CS 439: Wireless Networking

Multihop and Infrastructureless Wireless Networks

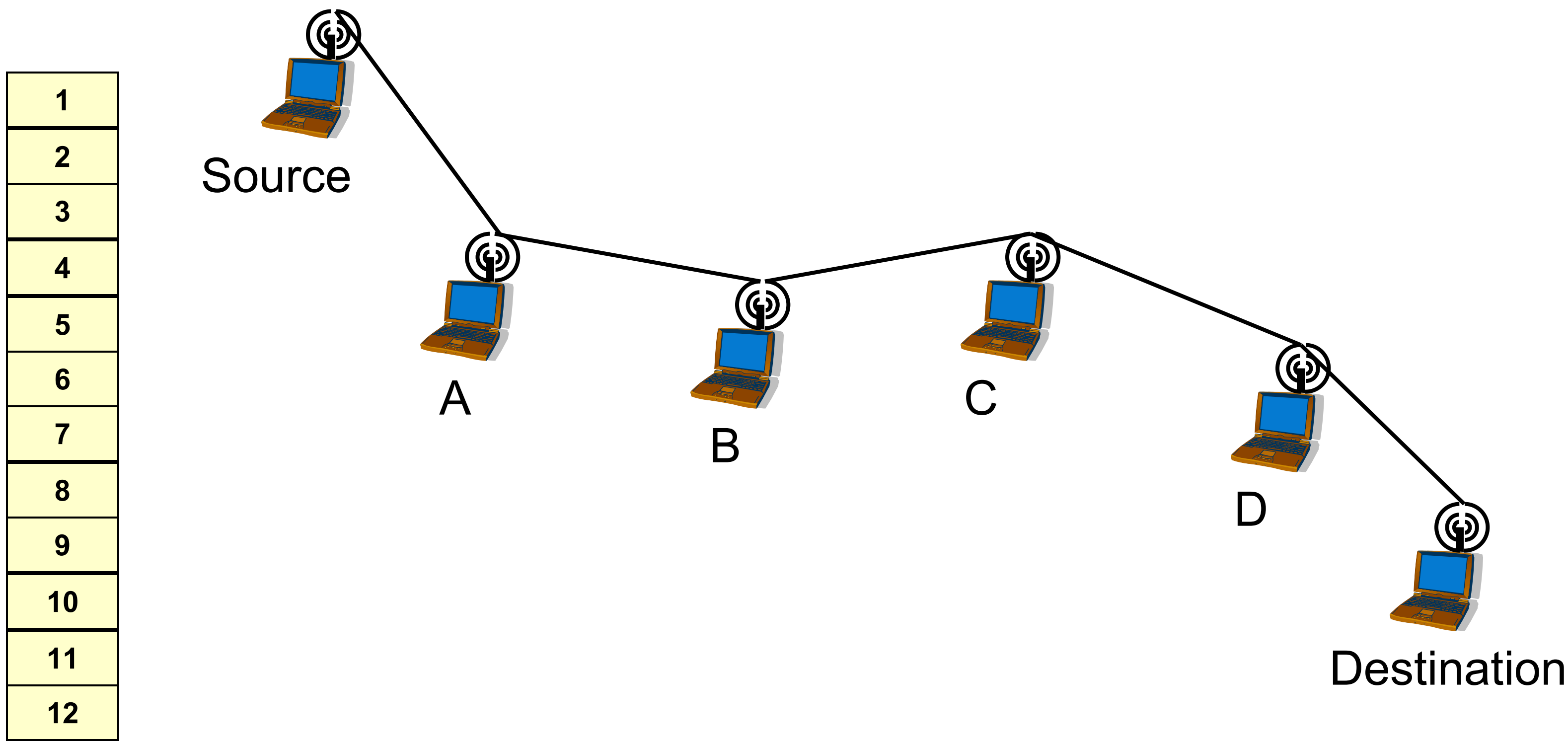
 Fall 2024

Wireless Multihop Networks

- Vehicular Networks
  - Delay Tolerant (batch) sending over several hops carry data to a base station
- Common in Sensor Network for periodically transmitting data
  - Infrastructure Monitoring
    - E.g., structural health monitoring of the Golden Gate Bridge
- Multihop networking for Internet connection sharing
  - Routing traffic over several hops to base station connected to Internet

Multi-Hop Wireless Networks

- In an ideal world …



Multi-Hop Wireless Networks

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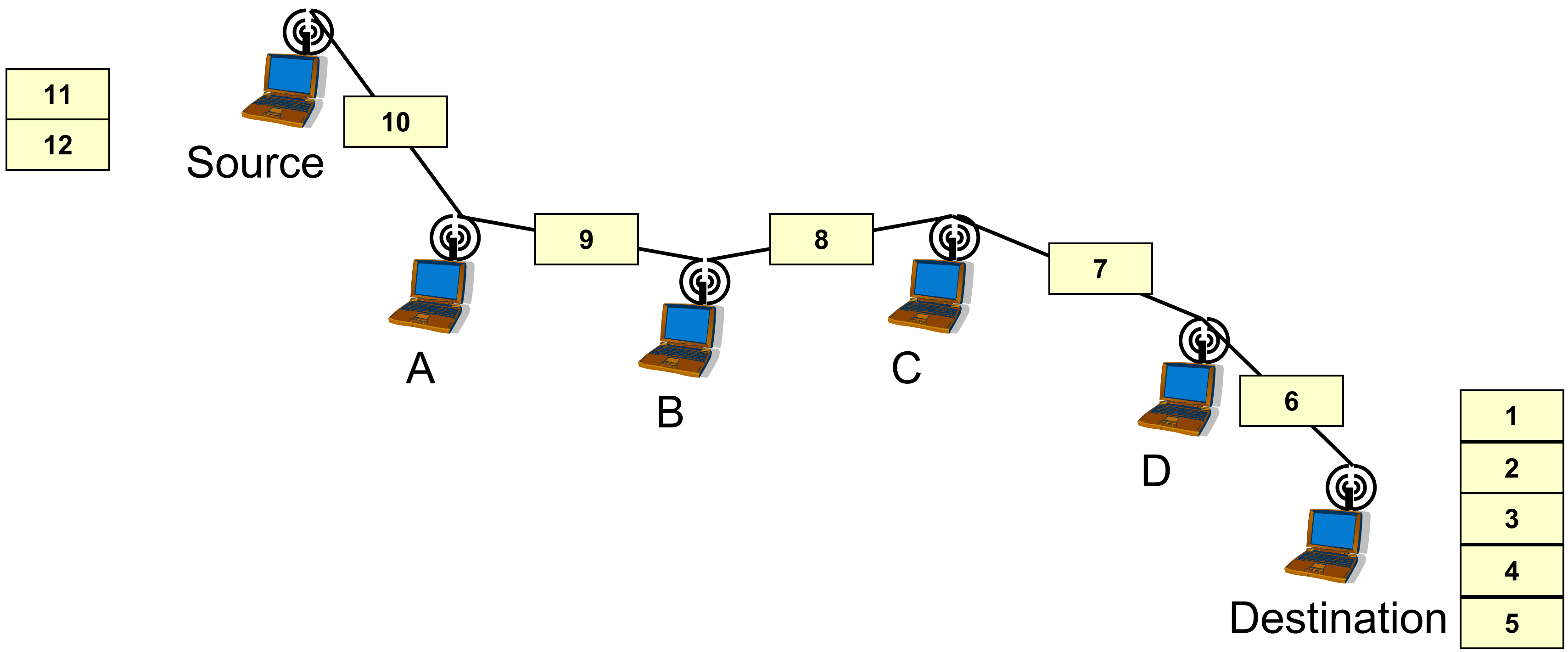
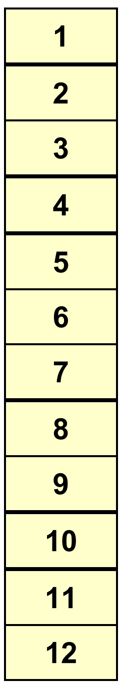
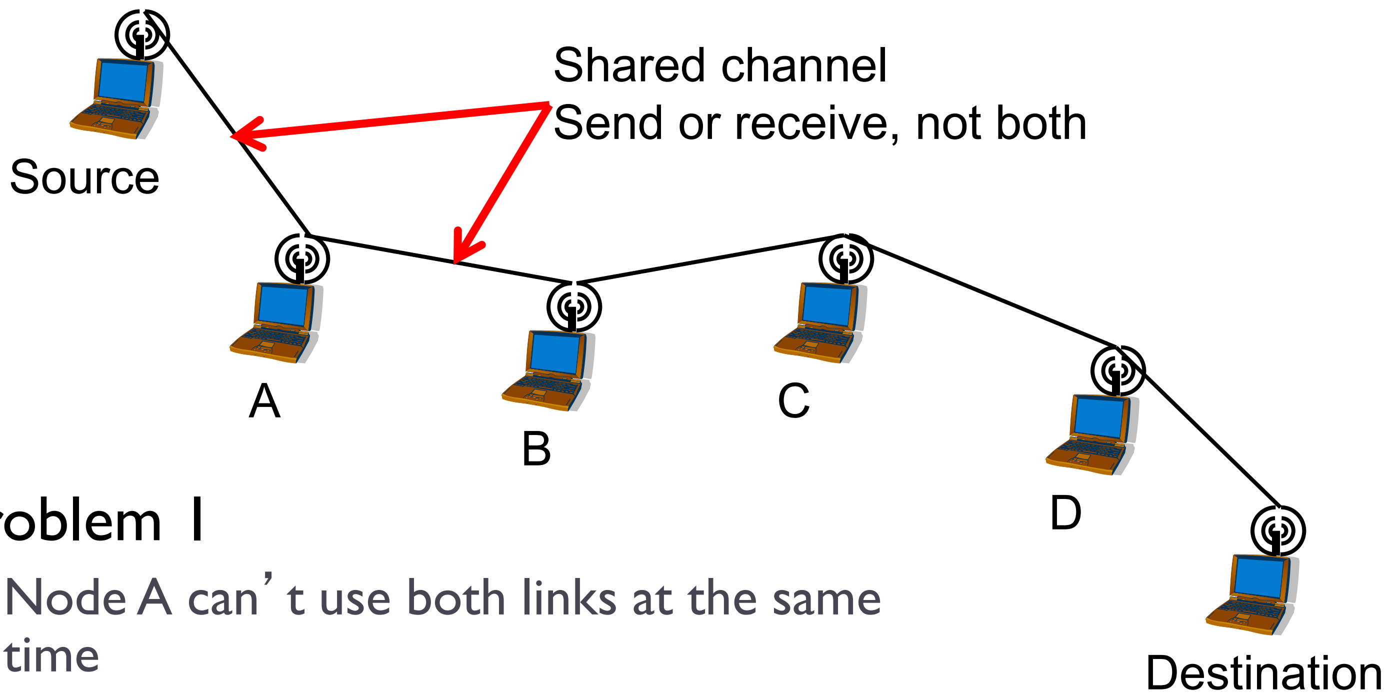


