Mobile Ad Hoc Networks

Routing

8th Week

13.06.-09.06.2007

CoNe Freiburg

University of Freiburg
Computer Networks and Telematics
Prof. Christian Schindelhauer

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Network Layer

- **Routing Protocol**
  - Find communication paths
  - Transport of information along this paths
- **Protocol Classes**
  - Proactive: routing tables, continuous updates
  - Reactive: update on demand
  - Hybrid: partial tables, partial on demand
- **Distributed Routing Variants**
  - Distance vektor protocols
  - Link state protocols
  - Further variants: flooding, potential algorithms, etc.

The Shortest Path Problem

- **Given:**
  - A directed Graph G=(V,E)
  - Start node
  - and edge weights $w : E \rightarrow \mathbb{R}$
- **Define Weight of Shortest Path**
  - $\delta(u,v)$ = minimal weight w(p) of a path p from u to v
  - w(p) = sum of all edge weights w(e) of edges e of path p
- **Find:**
  - The shortest paths from s to all nodes in G
- **Solution set:**
  - is described by a tree with root s
  - Every node points towards the root s

Shortest Paths of Edsger Wybe Dijkstra

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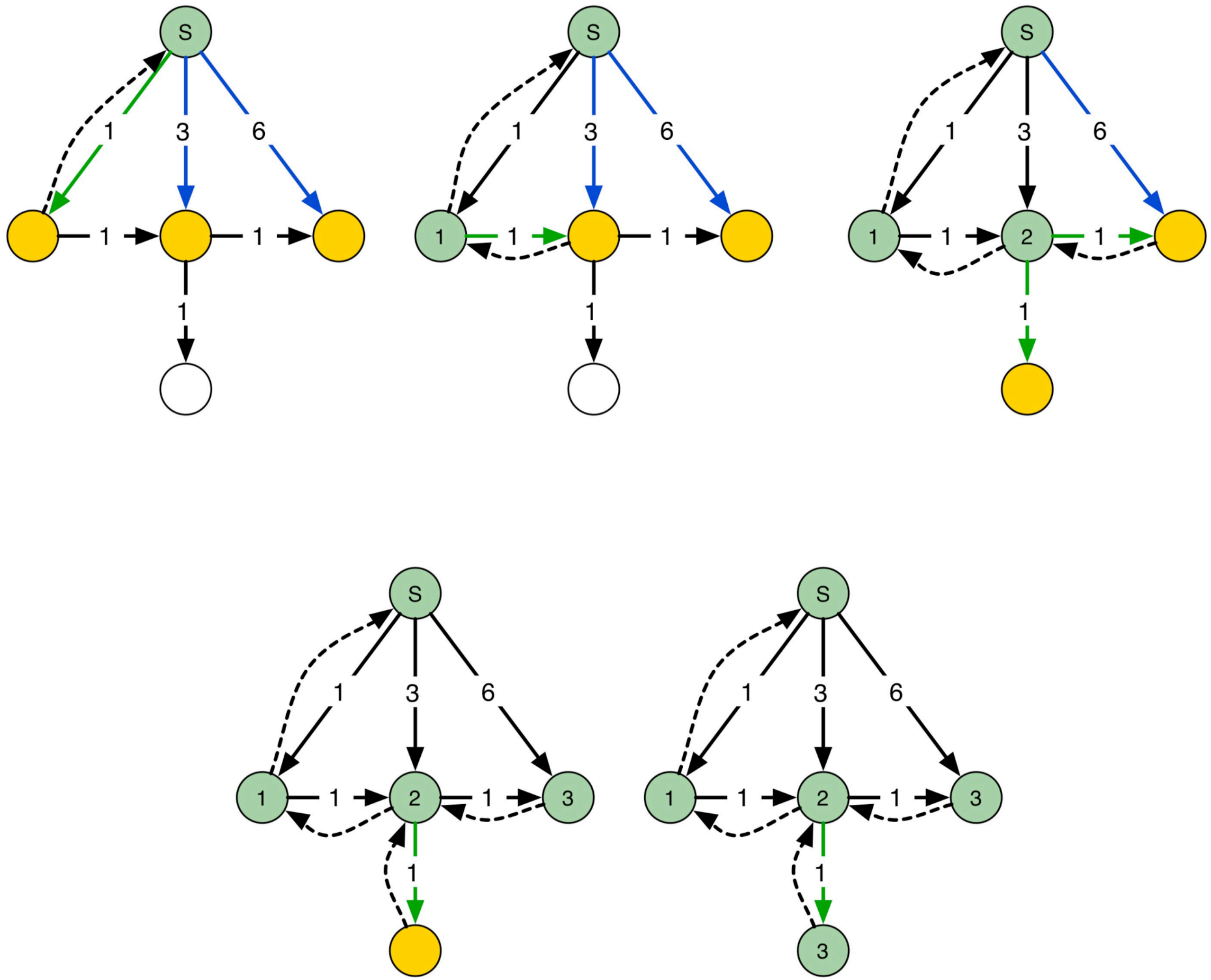
Dijkstra(G, w, s)
begin
  Init-Single-Source(G, w)
  $S \leftarrow \emptyset$
  $Q \leftarrow V$
  while $Q \neq \emptyset$ do
    $u \leftarrow$ Element aus Q mit minimalen Wert $d(u)$
    $S \leftarrow S \cup \{u\}$
    $Q \leftarrow Q \setminus \{u\}$
    for all $v \in$ Adj(u) do
      Relax(u, v)
    od
  od
end

Init-Single-Source(G, w, s)
begin
  for all $v \in V$ do
    $d(v) \leftarrow \infty$
    $\pi(v) \leftarrow v$
  od
  $d(s) \leftarrow 0$
end

Relax(u, v)
begin
  if $d(v) > d(u) + w(u, v)$ then
    $d(v) \leftarrow d(u) + w(u, v)$
    $\pi(v) \leftarrow u$
  fi
end

Dijkstra's algorithm has runtime
$\Theta(|E| + |V| \log |V|)$

Dijkstra: Example



Distance Vector Routing Protocol

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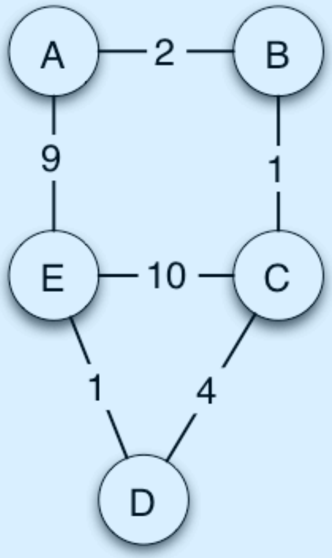
- **Distance Table Data Structure**
  - Every node has a
    - row for each target
    - column for each direct neighbor
- **Distributed Algorithm**
  - Every node communicates only with his neighbors
- **Asynchronous**
  - Nodes do not use a round model
- **Self-termination**
  - algorithm runs until no further changes occur



Distance Table für A

	von A	über B	E	Routing Tabellen Eintrag
nach	B	2	15	B
	C	3	14	B
	D	7	10	B
	E	13	9	E

Distance Table für C

	von C	über B	D	E	Routing Tabellen Eintrag
nach	A	3	11	18	B
	B	1	6	16	B
	D	5	4	11	D
	E	7	5	10	D

The “Count to Infinity” - Problem

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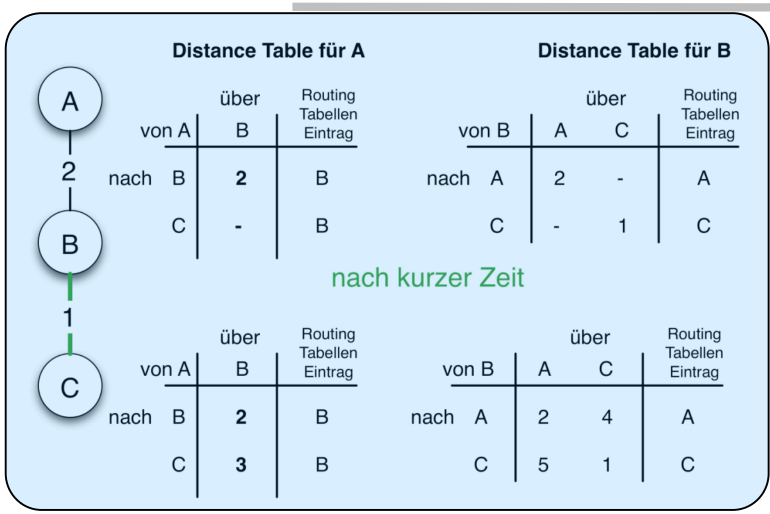
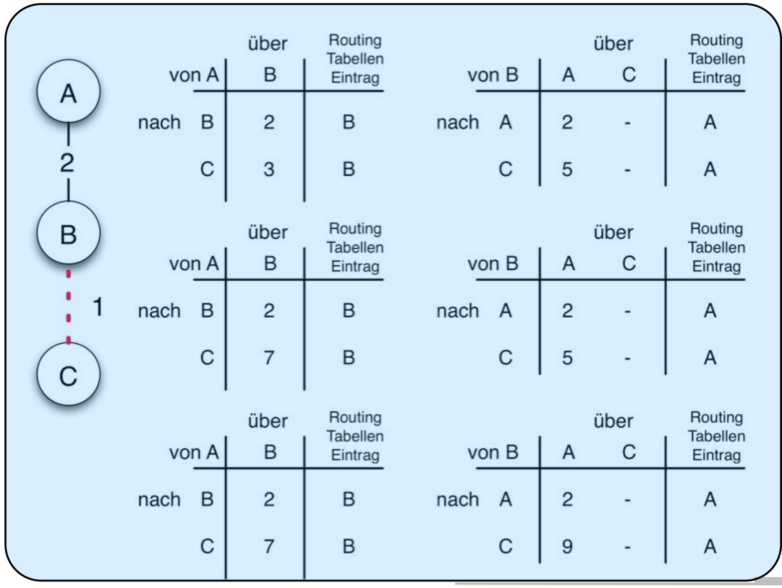
- **Good news travel fast**
  - A new connection is announced quickly.

- **Bad news travel slow**
  - Connection fails
  - Neighbors increase the distance counter
  - “Count to Infinity”-Problem





Link-State Protocol

- **Link State Routers**
  - exchange information using **link state packets** (LSP)
  - Every router uses a (centralized) shortest-path-algorithm
- **LSP contains**
  - ID of creator of LSP
  - Costs of all edges from the creator
  - Sequence no. (SEQNO)
  - TTL-entry (time to live)
- **Reliable Flooding**
  - The current LSP of every node are stored
  - Forwarding of LSPs to all neighbors
    - except sending nodes
  - Periodically new LSPs are generated
    - with incremented SEQNO
  - TTL is decremented after every transmission

Why is Routing in MANET 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

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Unicast Routing Protocols

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

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Routing Protocols

- **Proactive Protocols:**
  - Determine routes independent of traffic pattern
  - Traditional link-state and distance-vector routing protocols are proactive
    - Destination Sequenced Distance Vector (DSDV)
    - Optimized Link State Routing (OLSR)
- **Reactive 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
    - Zone Routing Protocol (ZRP)
    - Greedy Perimeter Stateless Routing (GPSR)

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**

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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**

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Flooding for Data Delivery

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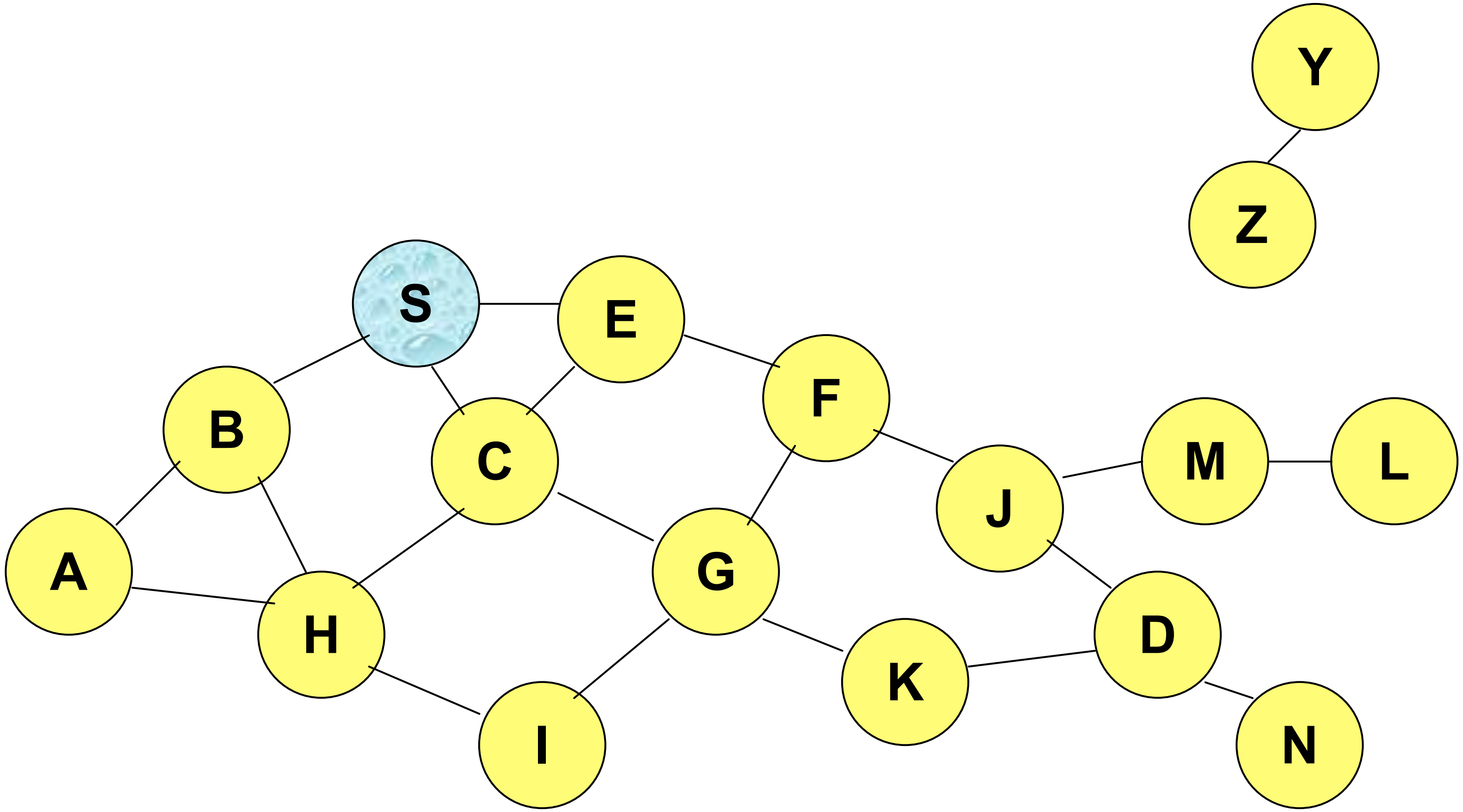

Represents a node that has received packet P

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

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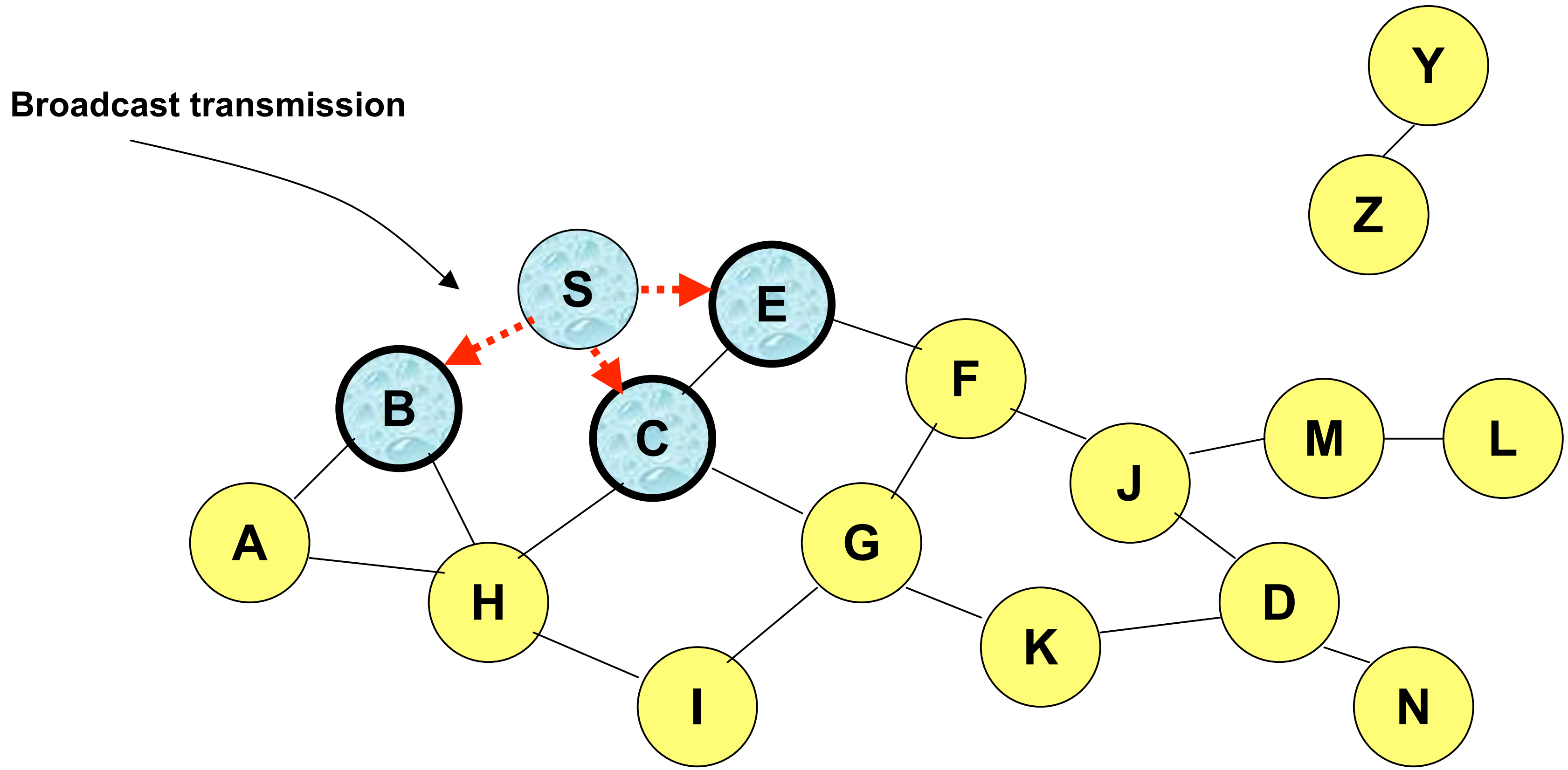
Flooding for Data Delivery



