MANET Routing

- Introduction to MANETs
- Fundamentals of Wireless Ad Hoc Networks
- Routing in MANETs
- Properties of MANETs

Graphics on MANET routing taken in parts from: Nitin H. Vaidya

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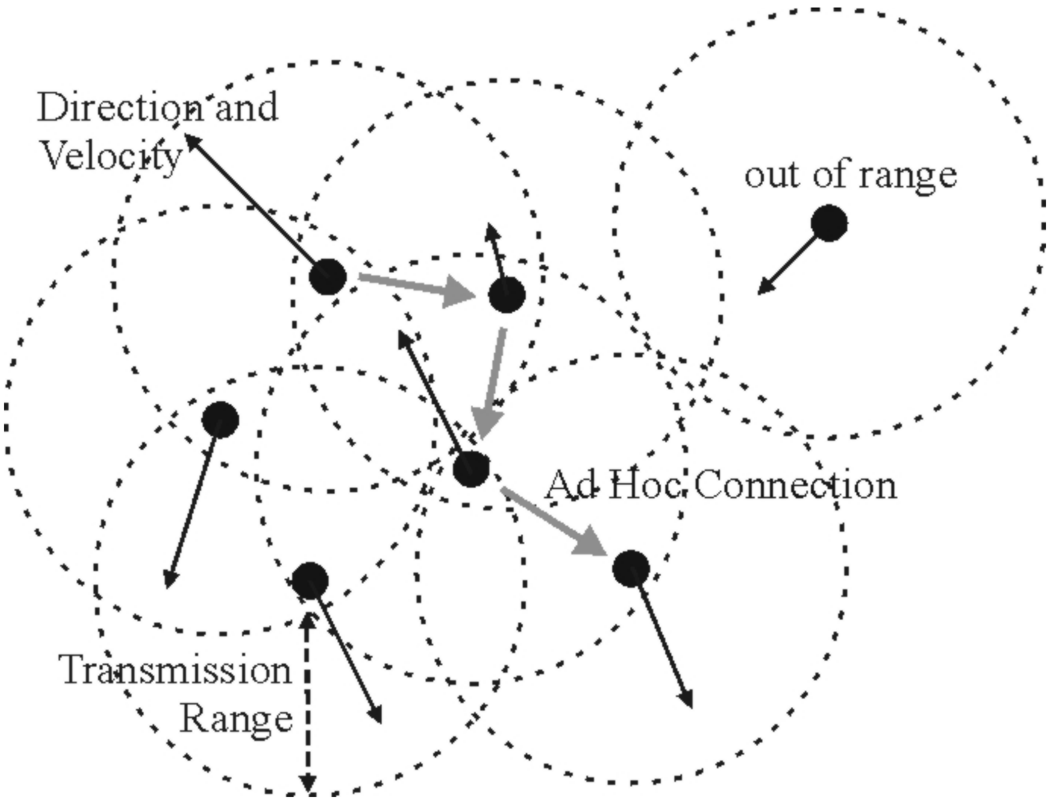
Distributed Systems in Mobile Environments

- Scenario 1: Mobile Overlay Members
  - Walking users at roaming devices …
  - Issues: Transfer of personal context,
    location-based context
  - Networking solution: application transparency of Mobile IP(v6)
- Scenario 2: Spontaneous Application Overlays
  - Collaborative applications in (local) Mobile Ad-Hoc Networks
  - Machine-to-machine settings in the Internet of Things (IoT)
  - Issues: Adapt to efficiency & proximity needed in MANETs,
    cope with unreliable, mobile underlay networks
  - P2P Systems and MANETs both void infrastructure

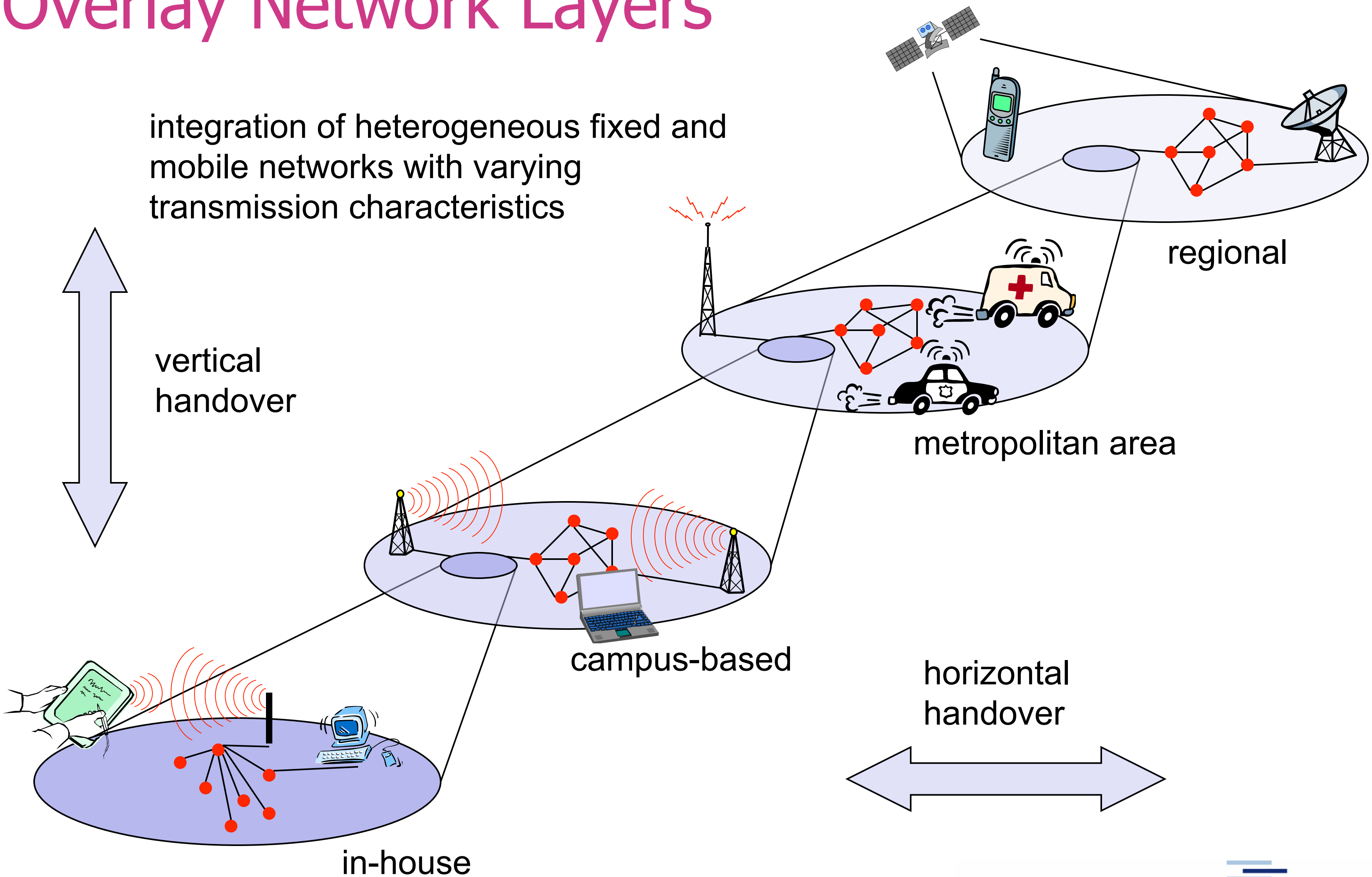
Ad Hoc Networks (WLAN, Bluetooth)



Characteristics:

- Self configuring
- Infrastructure free
- Wireless
- Unpredictable terminal mobility
- Limited radio transmission range
- Often: Low power & lossy
- Goal: provide communication between nodes

The Global View: Overlay Network Layers



Application Examples

- Sensors, Actuators & Relaying Nodes
- Single & Multiple Dedications of Nodes
- Common Examples:
  - Military, Rescue Services
  - Regional Mesh Networks
  - Collaborative Inter-Vehicular Communication
  - Sensor Networks
  - Personal Area Networking / Local Device Networks
  - Gaming, Edu-/Info-/Sociotainment
  - Home Automation

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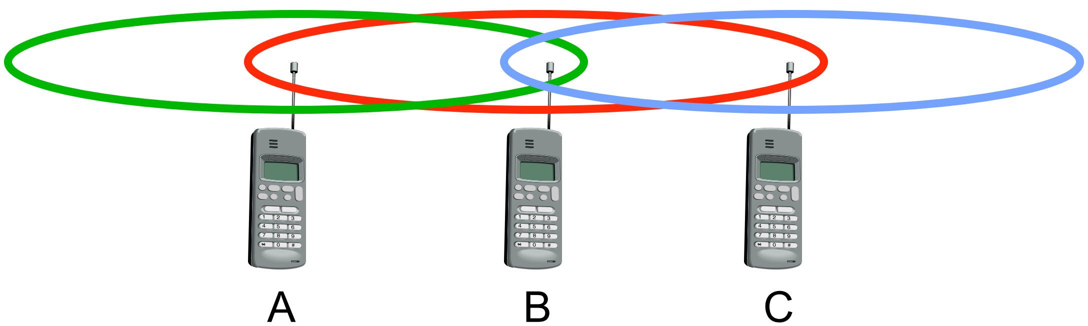
Mobile Ad Hoc Networks

- Formed by wireless hosts which may be mobile
- Without (necessarily) using a pre-existing infrastructure
- Routes between nodes may potentially contain multiple hops
- Motivations:
  - Ease of deployment, low costs
  - Speed of deployment
  - Decreased dependence on infrastructure

Hidden and exposed terminals

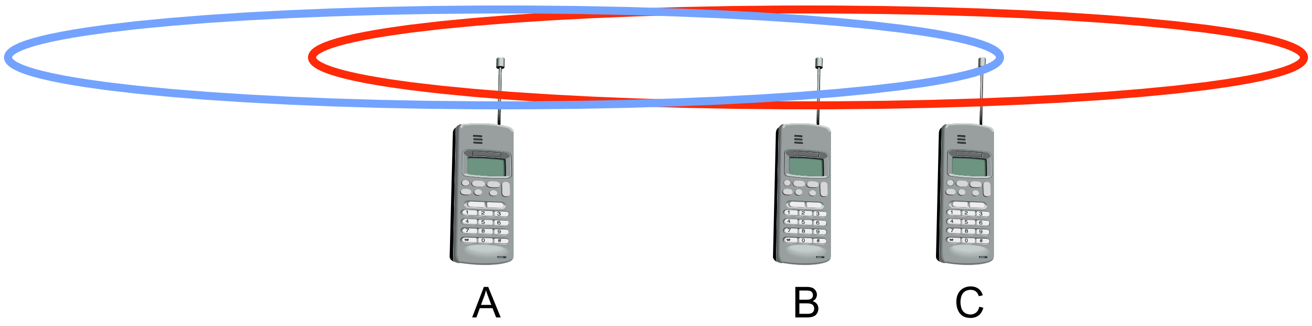
- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B, C senses a “free” medium (CS fails)
  - collision at B, A cannot receive the collision (CD fails)
  - A is “hidden” for C



- Exposed terminals
  - B sends to A, C wants to send to another terminal (not A or B)
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary
  - C is “exposed” to B

Near and far terminals

- Terminals A and B send, C receives
  - signal strength decreases proportional to the square of the distance
  - the signal of terminal B therefore drowns out A's signal
  - C cannot receive A



- If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer
- Also severe problem for CDMA-networks - precise power control needed!

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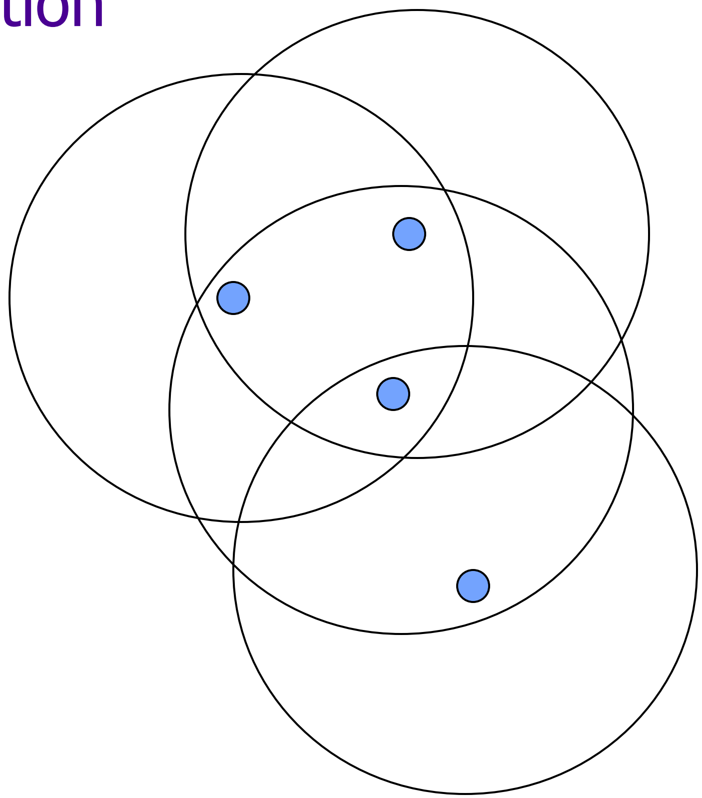
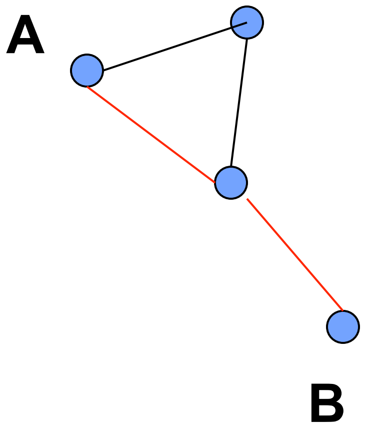
Mobile Ad Hoc Networks

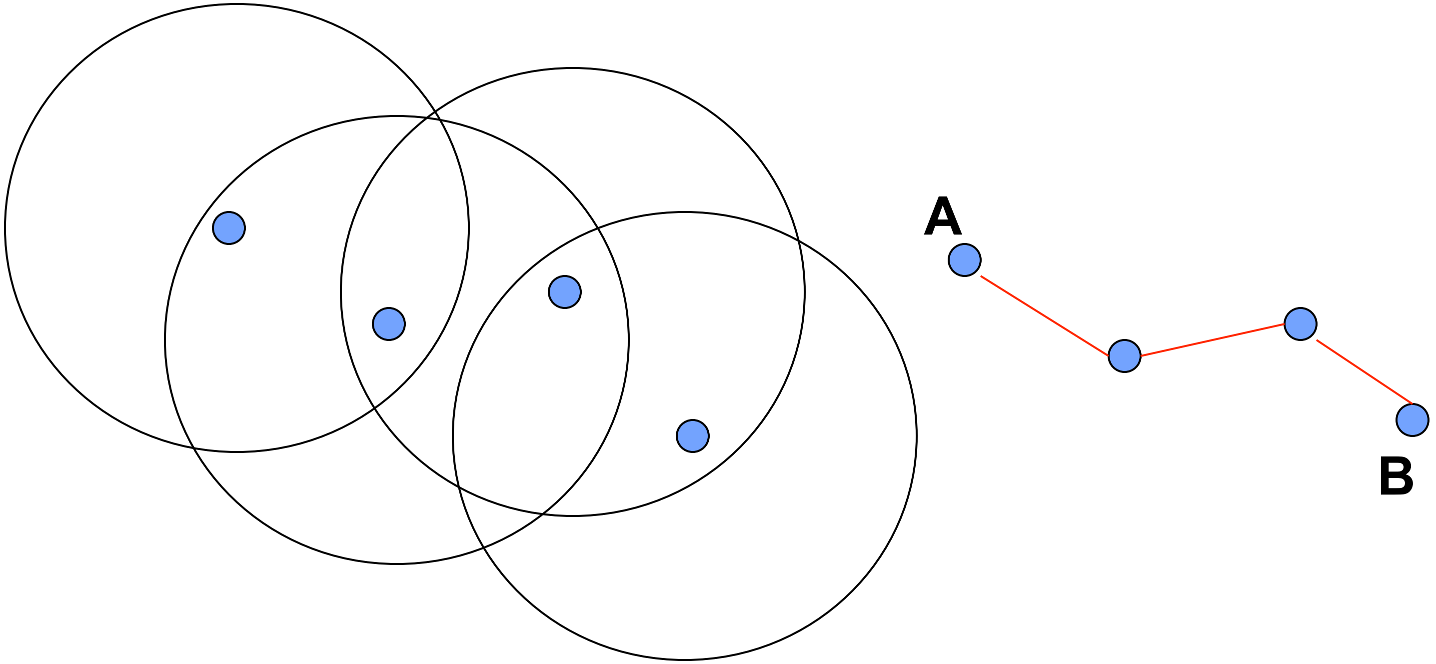
- May need to traverse multiple links to reach a destination





Mobile Ad Hoc Networks (MANET)

- Mobility causes route changes



Many Variations

- Fully Symmetric Environment
  - all nodes have identical capabilities and responsibilities
- Asymmetric Capabilities
  - transmission ranges and radios may differ (→ asymmetric links)
  - battery life at different nodes may differ
  - processing capacity may be different at different nodes
  - speed of movement
- Asymmetric Responsibilities
  - only some nodes may route packets
  - some nodes may act as leaders of nearby nodes (e.g., cluster head)
- Varying Traffic Characteristics

Unicast Routing in MANETs - Why is it different ?