Multi-Hop Wireless Networks

- Reality check …



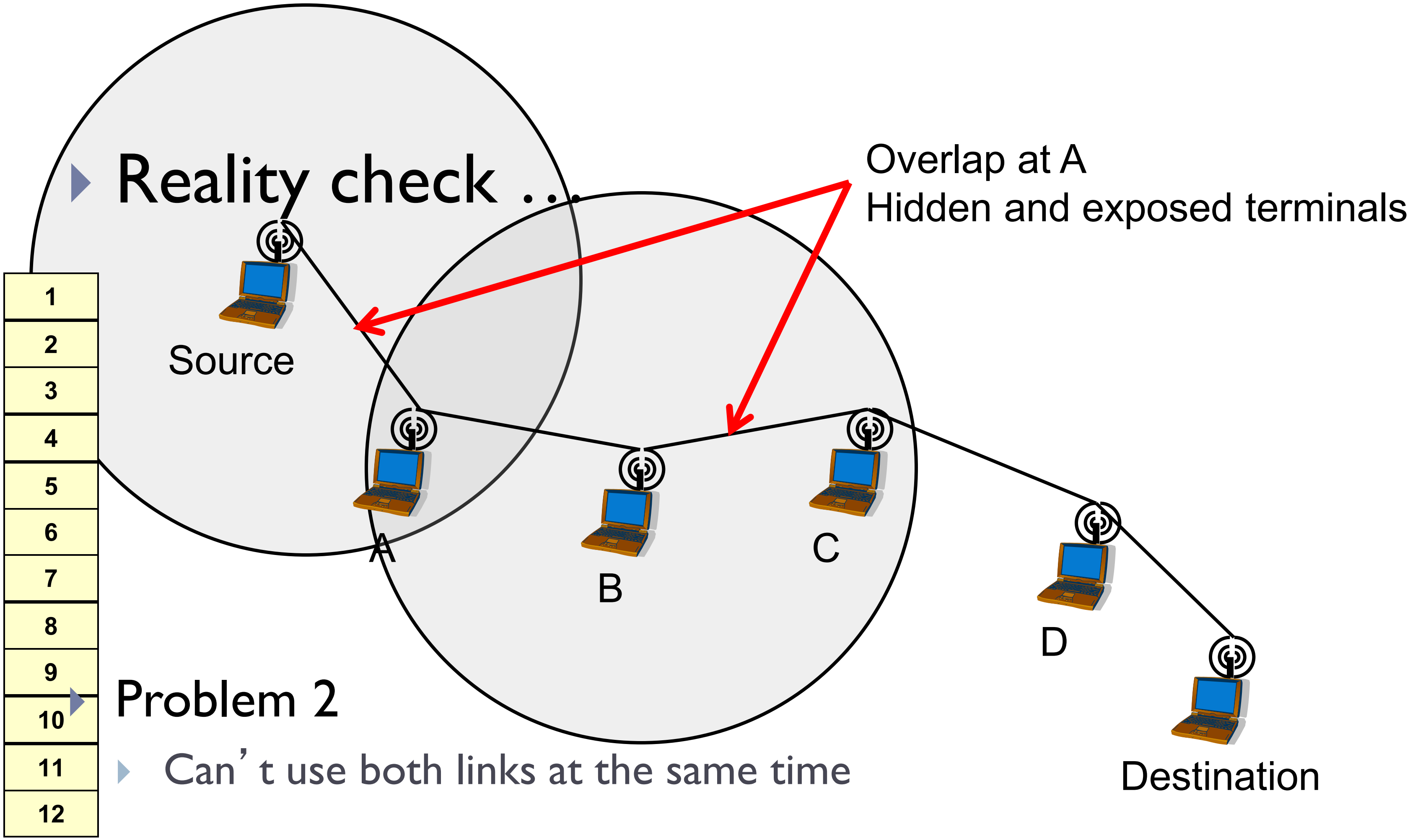


Problem 1

- Node A can't use both links at the same time

Multi-Hop Wireless Networks

- Reality check …

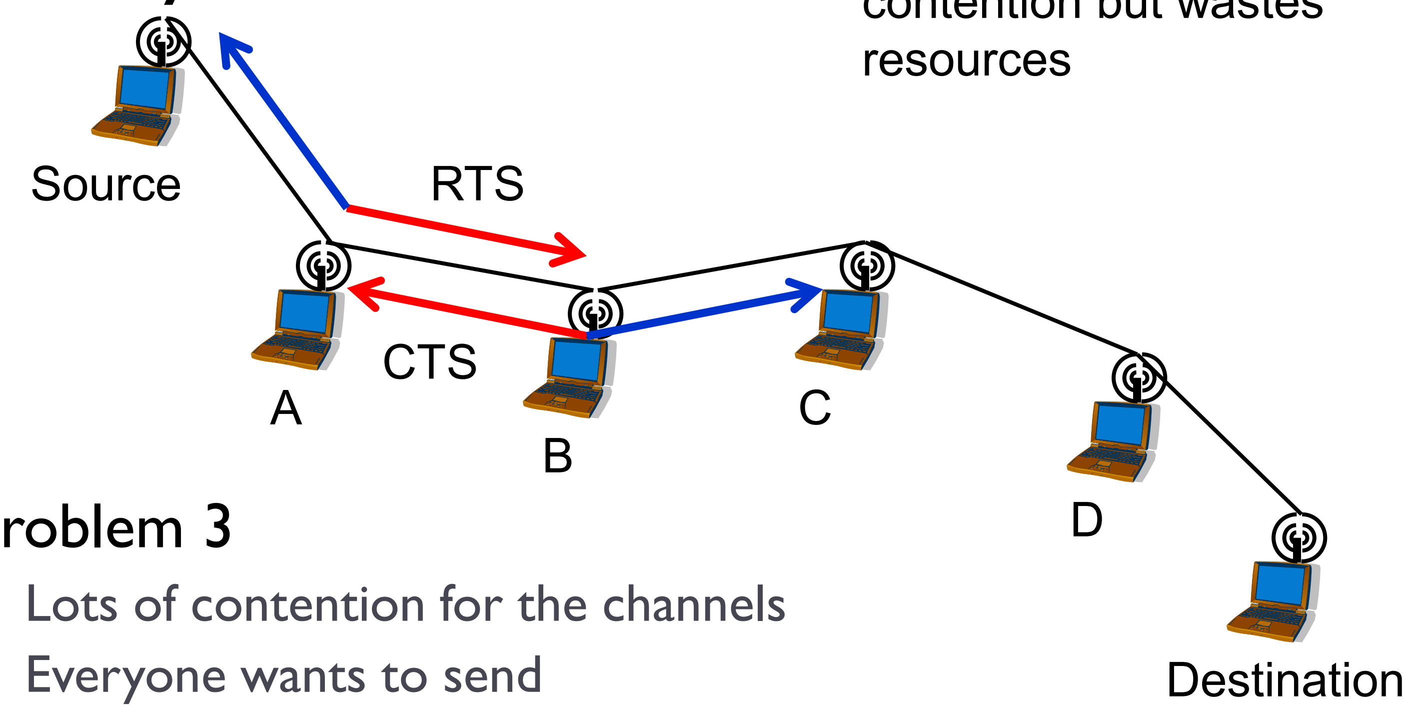


- Problem 2
  - Can't use both links at the same time

Multi-Hop Wireless Networks

- Reality check …

RTS/CTS helps with contention but wastes resources



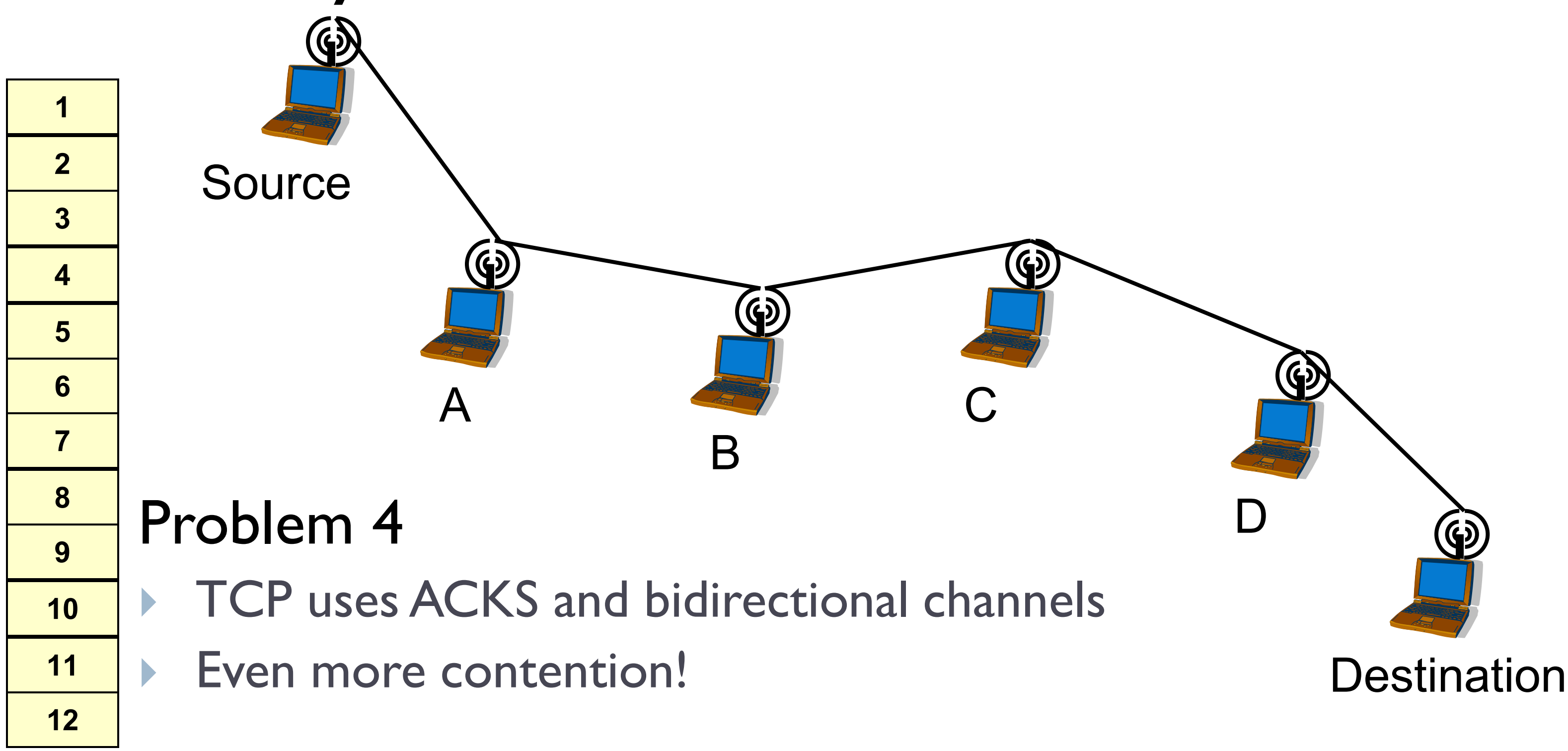
Problem 3

- Lots of contention for the channels
- Everyone wants to send

Multi-Hop Wireless Networks

- Reality check …

Higher layer protocols



Problem 4

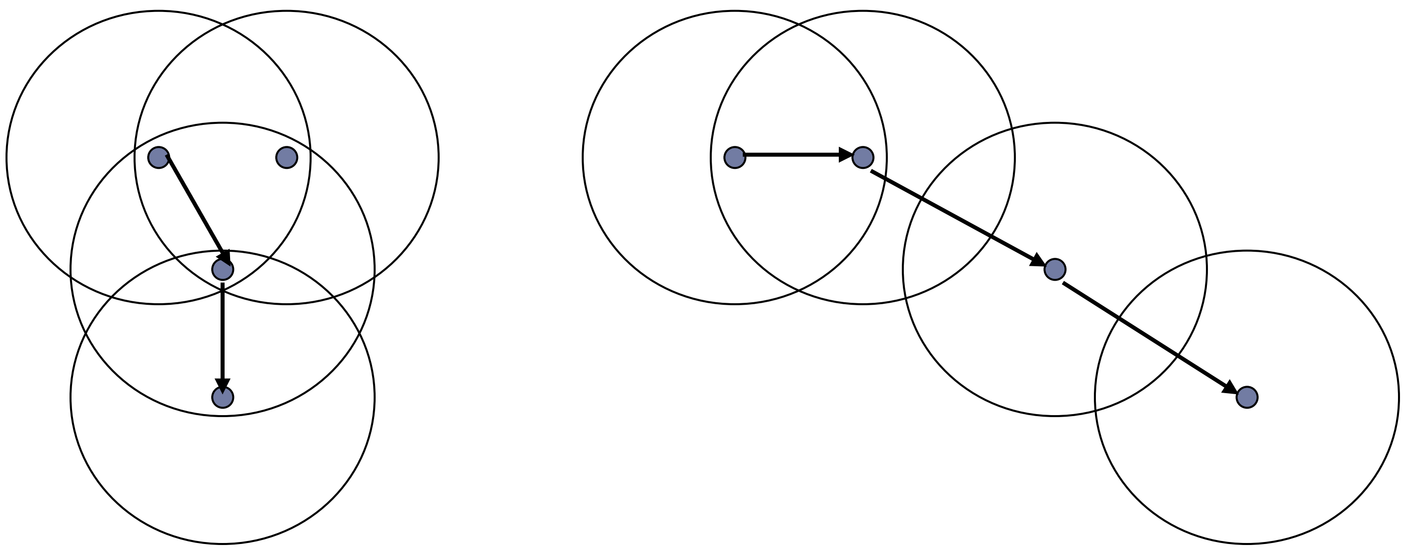
- TCP uses ACKS and bidirectional channels
- Even more contention!

When the network just isn't there …

- Ad hoc networks
  - Group of cooperating nodes
  - Nodes are mobile
  - Paths eventual exist between a src/dst pair
  - All nodes are routers
- Sensor networks
  - Similar to ad hoc networks
  - Nodes are typically non-mobile
  - Target long operating lifetimes
- Opportunistic networks
  - Nodes are mobile
  - Paths may never exist between a src/dst pair
  - Store-carry-forward

Ad Hoc Networks

- Formed by wireless hosts that may be mobile
- Without (necessarily) using a pre-existing infrastructure
- Routes between nodes may potentially contain multiple hops
  - Mobility causes route changes



Why Ad Hoc Networks ?

- Ease of deployment
- Speed of deployment
- Decreased dependence on infrastructure

Many Variations

- Fully Symmetric Environment
  - All nodes have identical capabilities and responsibilities
- Asymmetric Capabilities
  - Transmission ranges and radios may differ
  - 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)

Many Variations

- Traffic characteristics may differ in different ad hoc networks
  - Bit rate
  - Timeliness constraints
  - Reliability requirements
  - Unicast / multicast / geocast
  - Host-based addressing / content-based addressing / capability-based addressing
- May co-exist (and co-operate) with an infrastructure-based network

Many Variations

- Mobility characteristics
  - Speed
  - Predictability
    - Direction of movement
    - Pattern of movement
  - Uniformity (or lack thereof) of mobility characteristics among different nodes

Challenges

- Limited wireless transmission range
- Broadcast nature of the wireless medium
  - Hidden terminal problem
- Packet losses due to transmission errors
- Mobility-induced route changes
- Mobility-induced packet losses
- Battery constraints
- Potentially frequent network partitions
- Ease of snooping on wireless transmissions

The Holy Grail

- A one-size-fits-all solution
  - Perhaps using an adaptive/hybrid approach that can adapt to situation at hand
- Difficult problem
- Many solutions proposed trying to address a sub-space of the problem domain

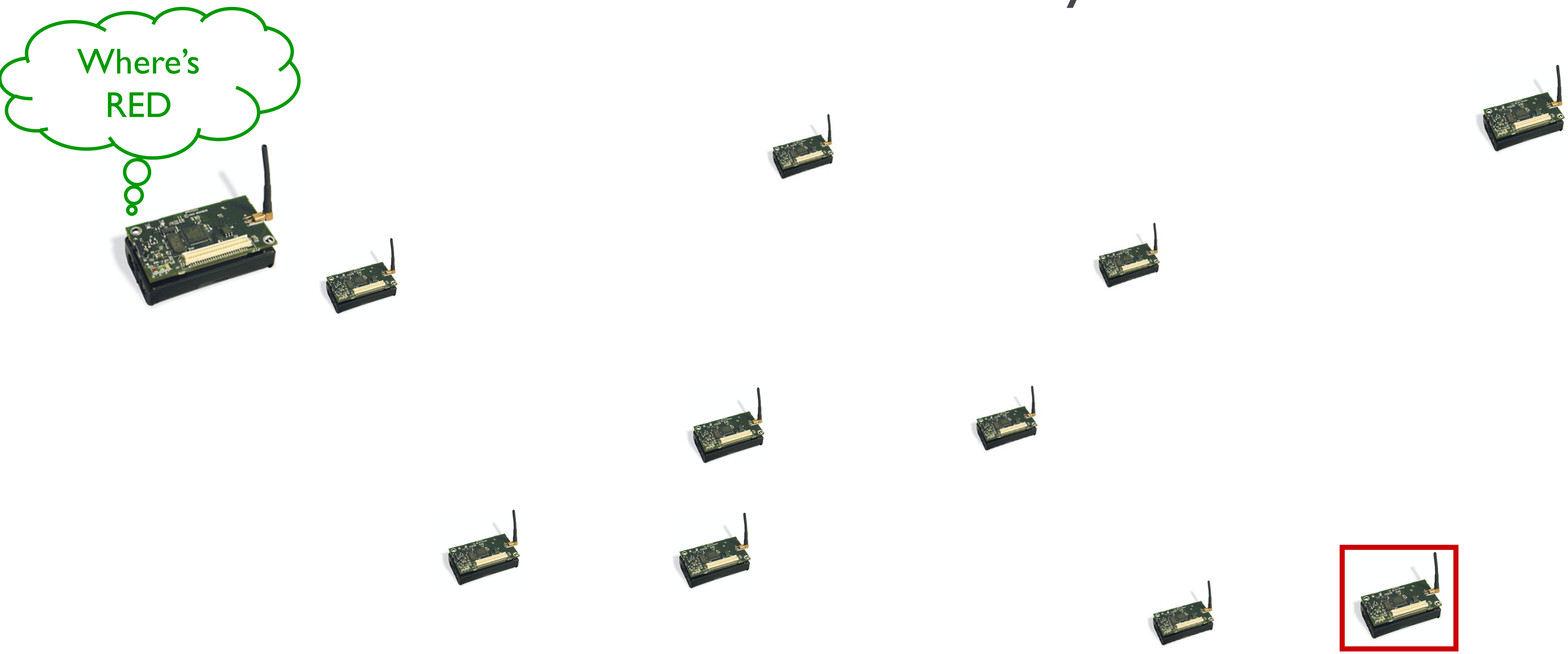
Unicast Routing in Ad Hoc Networks

Why is routing in wireless ad hoc networks different/difficult?

