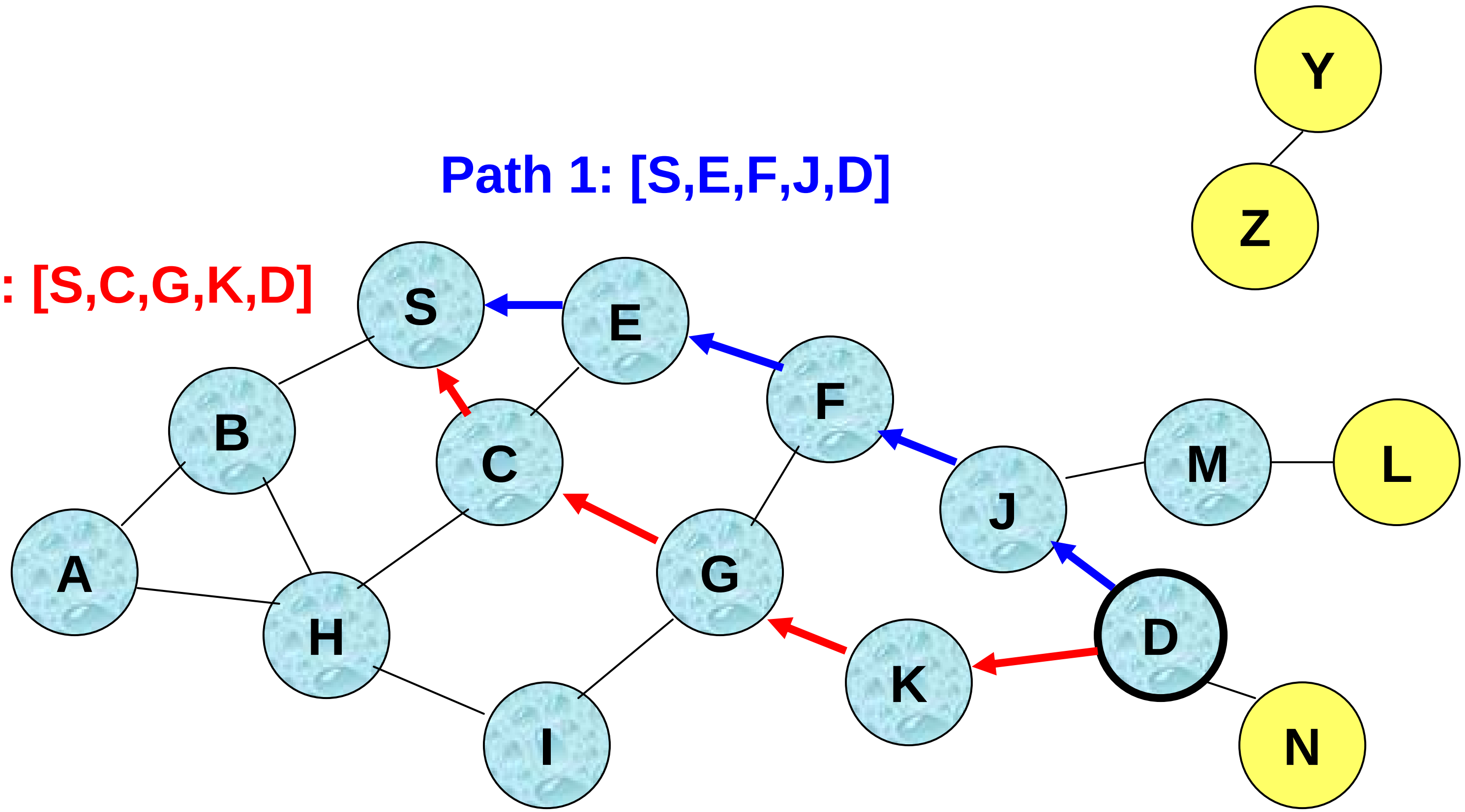
Route Discovery in DSR



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

Slide used with permission from: [V01]

Route Reply in DSR



- **Node D replies with a RouteReply message for each path**

DSR Optimizations [MM04]

- Route caching allowed at all nodes
  - Intermediate nodes can send RouteReply messages to the source
  - Limits flooding through the network
- Intermediate nodes can incorporate RouteError messages into their cached entries
- A data packet can be transmitted with the initial RouteRequest message

DSR Pros and Cons

- Advantages:
  - Less memory storage needed at each node if a full routing table is not needed
  - Lower overhead needed because no periodic update message are necessary
  - Nodes do not need to continually inform neighbors they are still operational
- Disadvantages:
  - Possible transmission latency due to reactive approach
  - Stale routes can occur if links change frequently
  - Message size increases as path length increases

Fuzzy Routing (FLWMR) [AJ03]

- Considers QoS built into routing protocol in multipath conditions
- Protocol steps:
  1. Reactively find maximal set of disjoint paths from source to destination with modified DSR
  2. Use fuzzy logic to determine how paths will carry traffic
- Attempts to maximize delivery rate while minimizing total control protocol delay in highly mobile situations

Fuzzy Routing [AJ03]

- Number of paths used factors in:
  - Priority of message
  - Signal quality
  - Fairness to others
  - Condition of network
- Results are preliminary
  - Better performance than "vanilla" DSR
  - Used disk model, no data on how signal quality was defined

Message Priority (x-axis)
vs.
Signal Quality (y-axis)

	Low	**Med**	**High**	**Urgent**
Poor	Drop	Many	Many	Flood
Low	Drop	One	Many	Flood
Med	One	One	Many	Many
High	One	One	One	Many

How to use paths

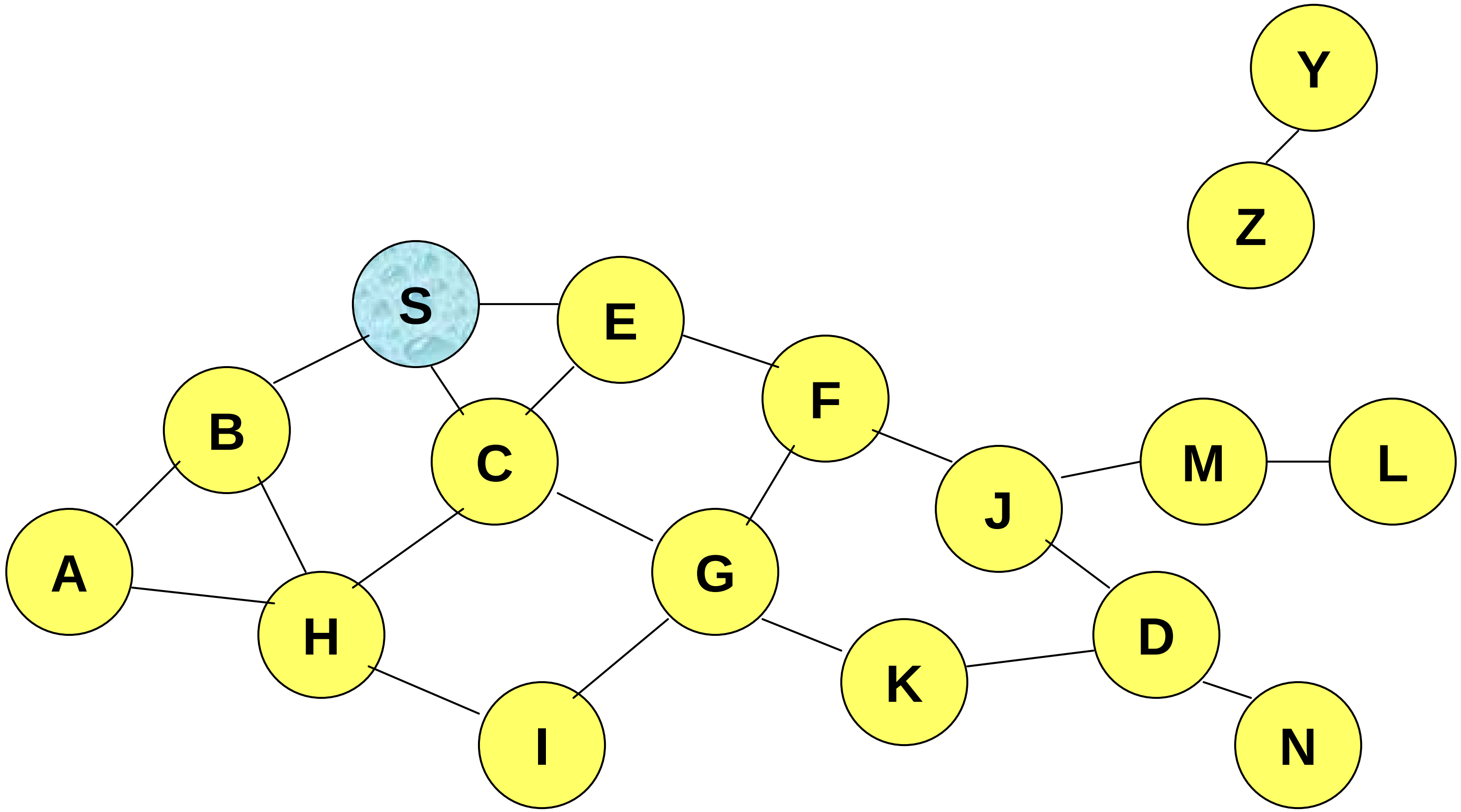
Ad Hoc On-Demand Distance Vector Routing Protocol (AODV)

- Reactive, source-based
- Uses sequence numbers to determine route age to prevent usage of stale routes
- Source assigns sequence number to RouteRequest
  - Intermediate node is allowed to send RouteReply *only if* its cached sequence number is greater than the source's assignment
- On link failure:
  - Detected by periodic acknowledgements
  - Nodes send RouteError message. Source must restart path-finding process to destination.