- Host mobility
  - link failure/repair due to mobility may have different characteristics than those due to other causes
- Rate of link failure/repair may be high when nodes move fast
- New performance criteria may be used
  - route stability despite mobility
  - energy consumption
- Many routing protocols proposed – no universal solution

Routing Protocols

- Proactive protocols
  - Determine routes independent of traffic pattern
  - Traditional link-state and distance-vector routing protocols are proactive
- Reactive protocols
  - Maintain routes only if needed
- Hybrid protocols

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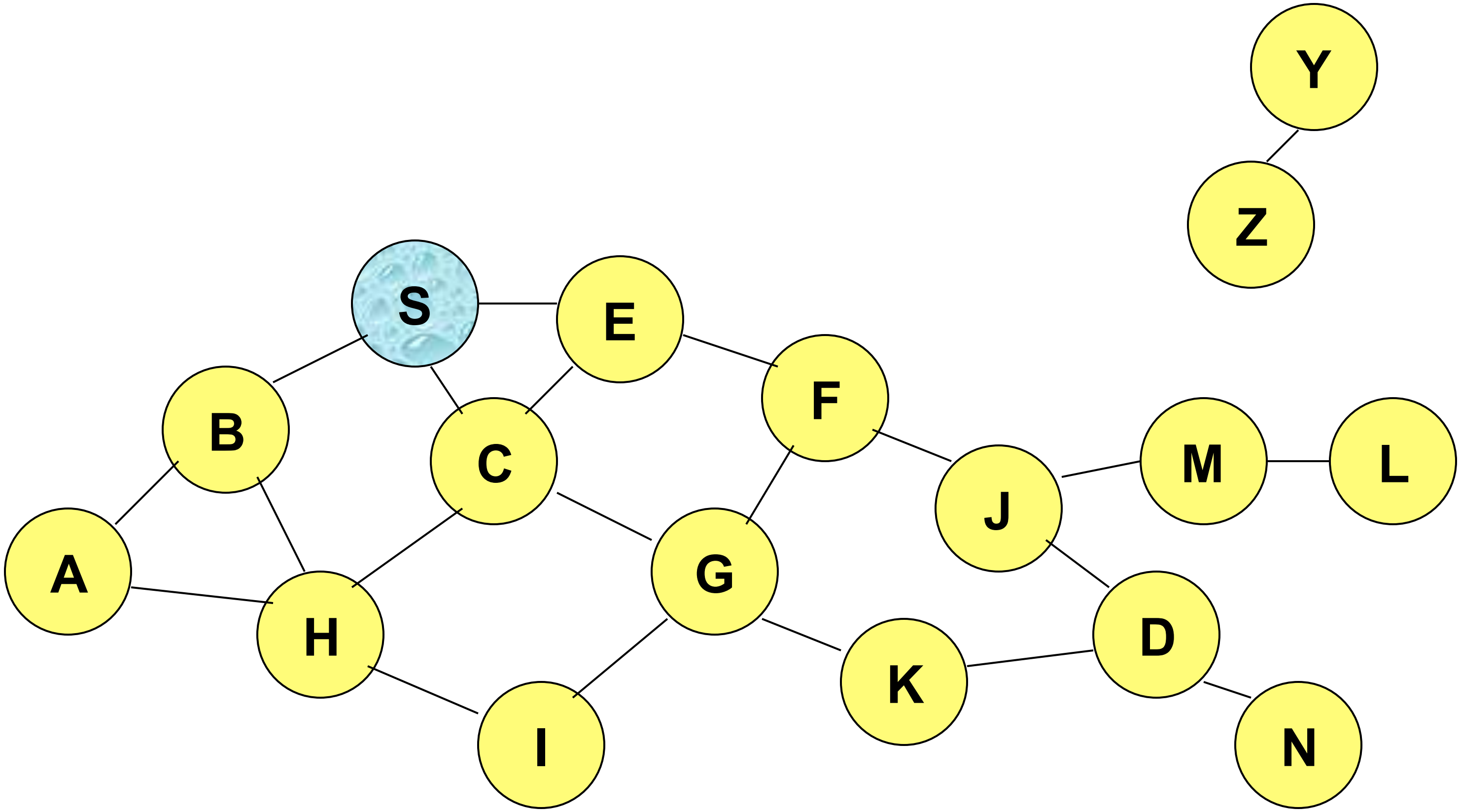
Trade-Off

- Latency of route discovery
  - Proactive protocols may have lower latency since routes are maintained at all times
  - Reactive protocols may have higher latency because a route from X to Y will be found only when X attempts to send to Y
- Overhead of route discovery/maintenance
  - Reactive protocols may have lower overhead since routes are determined only if needed
  - Proactive protocols can (but not necessarily) result in higher overhead due to continuous route updating
- Which approach achieves a better trade-off depends on the traffic and mobility patterns

Flooding for Data Delivery

- Sender S broadcasts data packet P to all its neighbors
- Each node receiving P forwards P to its neighbors
- Sequence numbers used to avoid the possibility of forwarding the same packet more than once
- Packet P reaches destination D provided that D is reachable from sender S
- Node D does not forward the packet

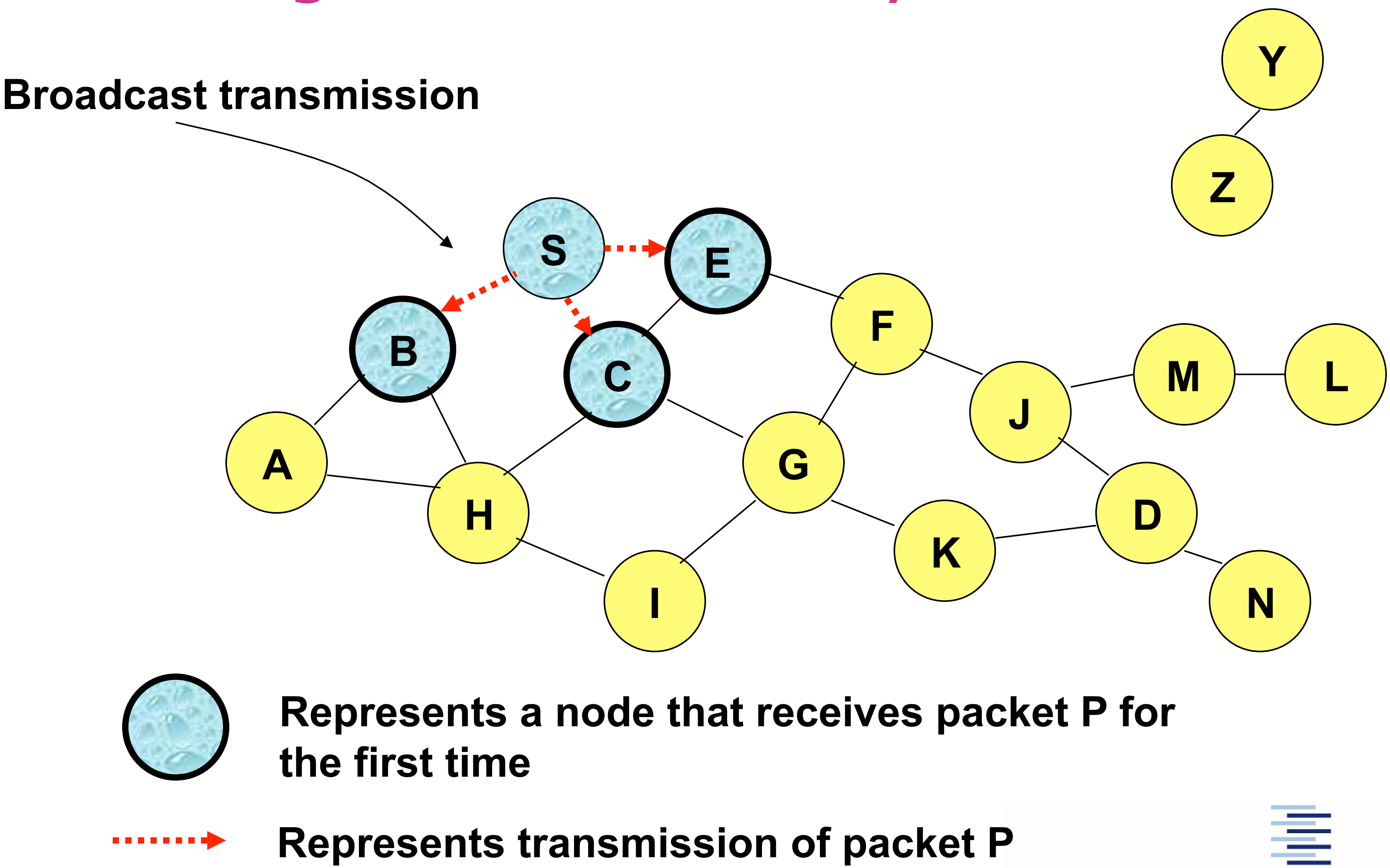
Flooding for Data Delivery



Represents a node that has received packet P

Represents that connected nodes are within each other's transmission range

Flooding for Data Delivery



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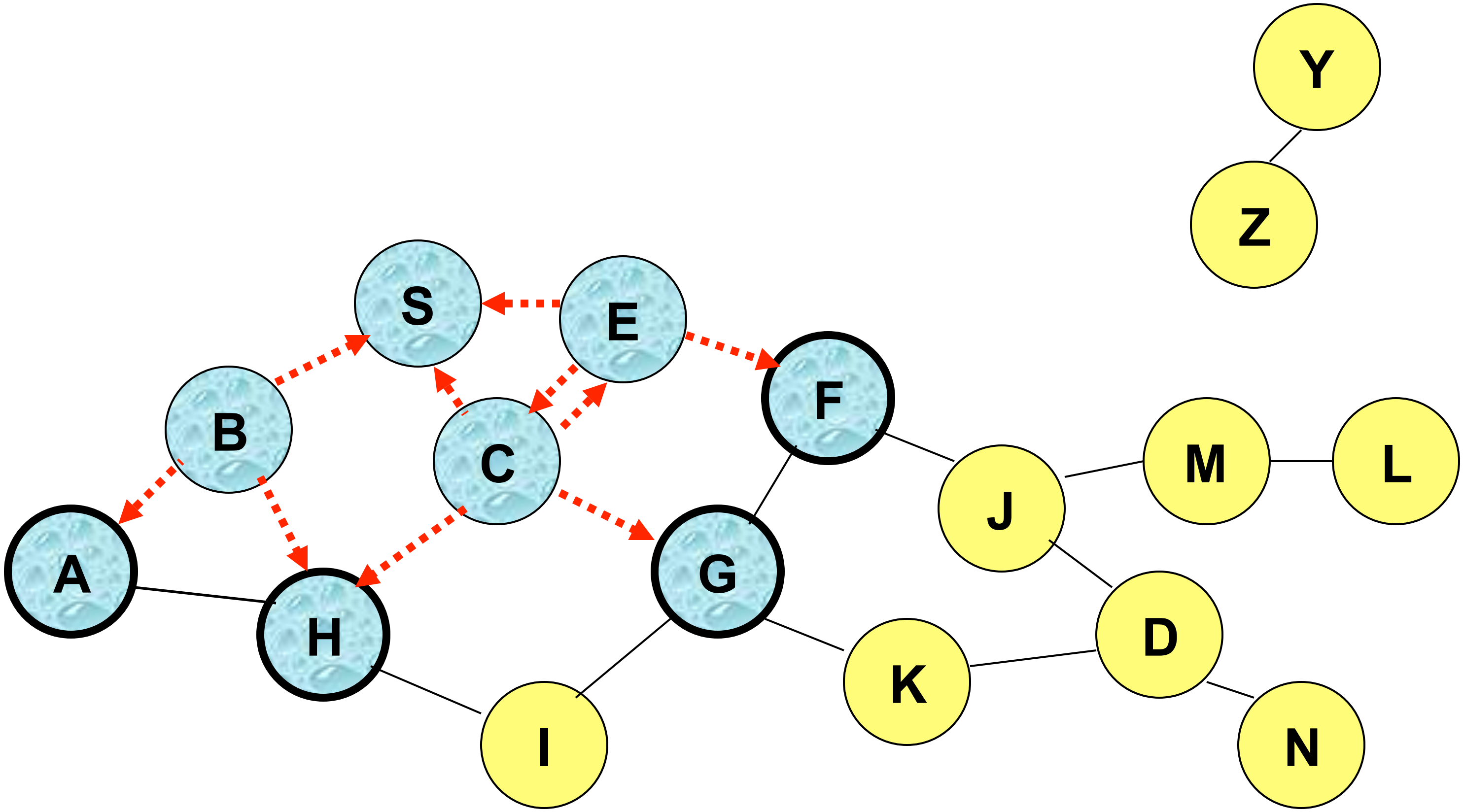
Flooding for Data Delivery



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

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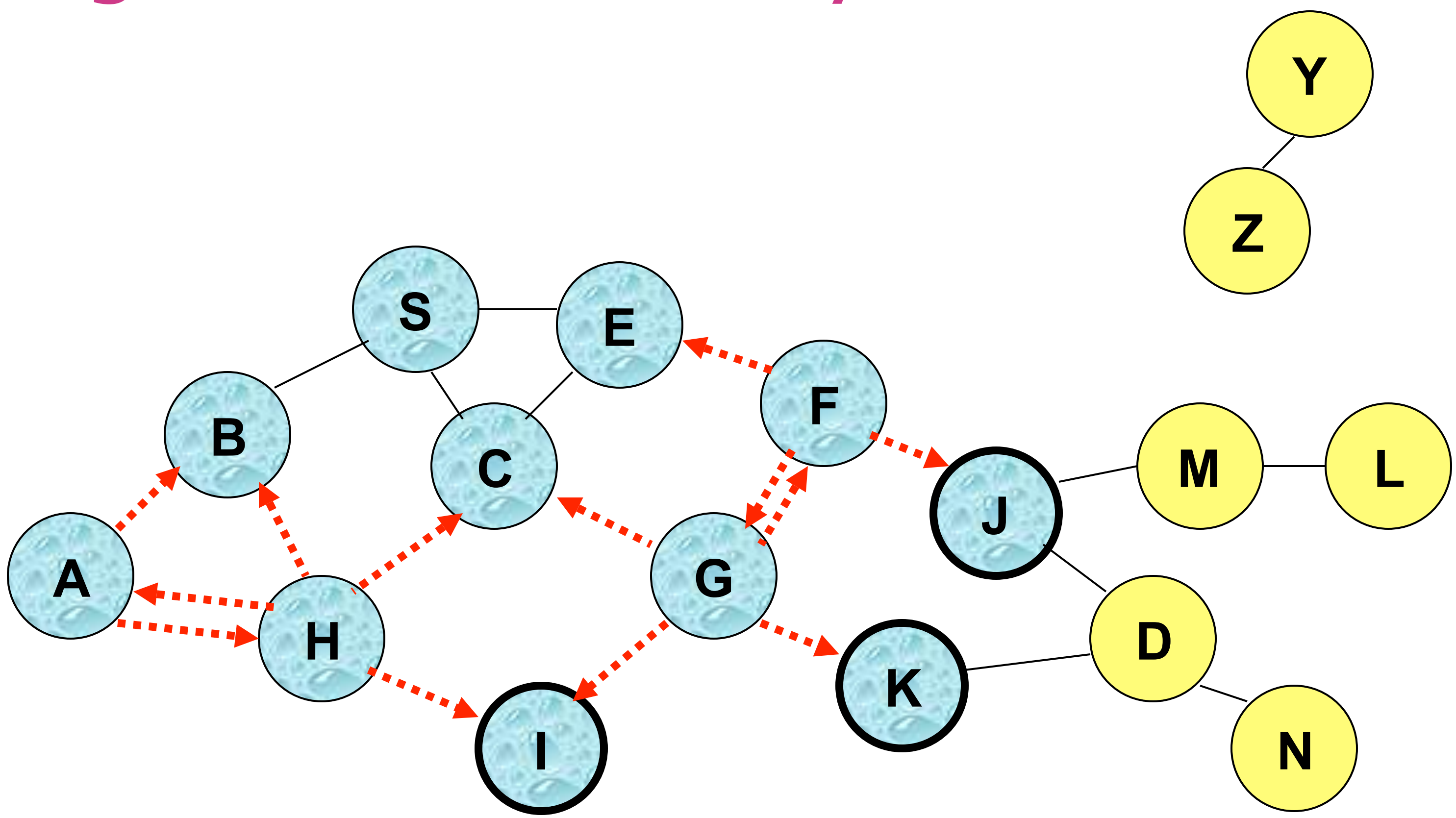
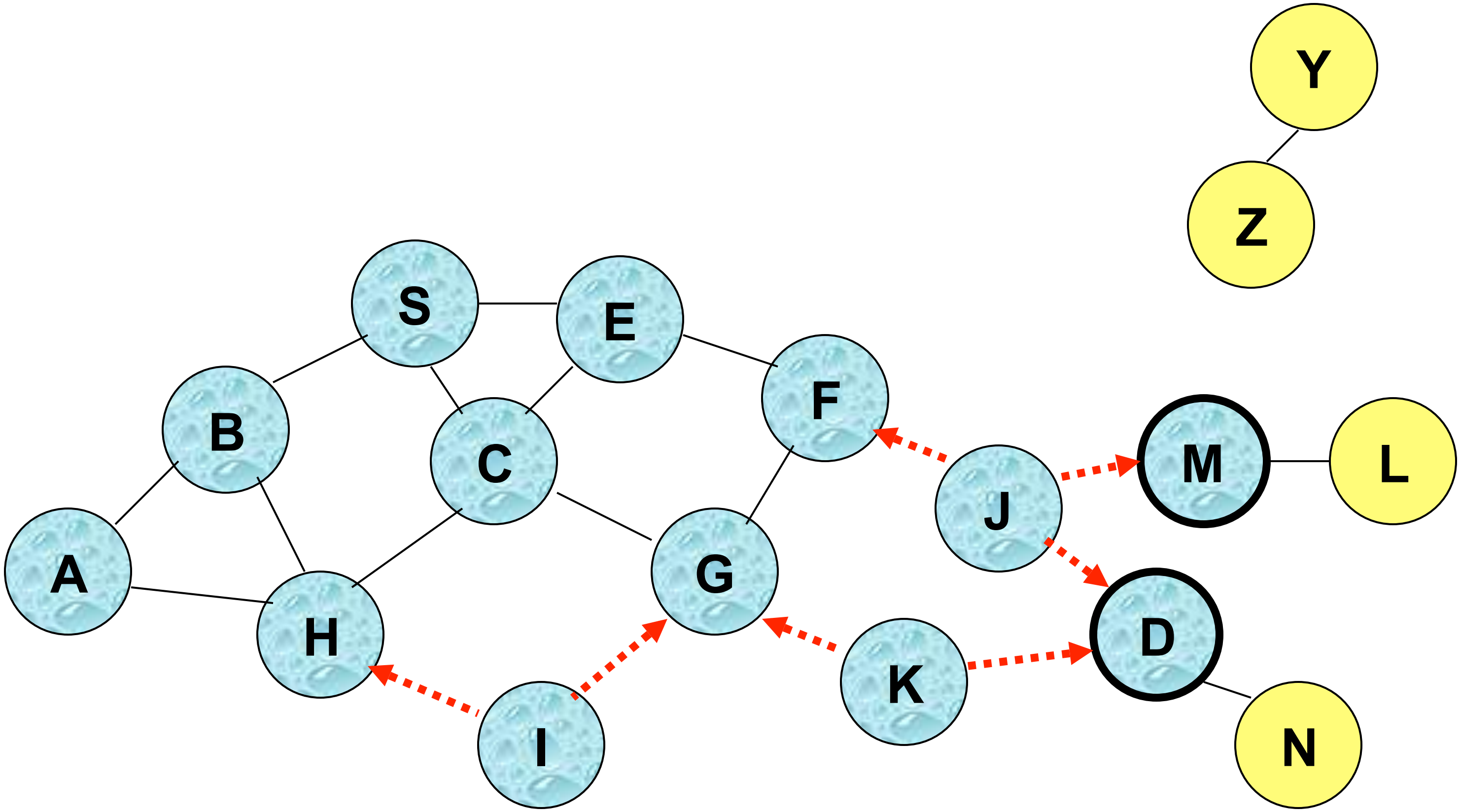
Flooding for Data Delivery