- Link instability causes many routing issues
  - Shortest hop routing often worst choice
  - Scarce bandwidth makes overhead conspicuous
  - Battery power a concern
  - Security and misbehavior …
- 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

Routing in Mobile Networks

- Imagine hundreds of hosts moving
  - Routing algorithm needs to cope up with varying wireless channel and node mobility



Unicast Routing Protocols

- Many protocols have been proposed
  - Some have been invented specifically for ad hoc networks
  - Others are adapted from wired network routing

- No single protocol works well in all environments
  - Some attempts made to develop adaptive protocols

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
  - Maintain routes to nearby nodes
  - Discover routes for far away nodes

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

Trade-Off

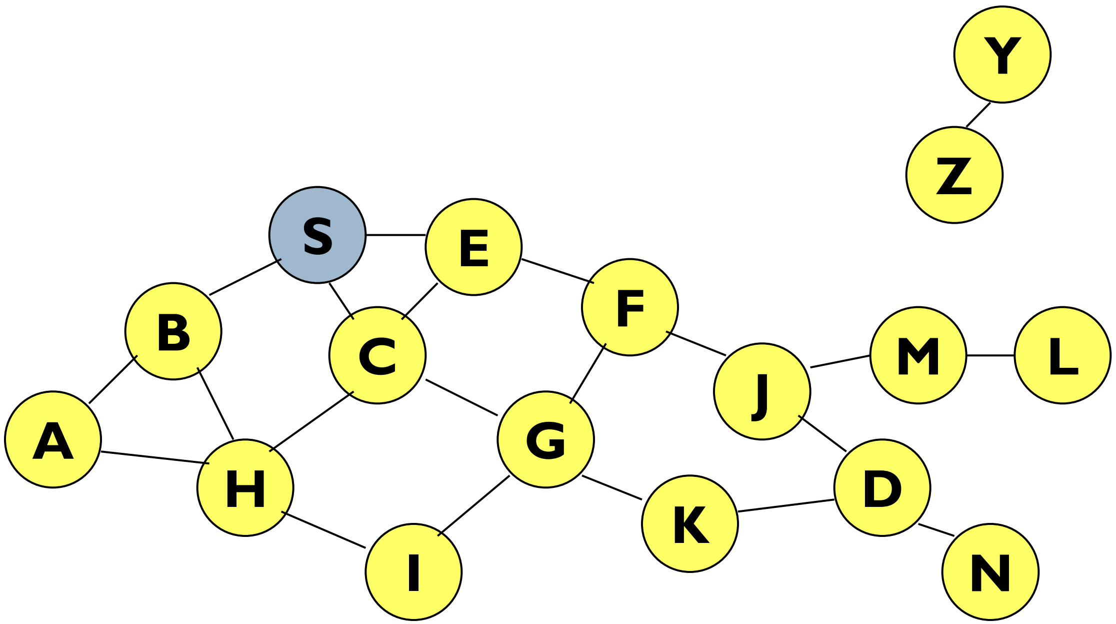
- Overhead of route discovery/maintenance
  - Reactive protocols
    - May have lower overhead since routes are determined only if needed
  - Proactive protocols
    - Can (but not necessarily) result in higher overhead due to continuous route updating

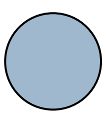
- Which approach achieves a better trade-off depends on the traffic and mobility patterns

Flooding for Data Delivery

- Sender
  - Broadcasts data packet P to all its neighbors
- Intermediate nodes
  - Forward P to its neighbors
- Sequence numbers
  - Used to avoid the possibility of forwarding the same packet more than once
- Destination
  - Packet P reaches destination D provided that D is reachable from sender S
  - Node D does not forward the packet