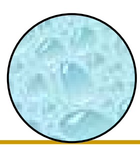
AODV

- To determine the route to a destination:
  1. Source floods RouteRequest message to neighbors with a sequence number to the destination
  2. If an intermediate node has a cached entry to the destination *with a higher* sequence number, it responds with a RouteReply message. Else, the previous hop information is cached and the request is flooded further
  3. If the request reaches the destination, a RouteReply is sent back along the path it was received. Intermediate nodes mark the next hop information in the cache.

Route Requests in AODV



G’s cache: [G,K,D], seq# 5



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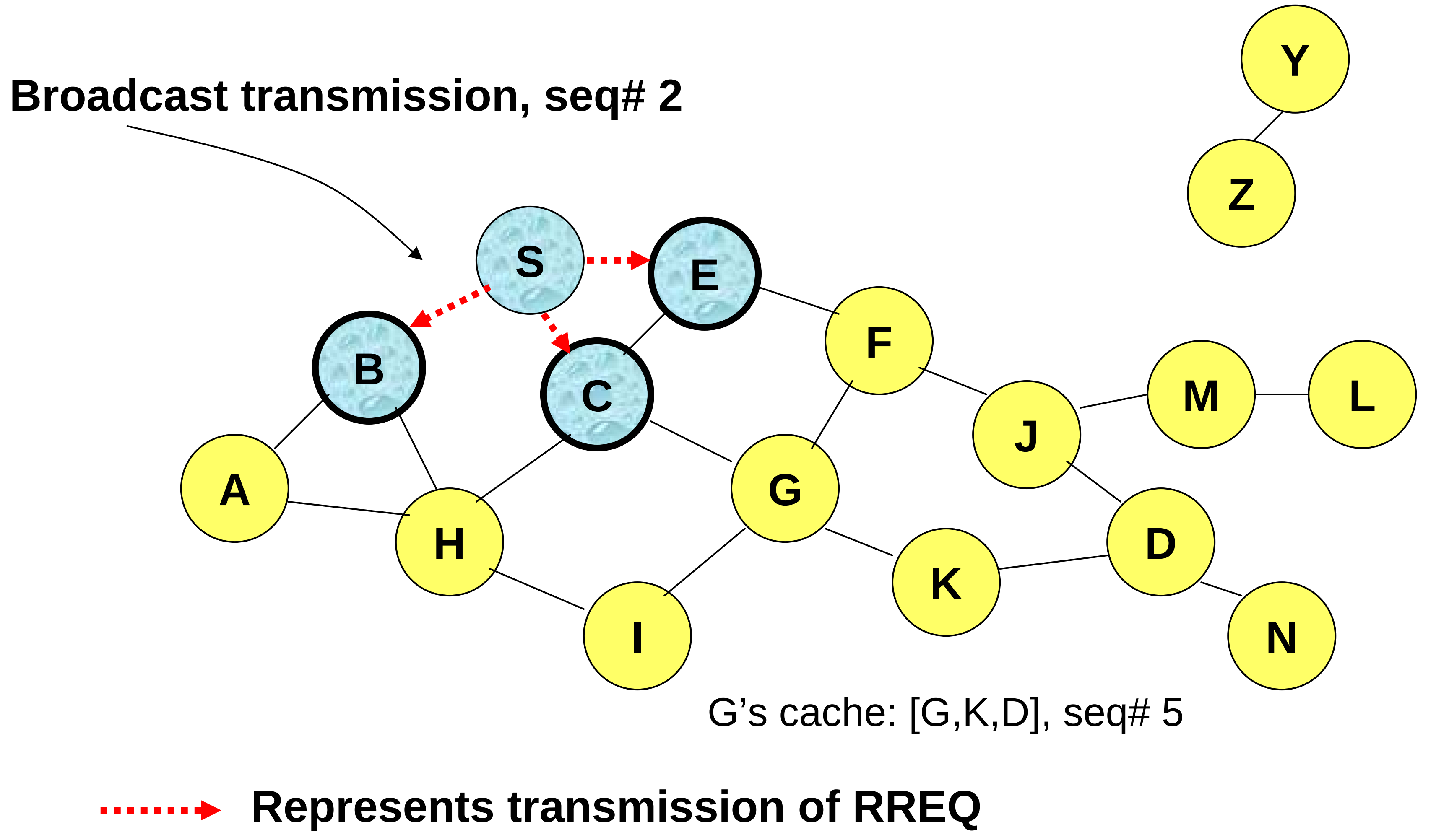
Route Requests in AODV



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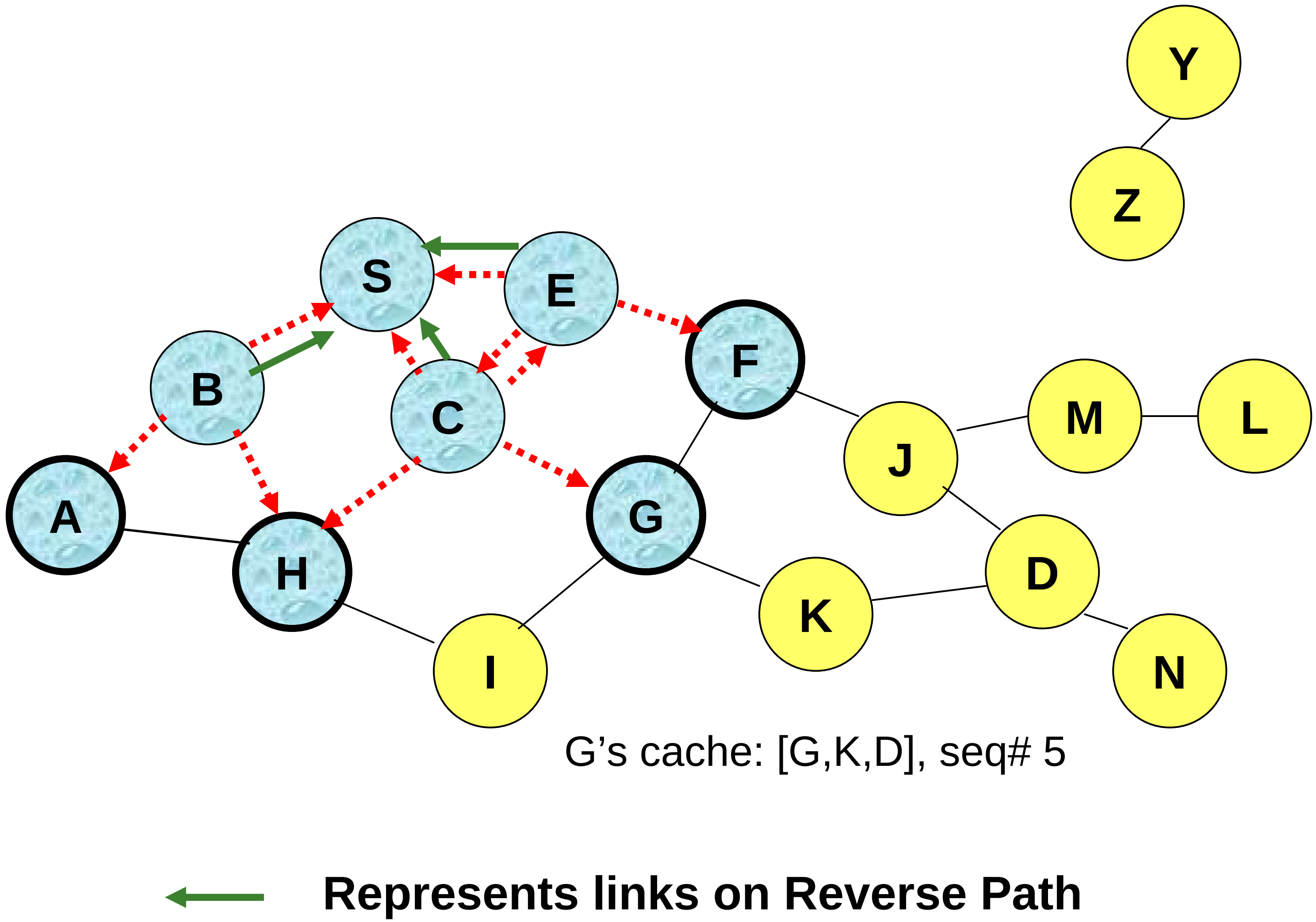
Route Requests in AODV