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

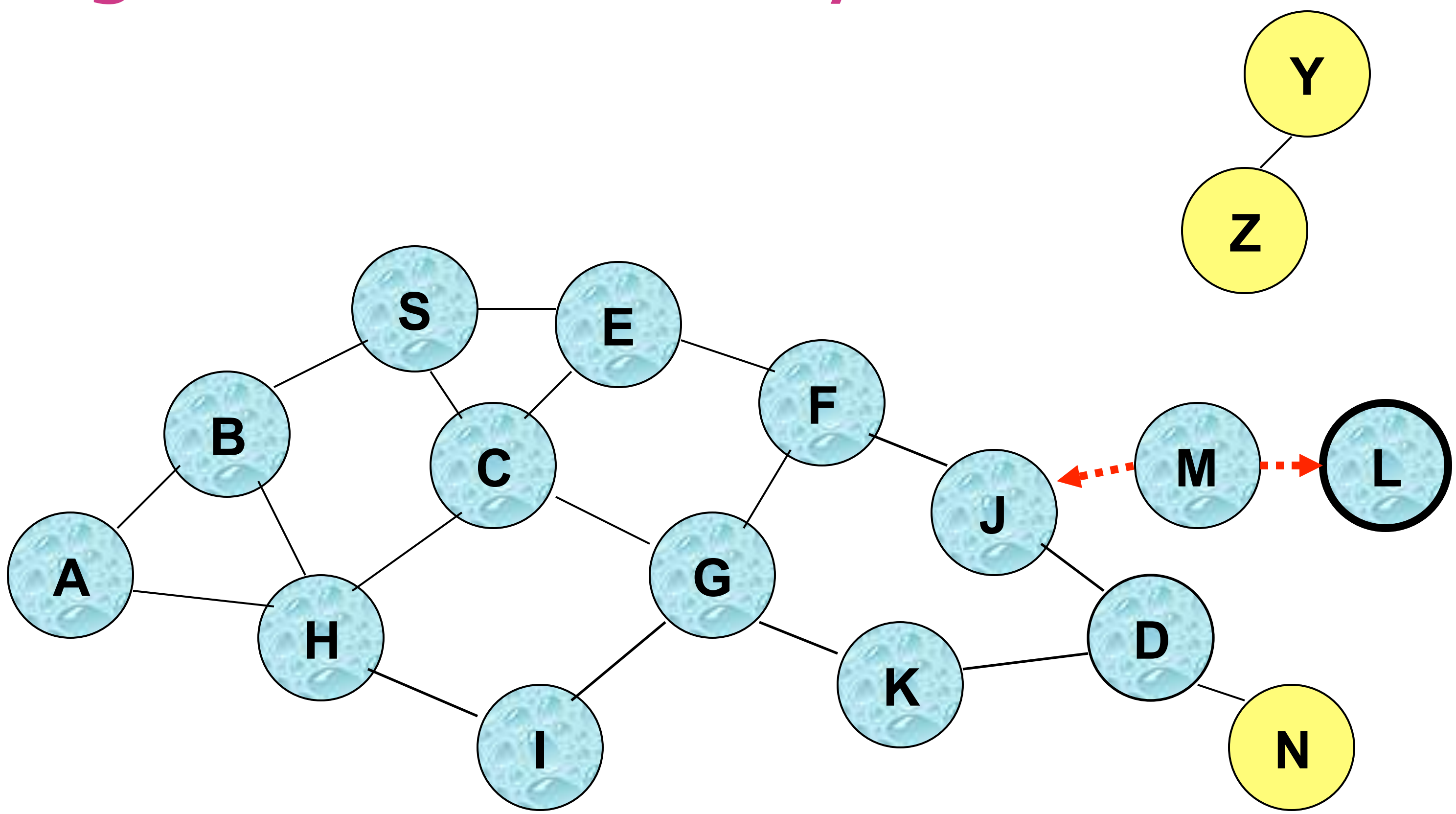
Flooding for Data Delivery



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

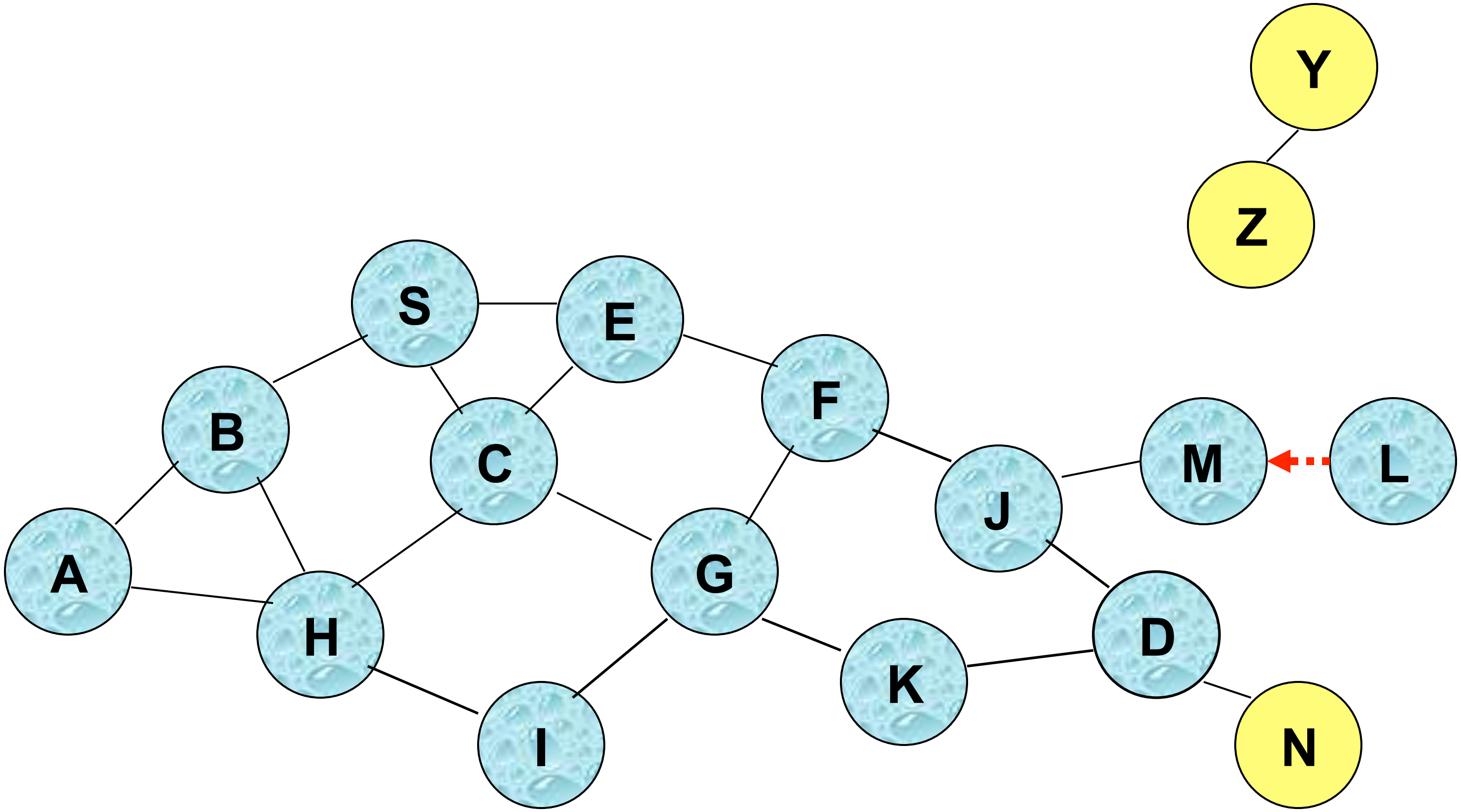
  => Packet P may not be delivered to node D at all, despite the use of flooding

Flooding for Data Delivery



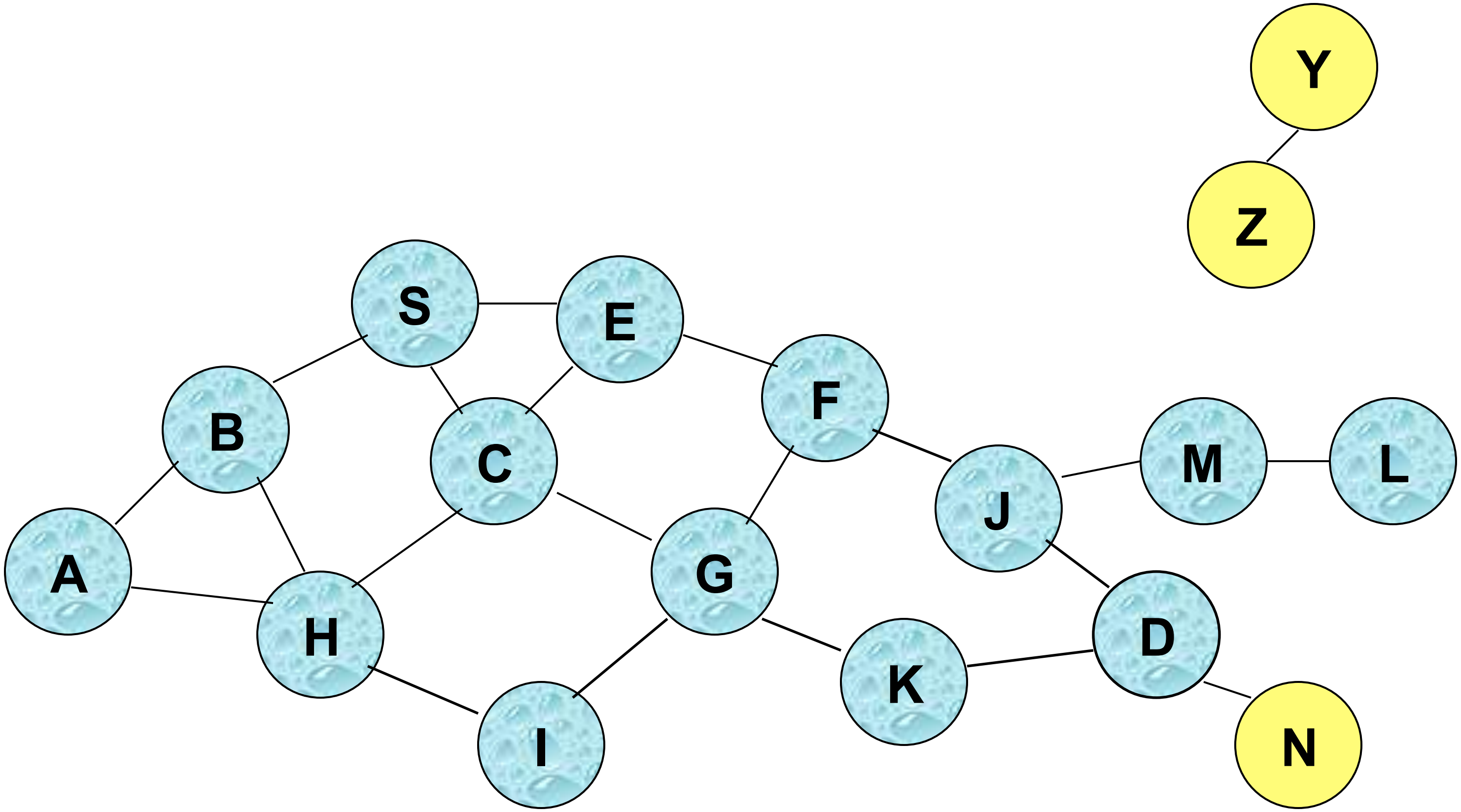
- **Node D does not forward packet P, because node D is the intended destination of packet P**

Flooding for Data Delivery



- Flooding completed
- Nodes unreachable from S do not receive packet P (e.g., node Z)
- Nodes for which all paths from S go through the destination D also do not receive packet P (example: node N)

Flooding for Data Delivery



- **Flooding may deliver packets to too many nodes (in the worst case, all nodes reachable from sender may receive the packet)**

Flooding for Data Delivery: Advantages

- Simplicity
- May be more efficient than other protocols when rate of information transmission is low enough that the overhead of explicit route discovery/maintenance incurred by other protocols is relatively higher
  - this scenario may occur, for instance, when nodes transmit small data packets relatively infrequently, and many topology changes occur between consecutive packet transmissions
- Potentially higher reliability of data delivery
  - Because packets may be delivered to the destination on multiple paths

Flooding for Data Delivery: Disadvantages

- Potentially, very high overhead
  - Data packets may be delivered to too many nodes who do not need to receive them
- Potentially lower reliability of data delivery
  - Flooding uses broadcasting -- hard to implement reliable broadcast delivery without significantly increasing overhead
    - Broadcasting in IEEE 802.11 MAC is unreliable
  - In our example, nodes J and K may transmit to node D simultaneously, resulting in loss of the packet
    - in this case, destination would not receive the packet at all

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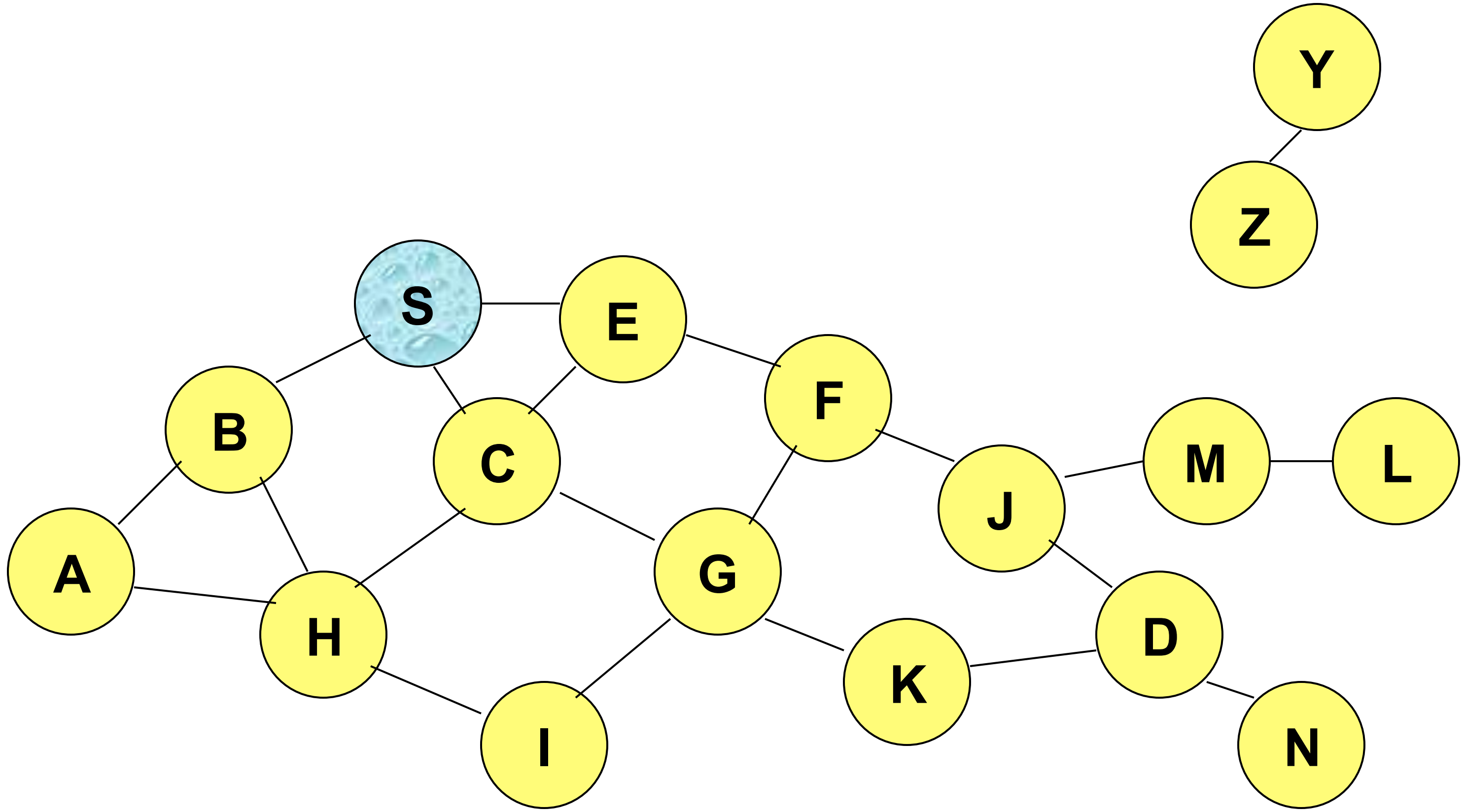
Flooding of Control Packets

- Many protocols perform (potentially *limited*) flooding of control packets, instead of data packets
- The control packets are used to discover routes
- Discovered routes are subsequently used to send data packet(s)
- Overhead of control packet flooding is amortized over data packets transmitted between consecutive control packet floods

Dynamic Source Routing (DSR) [Johnson96]