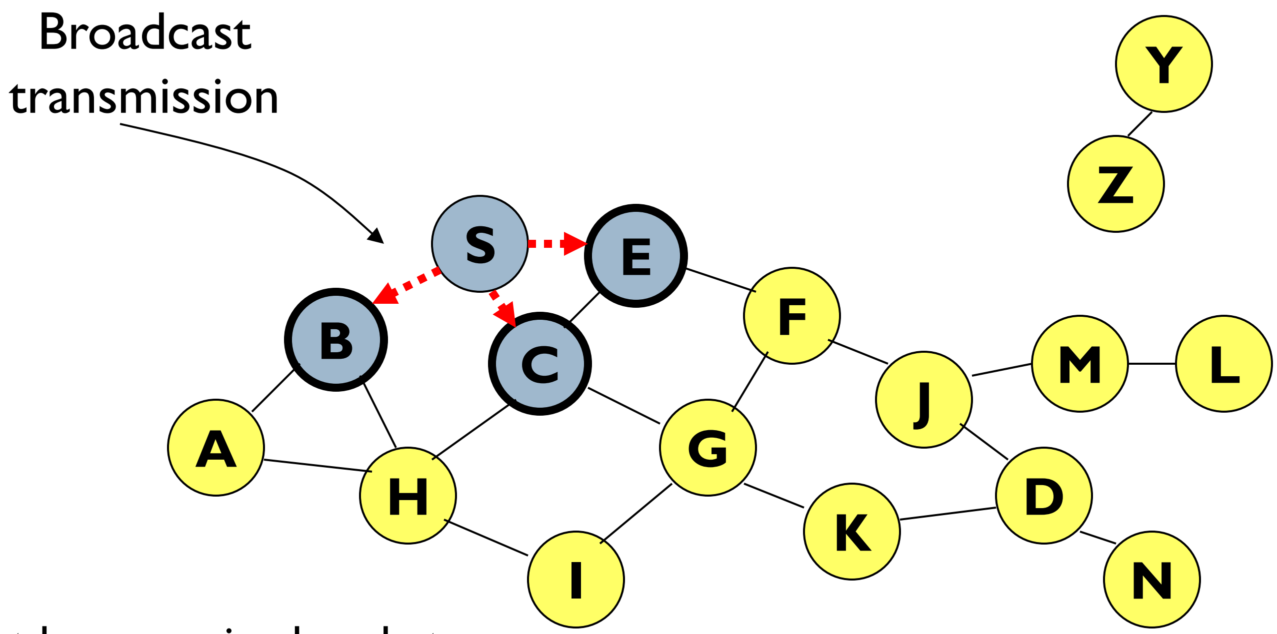
Flooding for Data Delivery

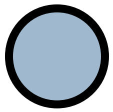




nodes that have received packet

Flooding for Data Delivery

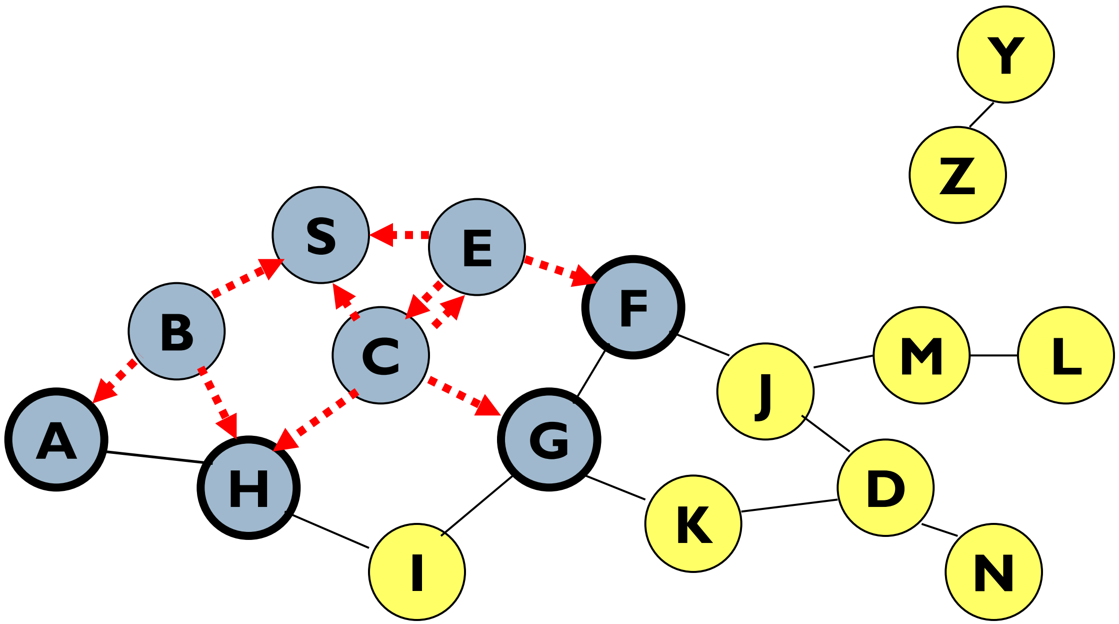




nodes that have received packet for the first time

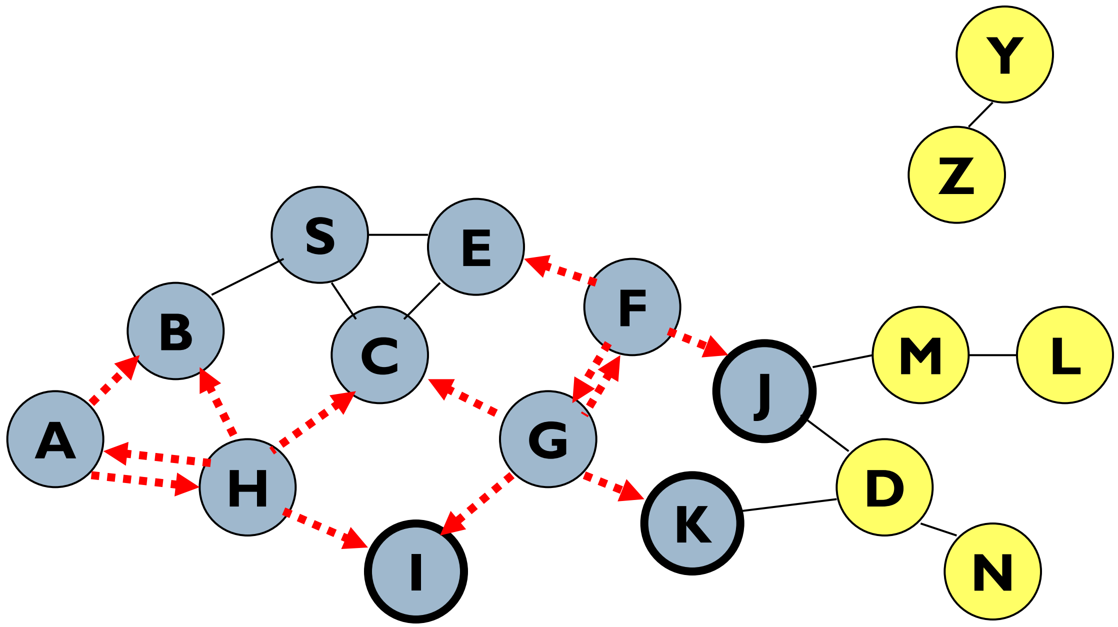
Flooding for Data Delivery

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



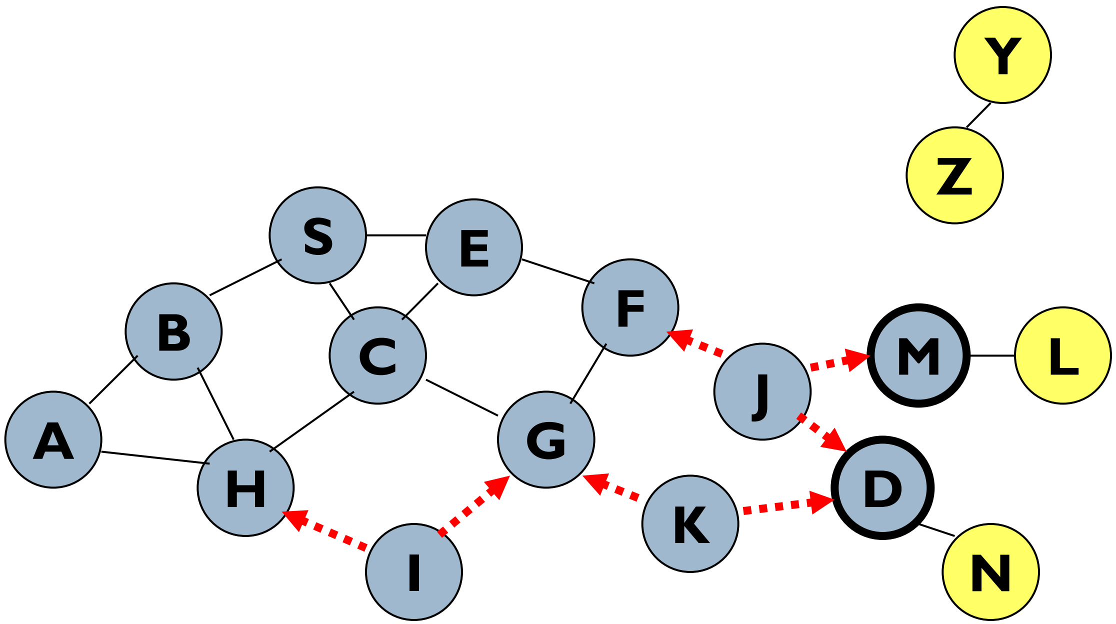
Flooding for Data Delivery

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



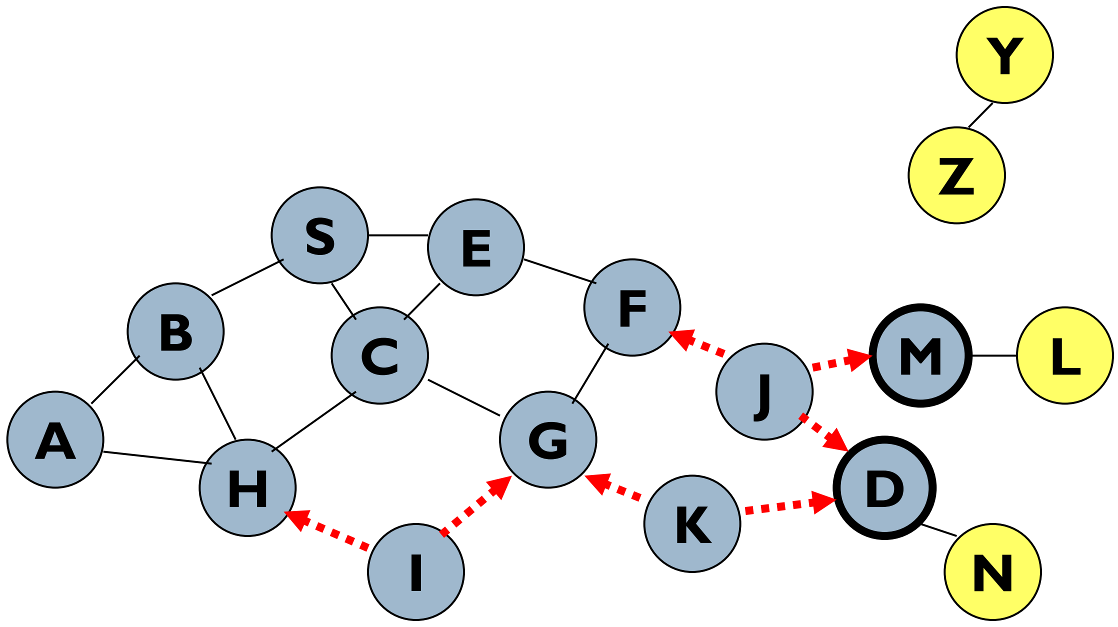
Flooding for Data Delivery

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



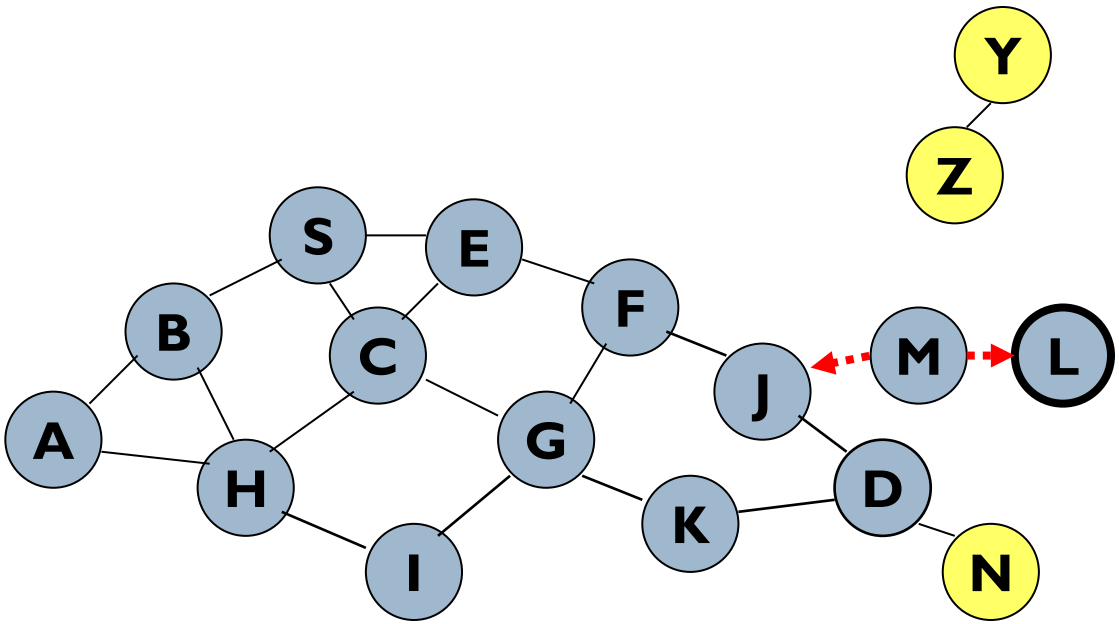
Flooding for Data Delivery

- Nodes J and K both broadcast packet to node D