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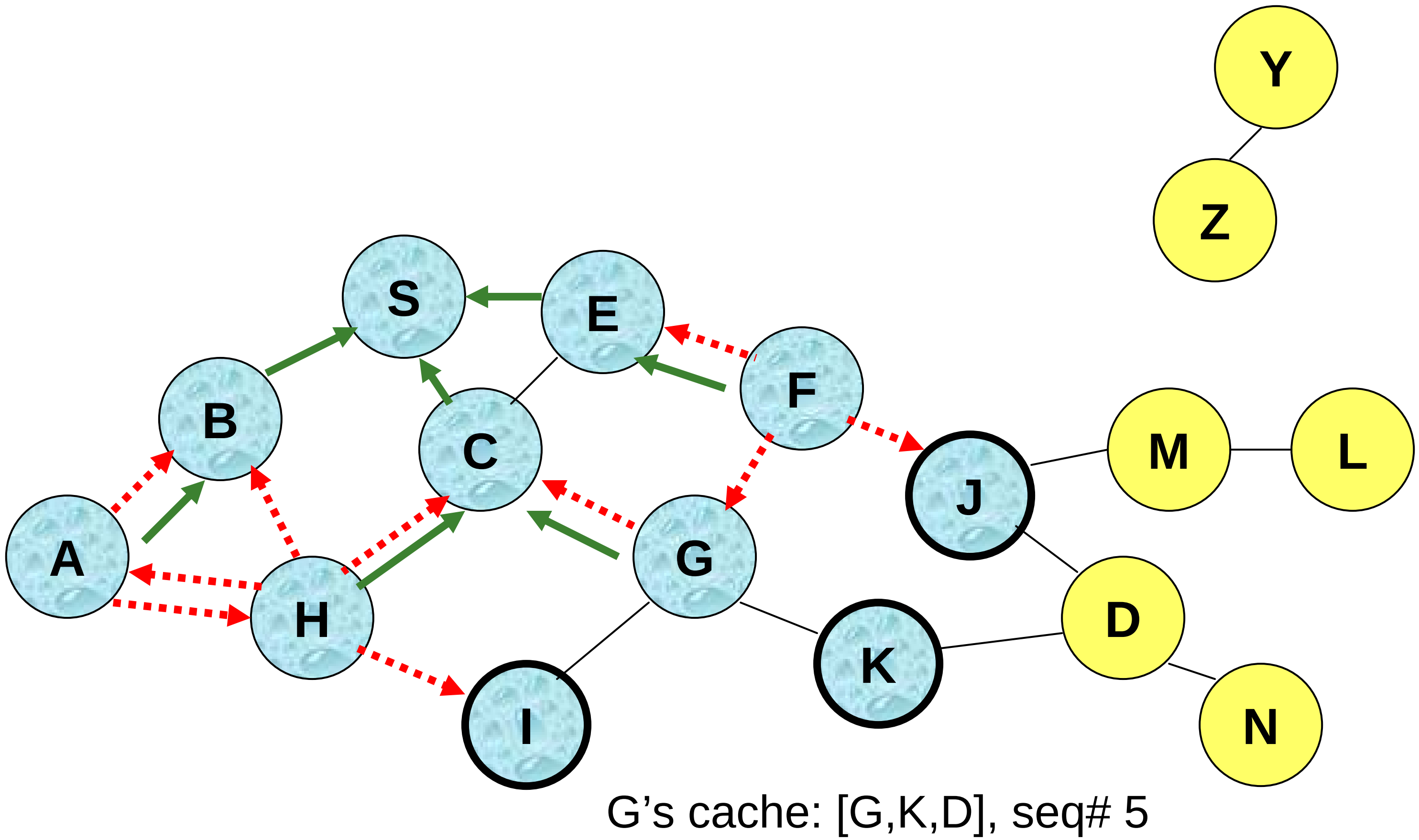
Reverse Path Setup in AODV



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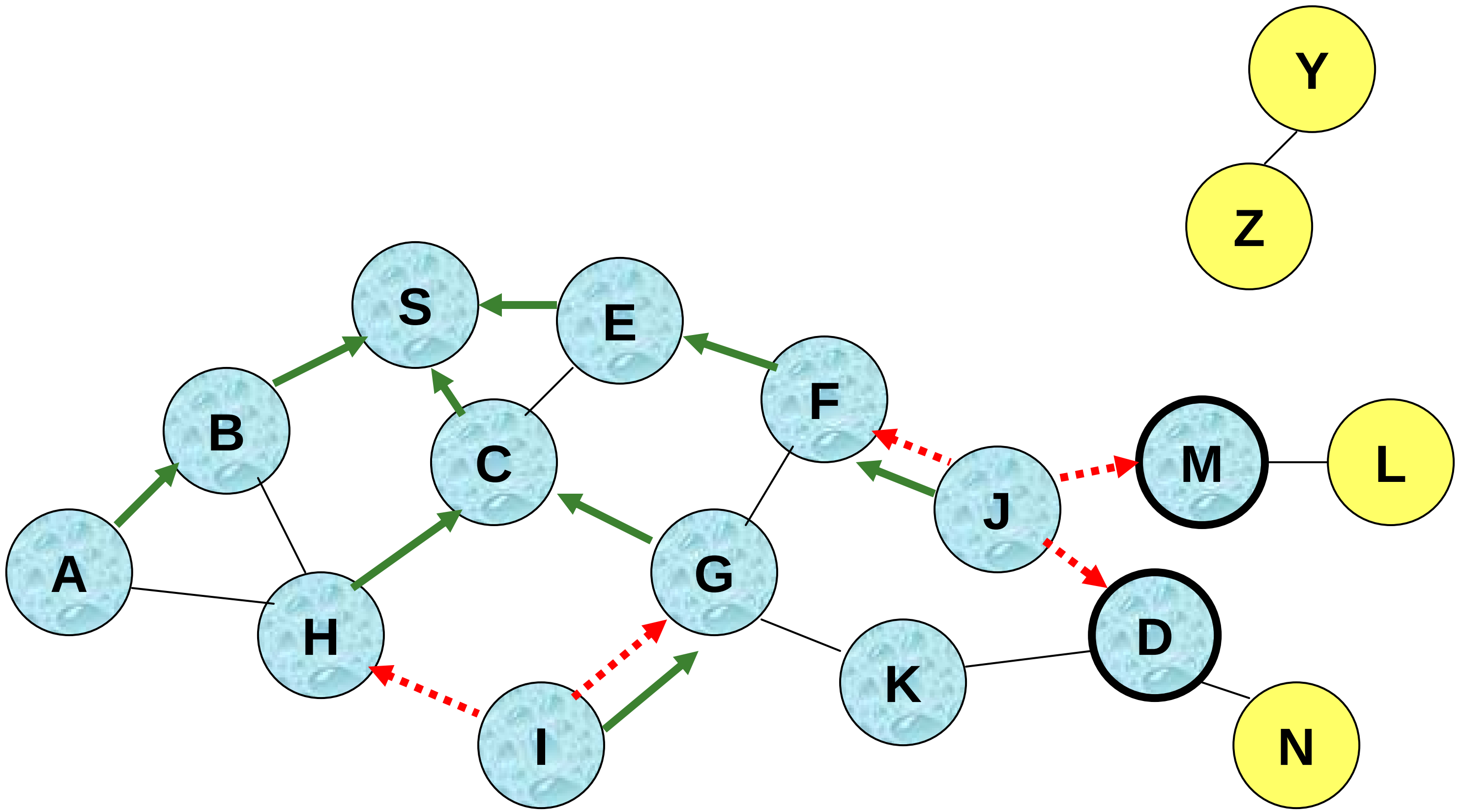
Reverse Path Setup in AODV