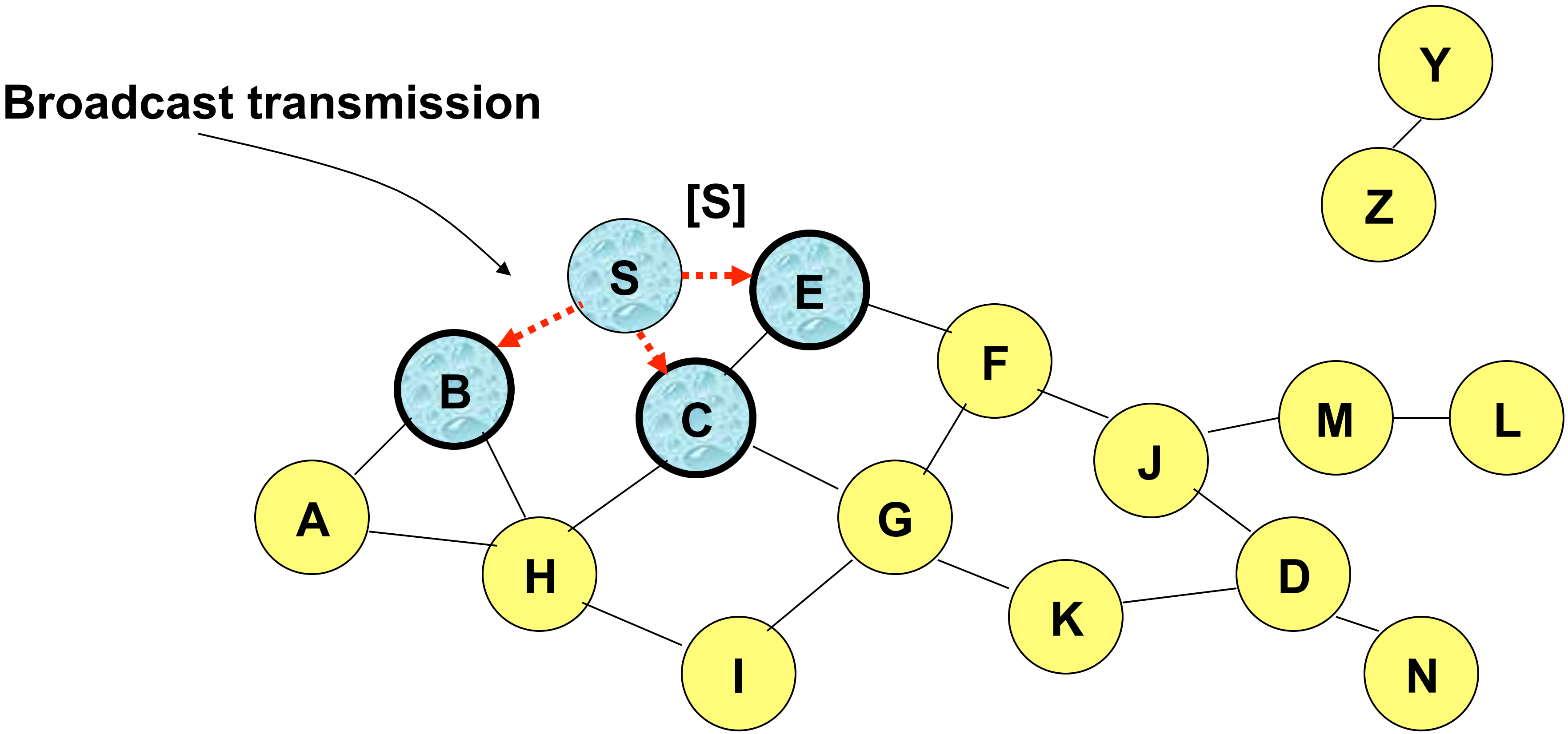
- When node S wants to send a packet to node D, but does not know a route to D, node S initiates a route discovery
- Source node S floods Route Request (RREQ)
- Each node appends own identifier when forwarding RREQ

Route Discovery in DSR



Represents a node that has received RREQ for D from S

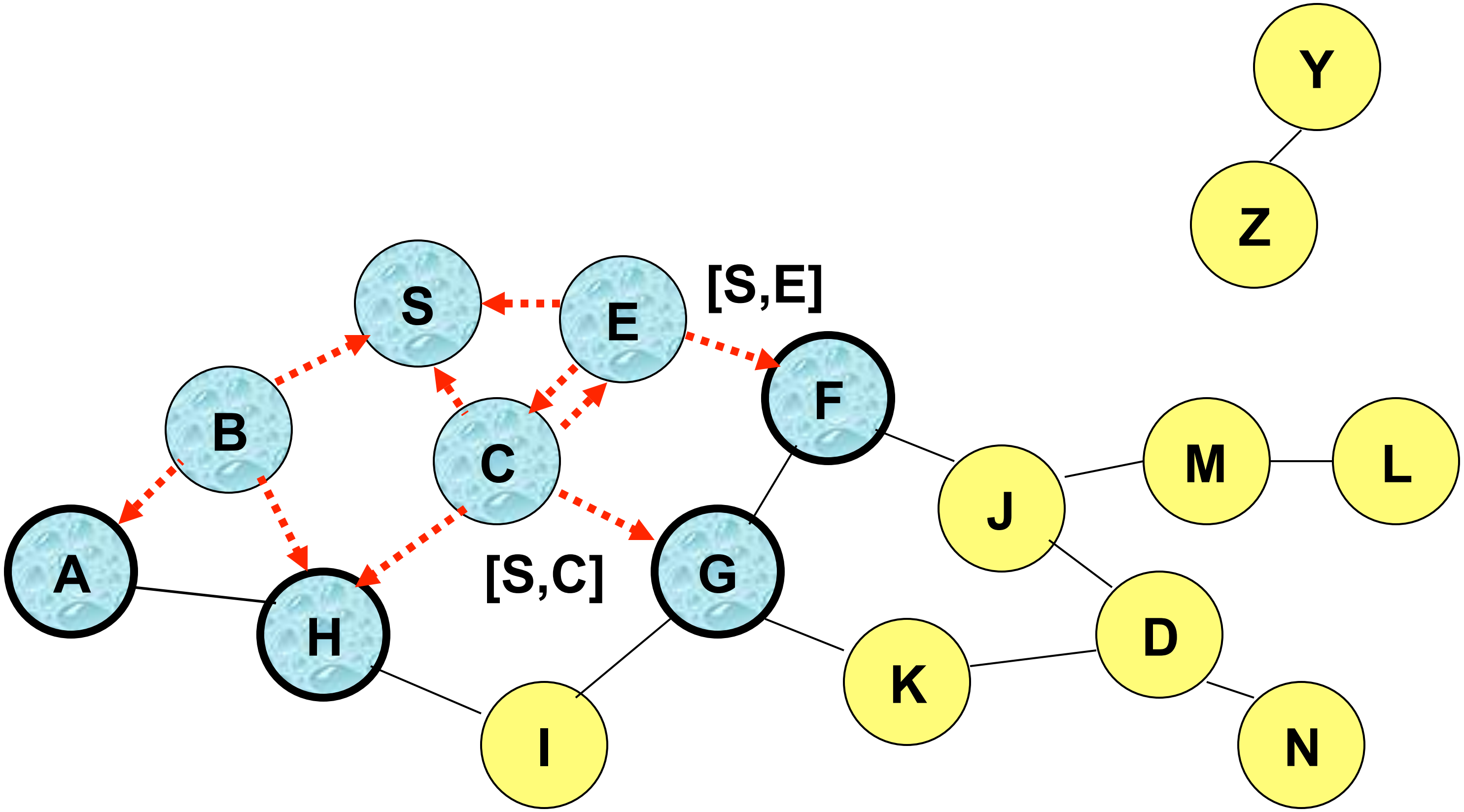
Route Discovery in DSR



Represents transmission of RREQ

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

Route Discovery in DSR



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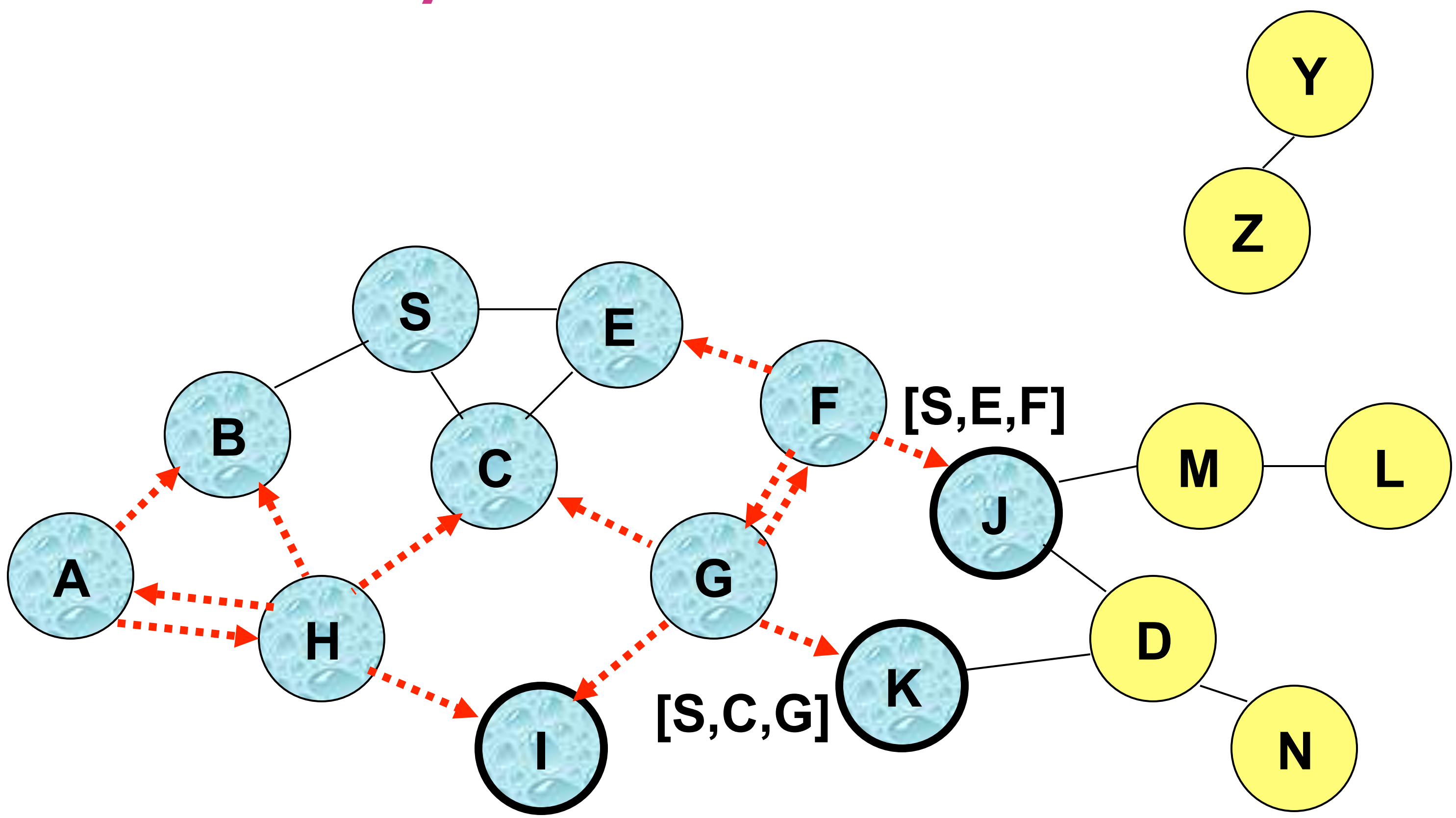
Route Discovery in DSR



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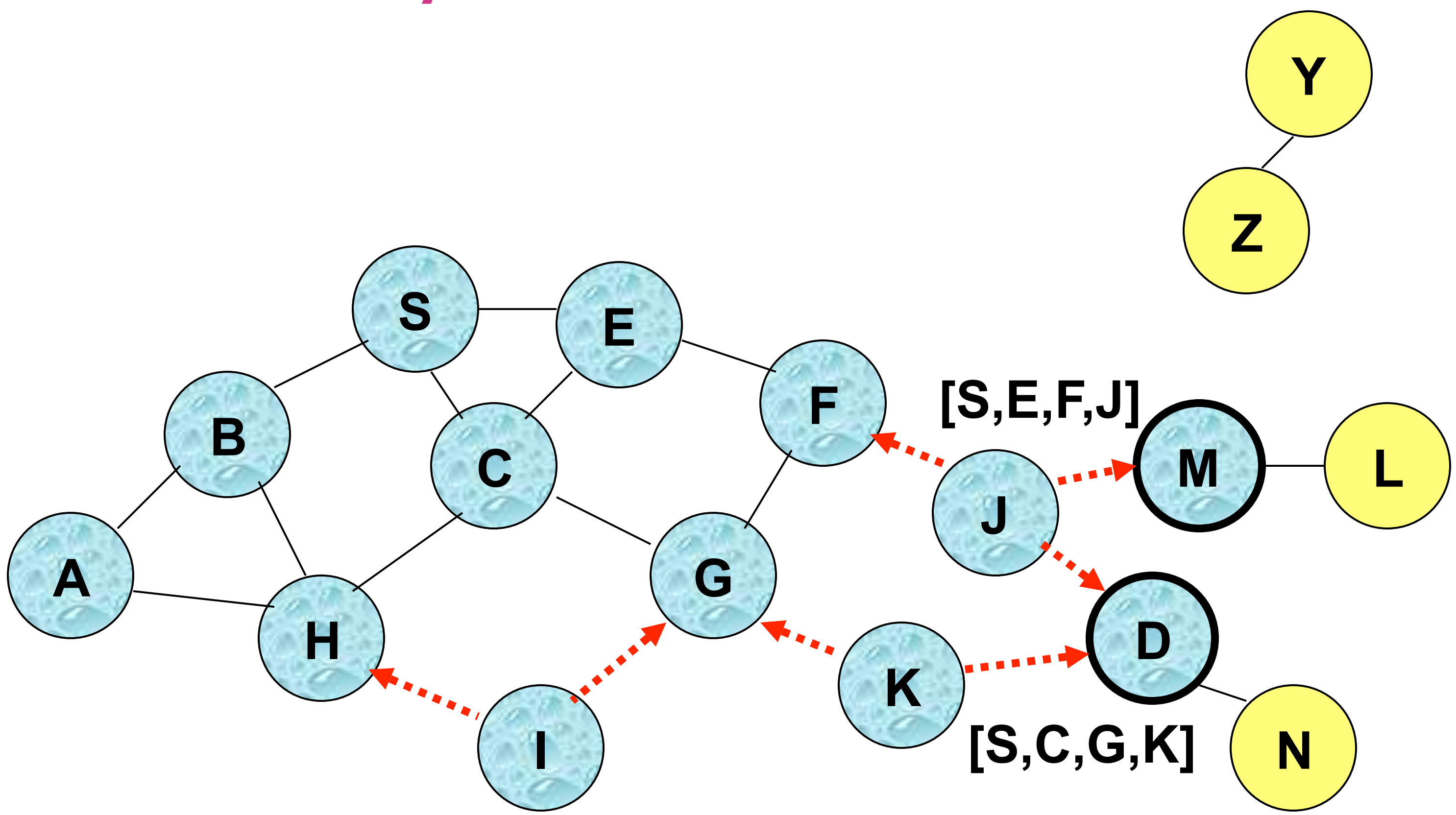

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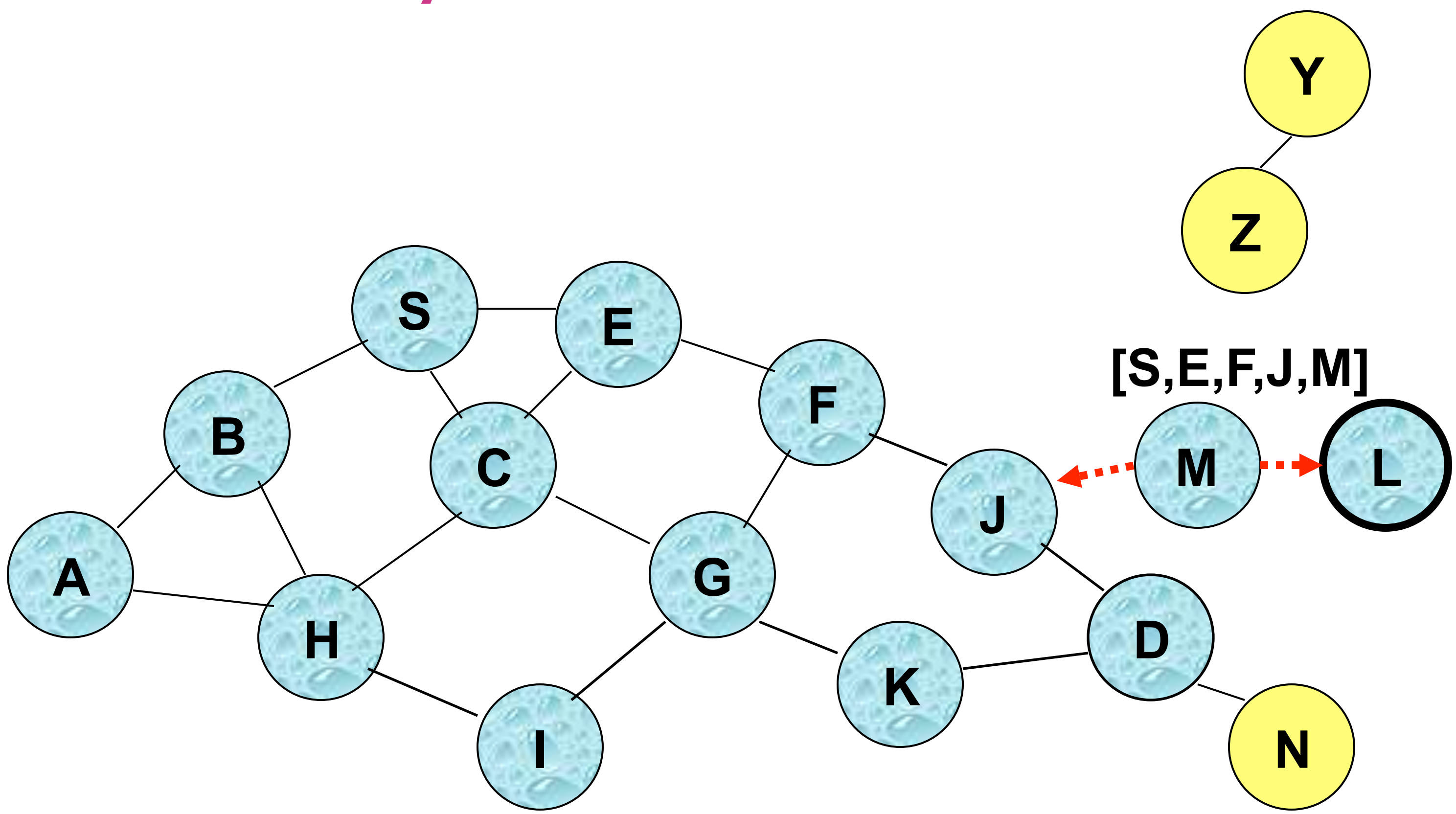
Route Discovery in DSR