  => Packet may not be delivered to node D at all, despite the use of flooding



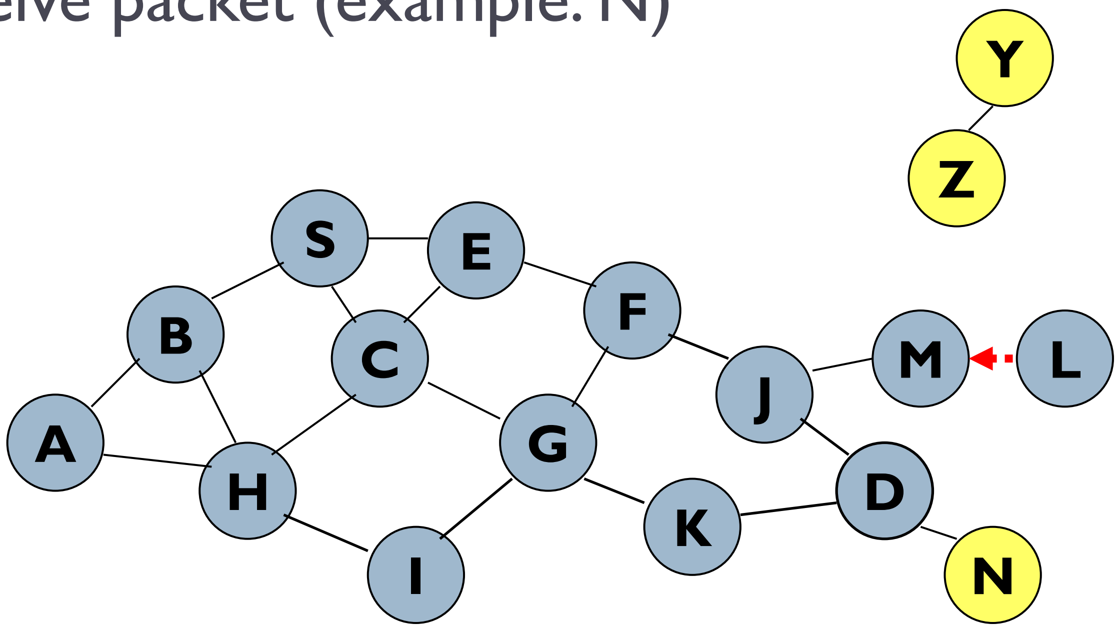
Flooding for Data Delivery

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



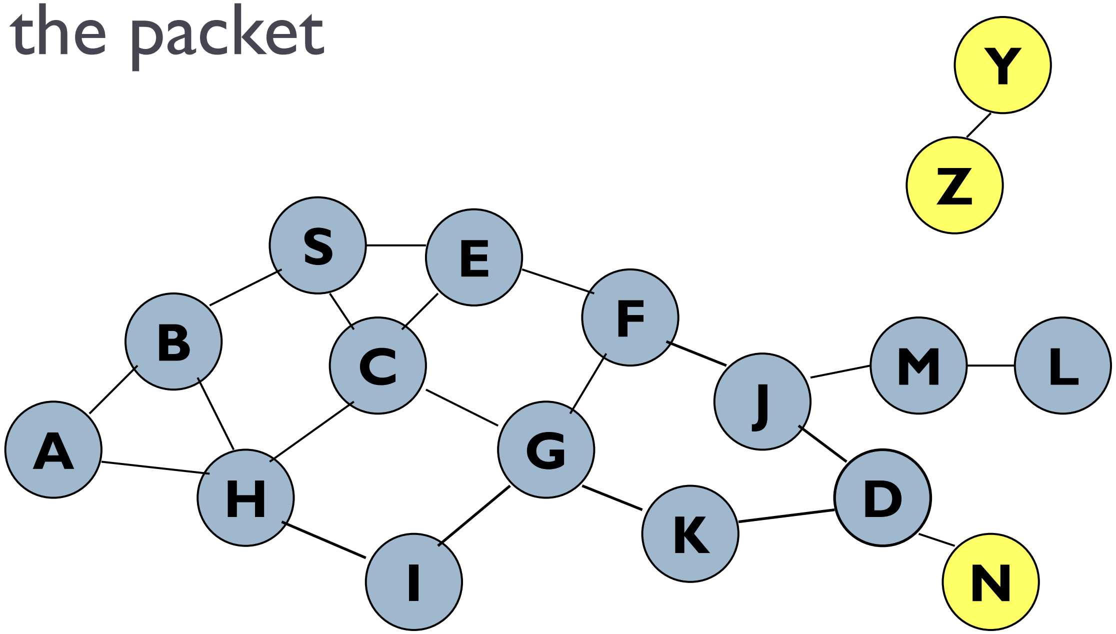
Flooding for Data Delivery

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



Flooding for Data Delivery

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



Flooding for Data Delivery: Advantages

- Simplicity
- Efficiency
  - Low rate of information transmission
    - Overhead of explicit route discovery/maintenance incurred by other protocols is relatively higher
    - For example, 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
      - Broadcast in IEEE 802.11 MAC is unreliable
    - e.g., 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