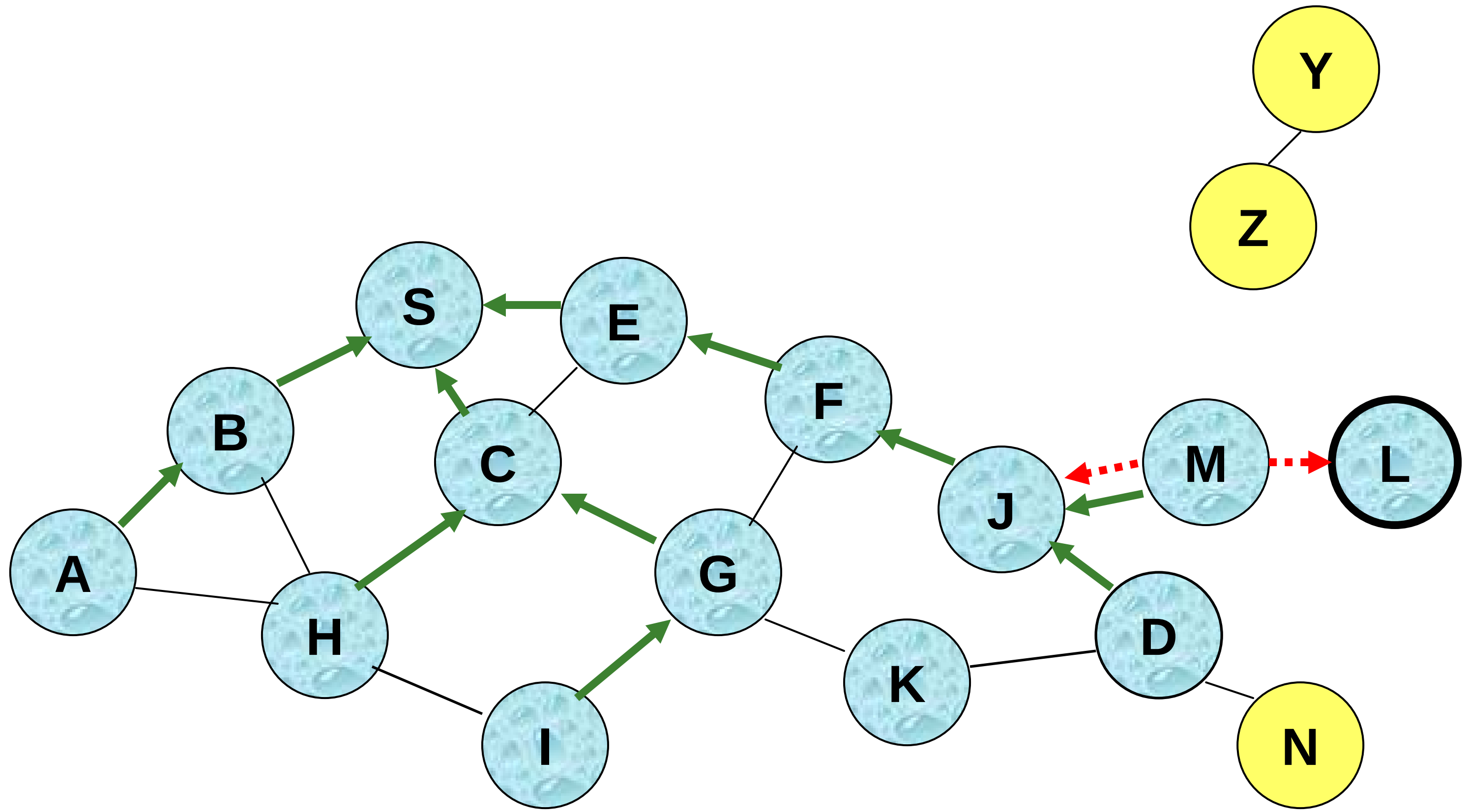


G's cache: [G,K,D], seq# 5

- **Node G** **does not forward** **RREQ, because node G has a cached path to D.**

Slide used with permission from: [V01]

Reverse Path Setup in AODV



- **Node D does not forward RREQ, because node D is the intended target of the RREQ**

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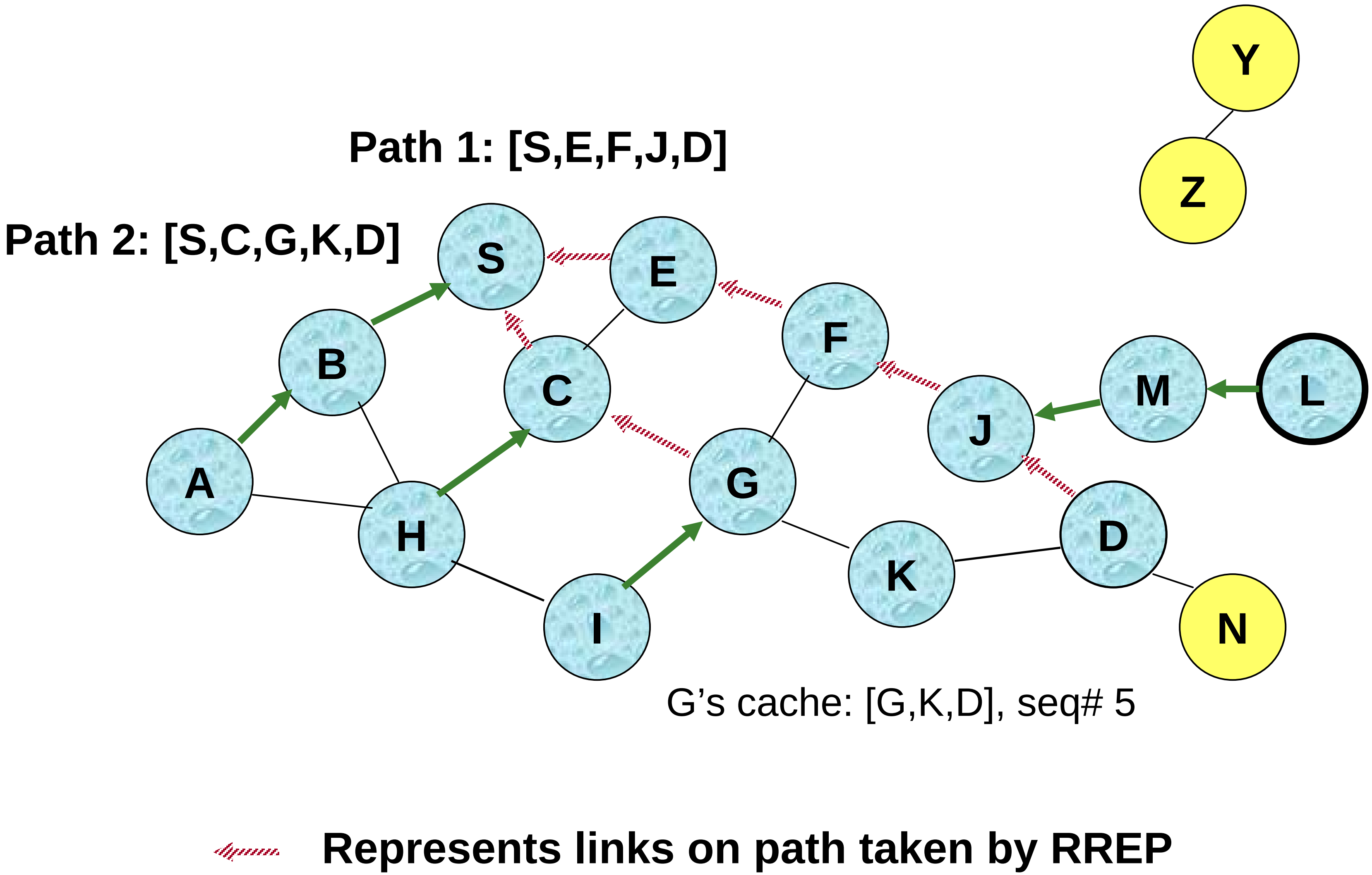
Route Reply in AODV



Slide used with permission from: [V01]

AODV Pros and Cons [MM04]

- Advantages:
  - Smaller message size than DSR since full route is not transmitted to source
  - Lower connection setup time than DSR
- Disadvantages:
  - If source sequence number is low and intermediate nodes have higher numbers but old routes, stale routes can be used
  - Still have possible latency before data transmission can begin
  - Link break detection adds overhead

Improving AODV Path Choice [ZMWW03]

- [ZMWW03] considers how to improve the source's path choice when multiple RouteReply messages are received
- Fields added to each node
  - *Count_Cycle*: Length of time for each measurement cycle
  - *Packets_Counter*: # packets sent within each measurement cycle
  - *V_node*: Measures the stability of the node by the equation: **V_node = 0.1*V_node + Packets_Counter**
  - *K_node*: Measures the load of the node by the ratio of the queue to the total buffer
- Fields added to each RoutRequest message:
  - *V_route*: The sum of V_node at each intermediate node
  - *K_route*: The sum of K_node at each intermediate node
- Path Selection equation:
  - $$W = a_1 * N + \frac{1}{N}\left(-a_2 * V\_route + a_3 * K\_route\right)$$
  - a1, a2, a3: weights of hop number, stability, traffic load
  - N: hop number

Improving AODV Path Choice [ZMWW03]

- Preliminary results:
  - Increased successful delivery ratio
  - Increased throughput
  - Decreased latency
  - Decreased number of broken links affecting transmission
- Tests performed with weight primarily on hop count and traffic load
- More tests should be performed to find the optimal weights for each value
- Need results on the processor load required for the calculations

AODV: Path Accumulation [GBP03]

- Combines the route information of DSR into AODV
- RouteRequest:
  - Upon receiving a RouteRequest message, a node will append its identifier to the header. The normal AODV procedure is then followed.
  - Intermediate nodes can change their table entries if a newer path, or lower hop count is detected in the header
- RouteReply:
  - A node will append its identifier to the header.
  - Intermediate nodes can change their table entries using the rule specified above.

AODV: PA [GBP03]

- Results:
  - Packet delivery ratio: Performed similar to AODV.
  - Routing load: Long term load is lower than AODV due to the higher probability of finding a cached route.
  - Delay: Less delay than AODV and DSR due to the lower number of RouteRequest messages needed to determine a path to the destination.
- Need results on the density of the network
- Does including the route in RouteReply packets make a significant difference?