Represents a node that receives packet P for the first time

Represents transmission of packet P

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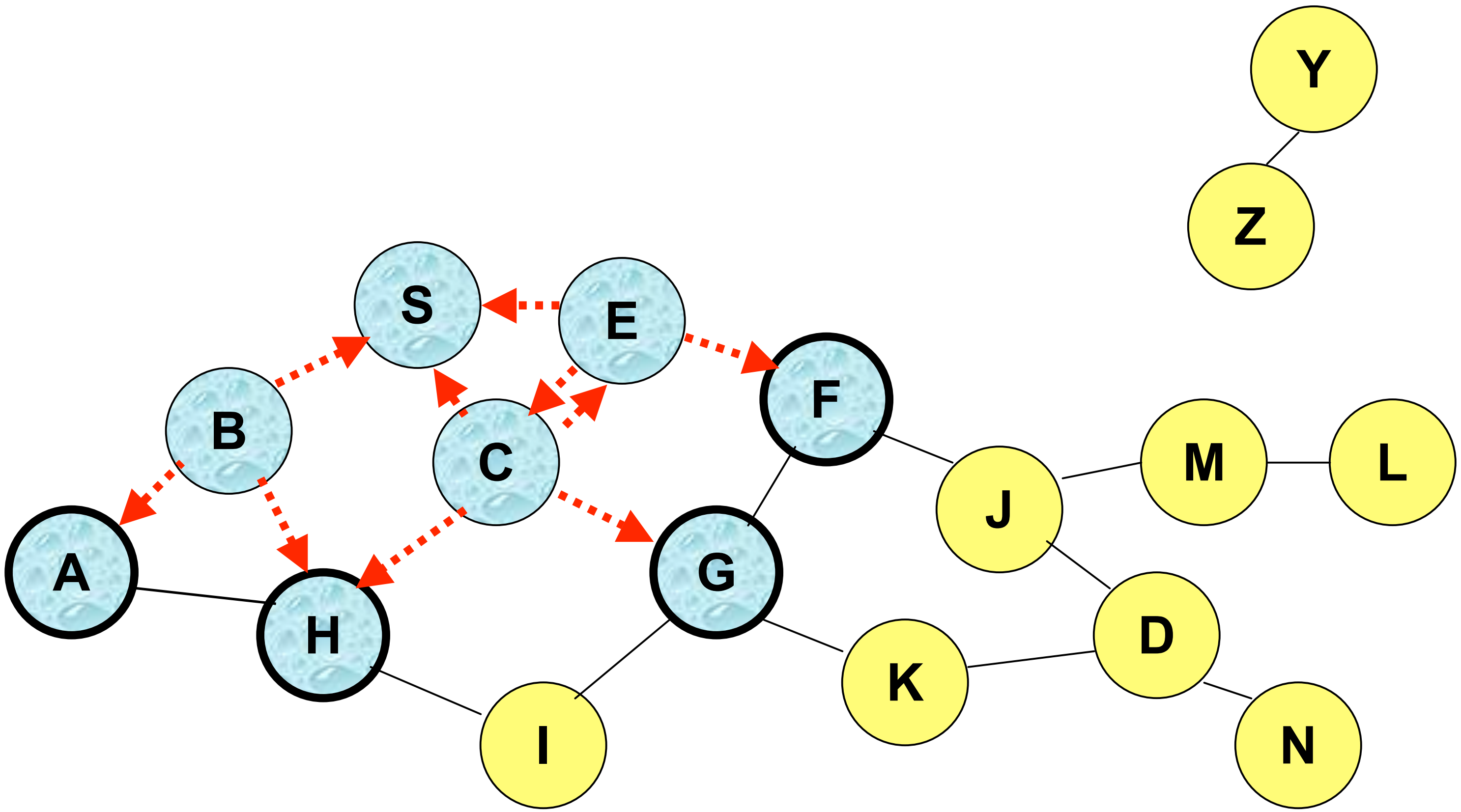
Flooding for Data Delivery



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

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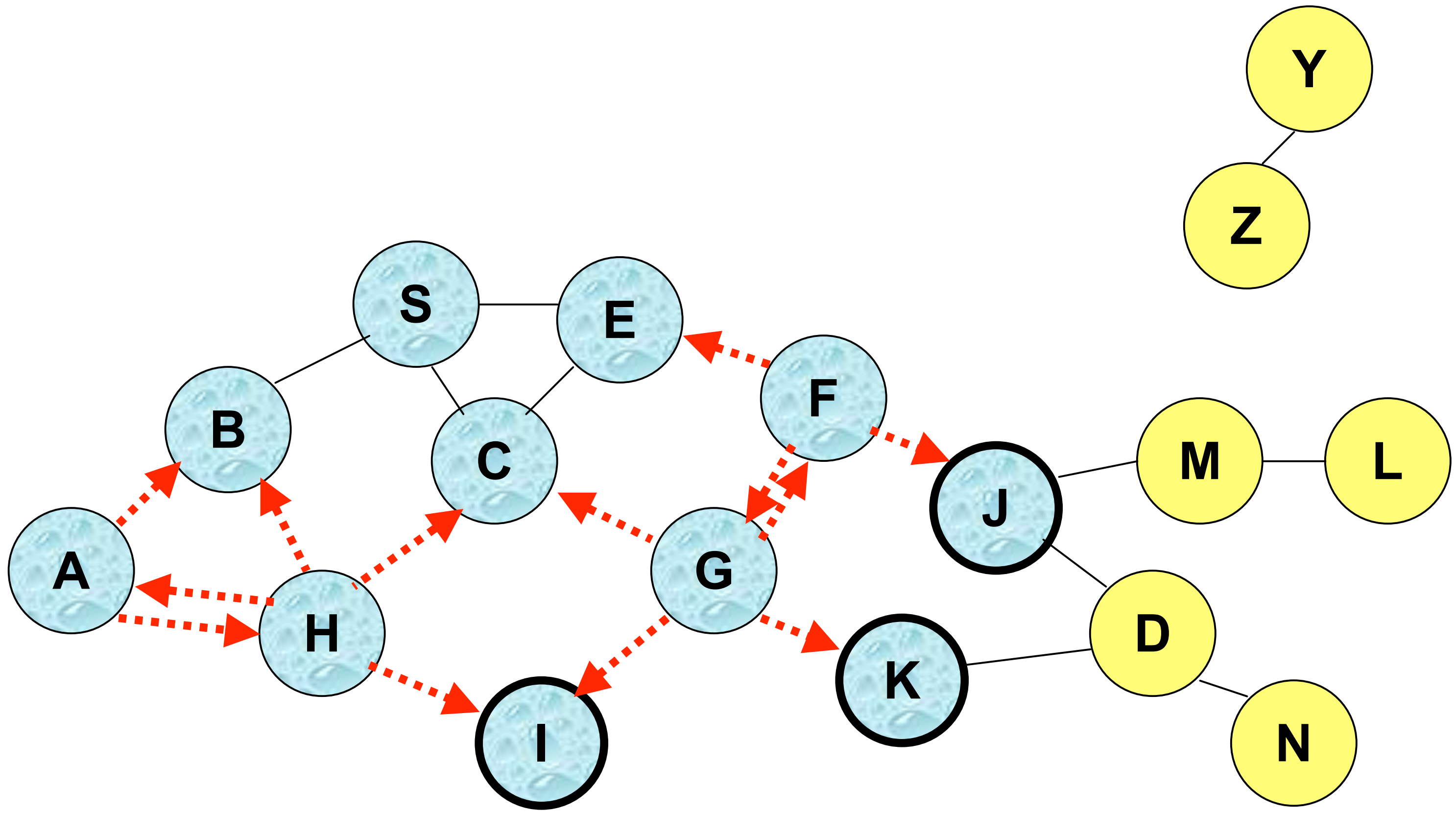

- **Node C receives packet P from G and H, but does not forward it again, because node C has already forwarded packet P once**

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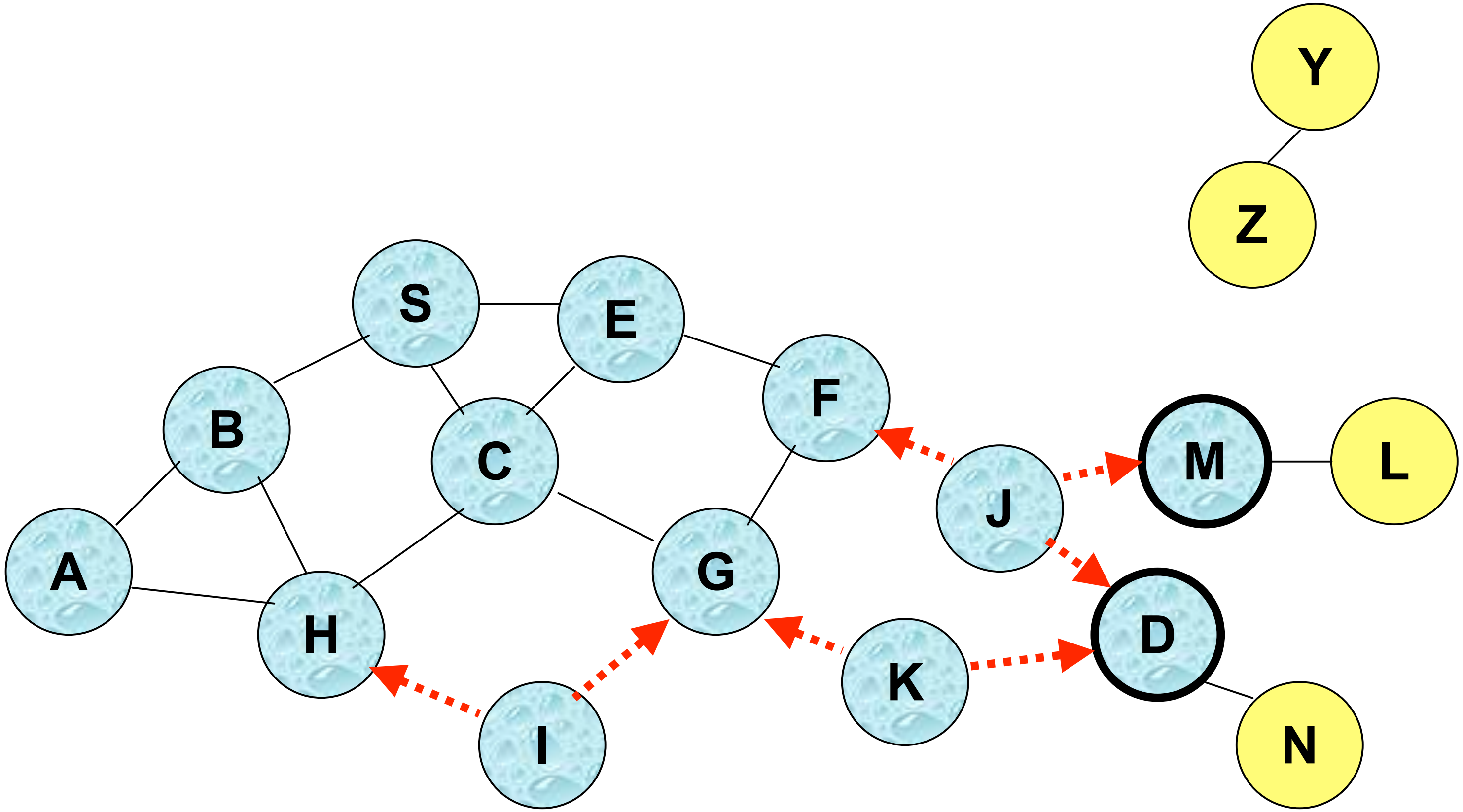
Flooding for Data Delivery



- 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

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Flooding for Data Delivery

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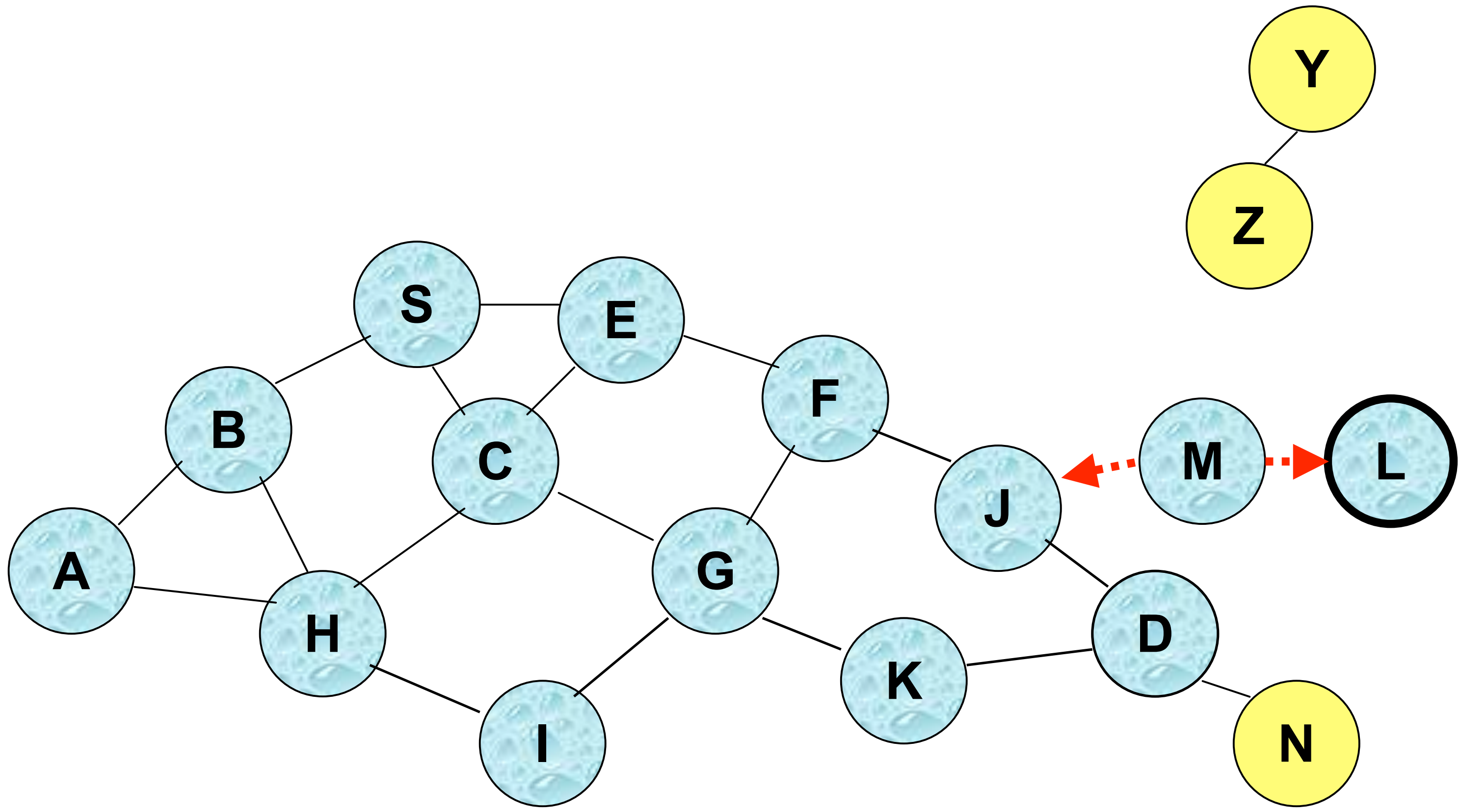

- Node D **does not forward** packet P, because node D is the **intended destination of packet P**