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

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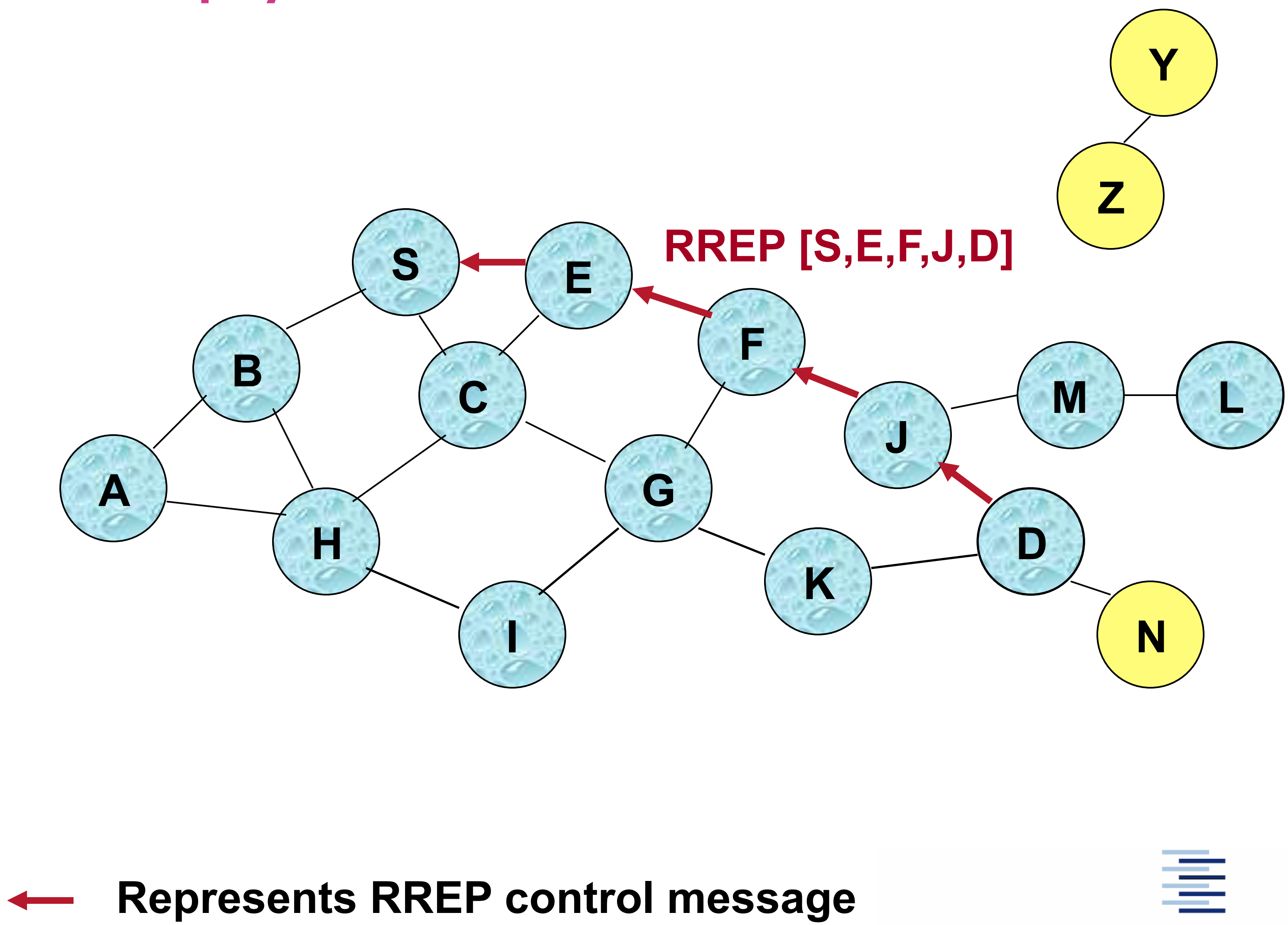
Route Discovery in DSR

- 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

Route Reply in DSR



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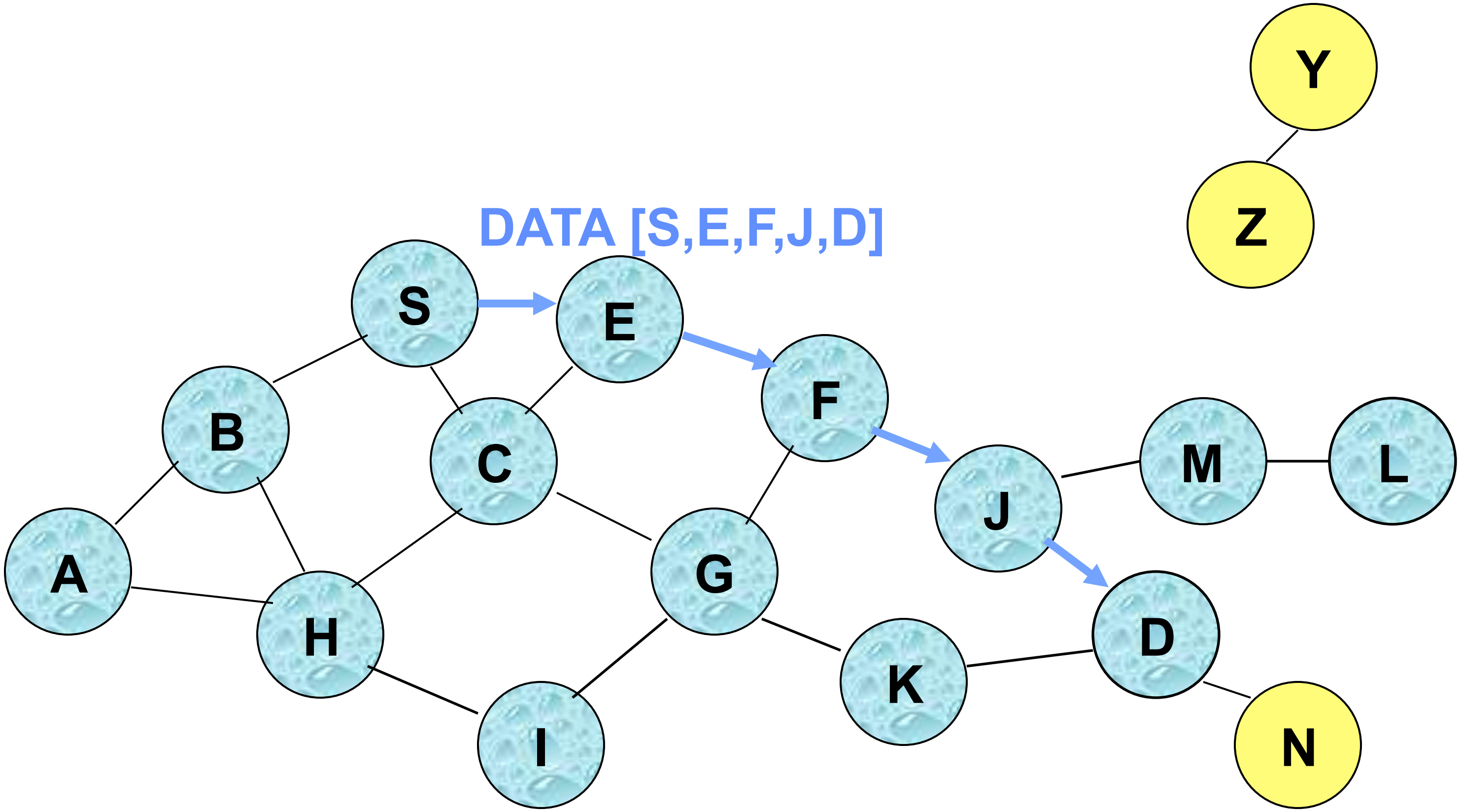
Route Reply in DSR

- Route Reply can be sent by reversing the route in Route Request (RREQ) only if links are guaranteed to be bi-directional
  - To ensure this, RREQ should be forwarded only if it received on a link that is known to be bi-directional
- If unidirectional (asymmetric) links are allowed, then RREP may need a route discovery for S from node D
  - Unless node D already knows a route to node S
  - If a route discovery is initiated by D for a route to S, then the Route Reply is piggybacked on the Route Request from D.
- If IEEE 802.11 MAC is used to send data, then links have to be bi-directional (since Ack is used)

Dynamic Source Routing (DSR)

- 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

Data Delivery in DSR



Packet header size grows with route length

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Dynamic Source Routing: Advantages

- Routes maintained only between nodes who need to communicate
  - reduces overhead of route maintenance
- Route caching can further reduce route discovery overhead
- A single route discovery may yield many routes to the destination, due to intermediate nodes replying from local caches

Dynamic Source Routing: Disadvantages

- Packet header size grows with route length due to source routing
- Flood of route requests may potentially reach all nodes in the network
- Care must be taken to avoid collisions between route requests propagated by neighboring nodes
  - insertion of random delays before forwarding RREQ
- Increased contention if too many route replies come back due to nodes replying using their local cache
  - Route Reply *Storm* problem
  - Reply storm may be eased by preventing a node from sending RREP if it hears another RREP with a shorter route

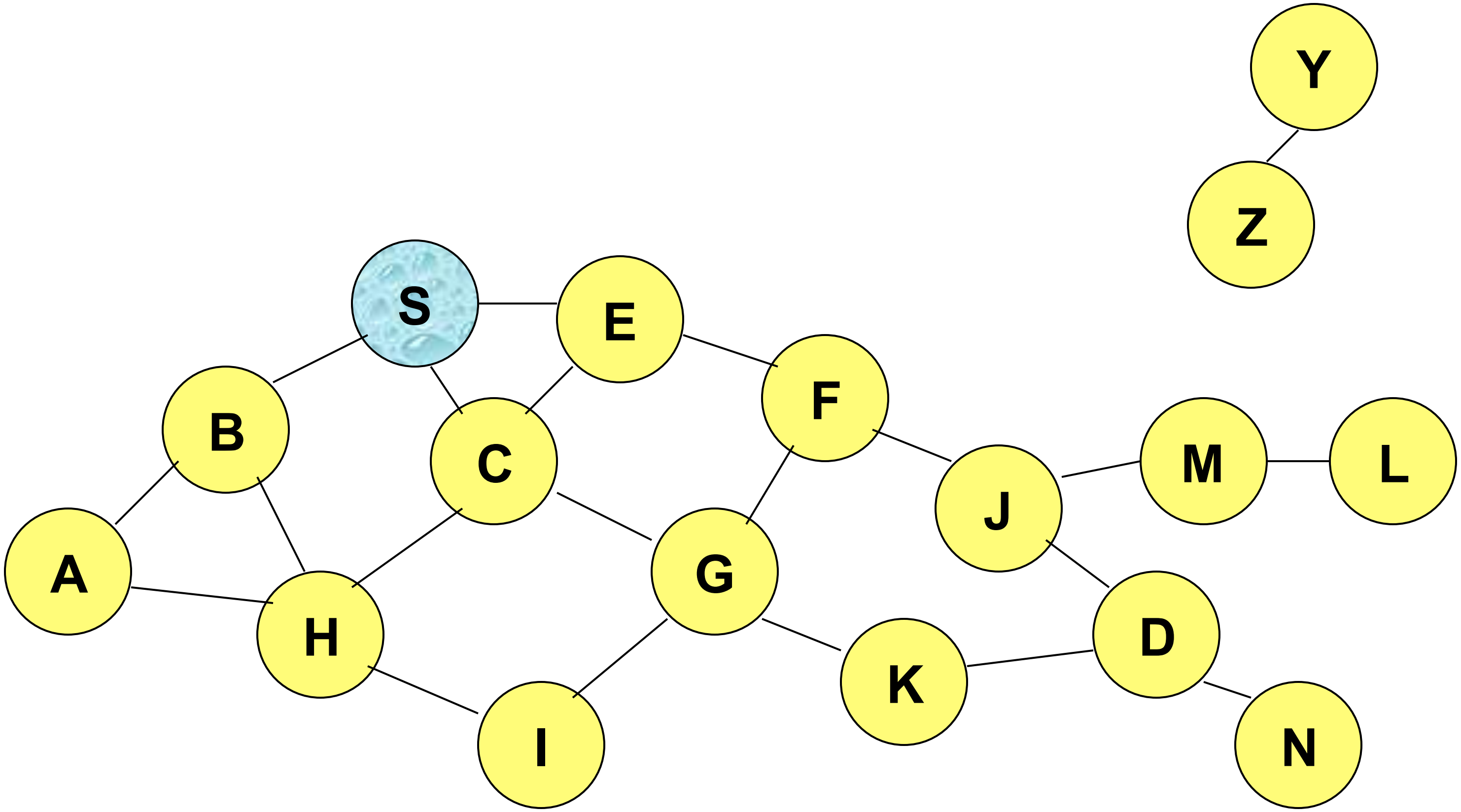
Ad Hoc On-Demand Distance Vector Routing (AODV) [Perkins99Wmcsa]

- DSR includes source routes in packet headers
- Resulting large headers can sometimes degrade performance
  - particularly when data contents of a packet are small
- AODV attempts to improve on DSR by maintaining routing tables at the nodes, so that data packets do not have to contain routes
- AODV retains the desirable feature of DSR that routes are maintained only between nodes which need to communicate

AODV

- Route Requests (RREQ) are forwarded in a manner similar to DSR
- When a node re-broadcasts a Route Request, it sets up a reverse path pointing towards the source
  - AODV assumes symmetric (bi-directional) links
- When the intended destination receives a Route Request, it replies by sending a Route Reply
- Route Reply travels along the reverse path set-up when Route Request is forwarded

Route Requests in AODV



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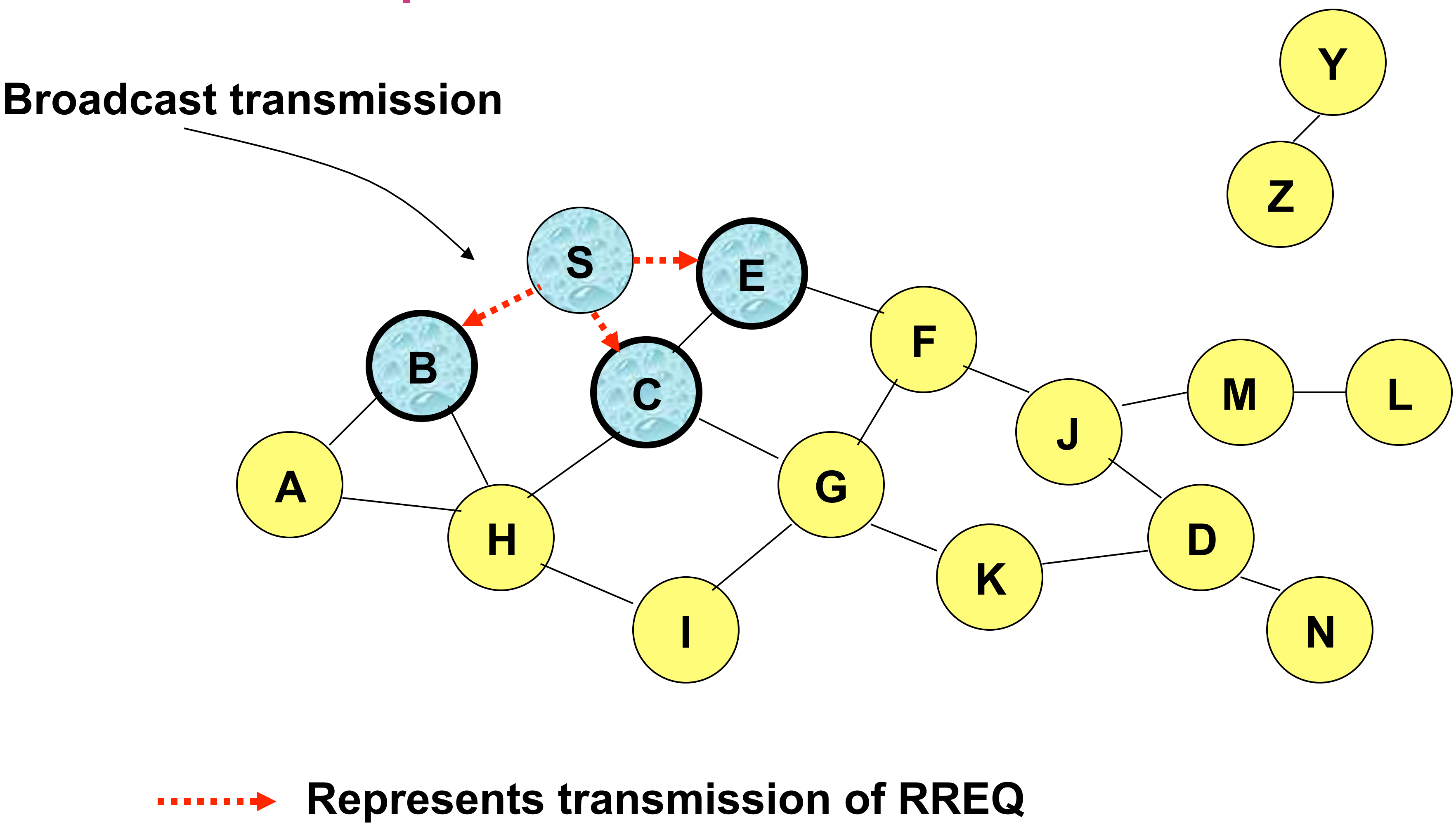
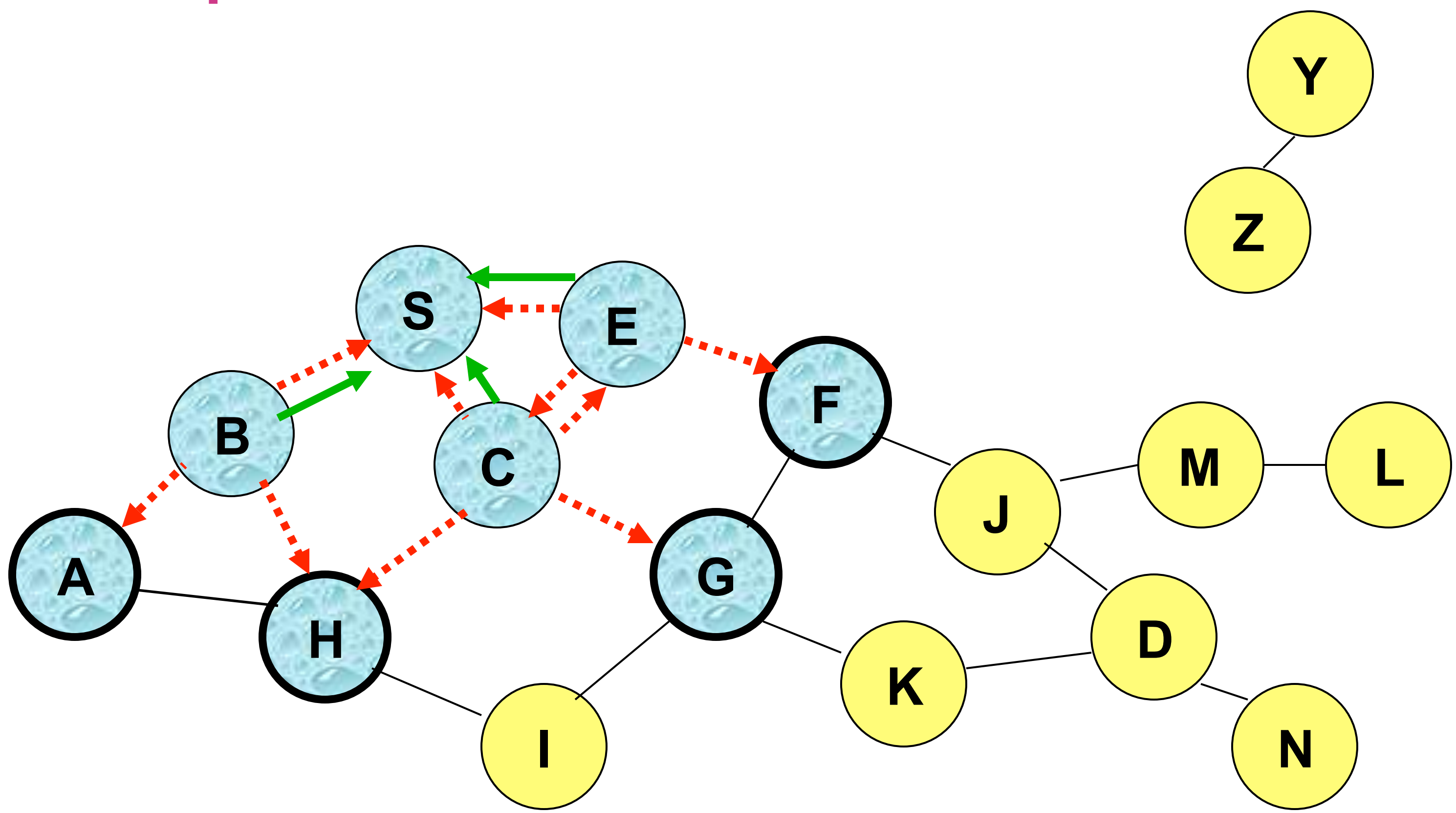
Route Requests in AODV