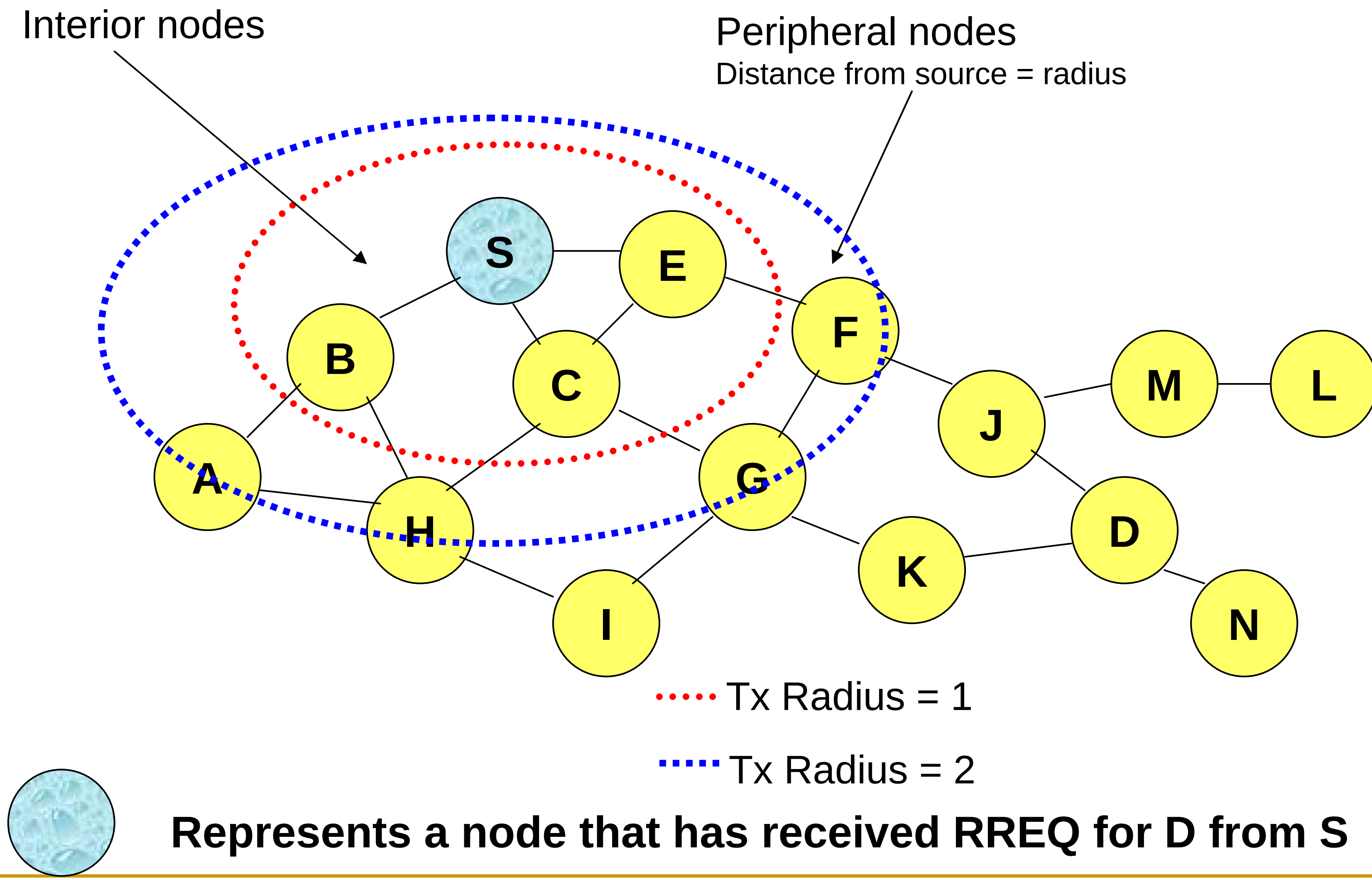
Zone Routing Protocol [MM04]

- Hybrid, source-based
- Uses reactive inter-zone (IERP) and proactive intra-zone (IARP) routing protocols to maintain routes
- Nodes use intra-zone routing protocol to maintain local routing tables to neighbors
- Nodes use inter-zone routing protocol to communicate with nodes outside of their zone
- On link failure:
  - Intermediate nodes find alternate routes to the destination and inform the sender. Can result in sub-optimal paths.
  - Sender must restart the path-finding process to find a more optimal path.
- Nodes have radius zones for transmission. All nodes use the same radius for zones.

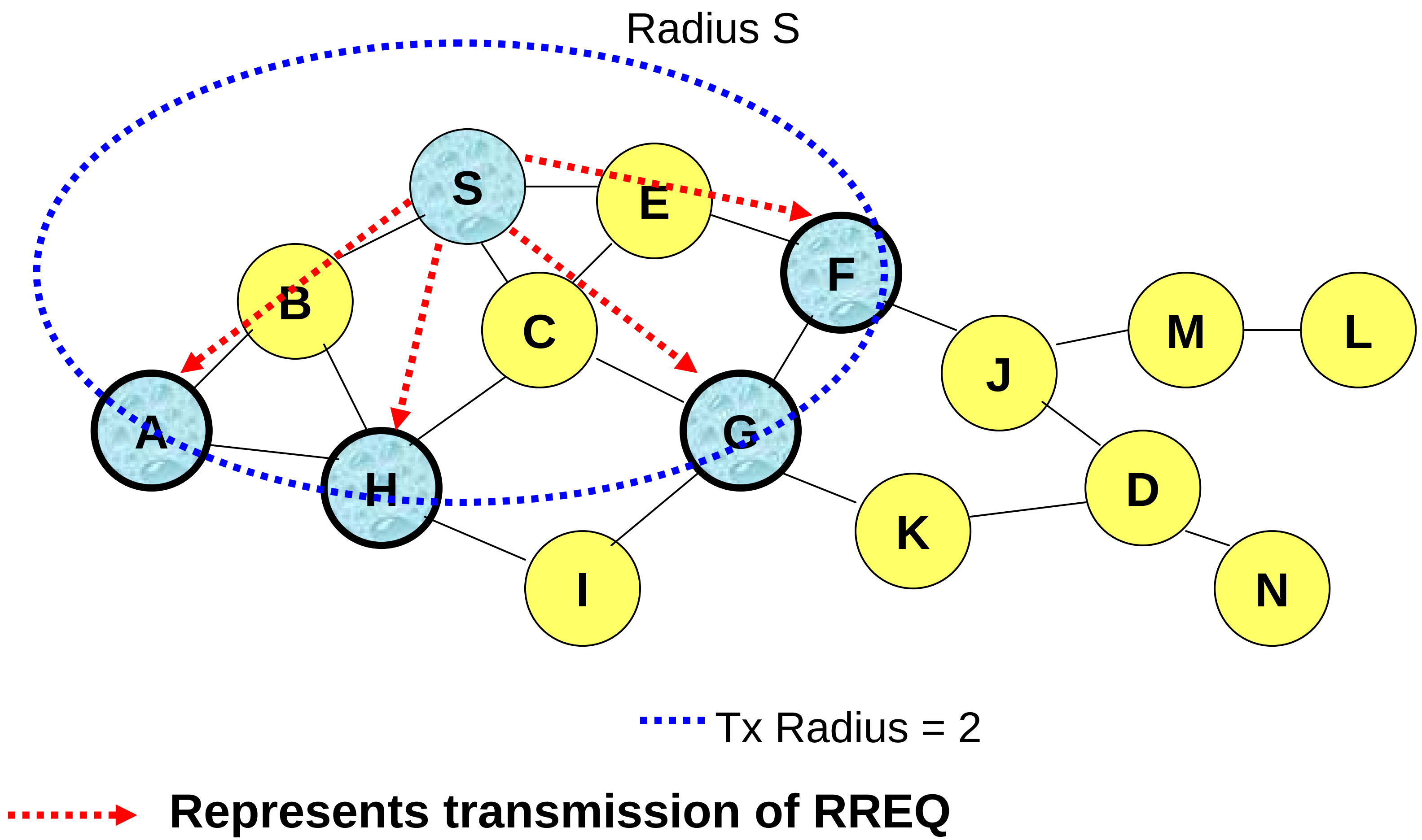
ZRP

- To determine a route to a destination:
  1. If destination is in source's zone, direct delivery of data. Else, source broadcasts RouteRequest to all peripheral nodes of its zone
  2. If destination is in border node's zone, *border node* responds with RouteReply.
  3. Source forwards data to appropriate border node to reach destination.
- Nodes will only forward a RREQ into new areas of the network. This is done by listening to neighbor transmissions.