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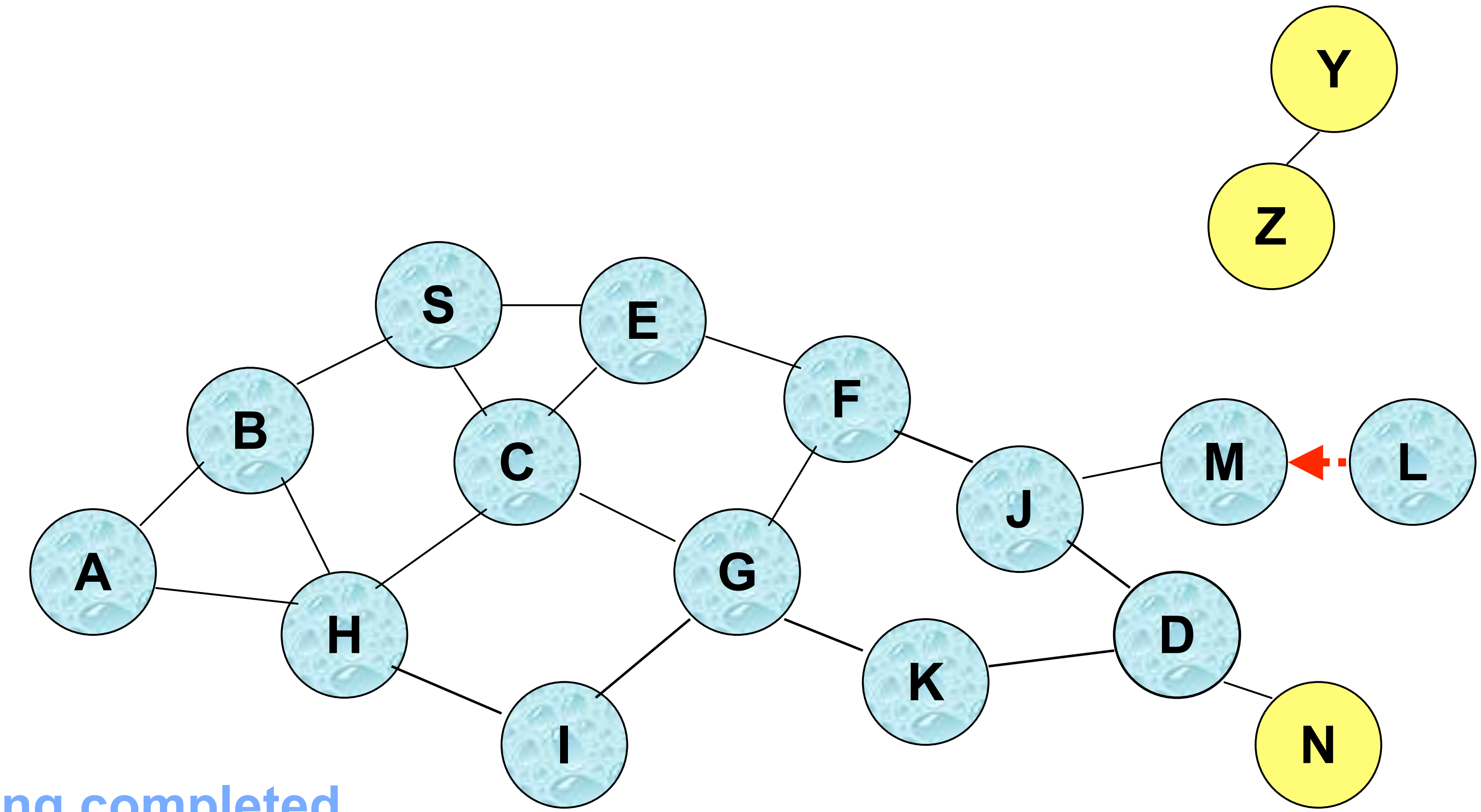
Flooding for Data Delivery



- 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)

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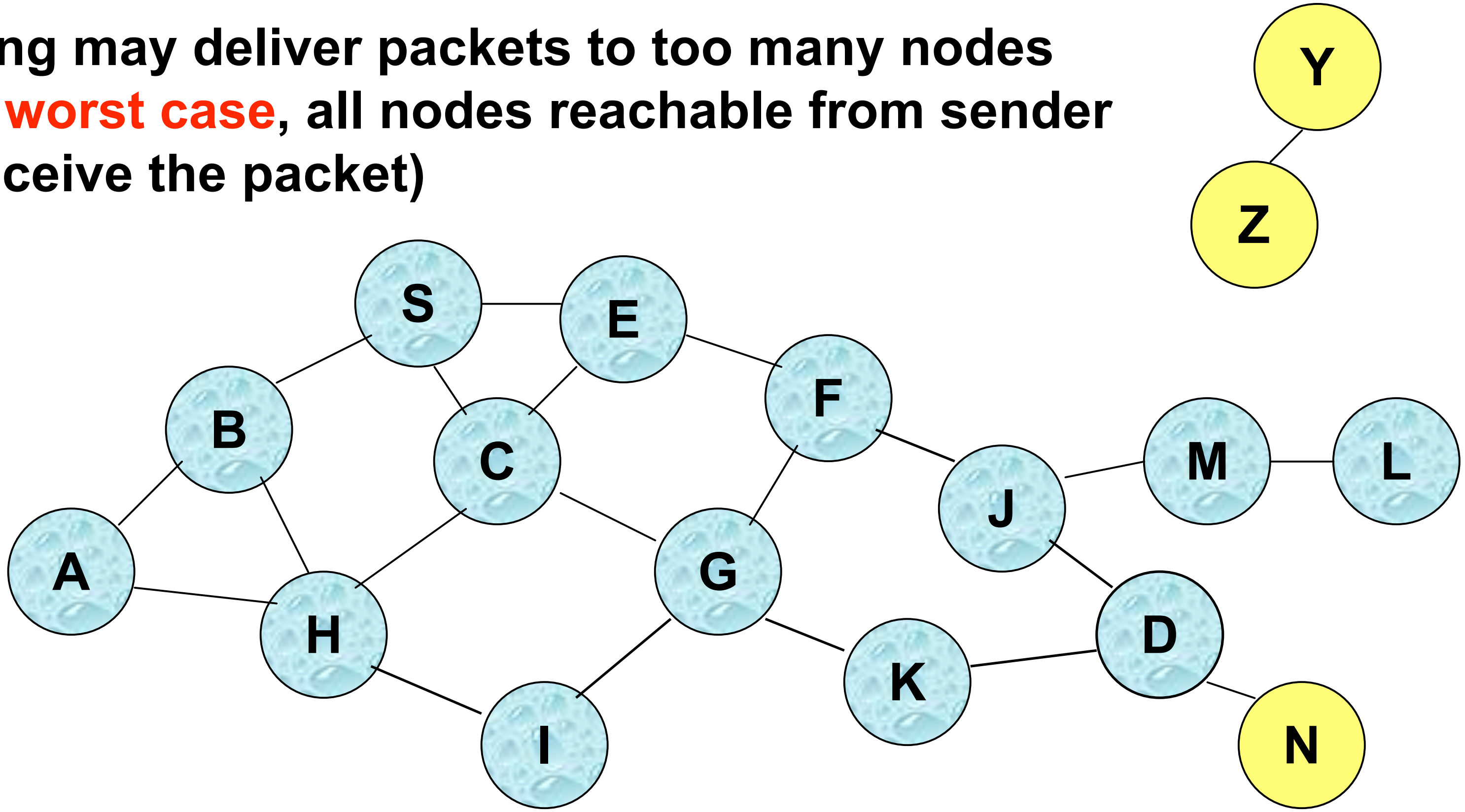
Flooding for Data Delivery

- **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

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

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Reactive protocols – DSR

- **In a reactive protocol, how to forward a packet to destination?**
  - Initially, no information about next hop is available at all
  - One (only?) possible recourse: Send packet to ***all*** neighbors – flood the network
  - Hope: At some point, packet will reach destination and an answer is sent pack – use this answer for ***backward learning*** the route from destination to source

- **Practically:** *Dynamic Source Routing (DSR)*
  - Use separate ***route request/route reply*** packets to discover route
    - Data packets only sent once route has been established
    - Discovery packets smaller than data packets
  - Store routing information in the discovery packets

DSR route discovery procedure

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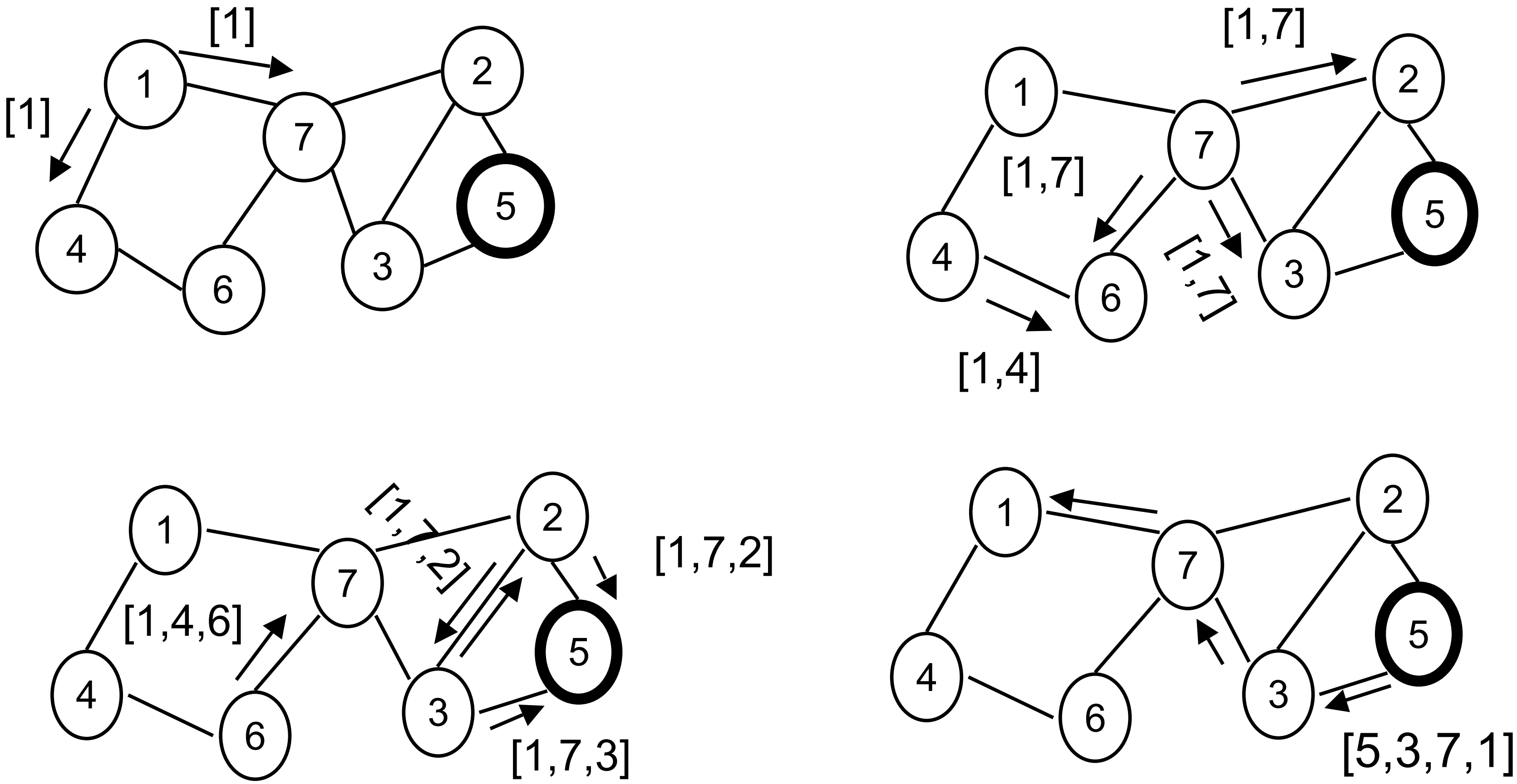
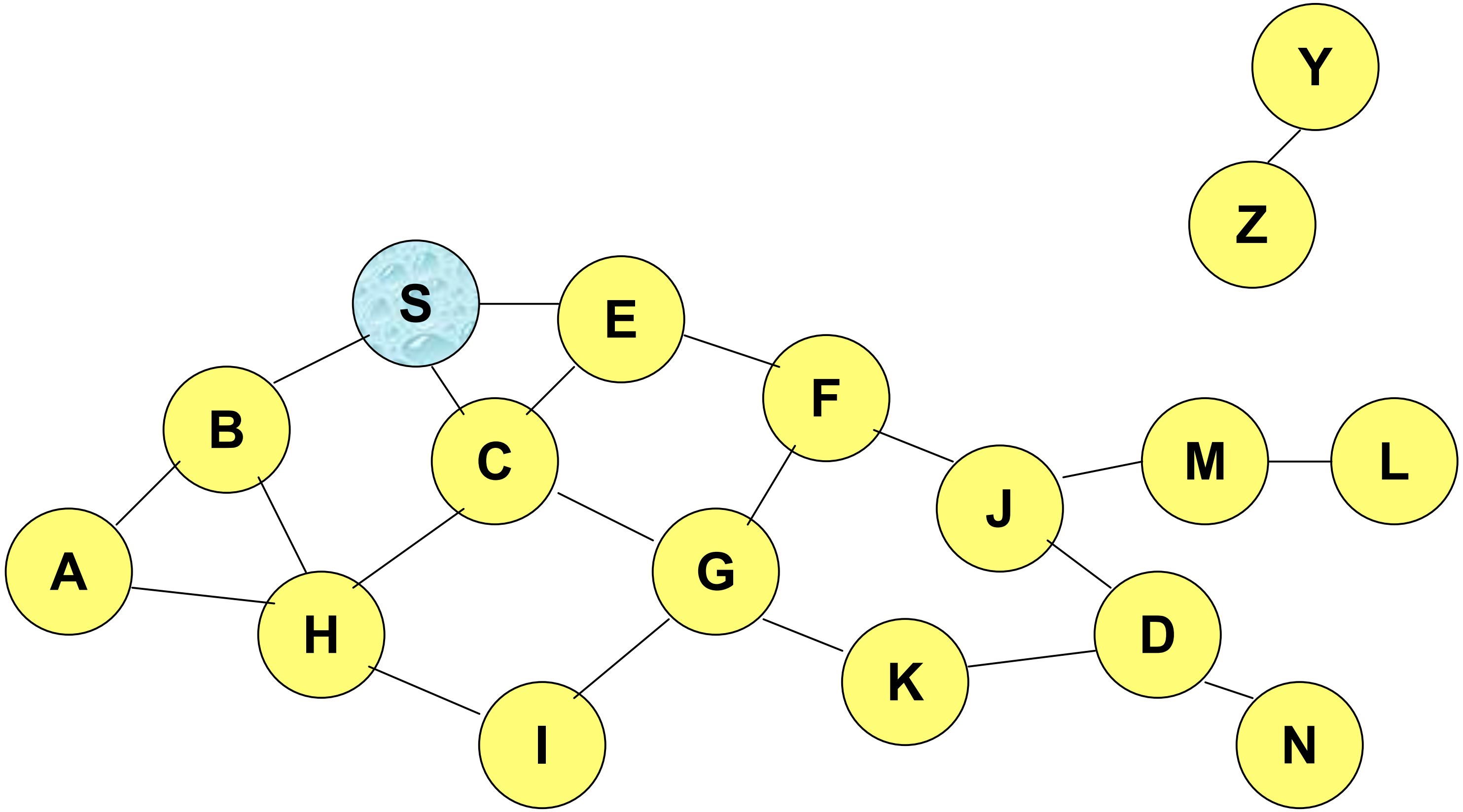
Search for route from 1 to 5



Node 5 uses route information recorded in RREQ to send back, via ***source routing***, a route reply