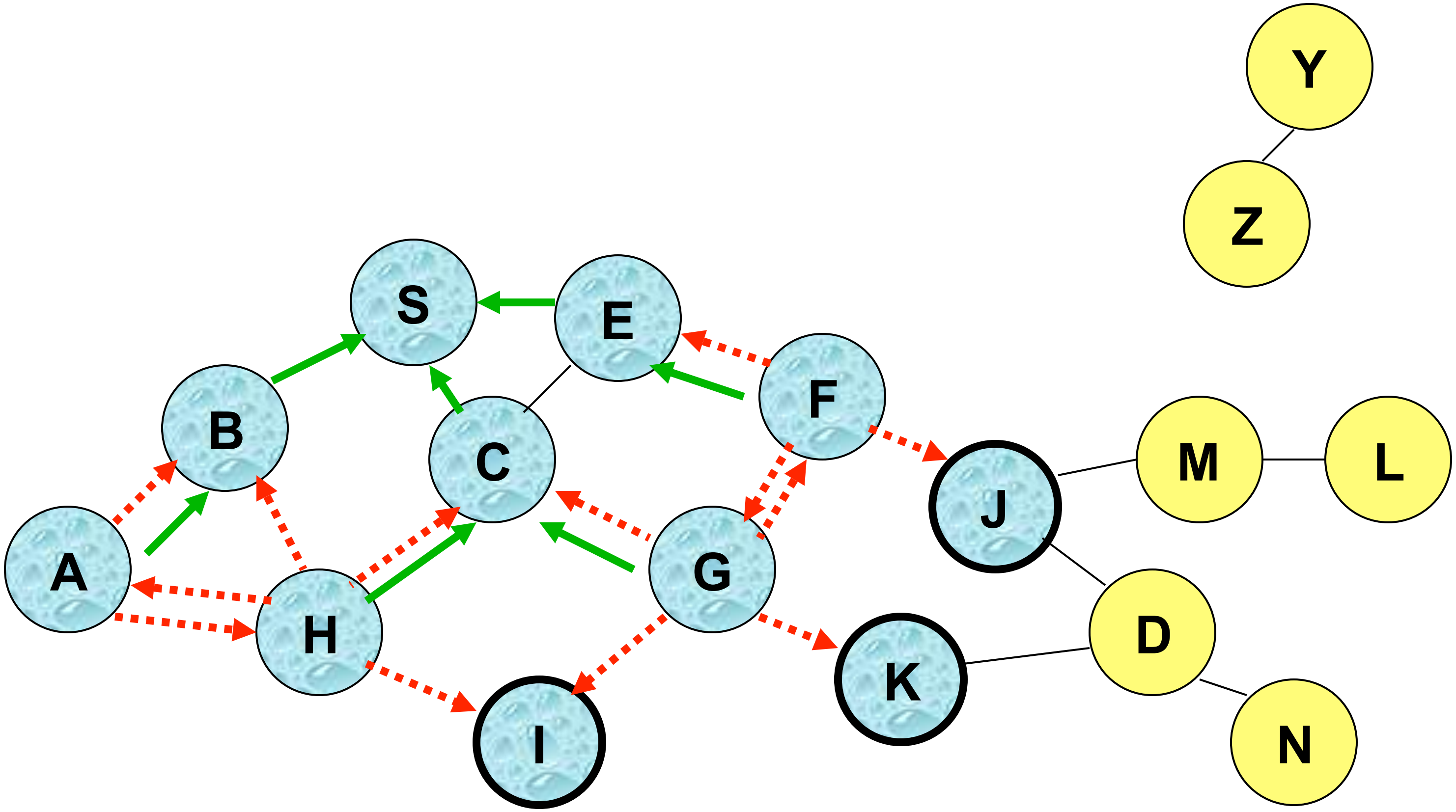


Route Requests in AODV



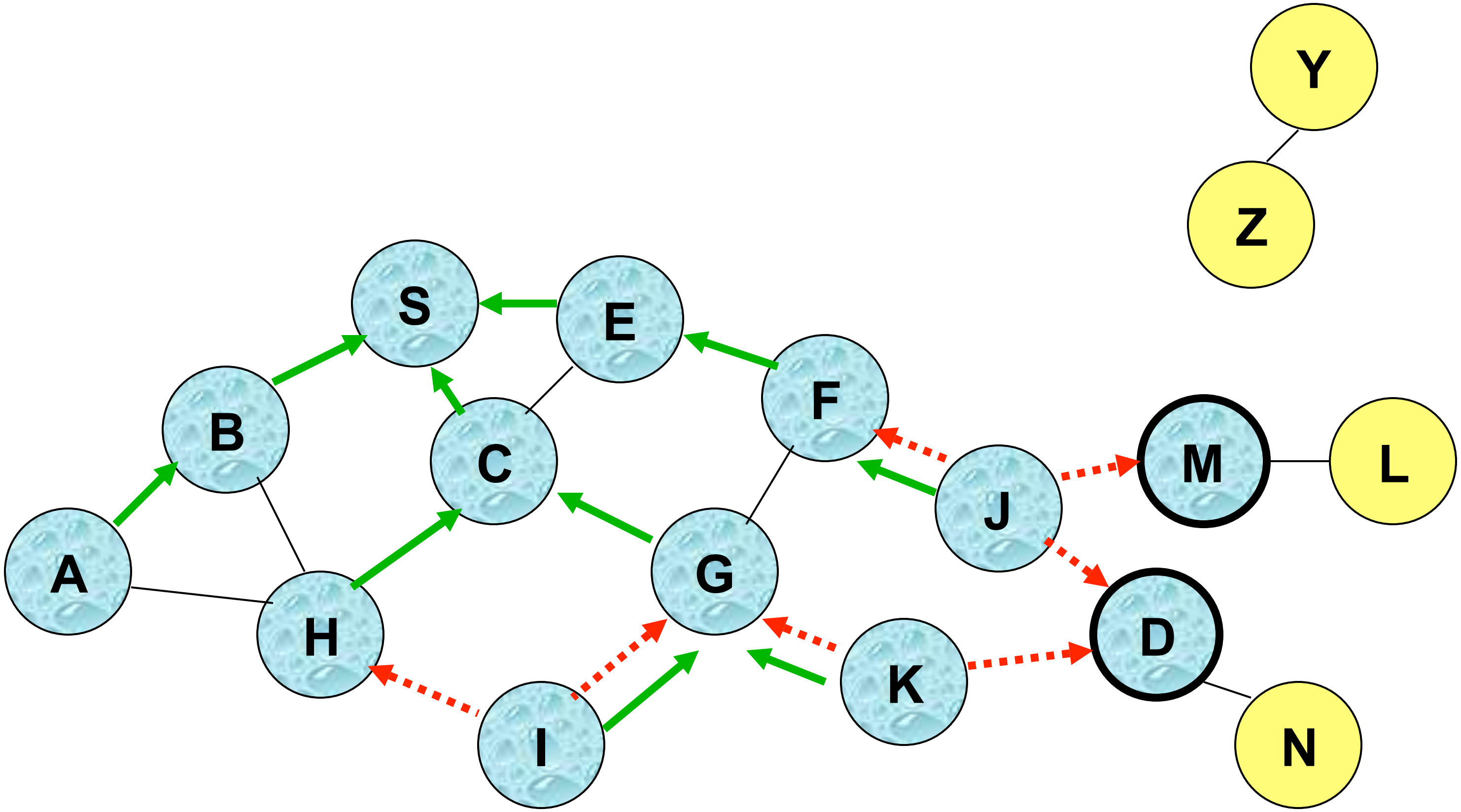
Represents links on Reverse Path

Reverse Path Setup in AODV



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

Reverse Path Setup in AODV



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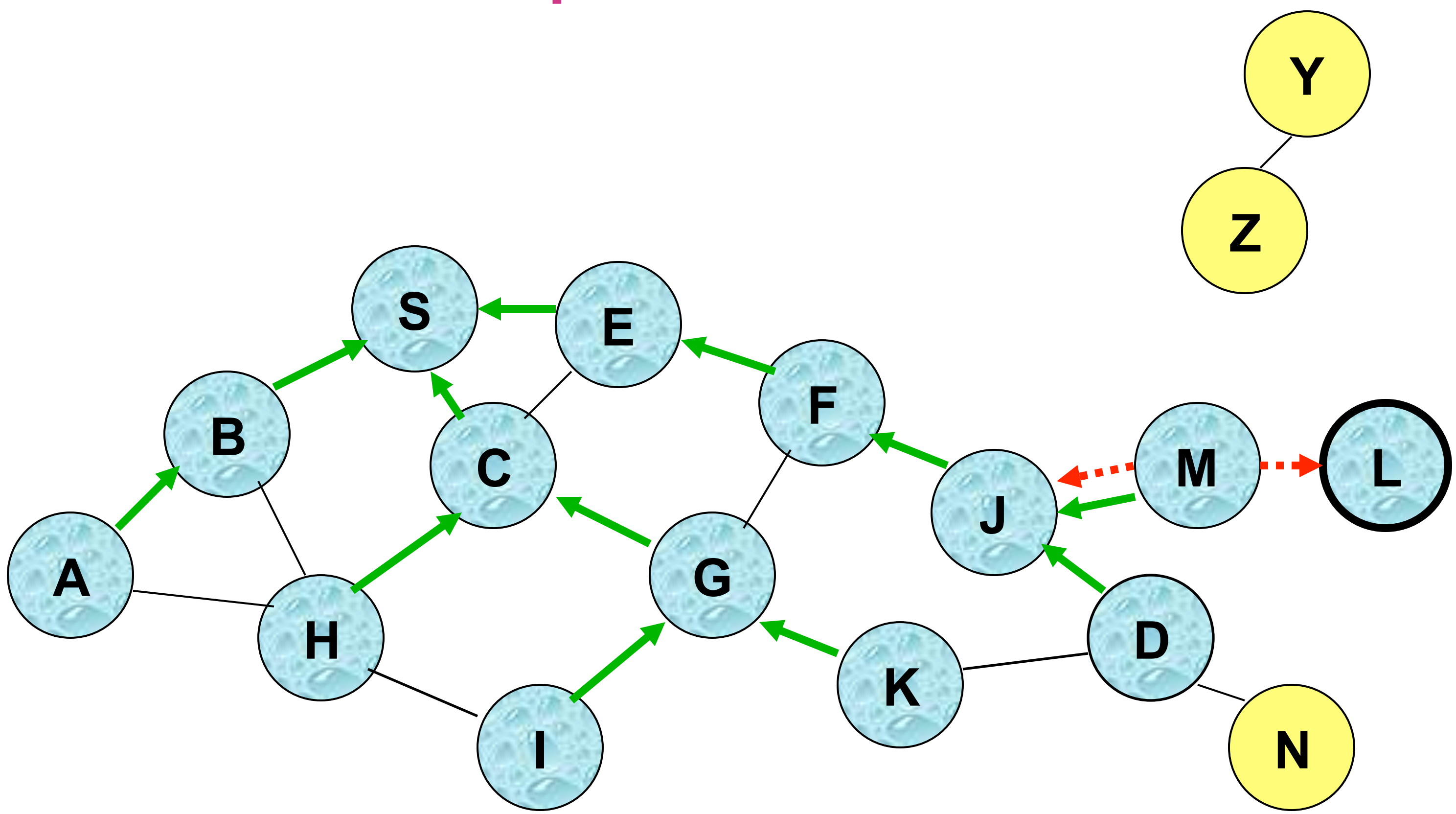
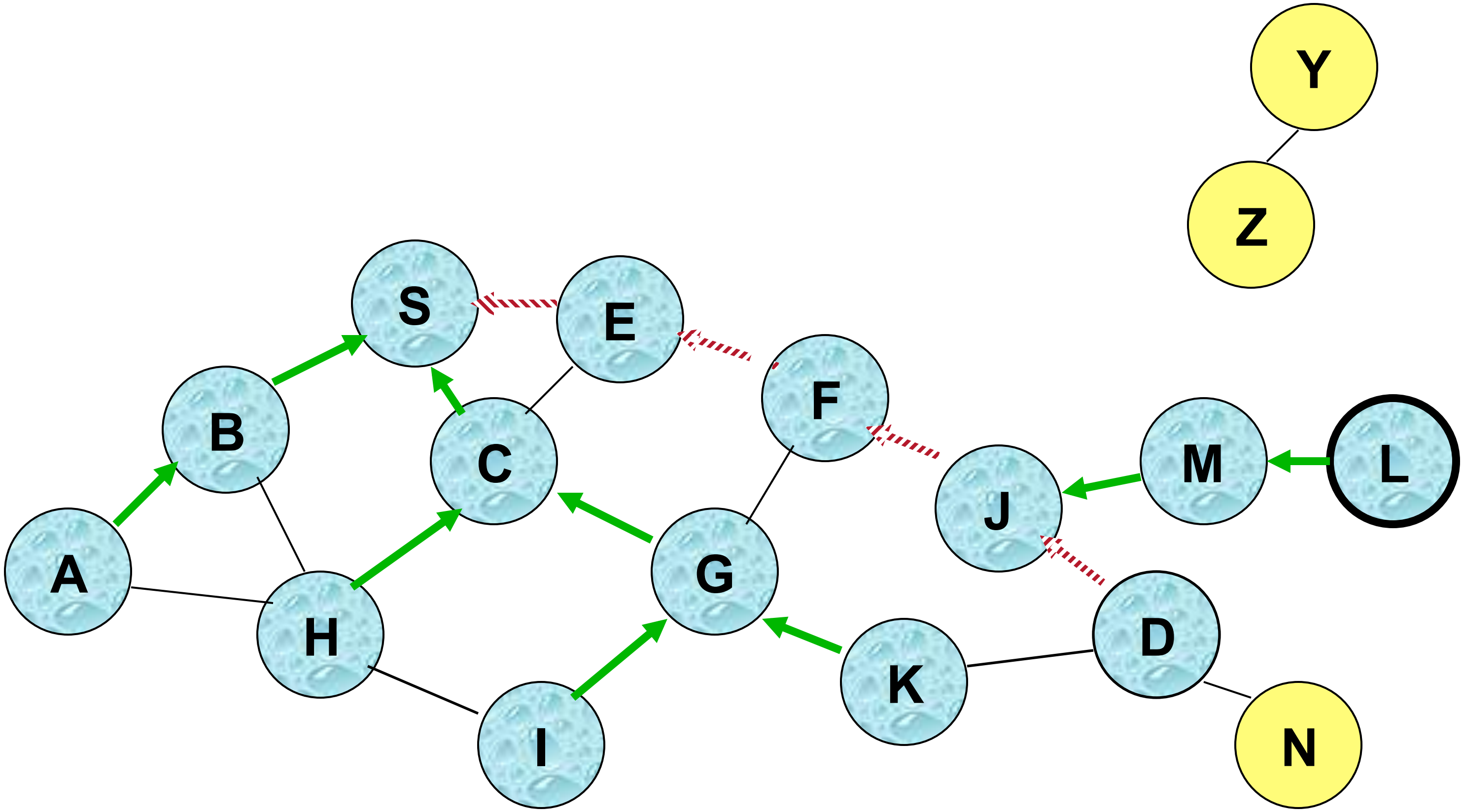
Reverse Path Setup in AODV