Route Determination in ZRP

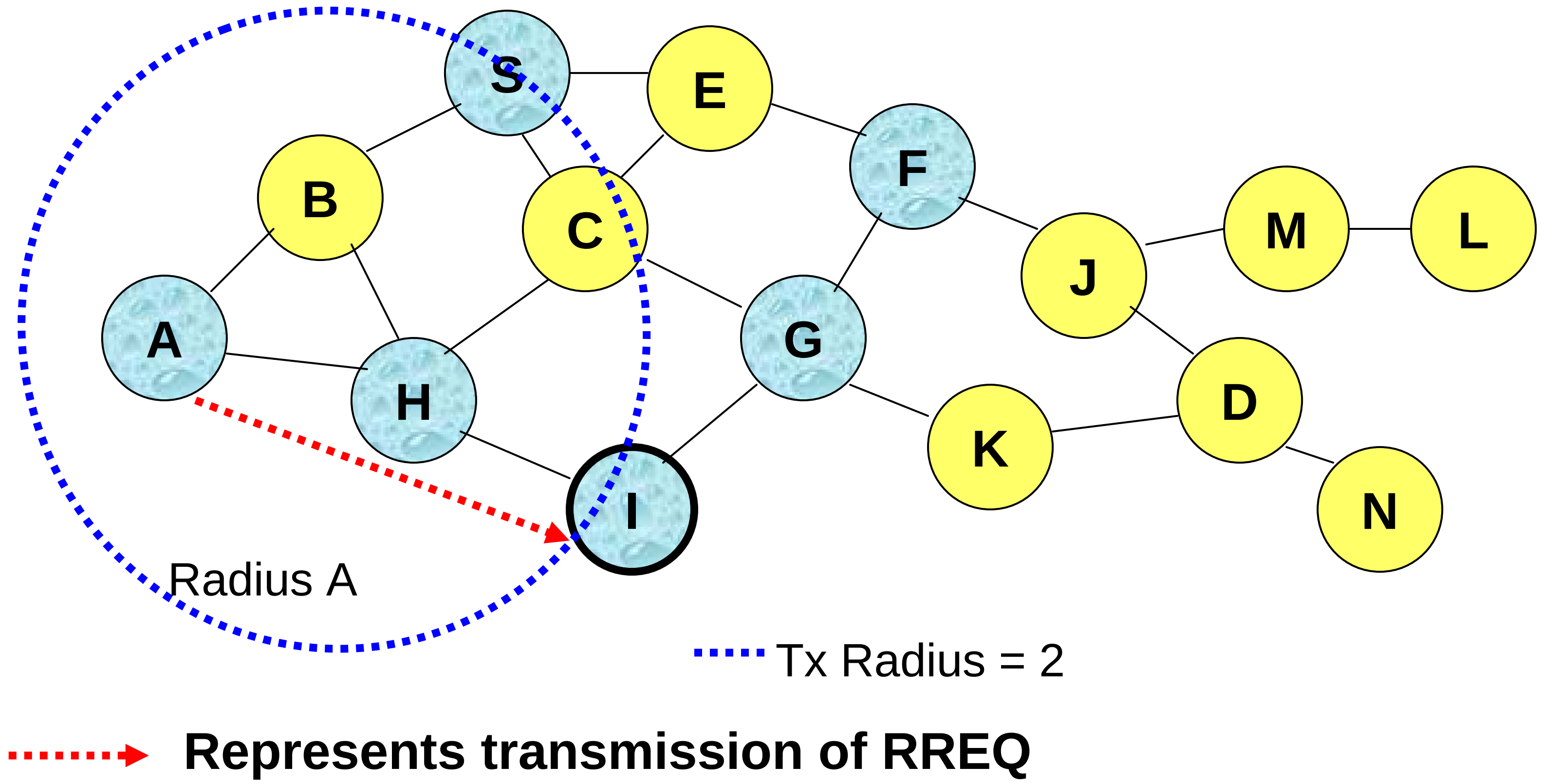


Route Determination in ZRP

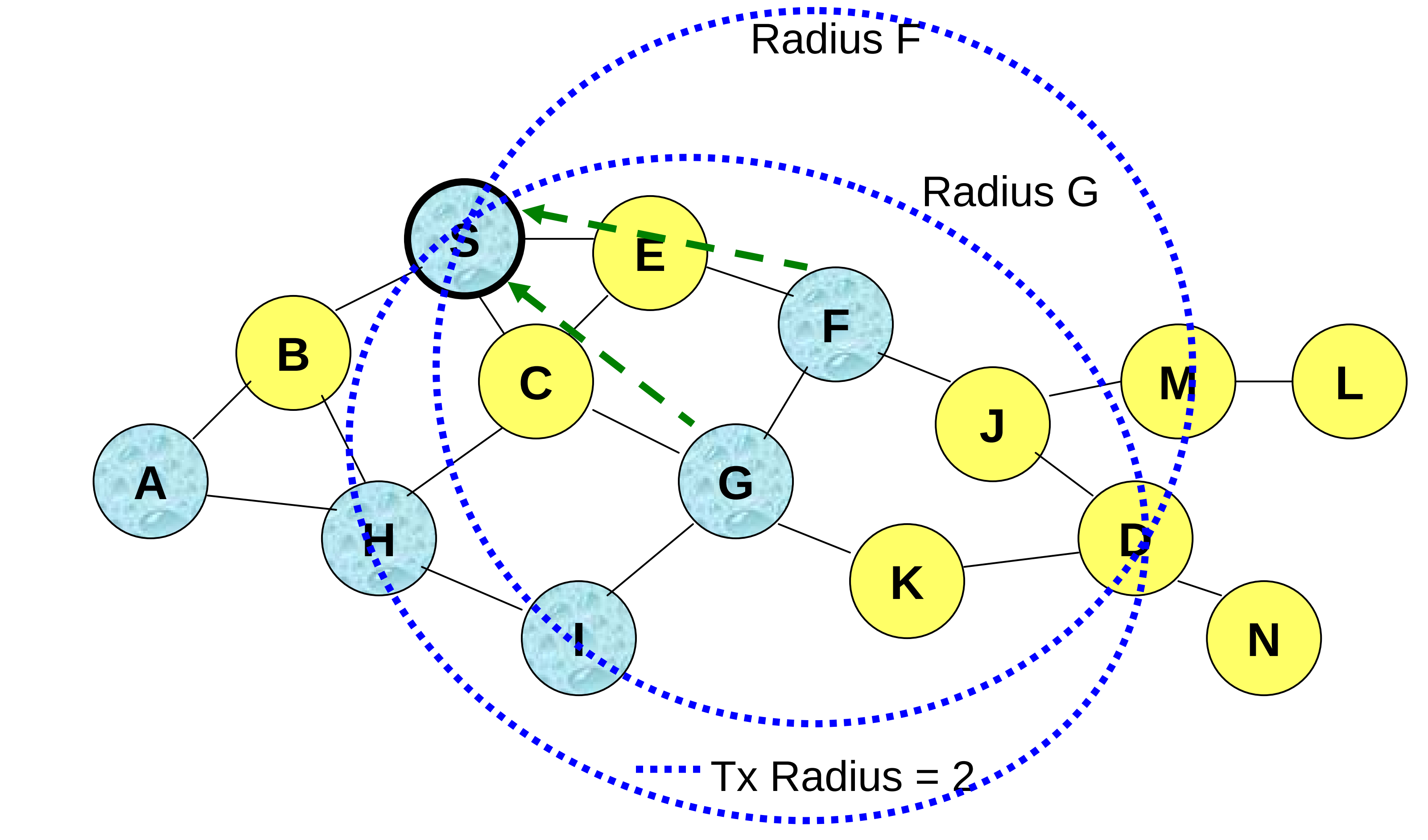


Route Determination in ZRP

A does not send the RREQ to C because C is within S's routing zone
H does not forward the RREQ because all 2-hop neighbors are within S's routing zone