Route Discovery in DSR



Represents a node that has received RREQ for D from S

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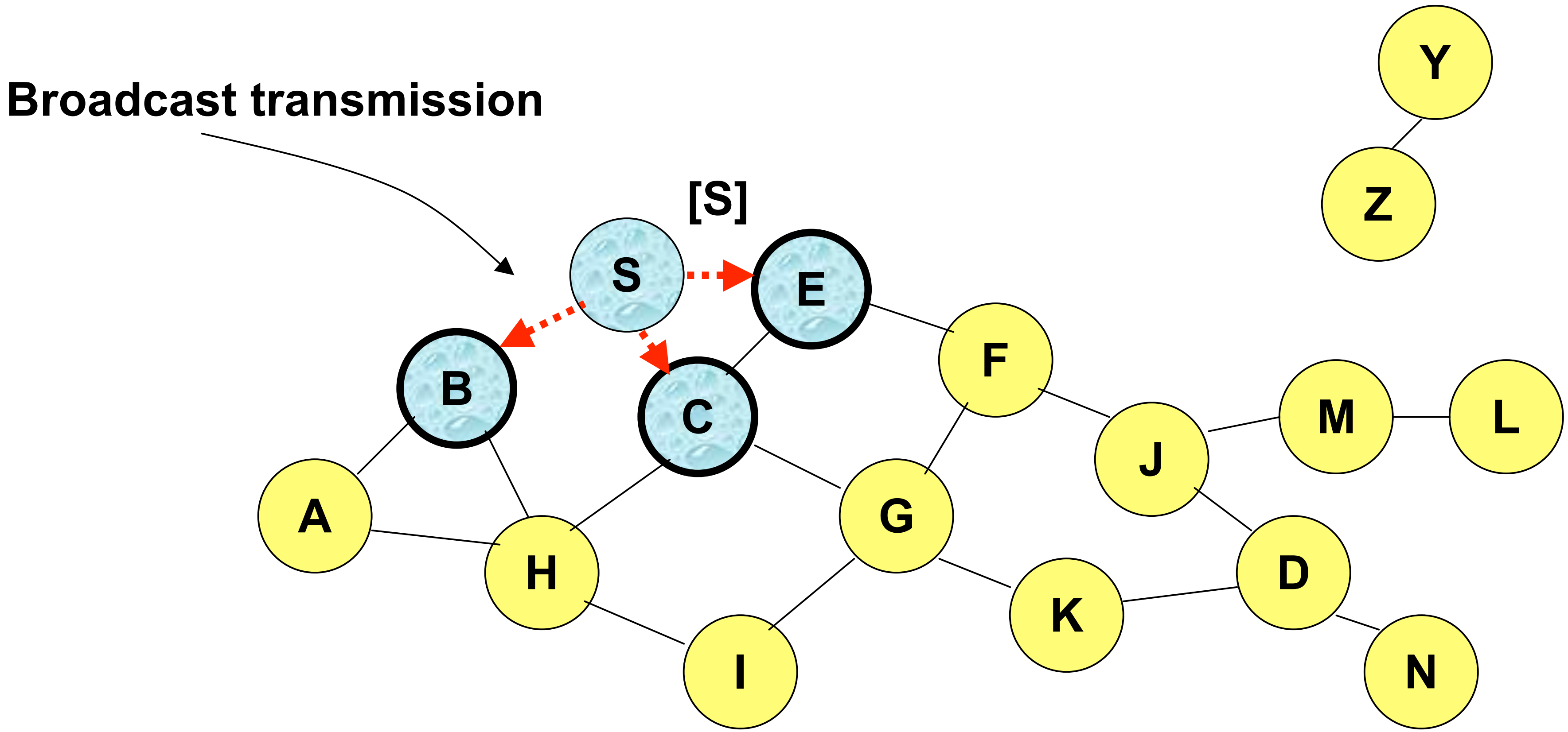
Route Discovery in DSR



Represents transmission of RREQ

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

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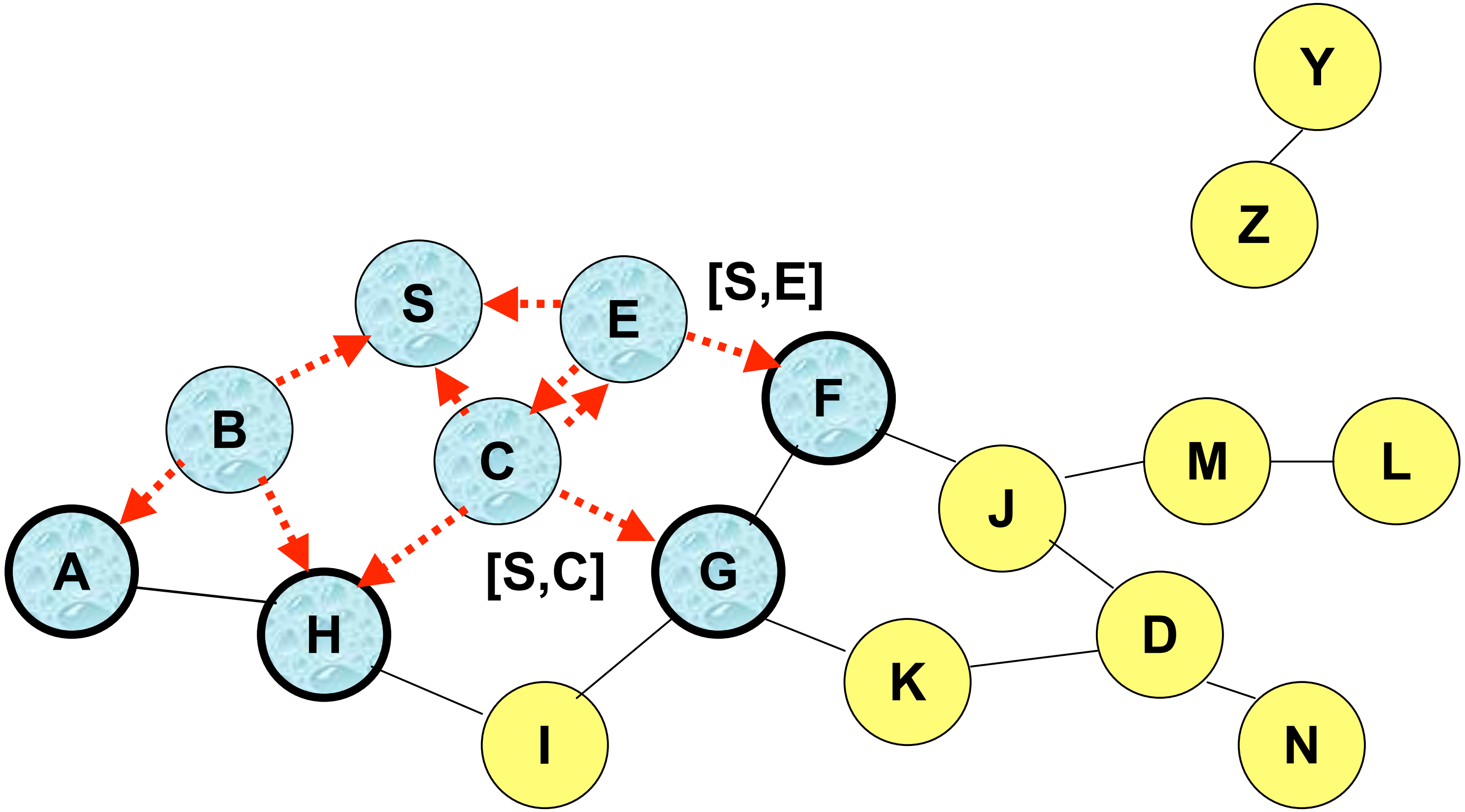
Route Discovery in DSR



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

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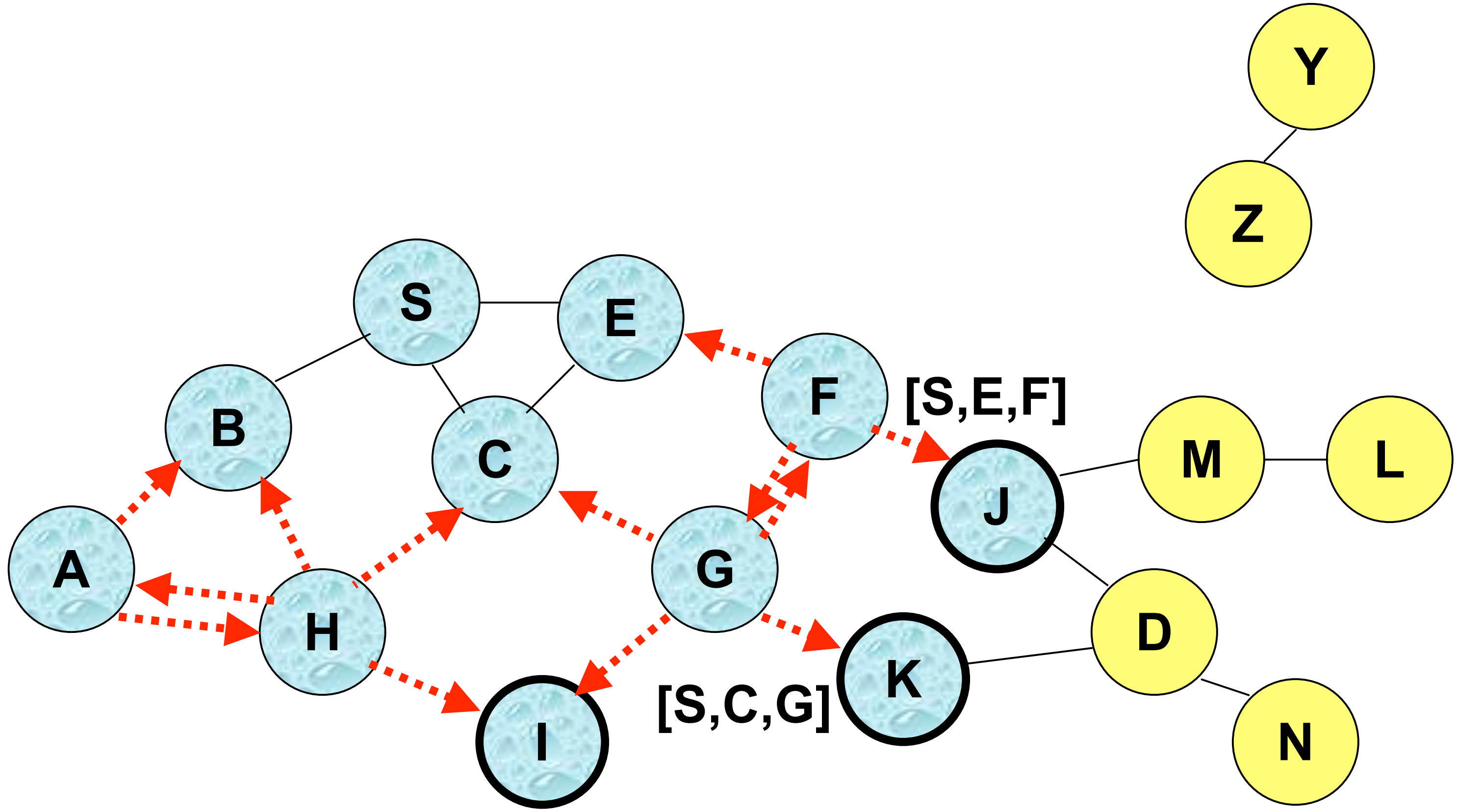
Route Discovery in DSR



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

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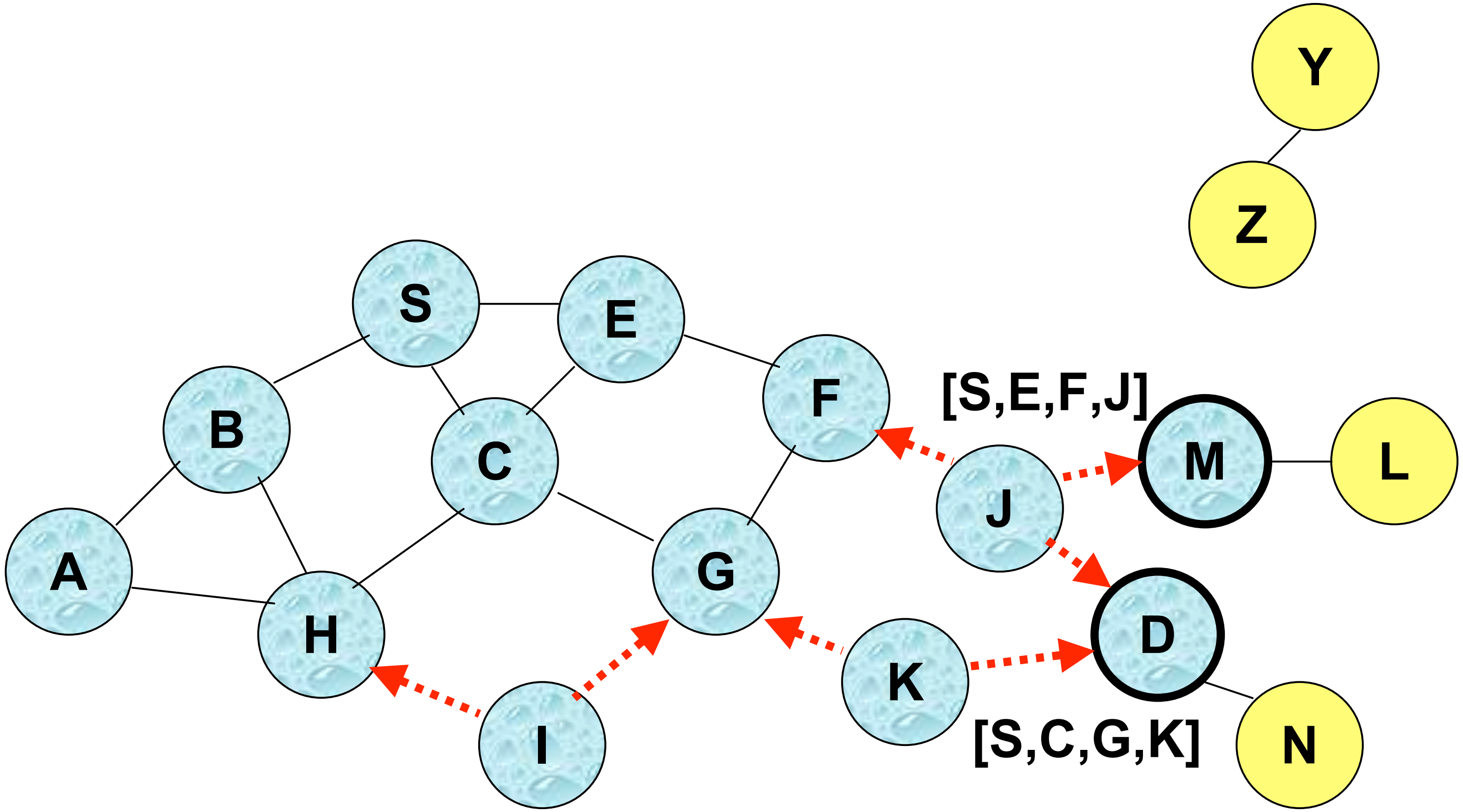
Route Discovery in DSR



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

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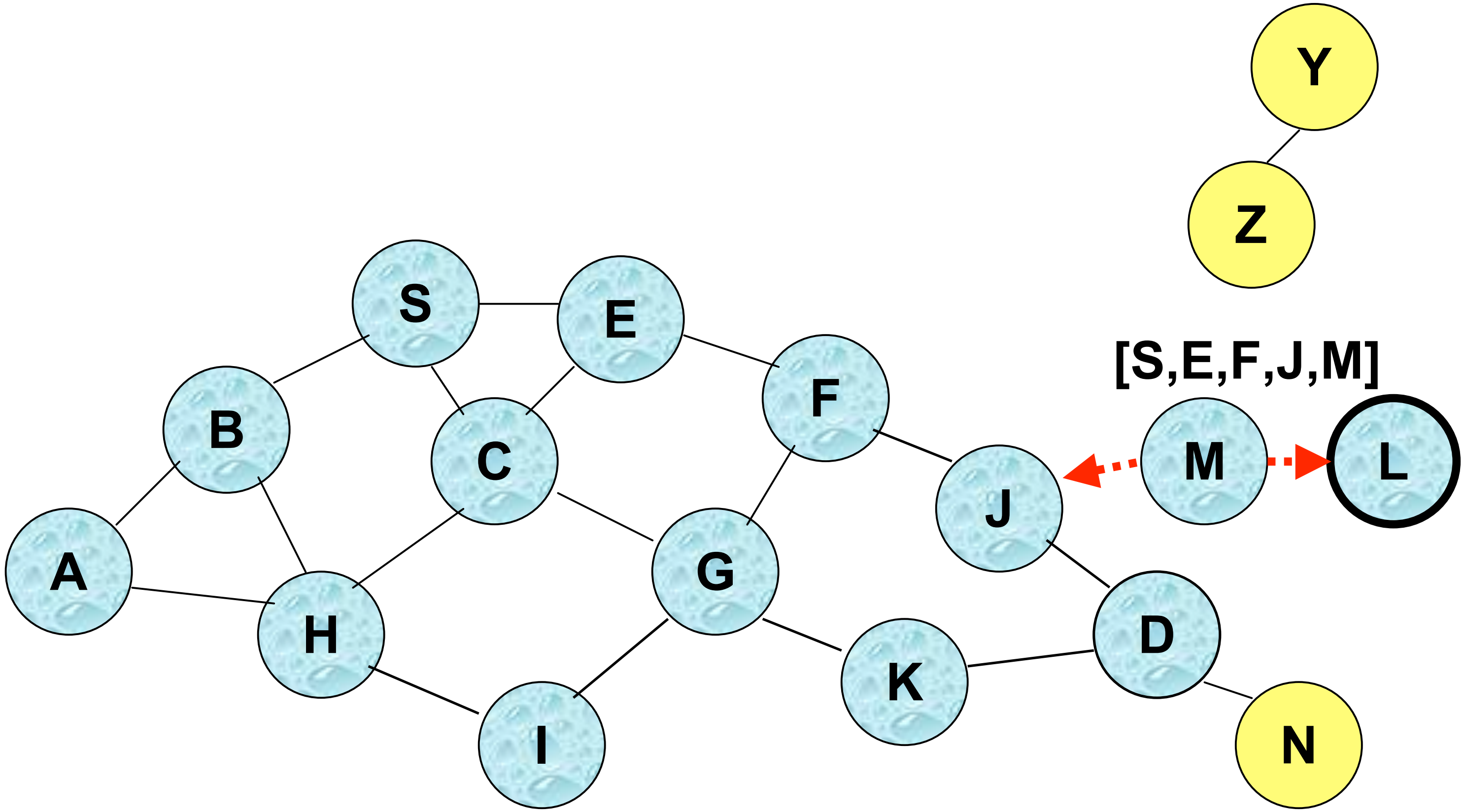
Route Discovery in DSR