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

Route Reply in AODV

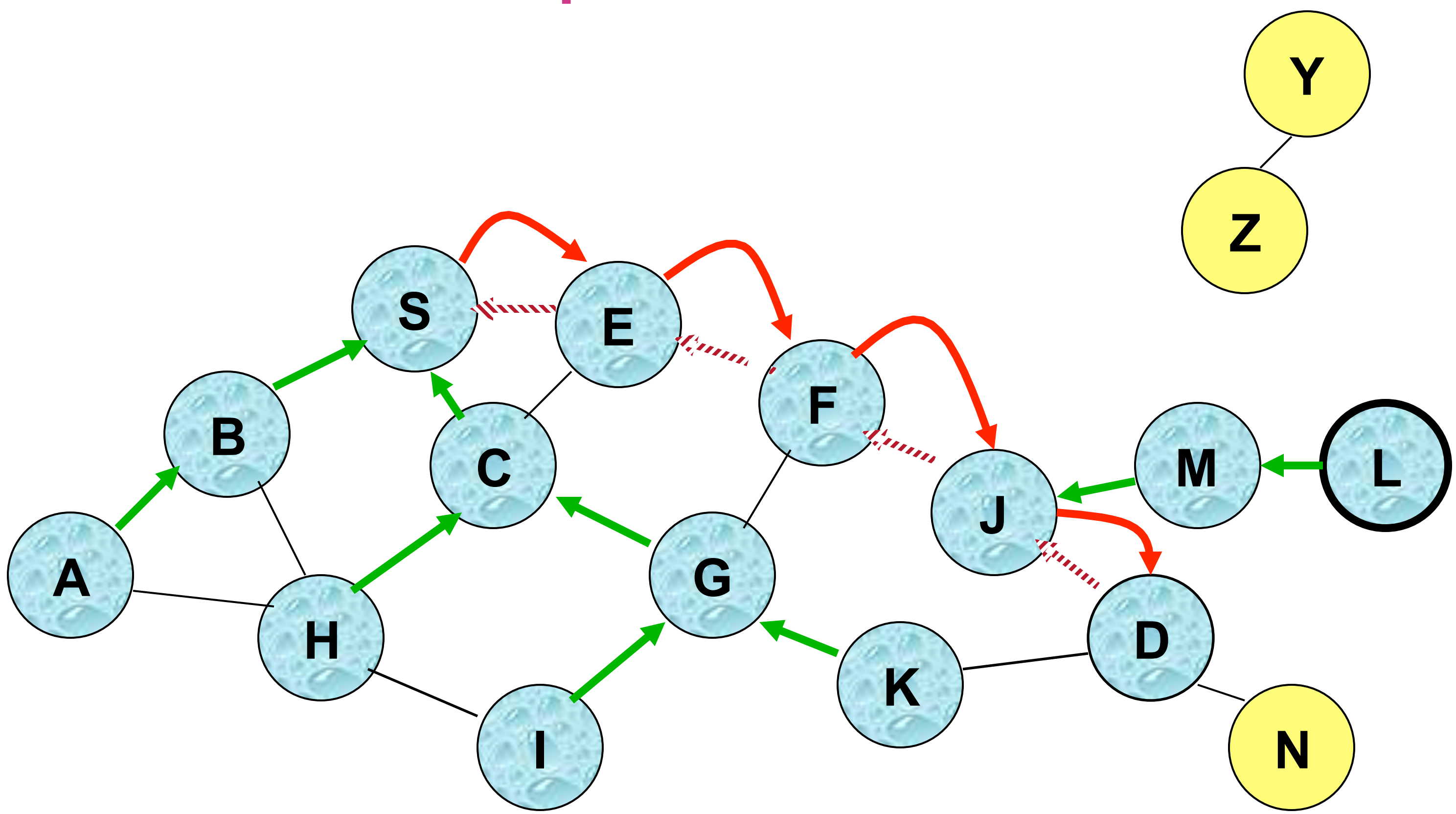


Represents links on path taken by RREP

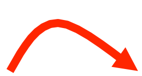
Route Reply in AODV

- An intermediate node (not the destination) may also send a Route Reply (RREP) provided that it knows a more recent path than the one previously known to sender S
- To determine whether the path known to an intermediate node is more recent, *destination sequence numbers* are used
- The likelihood that an intermediate node will send a Route Reply when using AODV is not as high as DSR
  - A new Route Request by node S for a destination is assigned a higher destination sequence number. An intermediate node, which knows a route, but with a smaller sequence number, cannot send Route Reply

Forward Path Setup in AODV



Forward links are setup when RREP travels along the reverse path



Represents a link on the forward path

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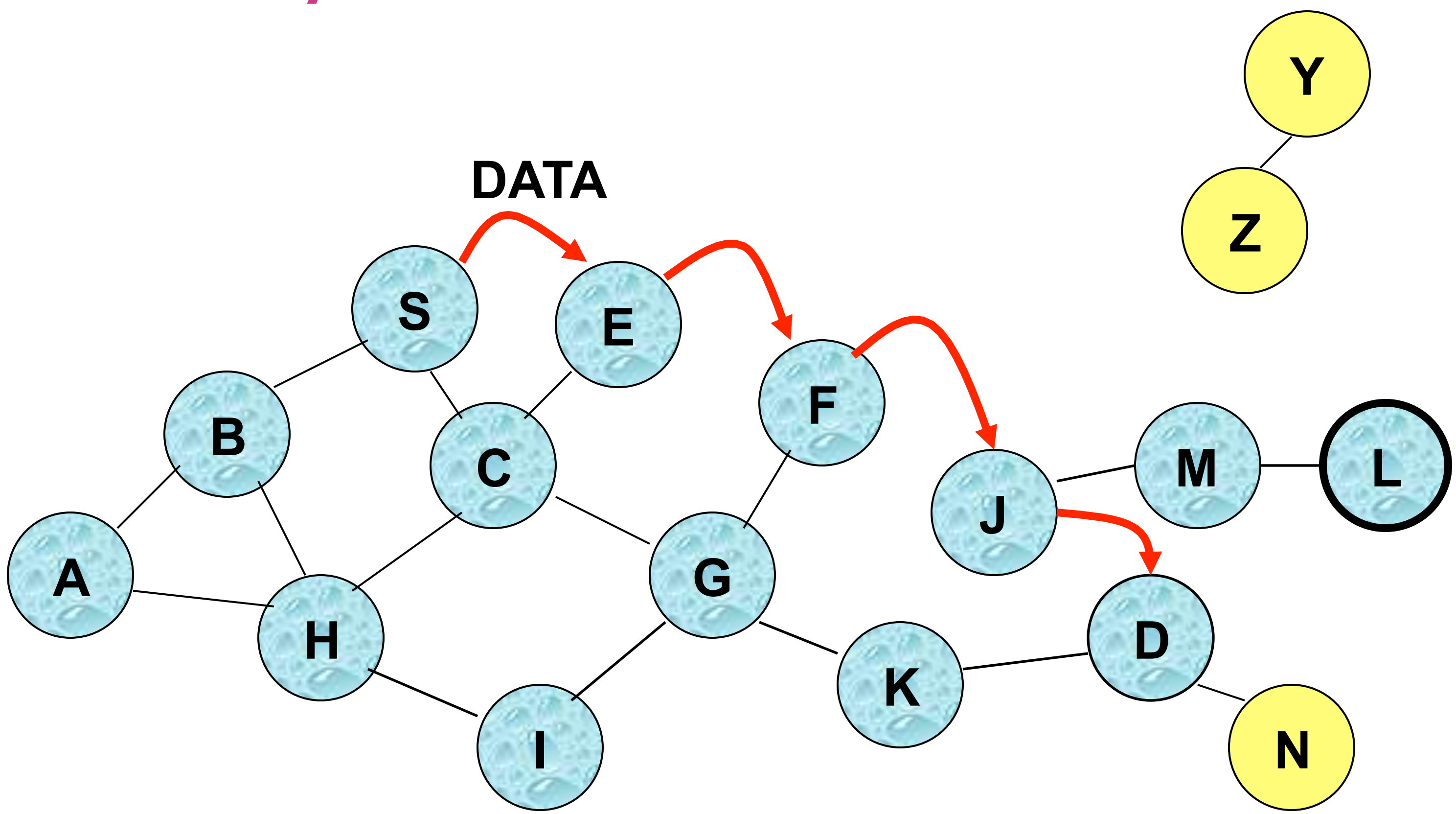
Data Delivery in AODV



Routing table entries used to forward data packet.
Route is *not* included in packet header.

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Summary: AODV

- Routes need not be included in packet headers
- Nodes maintain routing tables containing entries only for routes that are in active use
- At most one next-hop per destination maintained at each node
  - Multi-path extensions can be designed
  - DSR may maintain several routes for a single destination
- Unused routes expire even if topology does not change

Link State Routing [Huitema95]

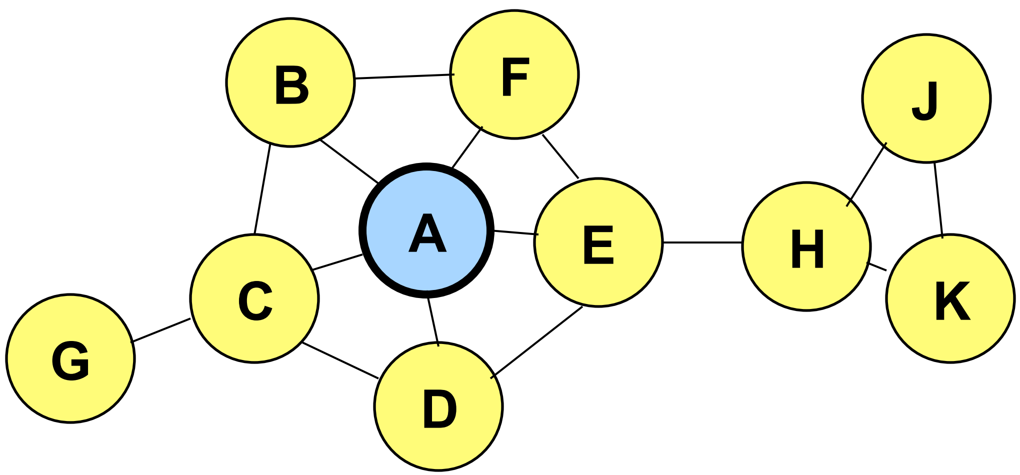
- Each node periodically floods status of its links
- Each node re-broadcasts link state information received from its neighbor
- Each node keeps track of link state information received from other nodes
- Each node uses above information to determine next hop to each destination

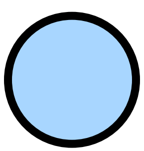
Optimized Link State Routing (OLSR)

- The overhead of flooding link state information is reduced by requiring fewer nodes to forward the information
- A broadcast from node X is only forwarded by its *multipoint relays*
- Multipoint relays of node X are its neighbors such that each two-hop neighbor of X is a one-hop neighbor of at least one multipoint relay of X
  - Each node transmits its neighbor list in periodic beacons, so that all nodes can know their 2-hop neighbors, in order to choose the multipoint relays

Optimized Link State Routing (OLSR)

- Nodes C and E are multipoint relays of node A





Node that has broadcast state information from A

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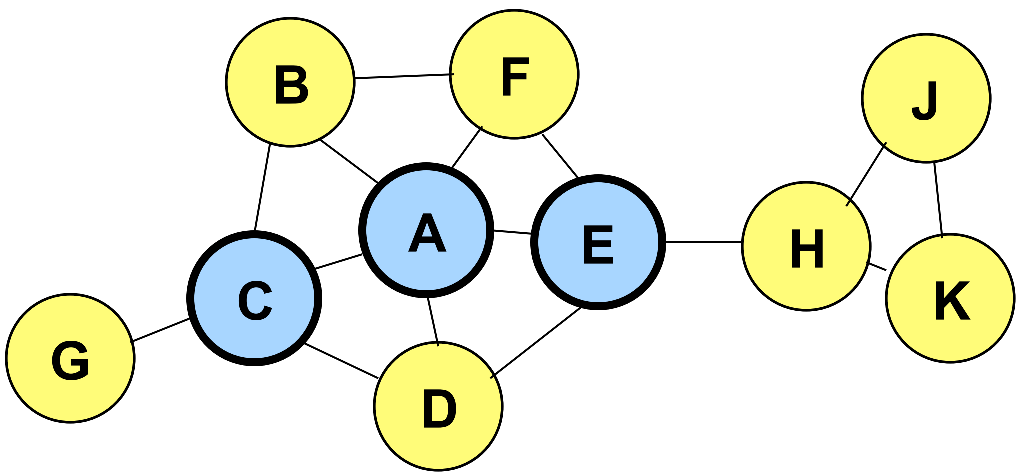
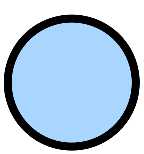
Optimized Link State Routing (OLSR)

- Nodes C and E forward information received from A




Node that has broadcast state information from A

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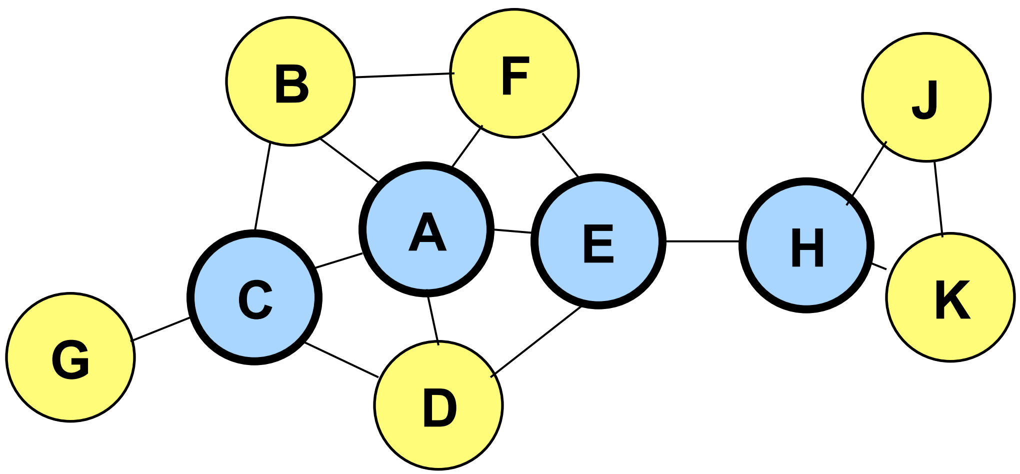
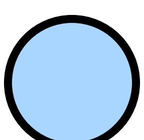
Optimized Link State Routing (OLSR)

- Nodes E and K are multipoint relays for node H
- Node K forwards information received from H
  - E has already forwarded the same information once





Node that has broadcast state information from A

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Summary: OLSR

- OLSR floods information through the multipoint relays
- The flooded information itself is for links connecting nodes to respective multipoint relays
- Nodes need to calculate routes (shortest path trees) based on link-state knowledge, typically using the Dijkstra algorithm
- Routes used by OLSR only include multipoint relays as intermediate nodes

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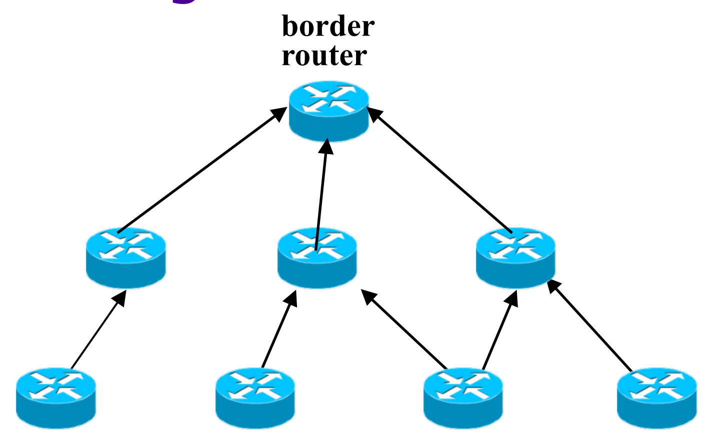
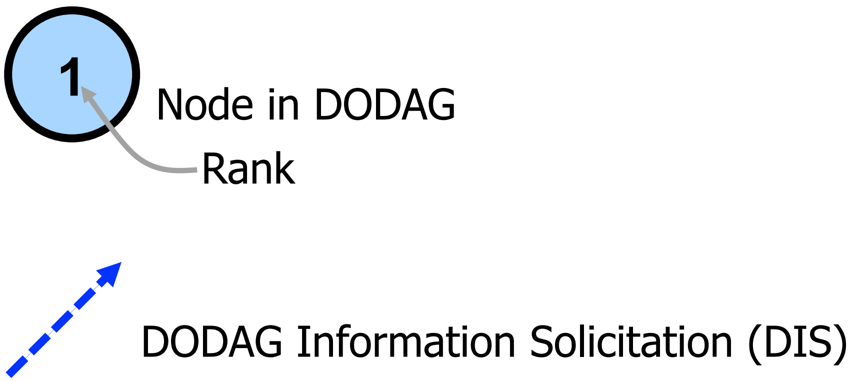
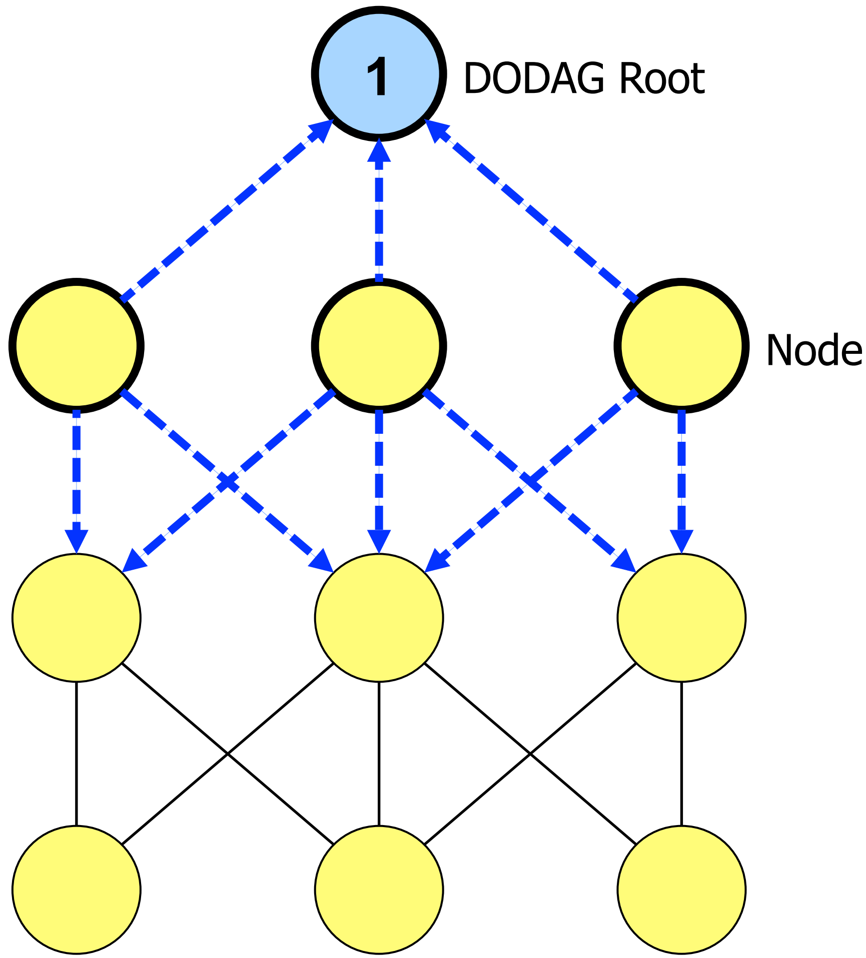
RPL - Routing Protocol for Low Power and Lossy Networks (LLN) – RFC 6550