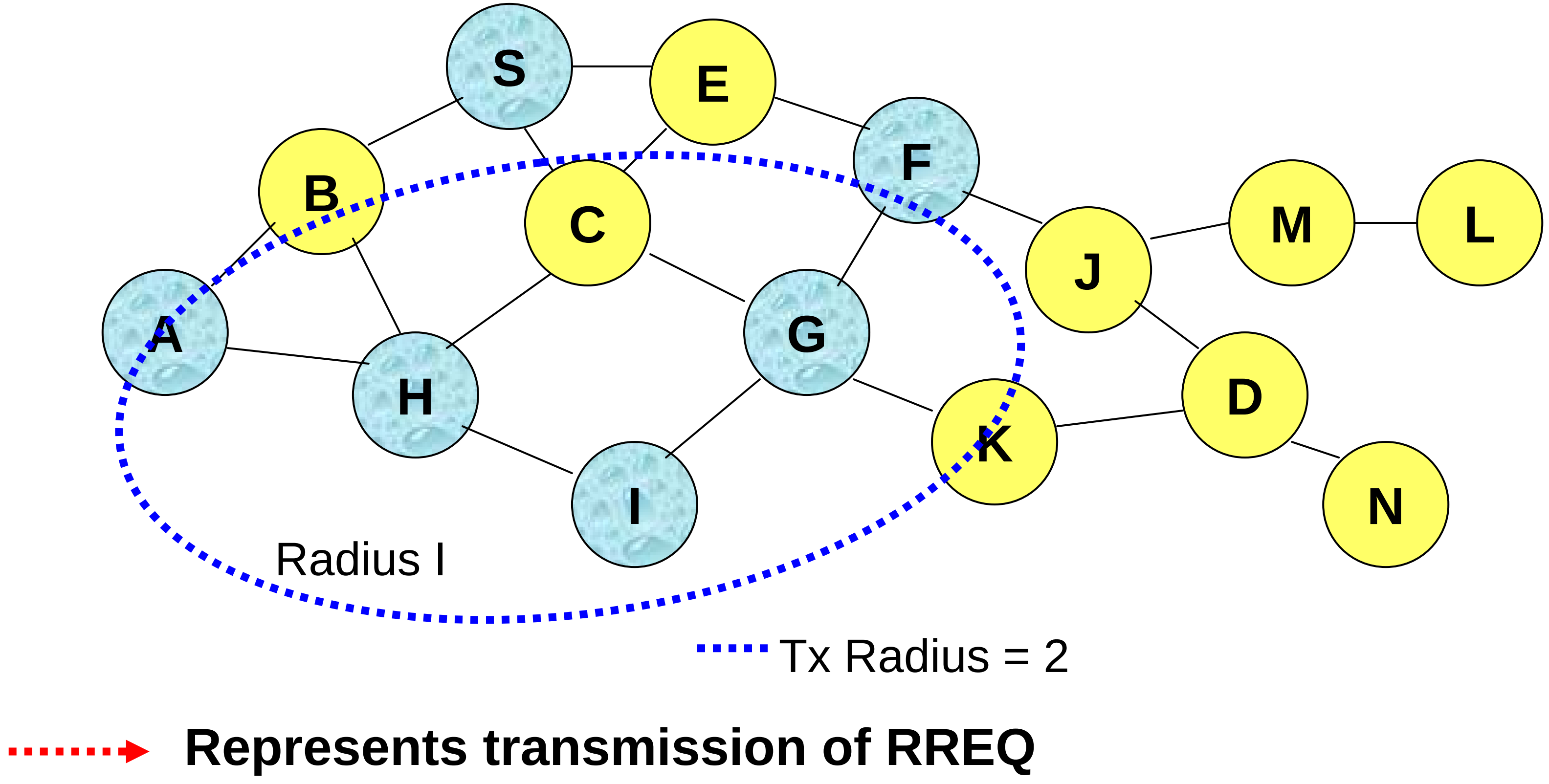


Route Determination in ZRP

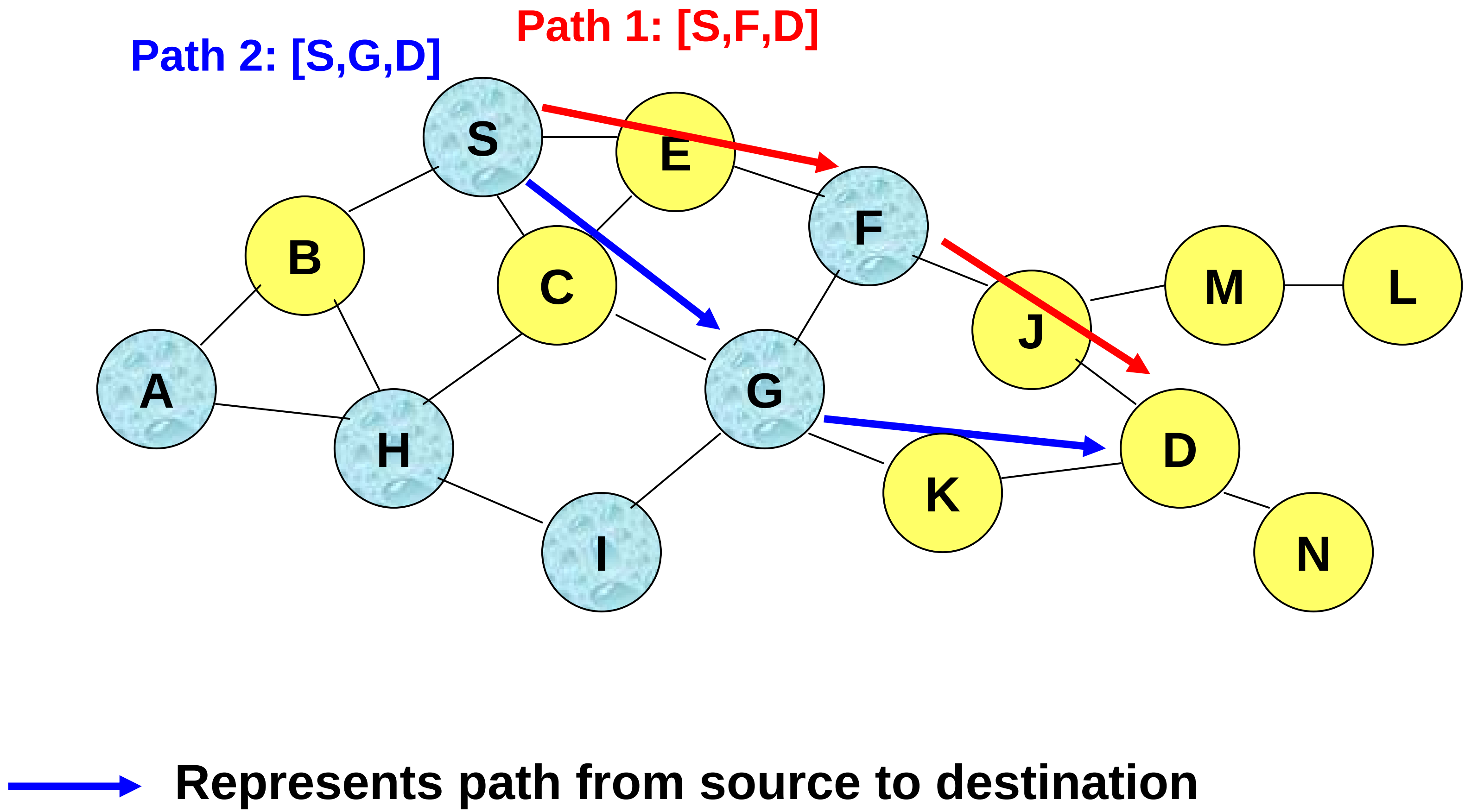


Route Determination in ZRP

I does not forward the RREQ because it heard G and F receive the request



Route Determination in ZRP



ZRP Pros and Cons [MM04]

- Advantages:
  - Theoretically reduces table maintenance inherent to proactive protocols
  - Theoretically reduces route determination delay inherent to reactive protocols
  - Can use single and multipath
- Disadvantages:
  - Realistically has higher overhead than proactive and reactive protocols
  - If zones greatly overlap, redundant RouteRequest messages are flooded through the network
  - Optimum zone radius must be determined for each situation
  - High stress for intermediate nodes on link failure

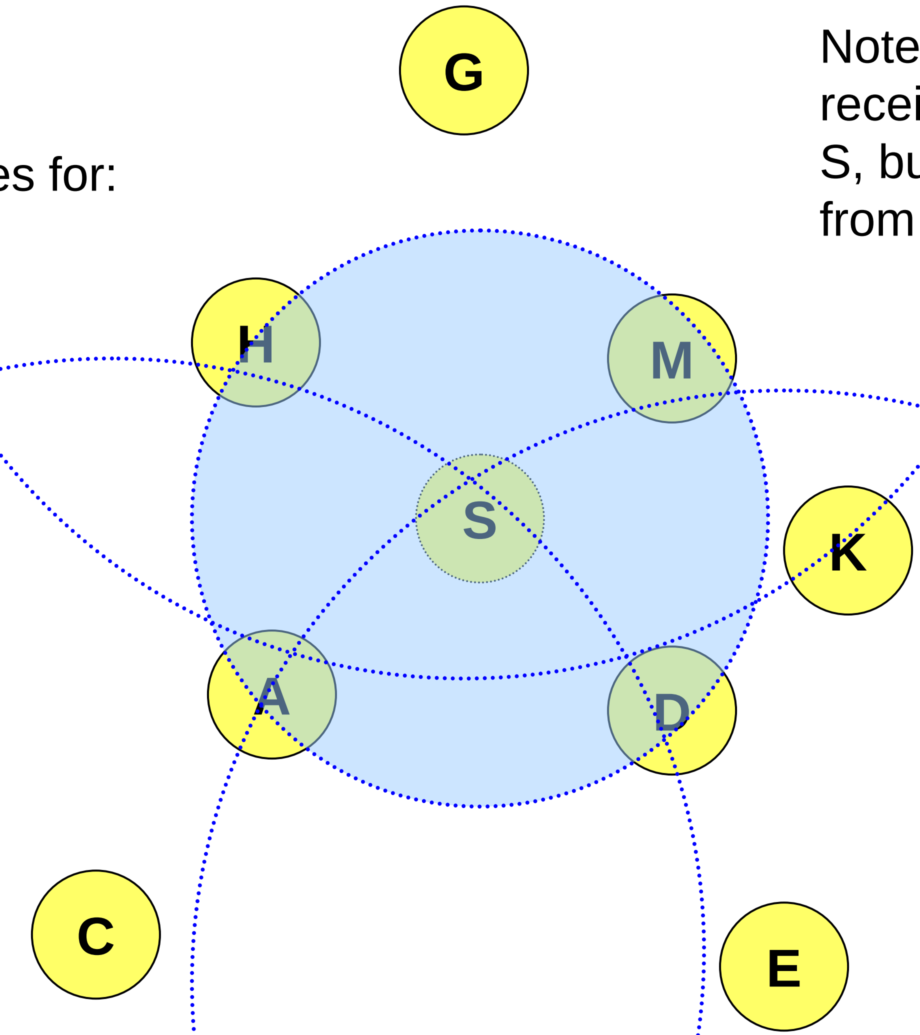
Independent Zone Routing (IZR) [SPH04]