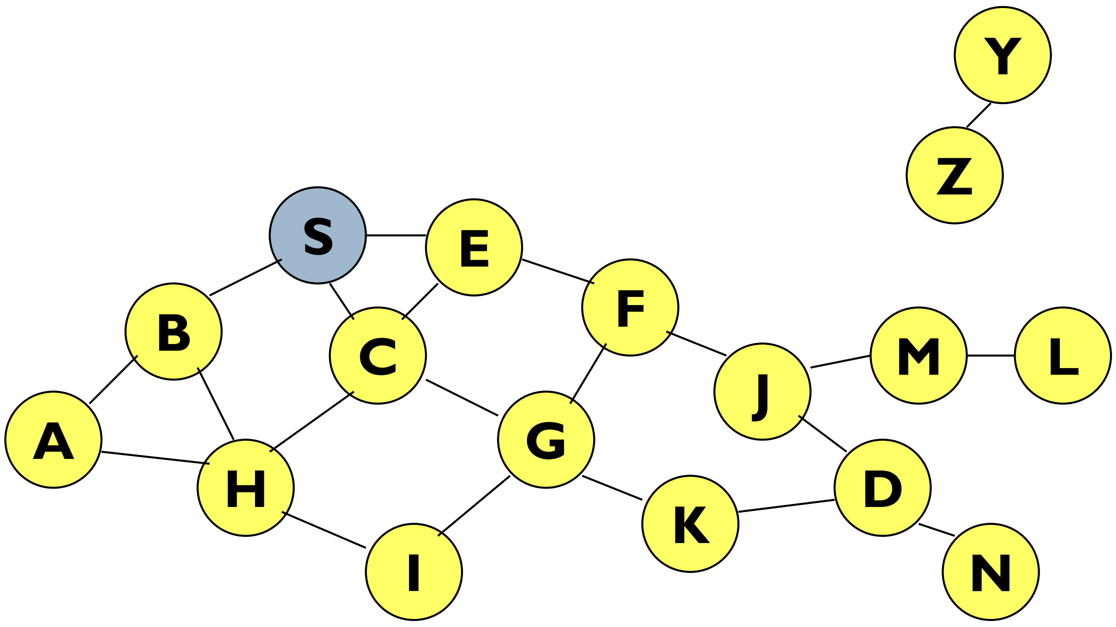
Flooding of Control Packets

- 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)

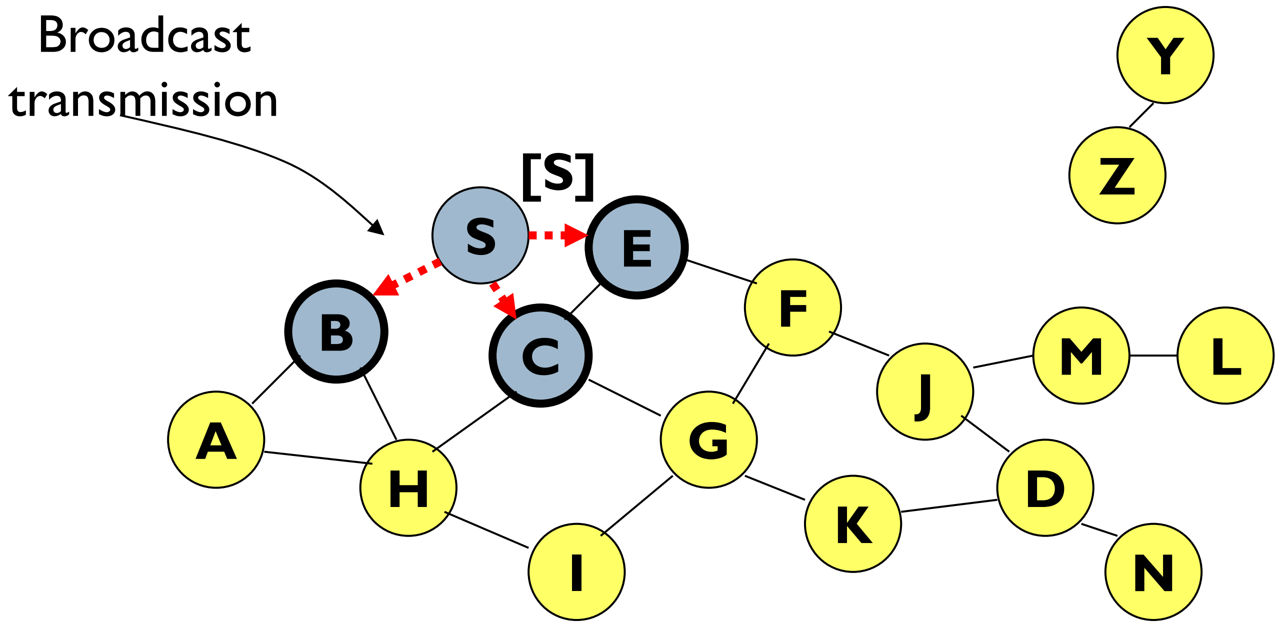
- Route Discovery
  - When node S wants to send a packet to node D, but does not know a route to D, node S initiates a route discovery
  - Source node S floods Route Request (RREQ)
  - Each node appends own identifier when forwarding RREQ

Route Discovery in DSR



Route Discovery in DSR

- [X,Y]: list of identifiers appended to RREQ



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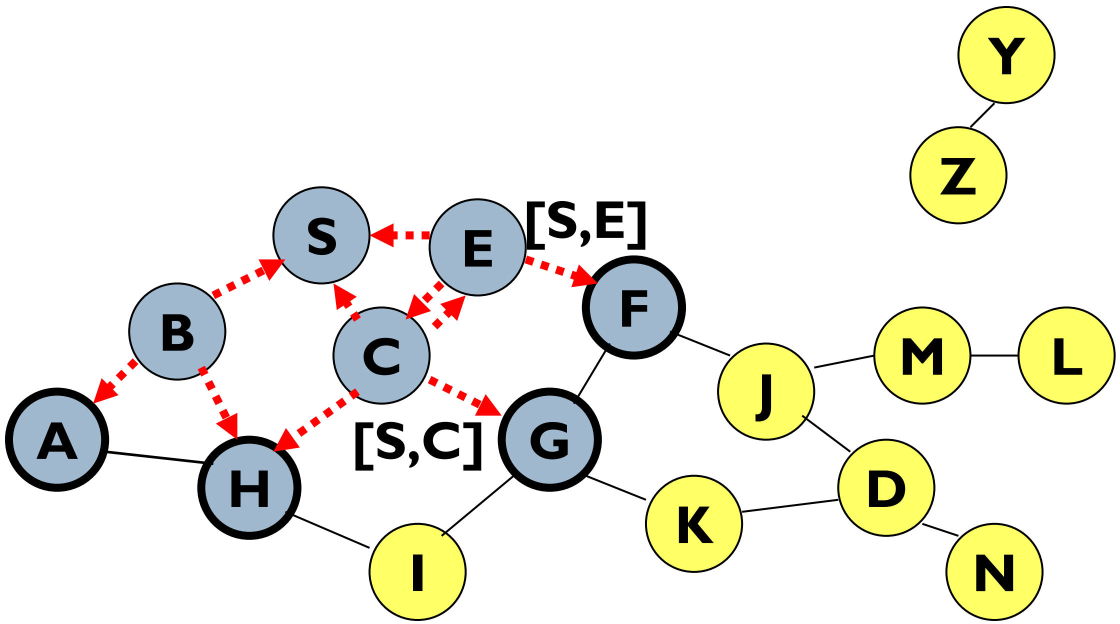

Route Discovery in DSR

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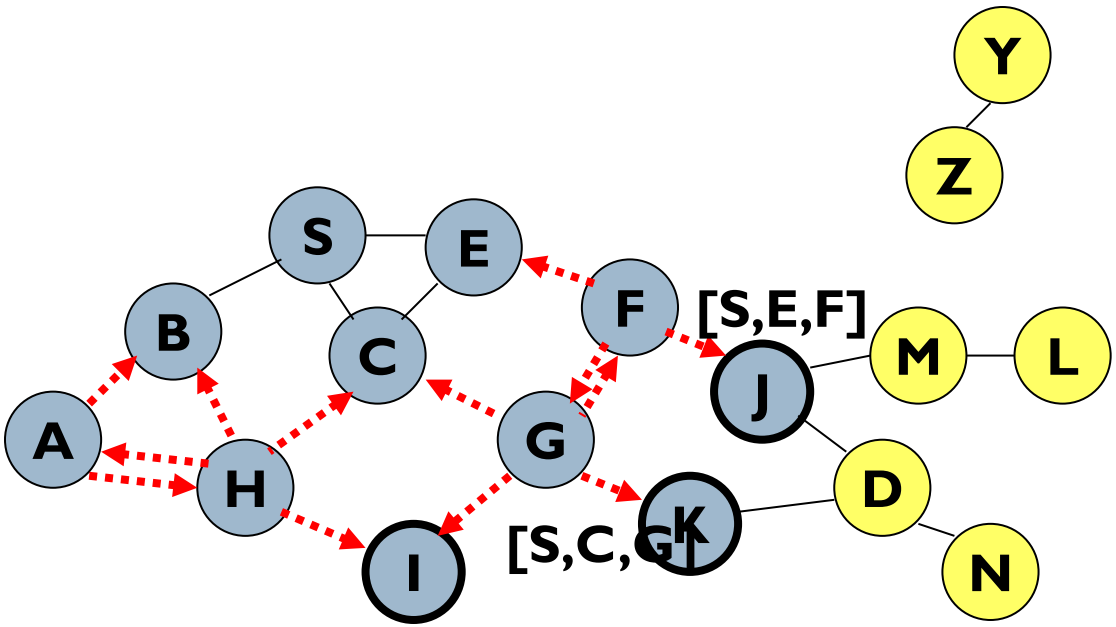