- Optimized for low-energy networks (without mobility)
- Destination Oriented Directed Acyclic Graph (DODAG)
- Routing state propagation
  - Conventional:
    - Link-state: scoped flooding
    - Distance-vector: periodic routing beacons
  - Trickle:
    - adaptive exchange rate
- Spatial diversity
  - A router maintains multiple potential parents
- Expressive link metrics
  - ETX: Estimated Number of Transmissions

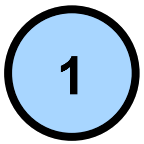


RPL Topology Creation - Upward

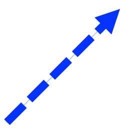


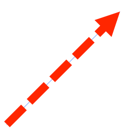


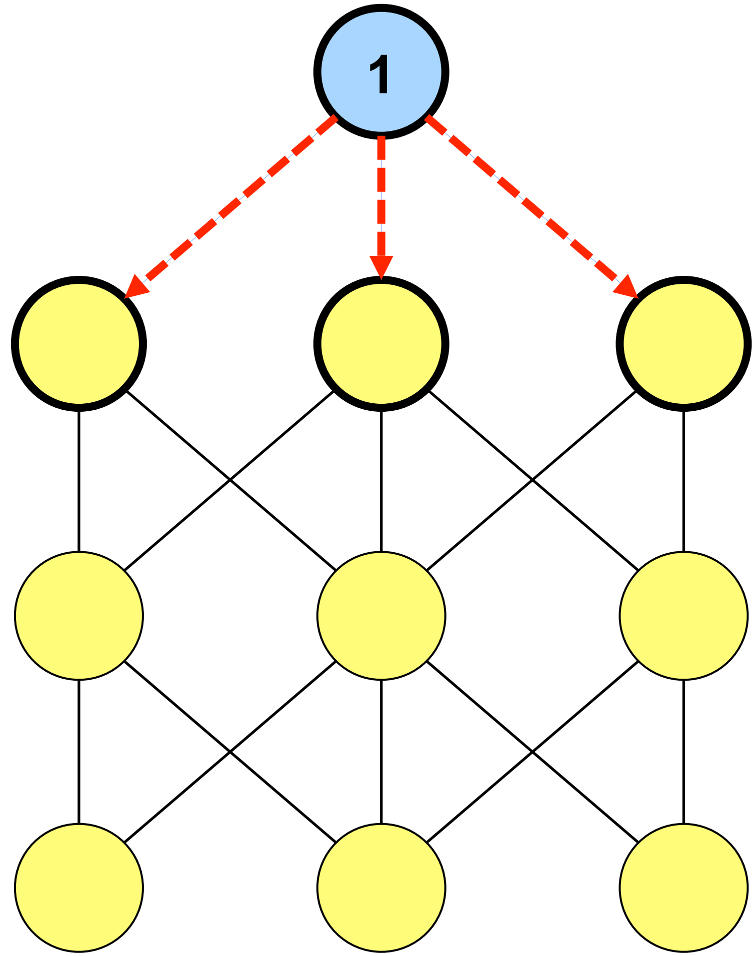
RPL Topology Creation - Upward



Node in DODAG


DODAG Information Solicitation (DIS)


DODAG Information Object (DIO)



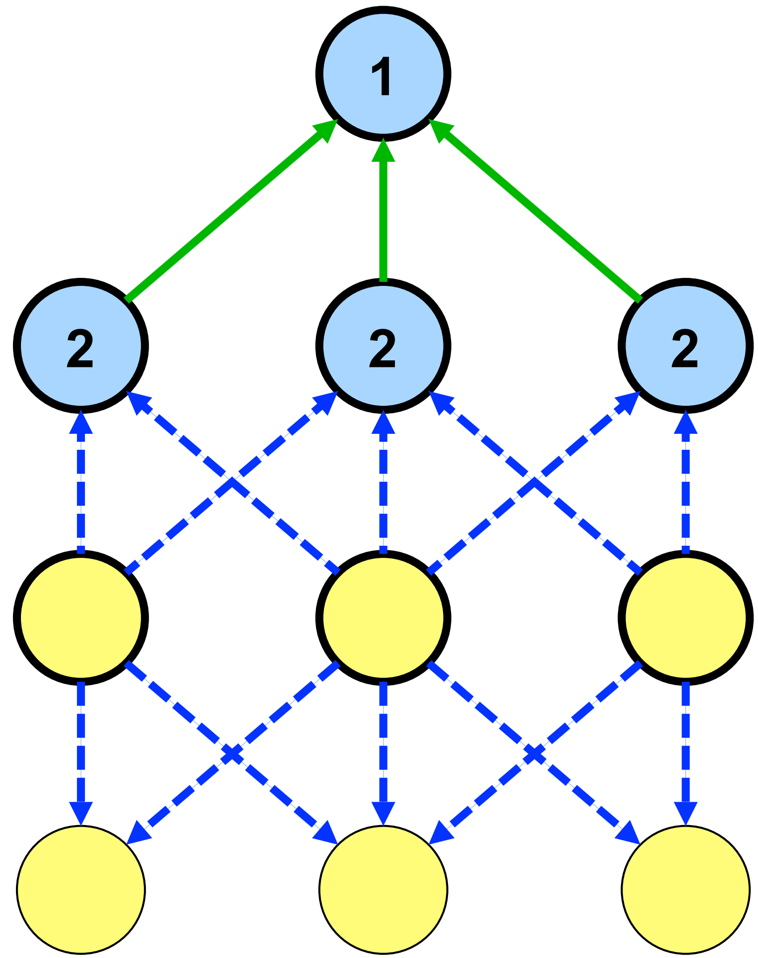
RPL Topology Creation - Upward

1 Node in DODAG

DODAG Information Solicitation (DIS)

DODAG Information Object (DIO)

DODAG Upward Link



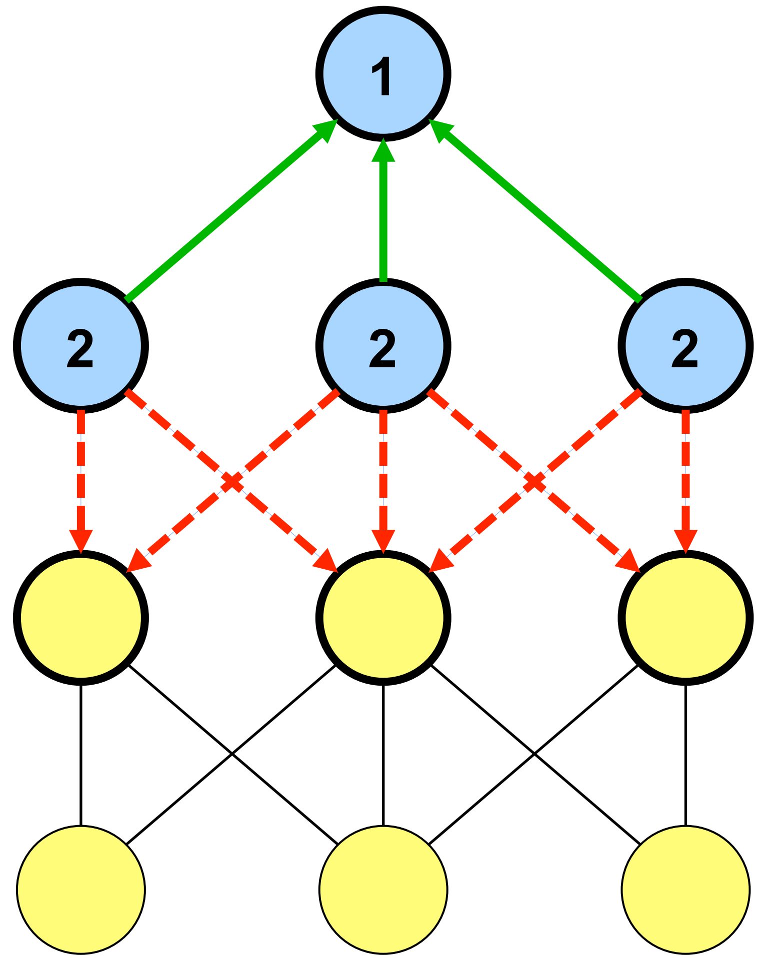
RPL Topology Creation - Upward

1 Node in DODAG

DODAG Information Solicitation (DIS)

DODAG Information Object (DIO)

DODAG Upward Link



RPL Topology Creation - Upward

Node in DODAG

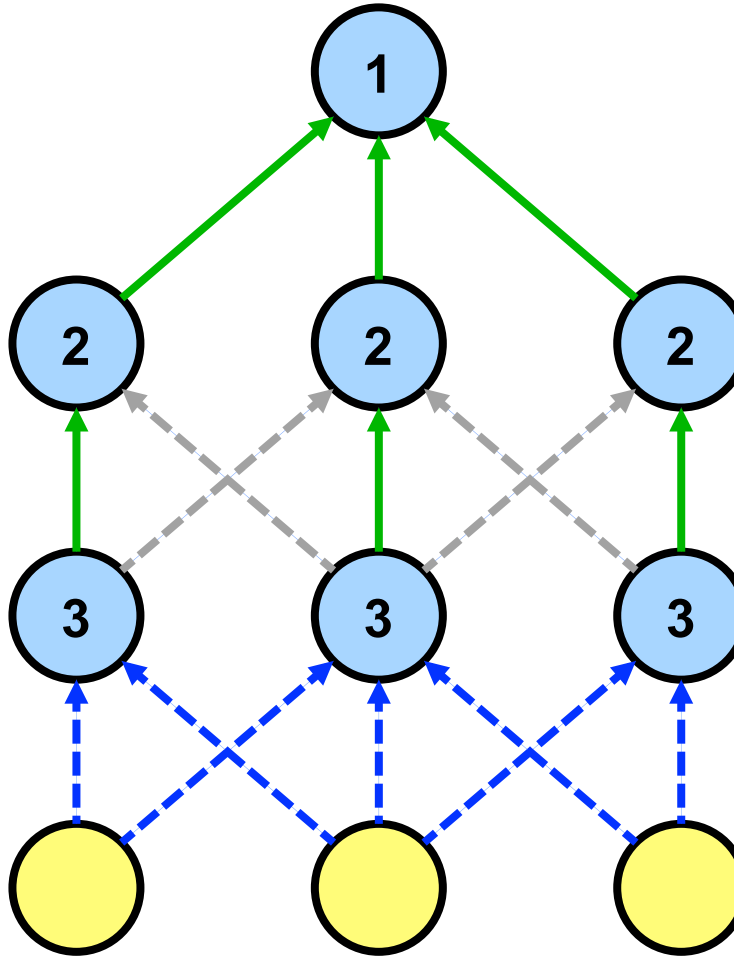
Rank

DODAG Information Solicitation (DIS)

DODAG Information Object (DIO)

DODAG Upward Link

Potential Parent



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RPL Topology Creation - Upward

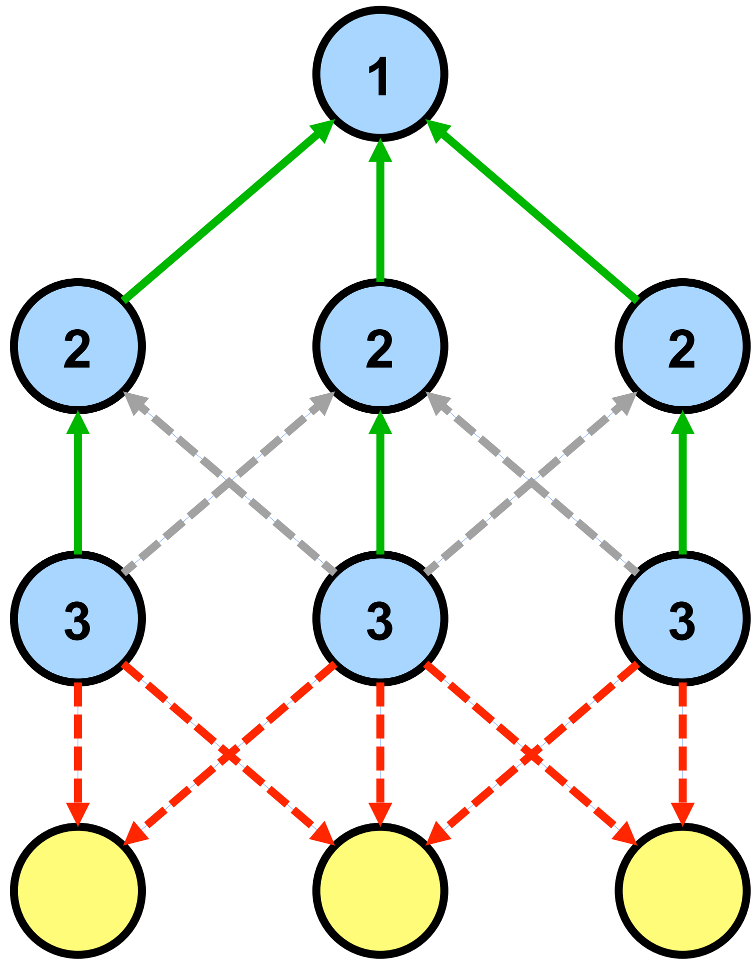
1 Node in DODAG

DODAG Information Solicitation (DIS)

DODAG Information Object (DIO)

DODAG Upward Link

Potential Parent



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RPL Topology Creation - Upward

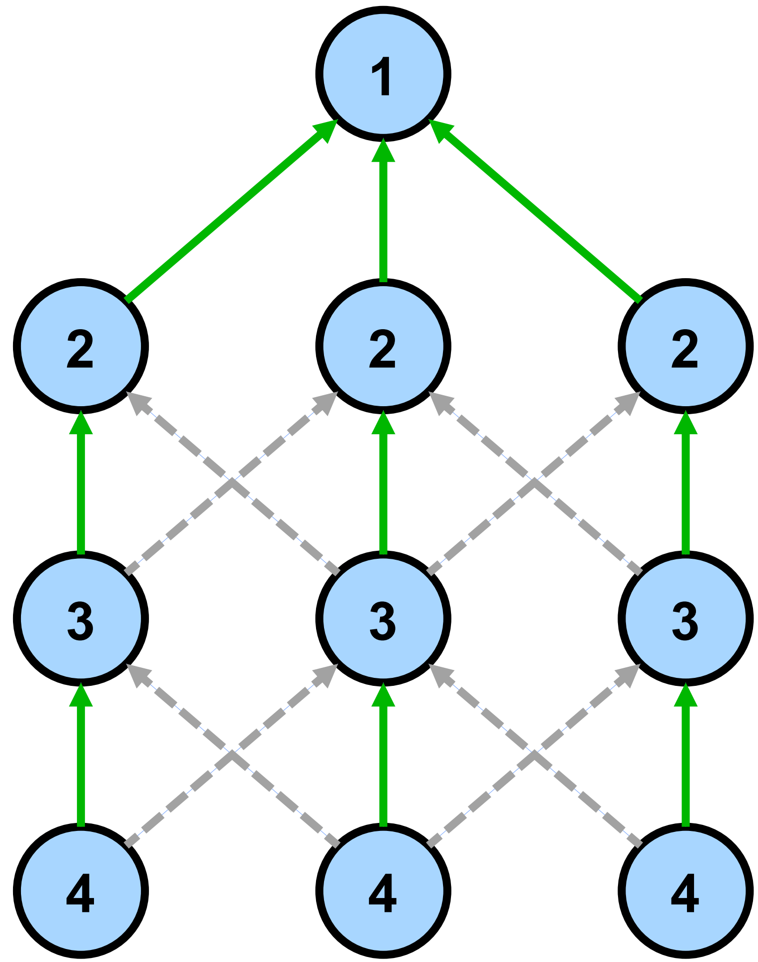
Node in DODAG

DODAG Information Solicitation (DIS)

DODAG Information Object (DIO)

DODAG Upward Link

Potential Parent



RPL Topology

- Downward routes created analogously
- Two routing modes
  - Non-storing: without local routing tables
    - Local routing: Uptree (default) to root
    - Source routes issued at root
  - Storing: with local routing tables
    - Local routing decisions forward directly into subtrees
- Topology maintenance: New DAG version created on request

Further Routing Approaches

- Improvements & Optimisations of Previous Protocols
- Location Aided Routing
- Clustering after Landmarking
- Hierarchic / Anchored Routing
- Power-Aware Routing
- …

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Performance Properties of MANETs

- One-Hop Capacity:
  Consider MANET of *n* equal nodes, each acting as router, with constant node density. Then the One-Hop Capacity grows linearly → O *(n)*
- Total Capacity surprisingly low:
  - Consider MANET of *n* equal nodes, each acting as router in an *optimal* set-up, then the Node Capacity to reach an arbitrary destination reads → $O(1/\sqrt{n})$
  - Node Capacity further decreases under wireless transmission → $O(1/\sqrt{n \ln(n)})$

Aspects in P2P over MANETs

- Manets consist of moving, unstable components
  → unsuitable for client-server, but P2P applications
- P2P applications built for failure tolerance
  → potential for compensating Manet drop-outs
- P2P and Manets cope with member mobility
  → provide capabilities of self-restructuring
- But: P2P routing (mainly) regardless of underlay capacities
  → Manet limitations require optimising adaptation
- P2P and Manet changes may amplify
  → Issues of cross-layer synchronisation

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