- Addresses the limitation of having all nodes use the same zone radius in ZRP
- Defines two different zones:
  - Send zone: the maximum number of hops away a node will send proactive reports for routing
  - Receive zone: the maximum number of hops away a node will accept proactive reports
- Receive zone can be different sizes for nodes
- Send zone shape dependent on receive zone size for neighboring nodes
- IARP must be modified to accommodate this

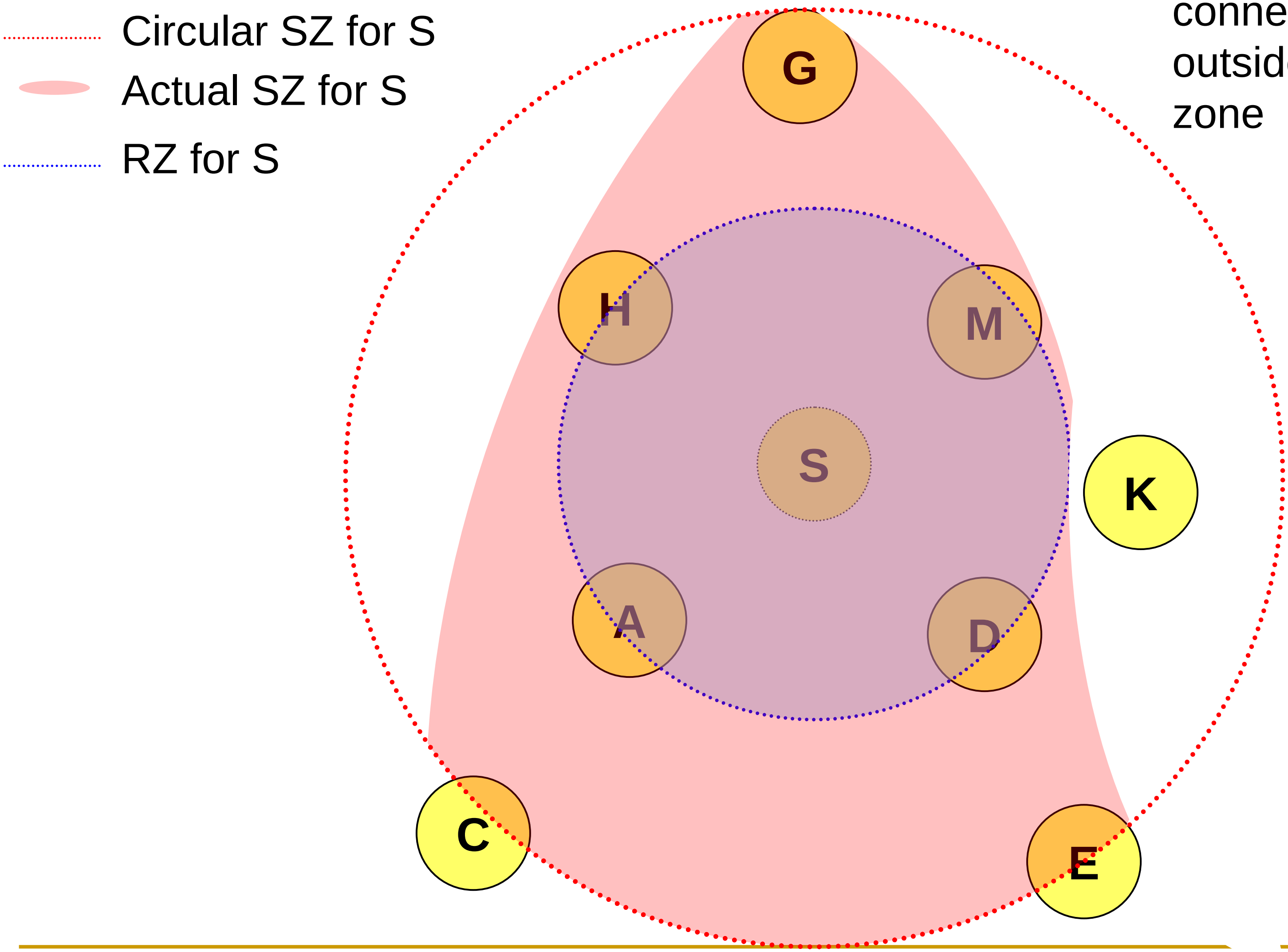
IZR Receive Zones Example

Receive Zones for:
C, E, G, S

Note how C, G, E all receive messages from S, but S does not receive from them



IZR Send Zone Example



Relies on indirect connections to nodes outside of receive zone

Independent Zone Routing (IZR) [SPH04]

- Routing performed similar to ZRP
- Zone radius found dynamically using:
  - Min Searching Algorithm: Minimize the amount of routing control traffic with Z(R+1) < Z(R) < Z(R-1)
  - Adaptive Traffic Estimation: Track the ratio of IARP traffic to IERP traffic, adjust radius based upon threshold and hysteresis term
    - Increasing radius increases IARP traffic
    - Decreasing radius increases IERP traffic
- Min Search used initially to find minimum control traffic curve. Adaptive Estimation then is used to find proper radius.
- Min Search only is used to deal with special cases:
  - Optimal radius == 1
  - Optimal radius == (network span) - 1

Independent Zone Routing (IZR) [SPH04]

- Results:
  - Routing control traffic: ZRP exponential increase; IZR constant
  - Zone radius: IZR average zone radius 2-3 hops for random mobile network at 0.5 m/s
  - Control traffic: Control traffic load is bounded and stabilizes at a near constant level as algorithm runs
- Need delay characteristics of the protocol. How do different zone sizes affect the end-to-end delay?
- All experiments conducted with constant velocity and then suddenly changing velocity. Need plots showing increasing velocity and packet delivery ratio to compare to other protocols.

Structured Routing (VBS) [SH01]

- Considers a hierarchical/zone routing scheme akin to cellular networks
- Protocol steps:
  1. Nodes in a zone elect a virtual base station (VBS) using lowest ID number
  2. VBSs “acquire” information about other VBSs and their zones with hello messages
  3. VBS stores next-hop information, not routes
  4. Nodes route inter-zone traffic through the VBS
  5. If a VBS moves or stops acknowledging its zone nodes, a new election occurs

Structured Routing [SH01]

- Results are sketchy at best
  - [SH01] reports delivery rates from 90% - 100%
  - Assumes elected nodes are stationary or move very rarely
  - No results on VBS death events or a network where all nodes are highly mobile
  - No information or results on the loading caused by a single election

Conclusion

- Many routing protocols exist
- Still much discussion over proactive vs. reactive approaches
- This is a very active area of research
- Much work still needs to be done because most research only answers part of the questions
- Need a better way to contrast and compare all available routing protocols

References

- [AJ03] G. Alandjani and E. Johnson, *Fuzzy routing in ad hoc networks*, IEEE Proc. Conf. Performance, Computing, and Communications, 2003.
- [DCYS98] S. Das, R. Castaneda, J. Yan, and R. Sengupta, *Comparative performance evaluation of routing protocols for mobile, ad hoc networks*, IEEE Proc. Seventh Int'l Conf. Computer Communications and Networks, 1998.
- [GBP03] S. Gwalani, E. Belding-Royer, and C. Perkins, *AODV-PA: AODV with path accumulation*, IEEE Int'l Conf. Communications, 2003.
- [H04] M. Haenggi, *Routing in ad hoc networks – A wireless perspective*, IEEE Proc. First Int'l Conf. Broadband Networks, 2004.
- [MM04] C. Murthy and B. Manoj, Ad Hoc Wireless Networks: Architectures and Protocols. Prentice Hall: Upper Saddle River, NJ. 2004.
- [SH01] A. Safwat and H. Hassanein, *Structured routing in wireless mobile ad hoc networks*, IEEE Proc. Sixth Symp. Computers and Communications, 2001.
- [SPH04] P. Samar, M. Pearlman, and Z. Haas, *Independent zone routing: an adaptive hybrid routing framework for ad hoc wireless networks*, IEEE Trans. Networking, vol. 12, no. 4, Aug 2004.
- [V01] N. Vaidya, *Mobile Ad Hoc Networks: Routing, MAC and Transport Issues*, Slide Presentation, 2001.
- [ZMWW03] X. Zhong, S. Mei, Y. Wang, and J. Wang, *Stable enhancement for AODV routing protocol*, IEEE Proc. Fourteenth Int'l Symp. Personal, Indoor and Mobile Radio Communication, 2003.