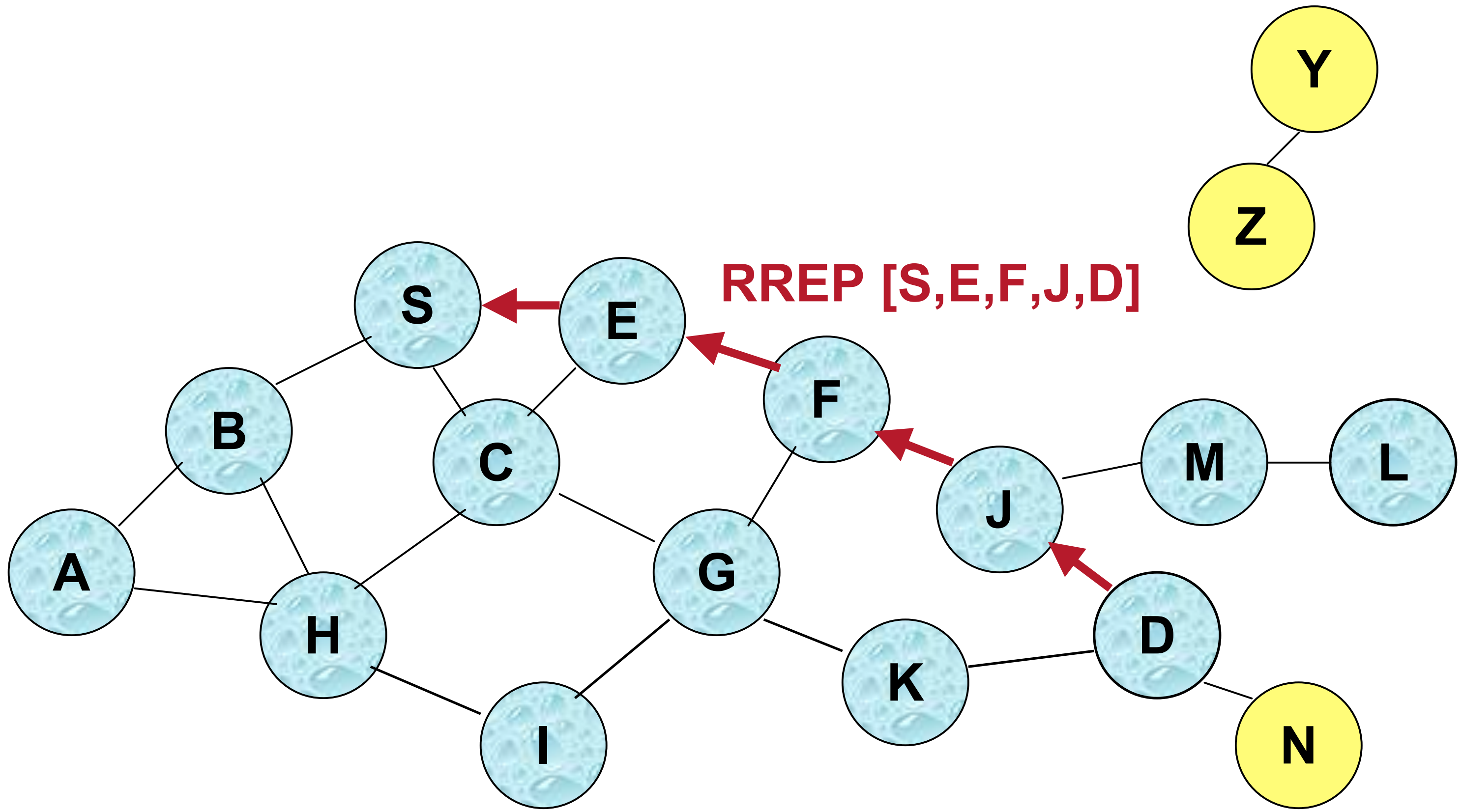


- Node D does not forward RREQ, because node D is the intended target of the route discovery

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



Represents RREP control message

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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)

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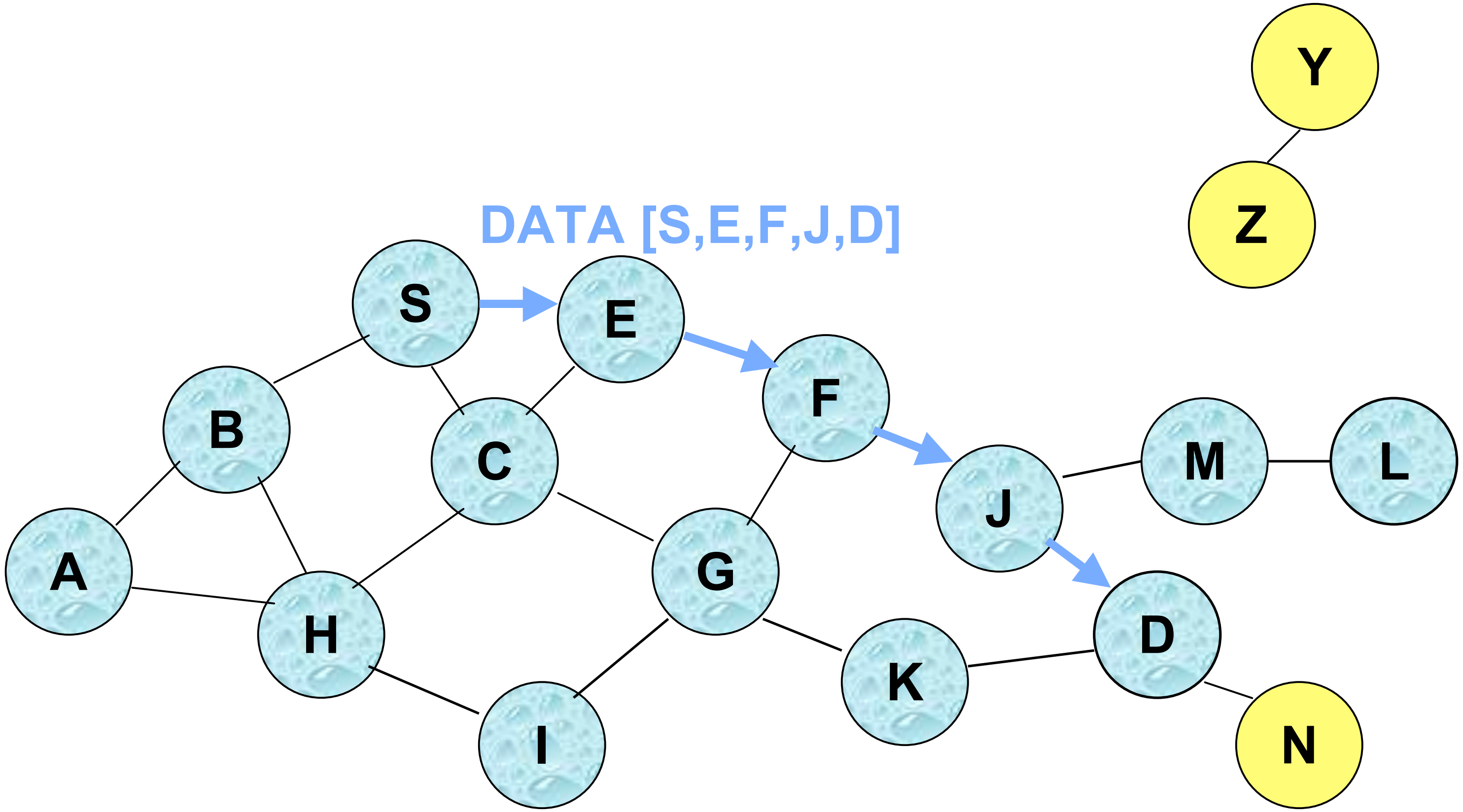
- **Node S on receiving RREP, caches the route included in the RREP**

- **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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When to Perform a Route Discovery

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- **When node S wants to send data to node D, but does not know a valid route node D**

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DSR modifications, extensions

- **Intermediate nodes may send route replies in case they already know a route**
  - Problem: stale route caches
- **Promiscuous operation of radio devices – nodes can learn about topology by listening to control messages**
- **Random delays for generating route replies**
  - Many nodes might know an answer – reply storms
  - NOT necessary for medium access – MAC should take care of it
- **Salvaging/local repair**
  - When an error is detected, usually sender times out and constructs entire route anew
  - Instead: try to locally change the source-designated route
- **Cache management mechanisms**
  - To remove stale cache entries quickly
  - Fixed or adaptive lifetime, cache removal messages, …

DSR Optimization: Route Caching

- Each node caches a new route it learns by *any means*
- When node S finds route [S,E,F,J,D] to node D, node S also learns route [S,E,F] to node F
- When node K receives Route Request [S,C,G] destined for node, node K learns route [K,G,C,S] to node S
- When node F forwards Route Reply RREP [S,E,F,J,D], node F learns route [F,J,D] to node D
- When node E forwards Data [S,E,F,J,D] it learns route [E,F,J,D] to node D
- A node may also learn a route when it overhears Data packets

Use of Route Caching

- **When node S learns that a route to node D is broken, it uses another route from its local cache, if such a route to D exists in its cache. Otherwise, node S initiates route discovery by sending a route request**

- **Node X on receiving a Route Request for some node D can send a Route Reply if node X knows a route to node D**

- **Use of route cache**
  - can speed up route discovery
  - can reduce propagation of route requests

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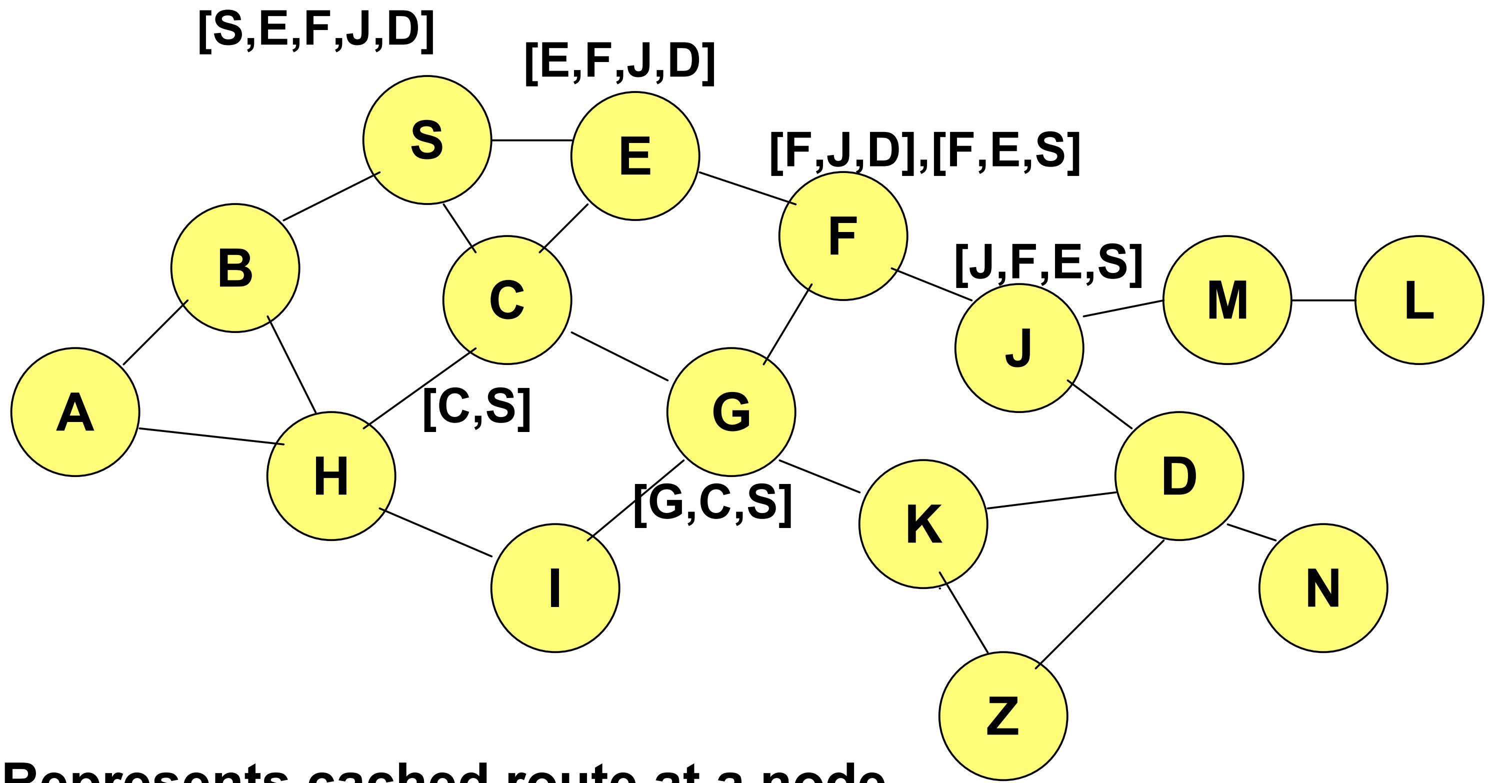
Use of Route Caching



[P,Q,R] Represents cached route at a node
(DSR maintains the cached routes in a tree format)

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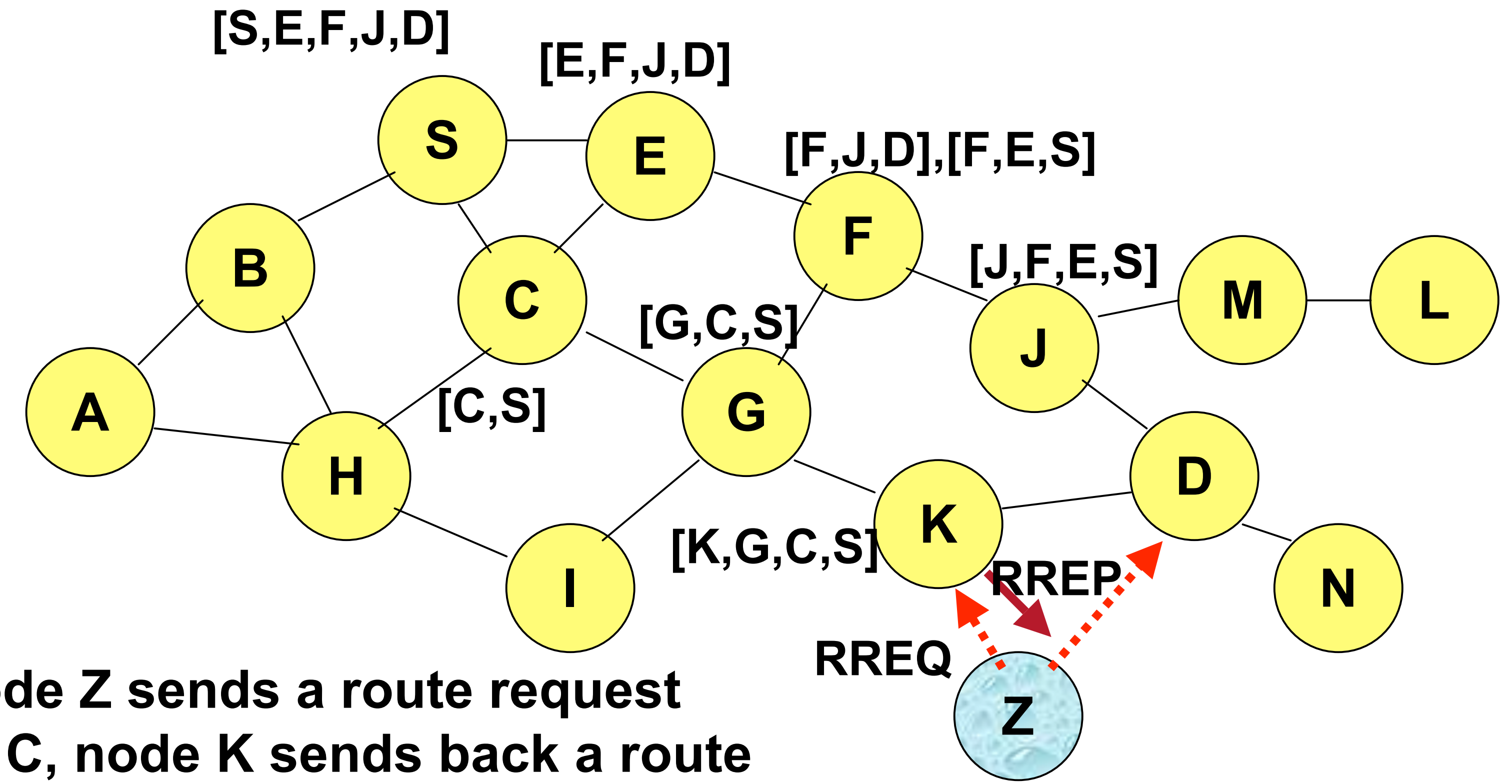
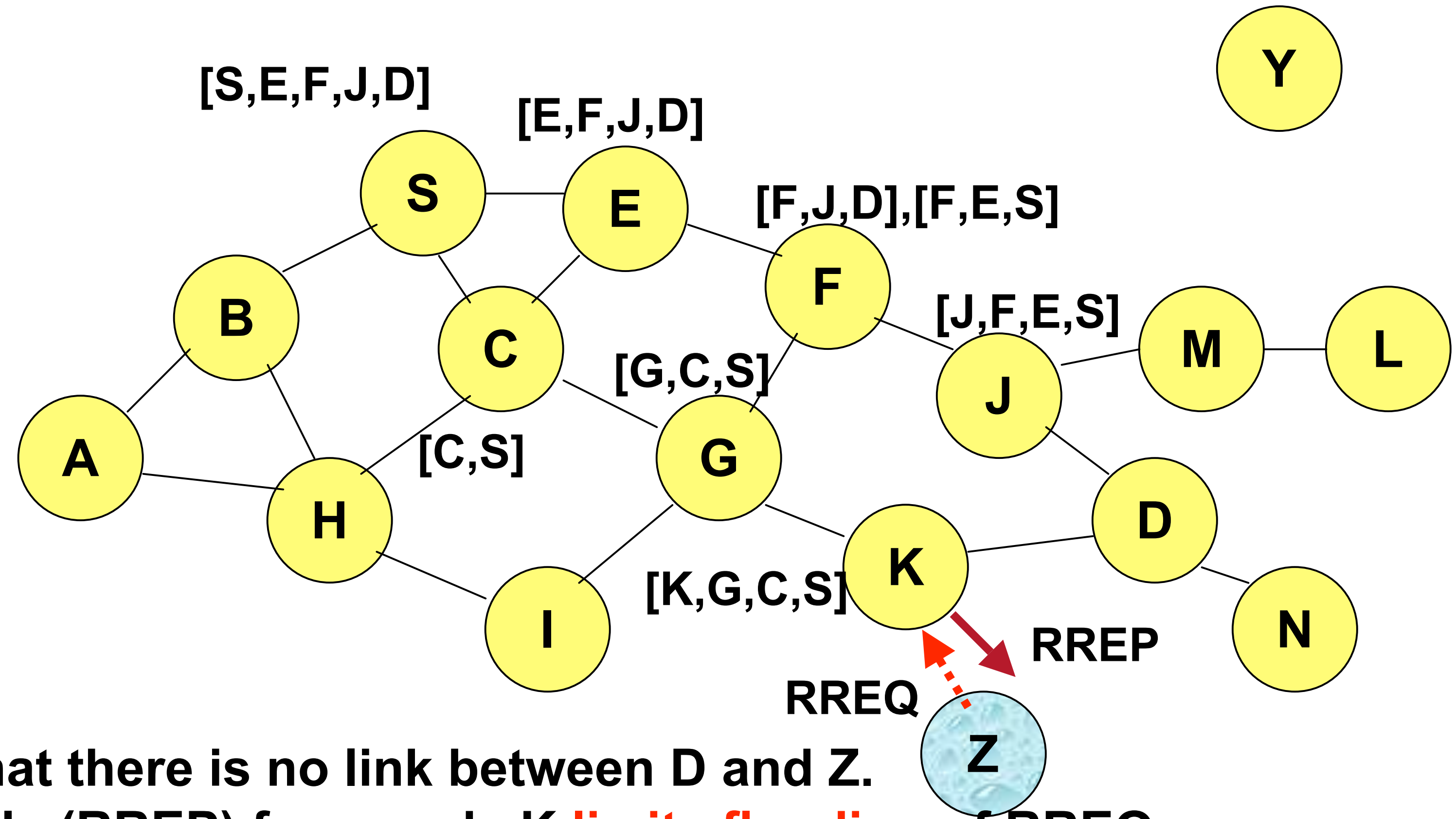
Use of Route Caching: Can Speed up Route Discovery