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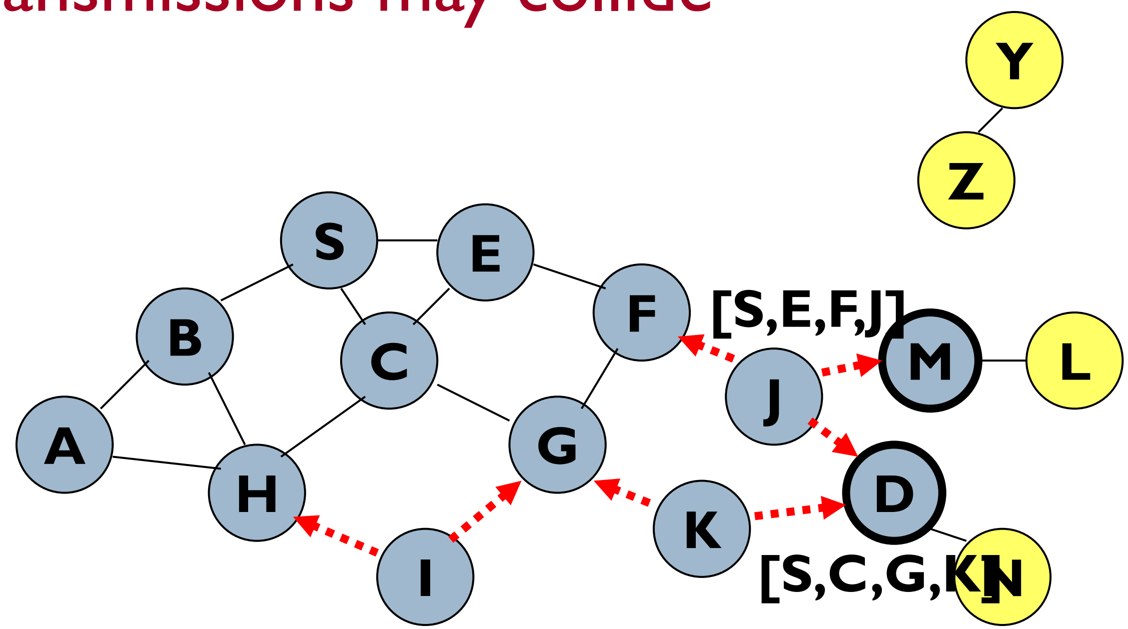
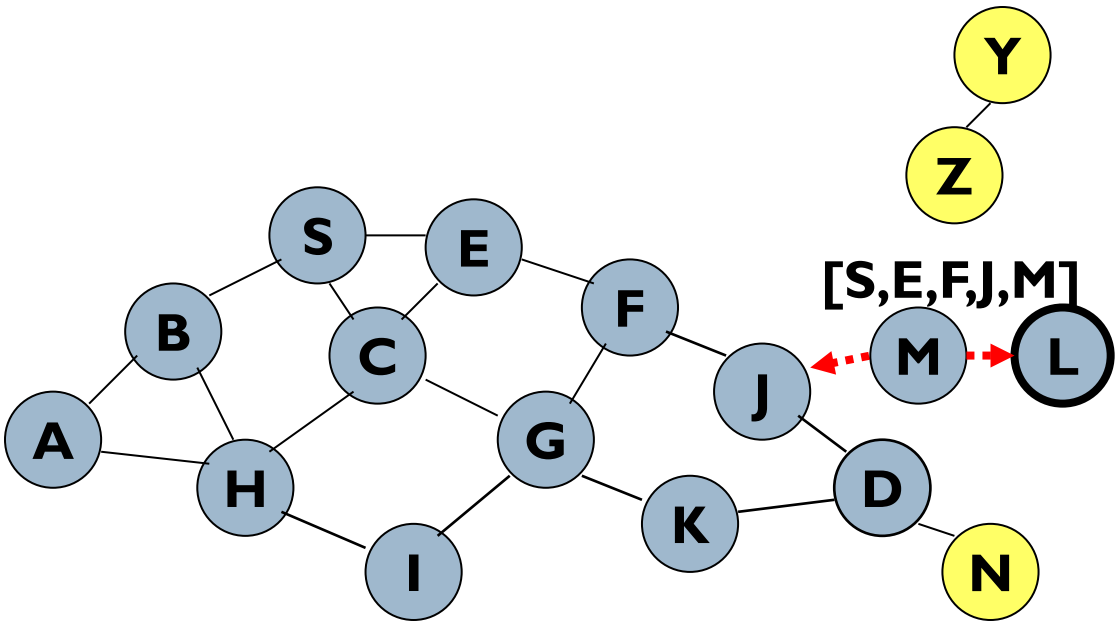


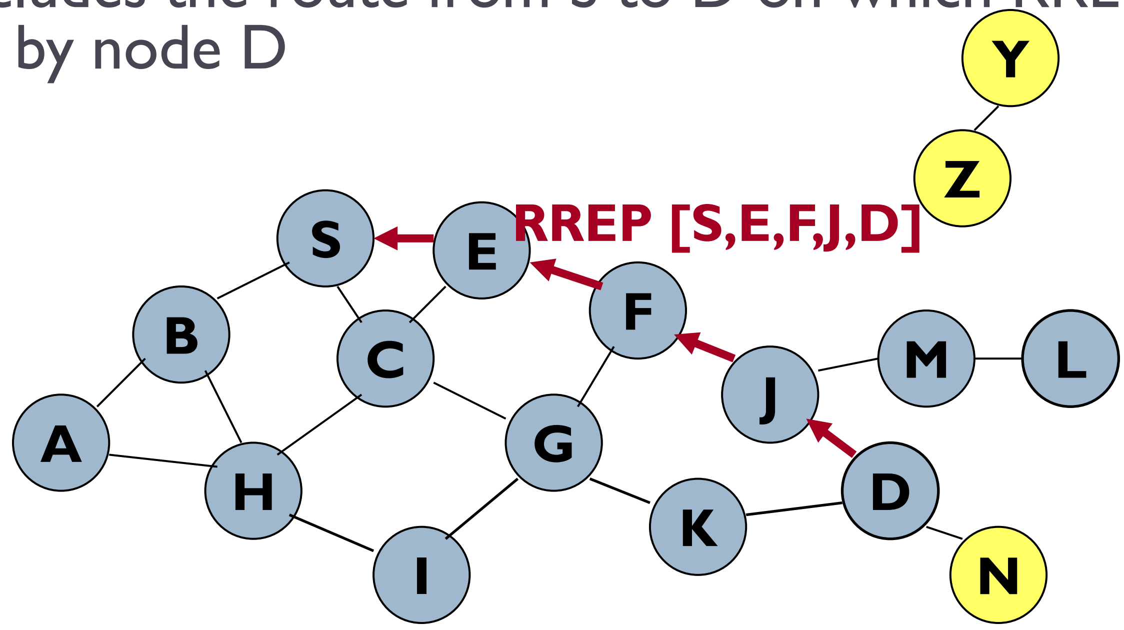
Route Discovery in DSR

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



Route Reply in DSR

- Destination D
  - On receiving the first RREQ, send 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

- Route Reply
  - Bi-directional links
    - Reverse route in Route Request (RREQ)
    - RREQ should be forwarded only if received on a link that is known to be bi-directional
  - Unidirectional (asymmetric) links
    - RREP may need a route discovery for S from node D
      - Route Reply is piggybacked on the Route Request from D
    - Unless node D already knows a route to node S

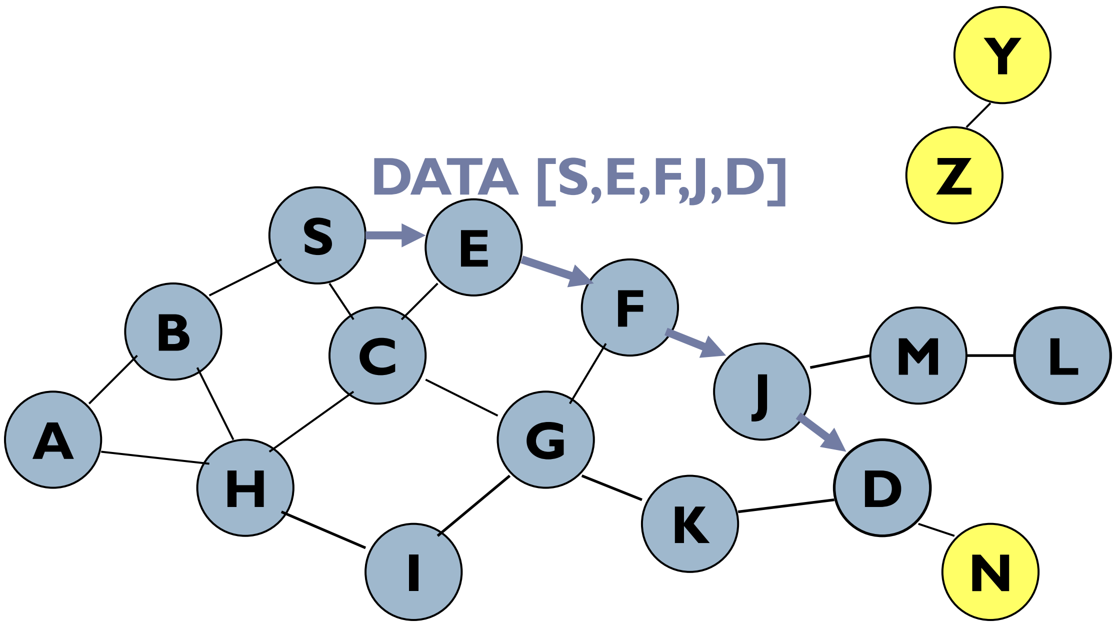
- IEEE 802.11 MAC
  - Links must be bi-directional (since ACK is used)

Dynamic Source Routing (DSR)

- On receiving RREP
  - Cache the route included in the RREP
- Sending
  - 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



When to Perform a Route Discovery

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

DSR Optimization: Route Caching

- Caching
  - Each node caches a new route it learns by any means
  - Snooping
    - A node may also learn a route when it overhears Data packets

- Use of Route Caching
  - Broken routes
    - Use another route from the local cache
    - Otherwise, initiate new route discovery
  - Intermediate response
    - On receiving a Route Request for some node D
      - Node X can send a Route Reply if node X knows a route to node D
  - Use of route cache
    - Speed up route discovery
    - Reduce propagation of route requests