When node Z sends a route request for node C, node K sends back a route reply [Z,K,G,C] to node Z using a locally cached route

Use of Route Caching:
Can Reduce Propagation of Route Requests



Assume that there is no link between D and Z.
Route Reply (RREP) from node K limits flooding of RREQ.
In general, the reduction may be less dramatic.

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Route Error (RERR)

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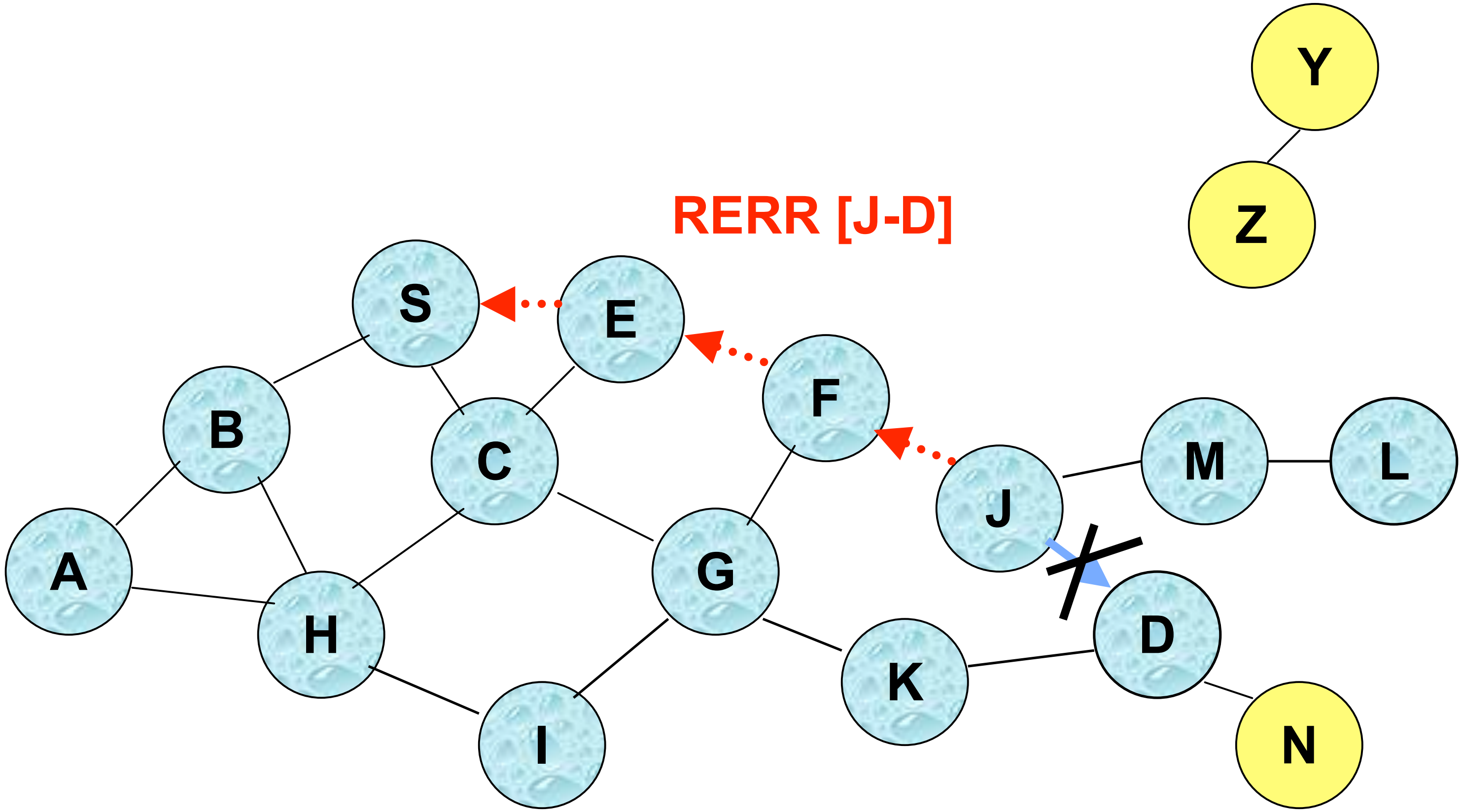

J sends a route error to S along route J-F-E-S when its attempt to forward the data packet S (with route SEFJD) on J-D fails

Nodes hearing RERR update their route cache to remove link J-D

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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**

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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

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Dynamic Source Routing: Disadvantages

- **An intermediate node may send Route Reply using a stale cached route, thus polluting other caches**
- **This problem can be eased if some mechanism to purge (potentially) invalid cached routes is incorporated.**
- **For some proposals for cache invalidation, see [Hu00Mobicom]**
  - Static timeouts
  - Adaptive timeouts based on link stability

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Flooding of Control Packets

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- **How to reduce the scope of the route request flood ?**
  - Location Aided Routing LAR [Ko98Mobicom]
  - Query localization [Castaneda99Mobicom]

- **How to reduce redundant broadcasts ?**
  - The Broadcast Storm Problem [Ni99Mobicom]

Location Aided Routing (LAR)

- **Advantages**
  - reduces the scope of route request flood
  - reduces overhead of route discovery

- **Disadvantages**
  - Nodes need to know their physical locations
  - Does not take into account possible existence of obstructions for radio transmissions

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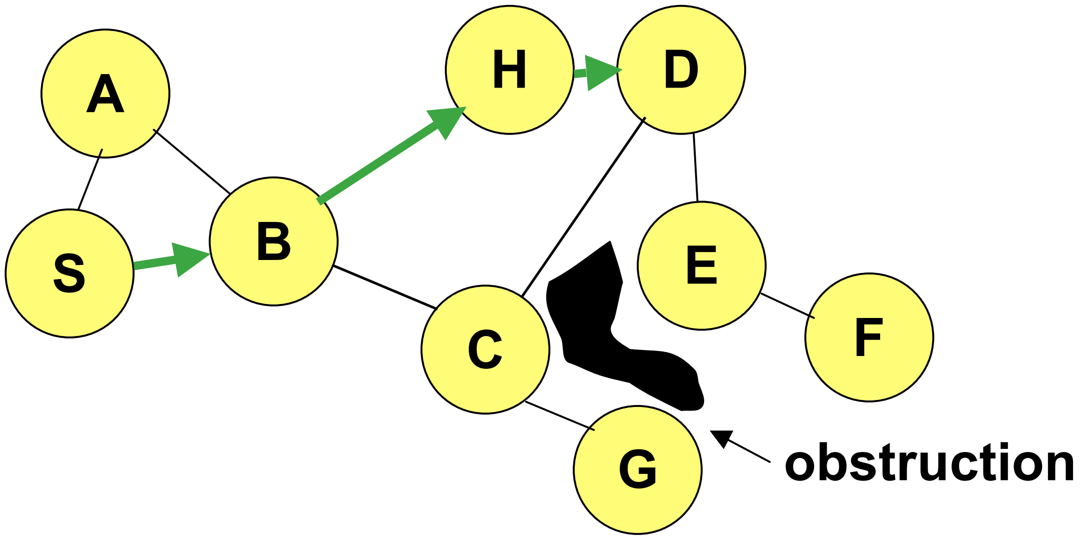
Geographic Distance Routing (GEDIR) [Lin98]

- Location of the destination node is assumed known
- Each node knows location of its neighbors
- Each node forwards a packet to its neighbor closest to the destination
- Route taken from S to D shown below



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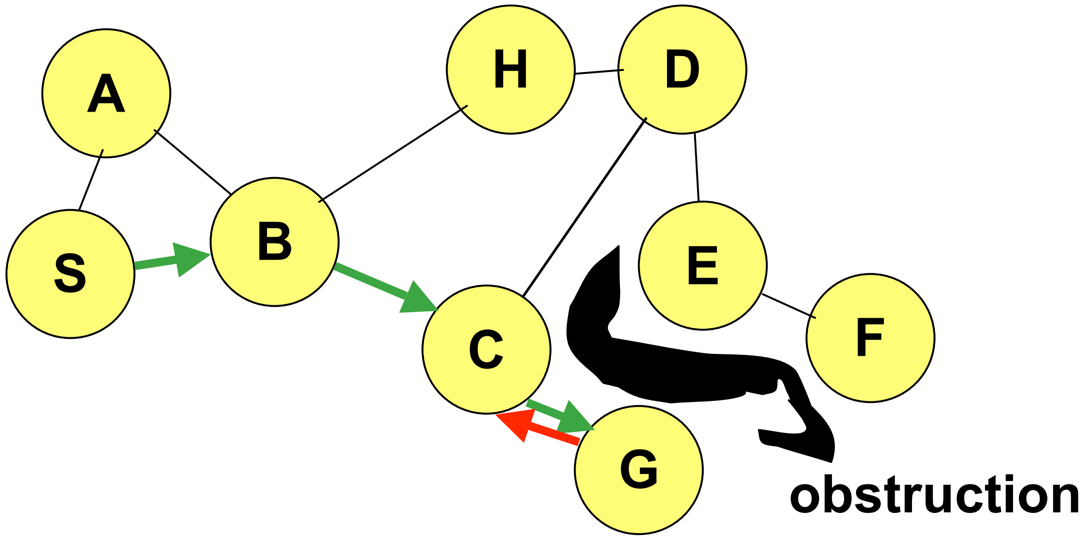
Geographic Distance Routing (GEDIR) [Stojmenovic99]

- **The algorithm terminates when same edge traversed twice consecutively**
- **Algorithm fails to route from S to E**
  - Node G is the neighbor of C who is closest from destination E, but C does not have a route to E



Routing with Guaranteed Delivery [Bose99Dialm]

- Improves on GEDIR [Lin98]
- Guarantees delivery (using location information) provided that a path exists from source to destination
- Routes around obstacles if necessary
- A similar idea also appears in [Karp00Mobicom]

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Reactive protocols – AODV

- **Ad hoc On Demand Distance Vector routing (AODV)**
  - Very popular routing protocol
  - Essentially same basic idea as DSR for discovery procedure
  - Nodes maintain routing tables instead of source routing
  - Sequence numbers added to handle stale caches
  - Nodes remember from where a packet came and populate routing tables with that information

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

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- **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**

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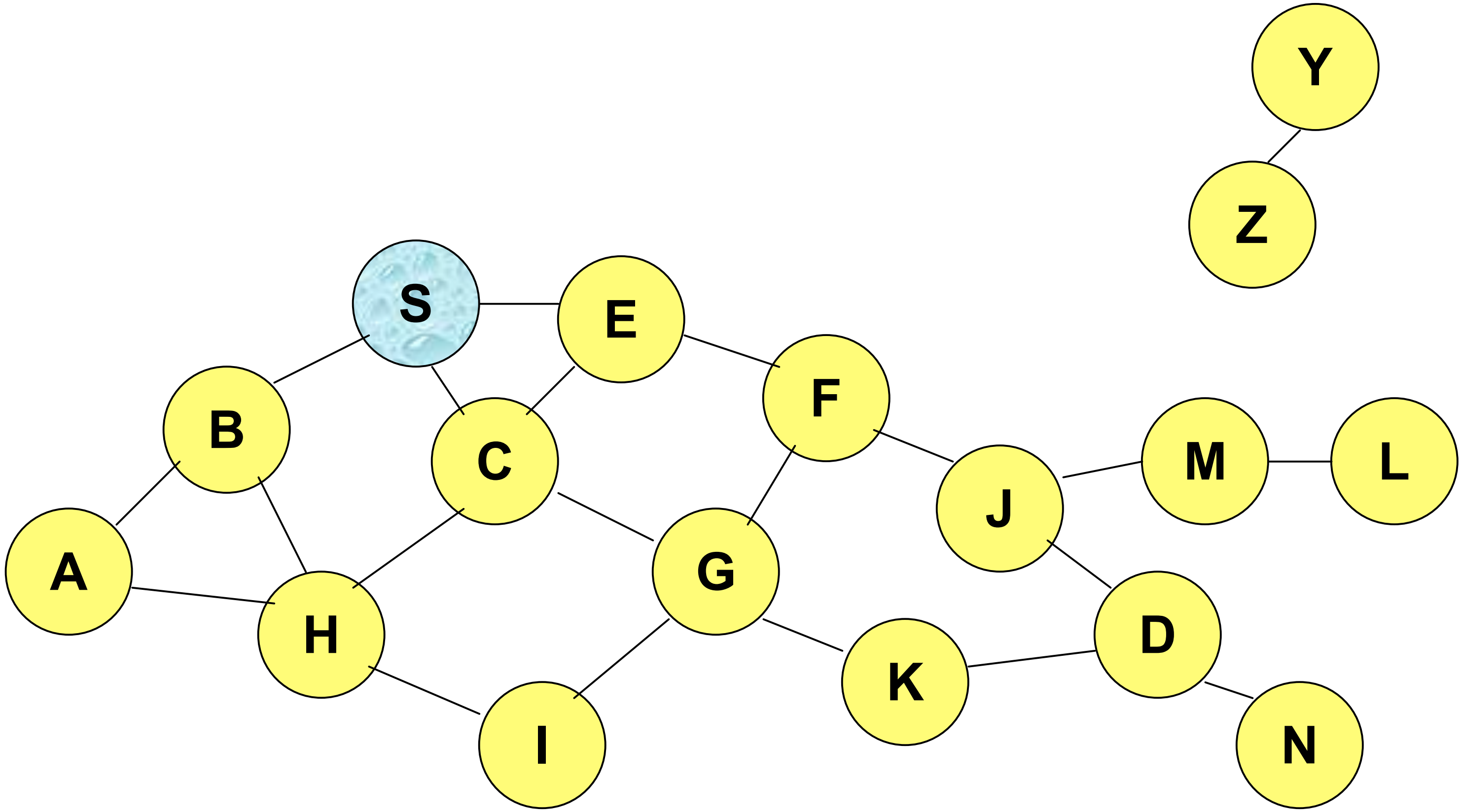
Route Requests in AODV



Represents a node that has received RREQ for D from S

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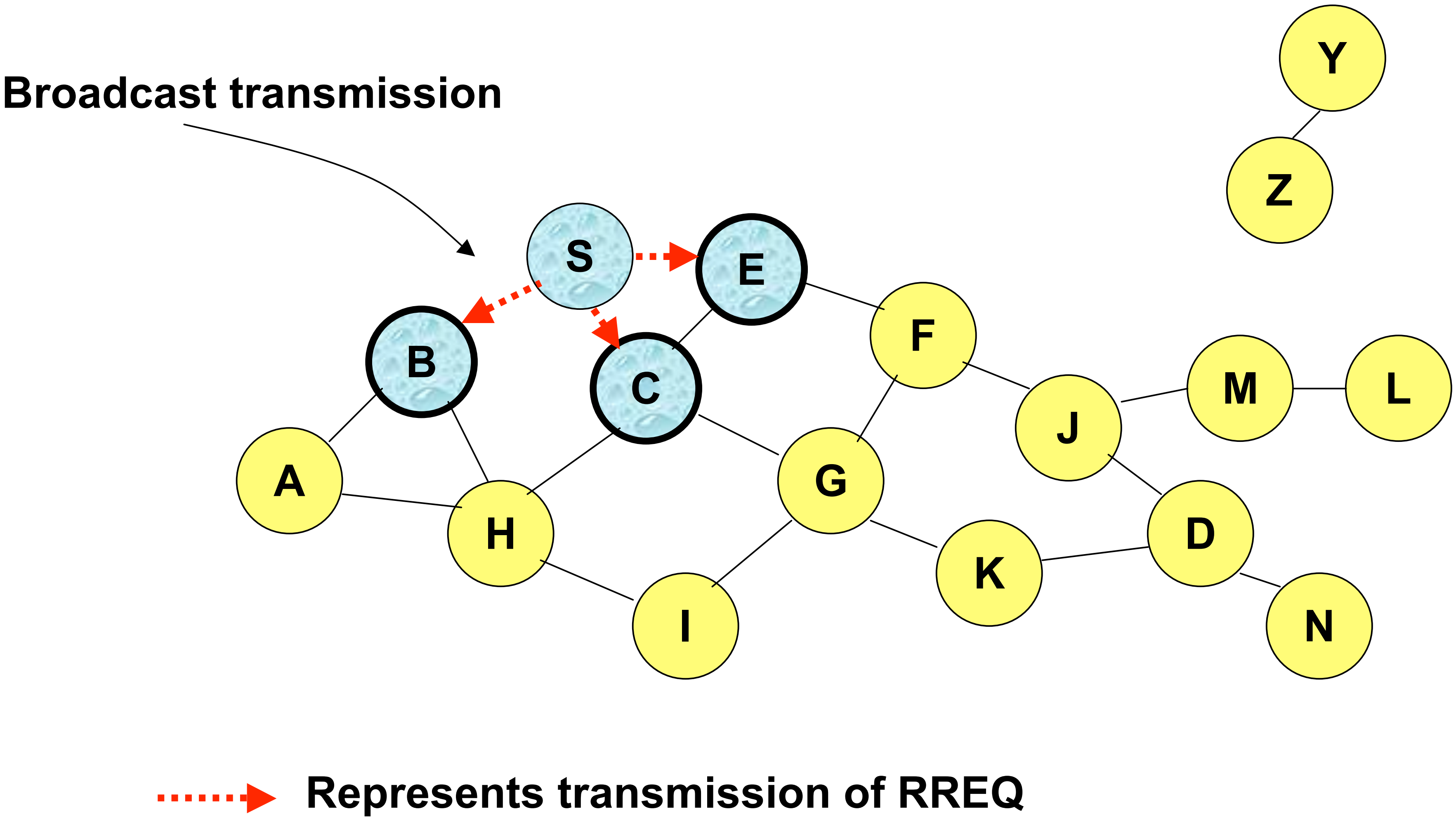
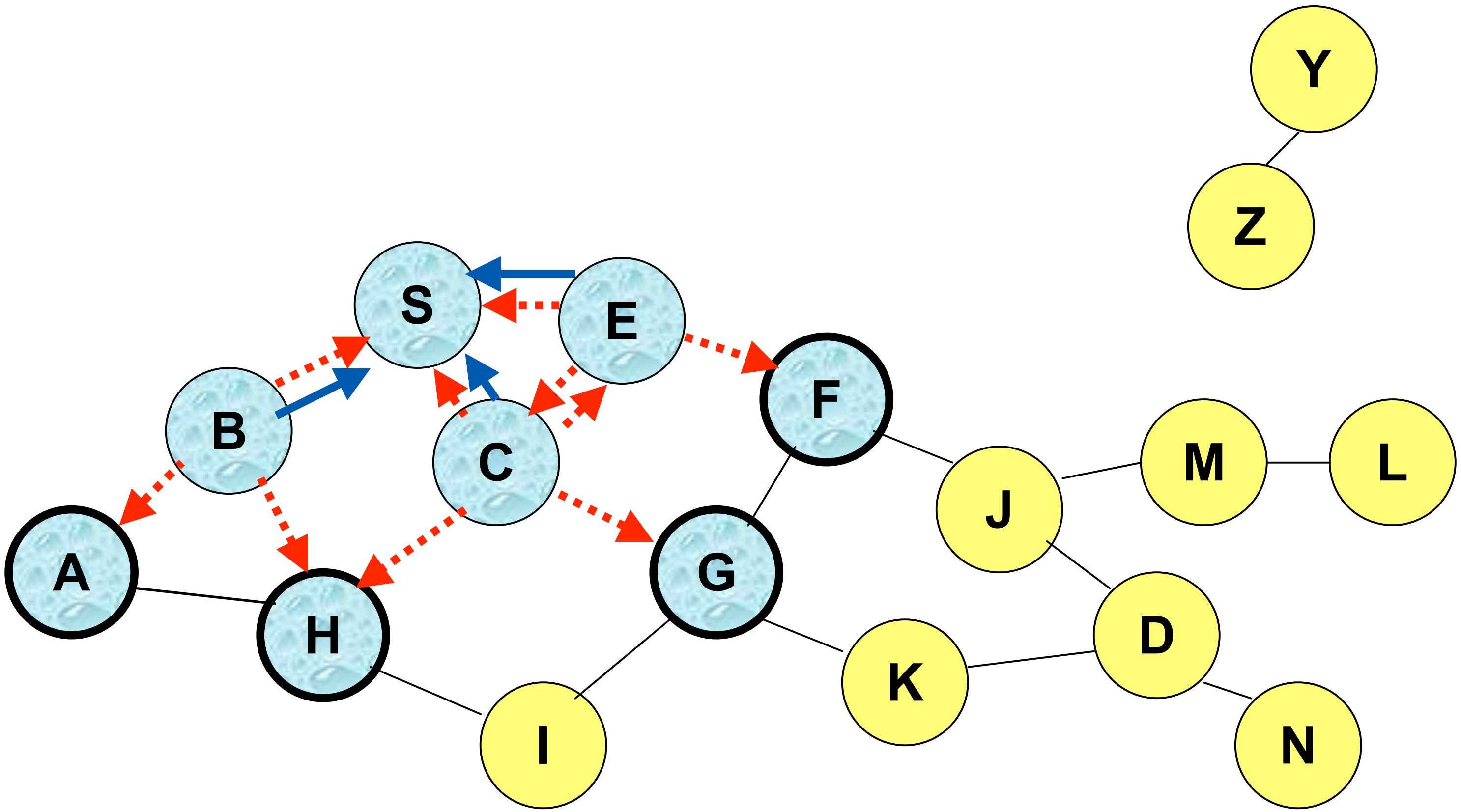
Route Requests in AODV



Route Requests in AODV



Represents links on Reverse Path

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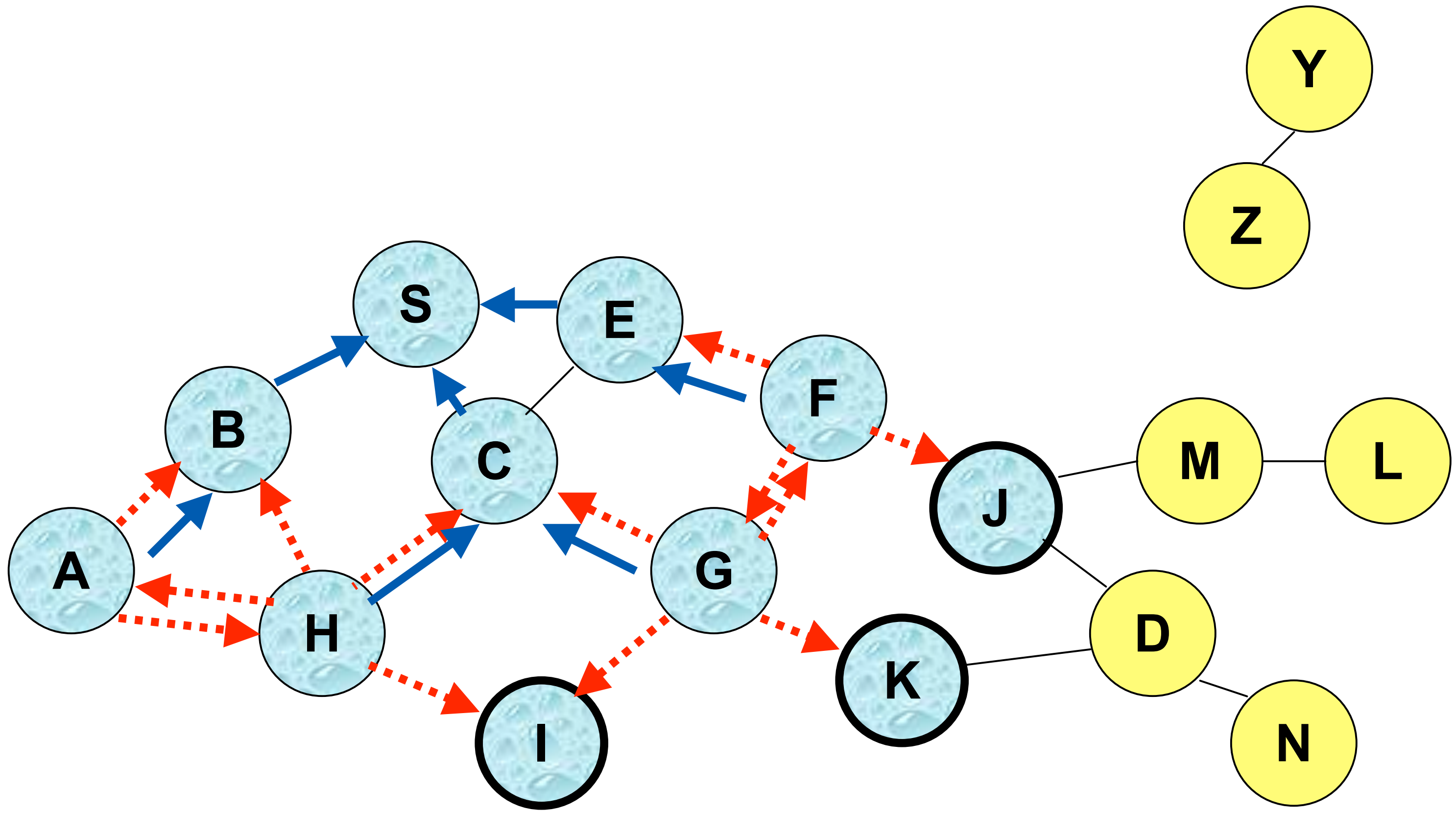
Reverse Path Setup in AODV



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

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Reverse Path Setup in AODV

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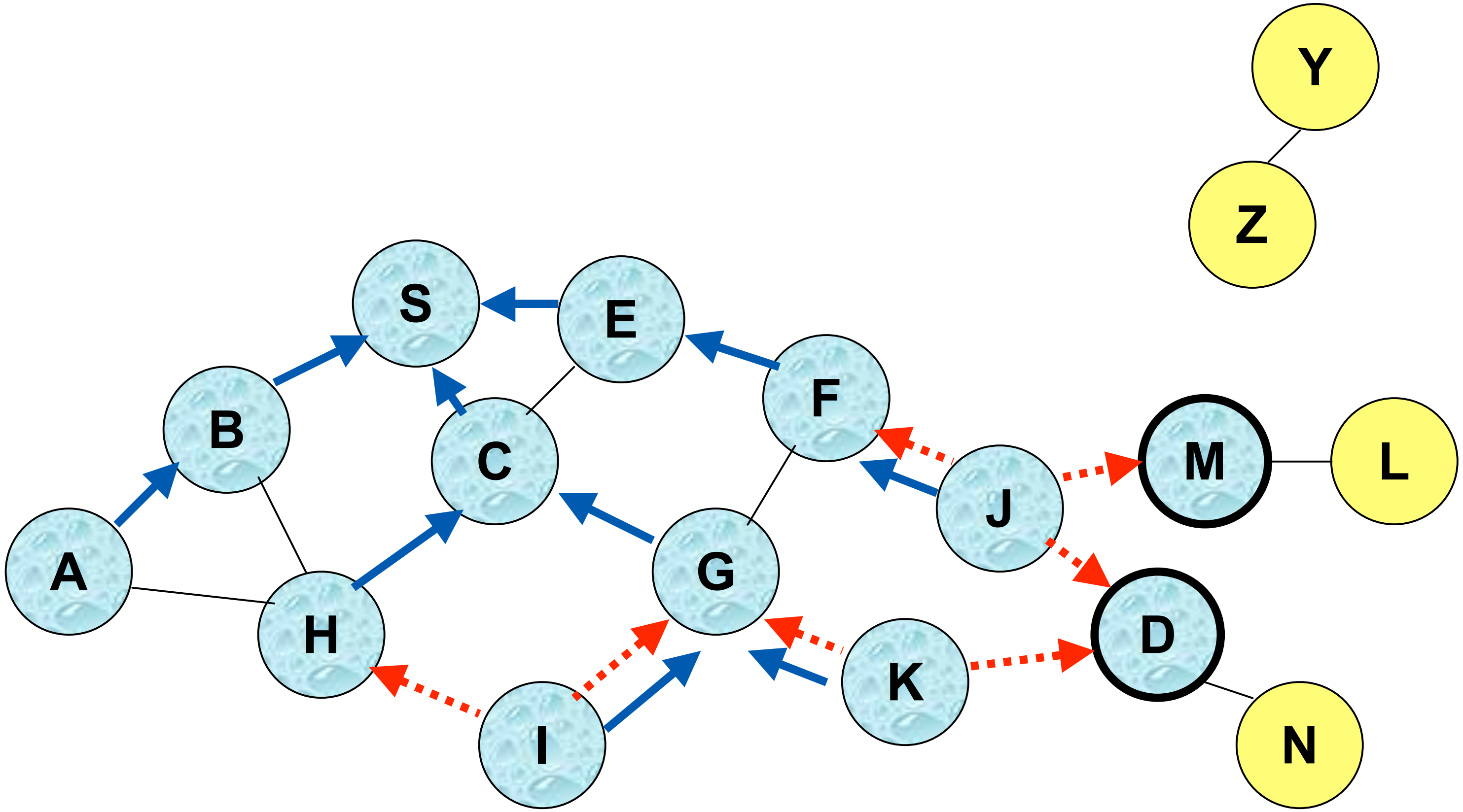

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Reverse Path Setup in AODV

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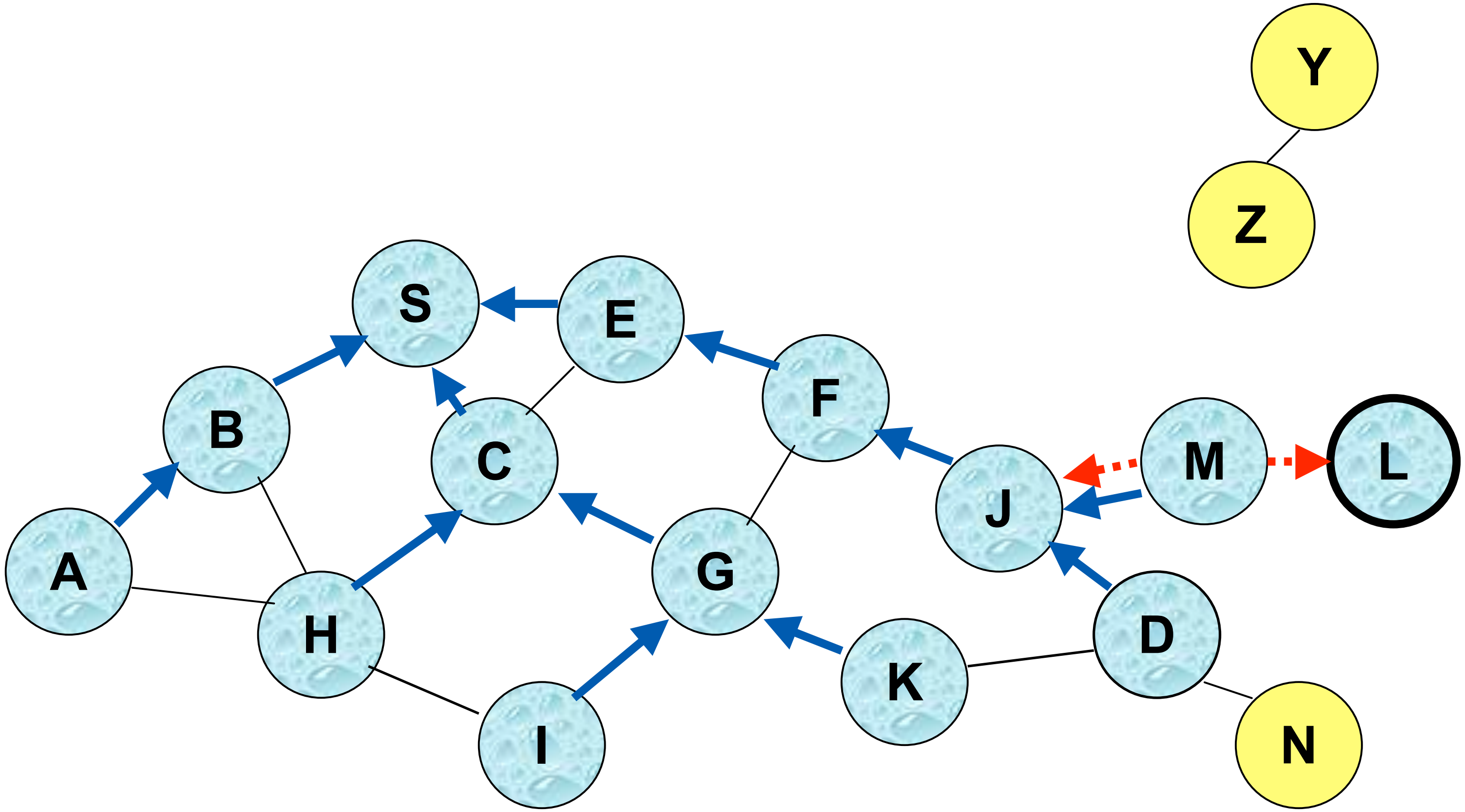

- Node D does not forward RREQ, because node D is the intended target of the RREQ

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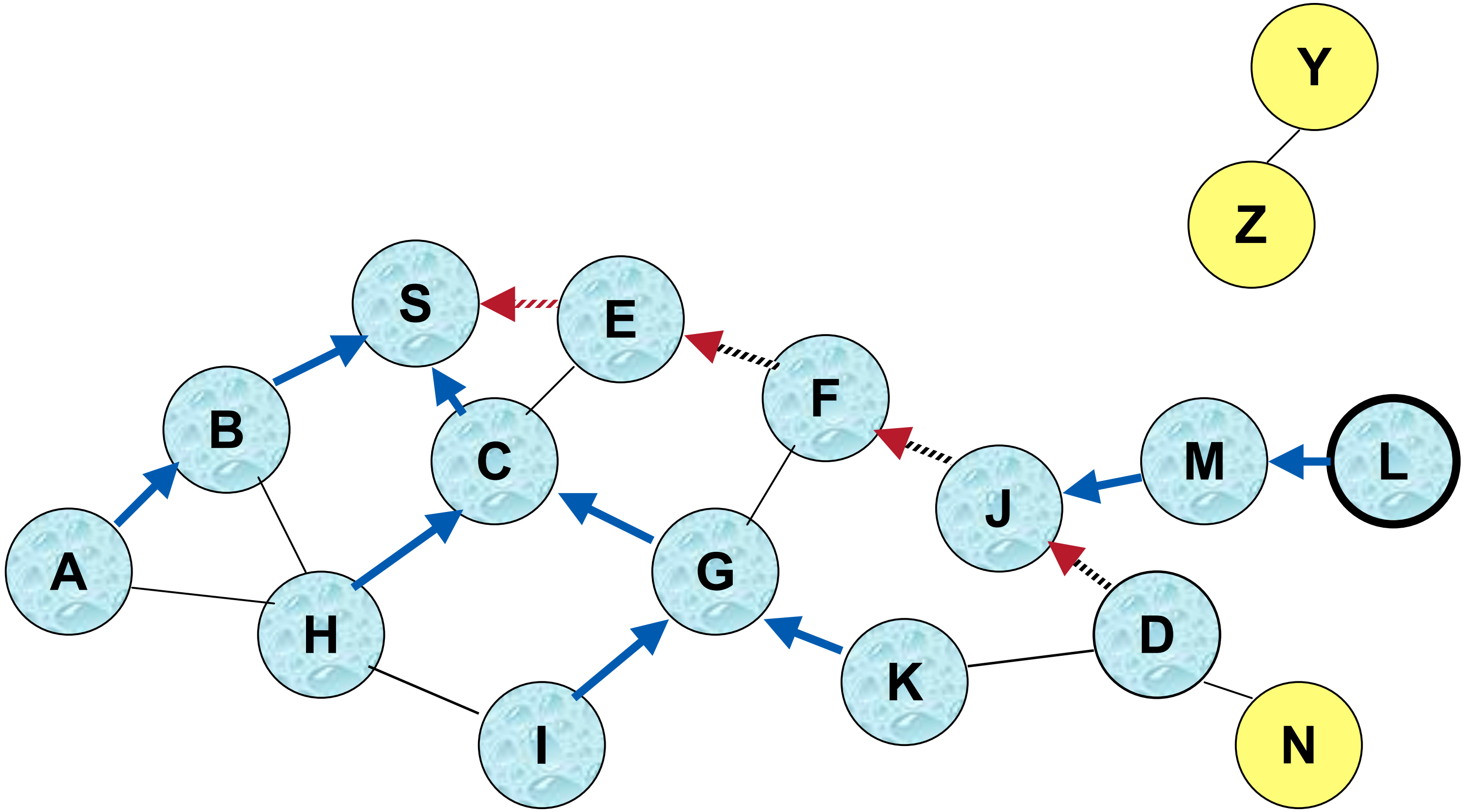
Route Reply in AODV



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 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

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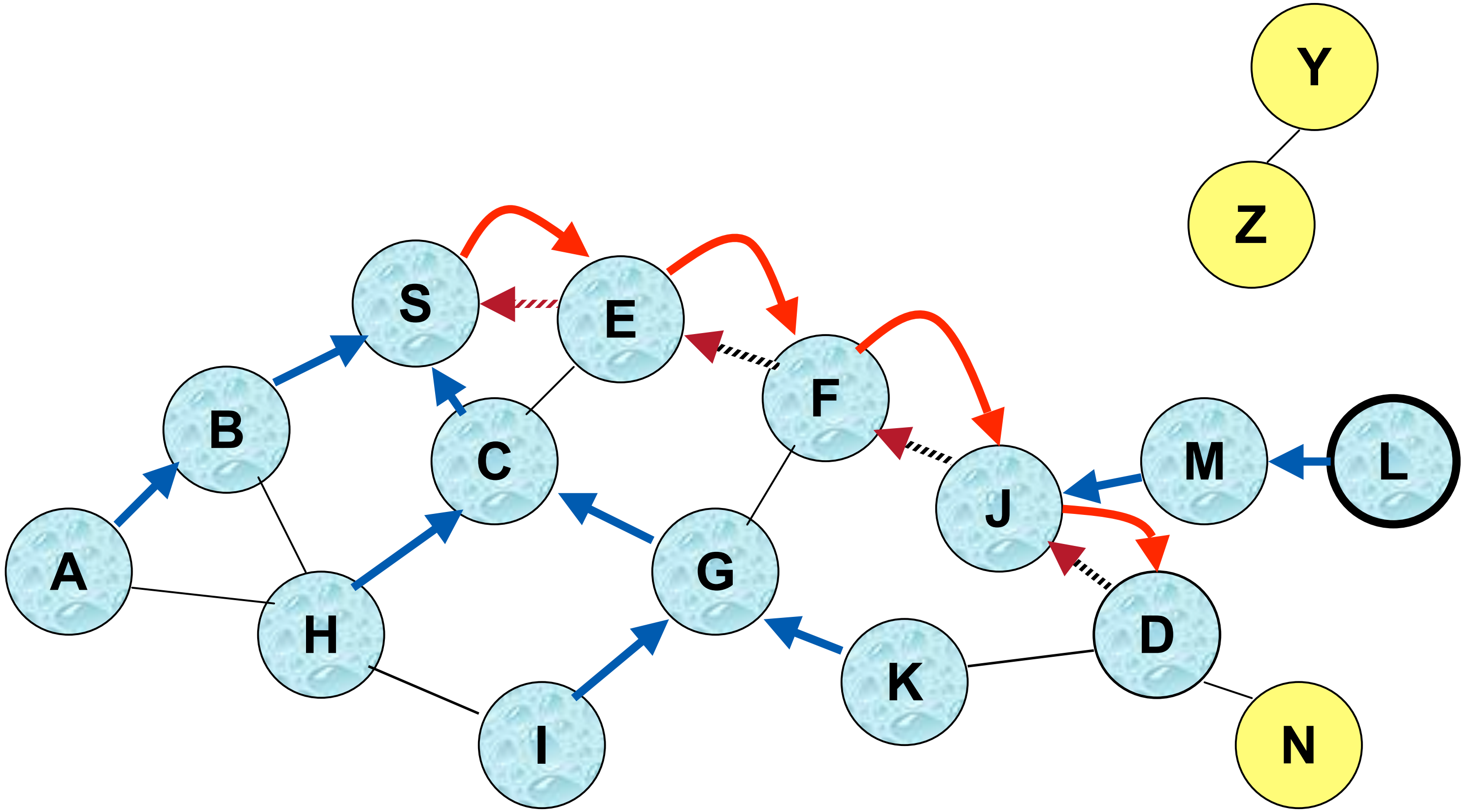
Forward Path Setup in AODV



Forward links are setup when RREP travels along the reverse path


Represents a link on the forward path

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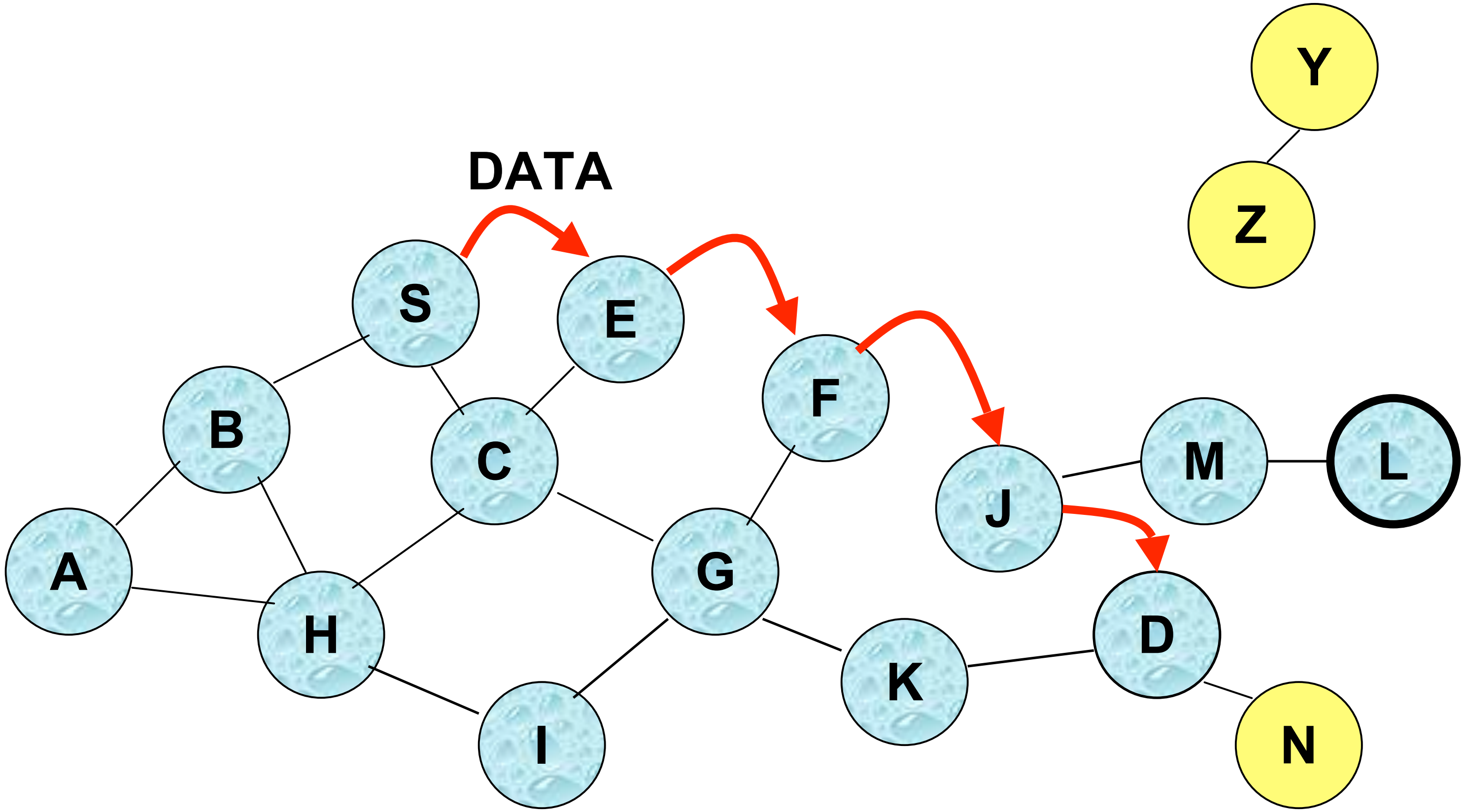
Data Delivery in AODV



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

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Timeouts

- **A routing table entry maintaining a reverse path is purged after a timeout interval**
  - timeout should be long enough to allow RREP to come back

- **A routing table entry maintaining a forward path is purged if *not used* for a *active_route_timeout* interval**
  - if no data is being sent using a particular routing table entry, that entry will be deleted from the routing table (even if the route may actually still be valid)

Link Failure Reporting

- A neighbor of node X is considered active for a routing table entry if the neighbor sent a packet within *active_route_timeout* interval which was forwarded using that entry
- When the next hop link in a routing table entry breaks, all active neighbors are informed
- Link failures are propagated by means of Route Error messages, which also update destination sequence numbers

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Route Error

- **When node X is unable to forward packet P (from node S to node D) on link (X,Y), it generates a RERR message**
- **Node X increments the destination sequence number for D cached at node X**
- **The incremented sequence number *N* is included in the RERR**
- **When node S receives the RERR, it initiates a new route discovery for D using destination sequence number at least as large as *N***

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Link Failure Detection

- *Hello* messages: Neighboring nodes periodically exchange hello message
- Absence of hello message is used as an indication of link failure
- Alternatively, failure to receive several MAC-level acknowledgement may be used as an indication of link failure
- When node D receives the route request with destination sequence number N, node D will set its sequence number to N, unless it is already larger than N

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Why Sequence Numbers in AODV

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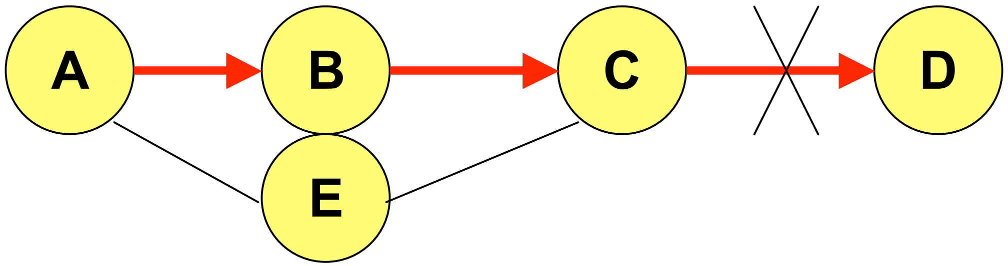
- **To avoid using old/broken routes**
  - To determine which route is newer

- **To prevent formation of loops**



  - Assume that A does not know about failure of link C-D because RERR sent by C is lost
  - Now C performs a route discovery for D. Node A receives the RREQ (say, via path C-E-A)
  - Node A will reply since A knows a route to D via node B
  - Results in a loop (for instance, C-E-A-B-C)

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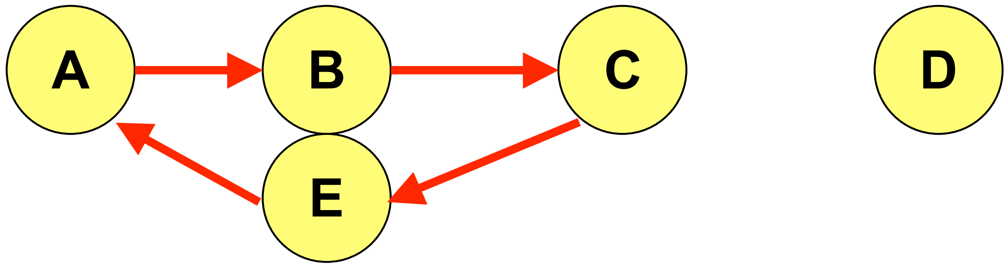

– Loop C-E-A-B-C

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Optimization: Expanding Ring Search

- **Route Requests are initially sent with small Time-to-Live (TTL) field, to limit their propagation**
  - DSR also includes a similar optimization
- **If no Route Reply is received, then larger TTL tried**

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**

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Thank you!

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8th Week
13.06.2007