Use of Route Caching

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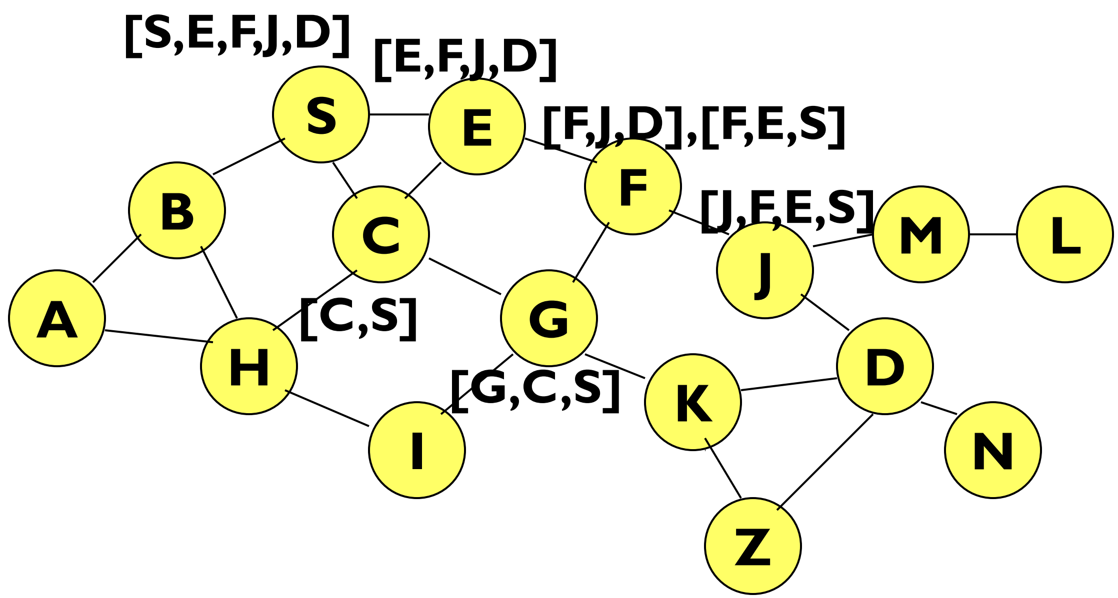
  - Reduce propagation of route requests

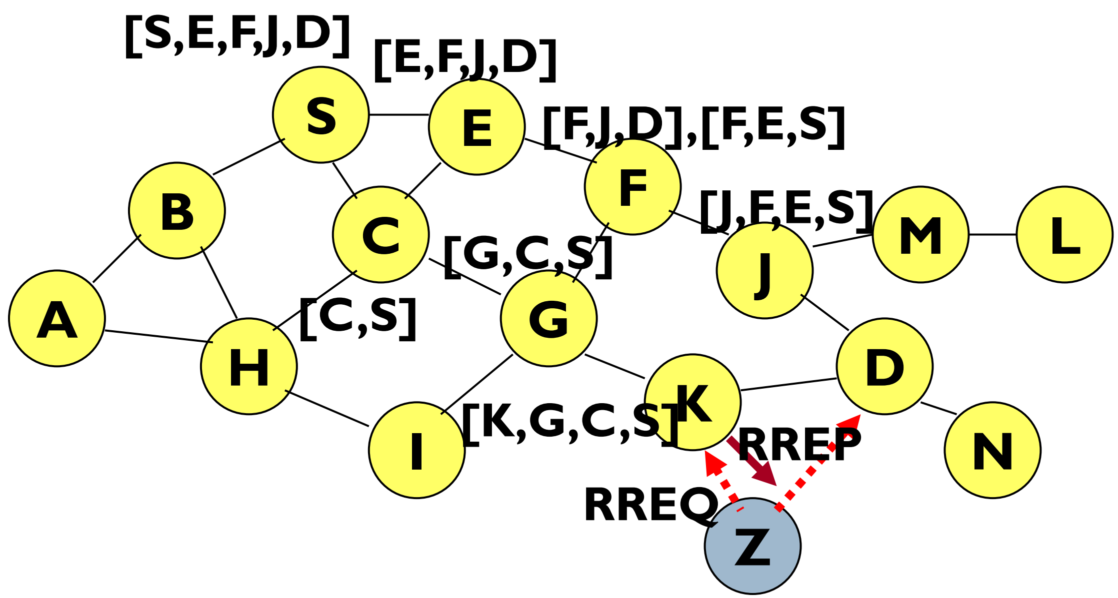
Use of Route Caching

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



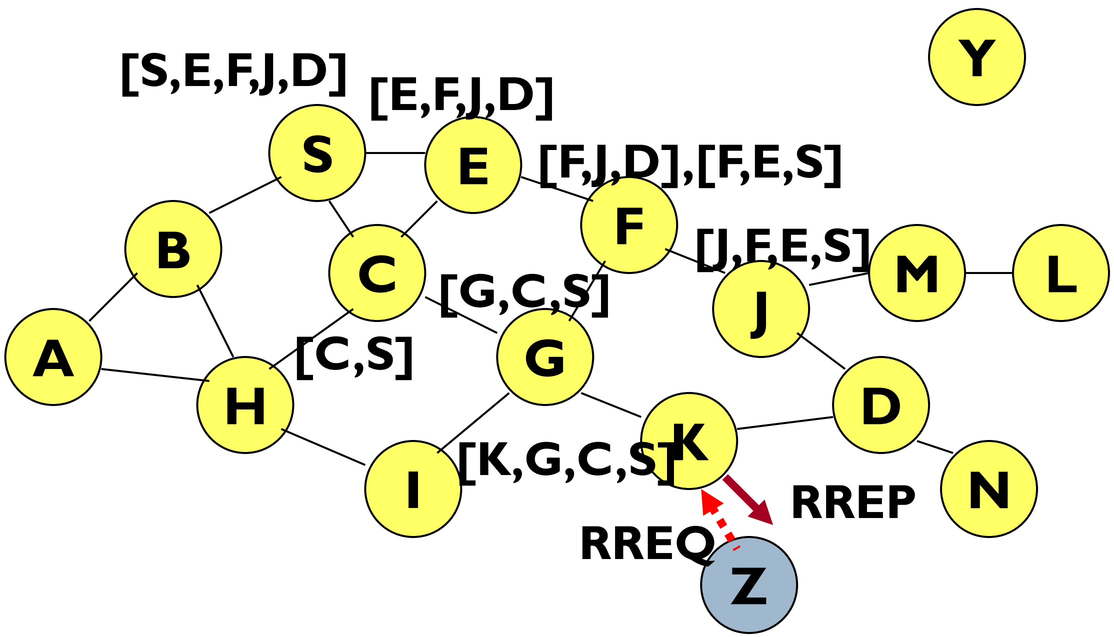
Use of Route Caching: Speed up Route Discovery

- 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



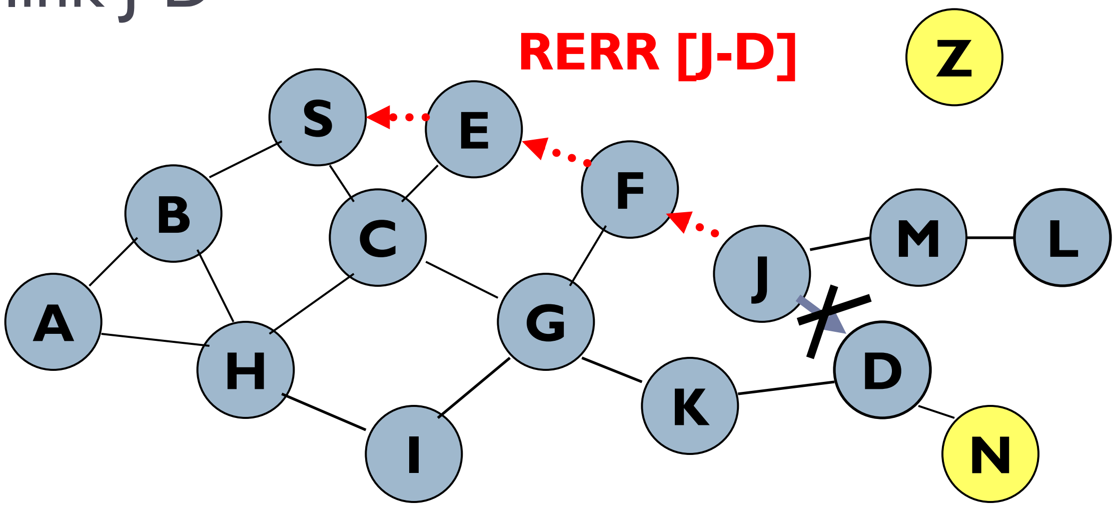
Use of Route Caching:
Reduce of Route Requests

- No link between D and Z
  - Route Reply (RREP) from node K limits flooding of RREQ
  - In general, the reduction may be less dramatic.



Route Error (RERR)

- When attempt to forward the data packet S (with route SEFJD) on J-D fails
  - J sends a route error to S along J-F-E-S
  - Nodes hearing RERR update their route cache to remove link J-D



Route Caching: Beware!

- Stale caches
  - Can adversely affect performance
- Timeliness
  - With passage of time and host mobility, cached routes may become invalid
- Know when to give up
  - A sender host may try several stale routes (obtained from local cache, or replied from cache by other nodes), before finding a good route

Dynamic Source Routing: Advantages

- On-demand
  - Routes maintained only between nodes that 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

- Size
  - Packet header size grows with route length
- Packets
  - Flood of route requests may reach all nodes
- Timing
  - Must avoid route requests collisions
    - Insertion of random delays before forwarding RREQ
  - Route Reply Storm problem
    - Too many nodes reply using local cache
    - Prevent a node from sending RREP if it hears another RREP with a shorter route

Dynamic Source Routing: Disadvantages

- Pollution
  - An intermediate node may send Route Reply using a stale cached route
  - Need some mechanism to purge (potentially) invalid cached routes
- For some proposals for cache invalidation
  - Static timeouts
  - Adaptive timeouts based on link stability

Flooding of Control Packets

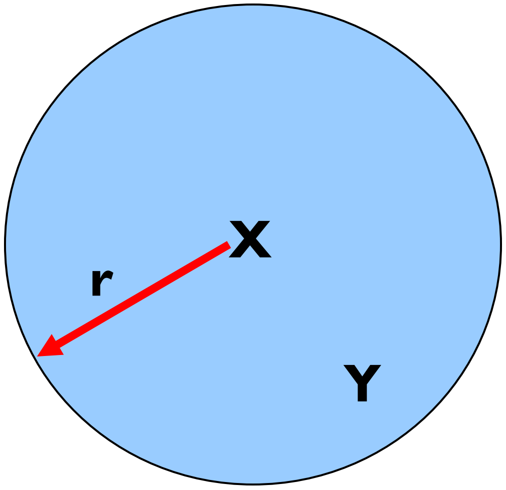
- How to reduce the scope of the route request flood ?
  - LAR
- How to reduce redundant broadcasts ?
  - The Broadcast Storm Problem

Location-Aided Routing (LAR)

- Exploit location information to limit scope of flood
  - Location information may be obtained using GPS
- Expected Zone
  - A region that is expected to hold the current location of the destination
  - Determined based on potentially old location information and knowledge of the destination's speed
- Route requests limited to a Request Zone that contains the Expected Zone and location of the sender node

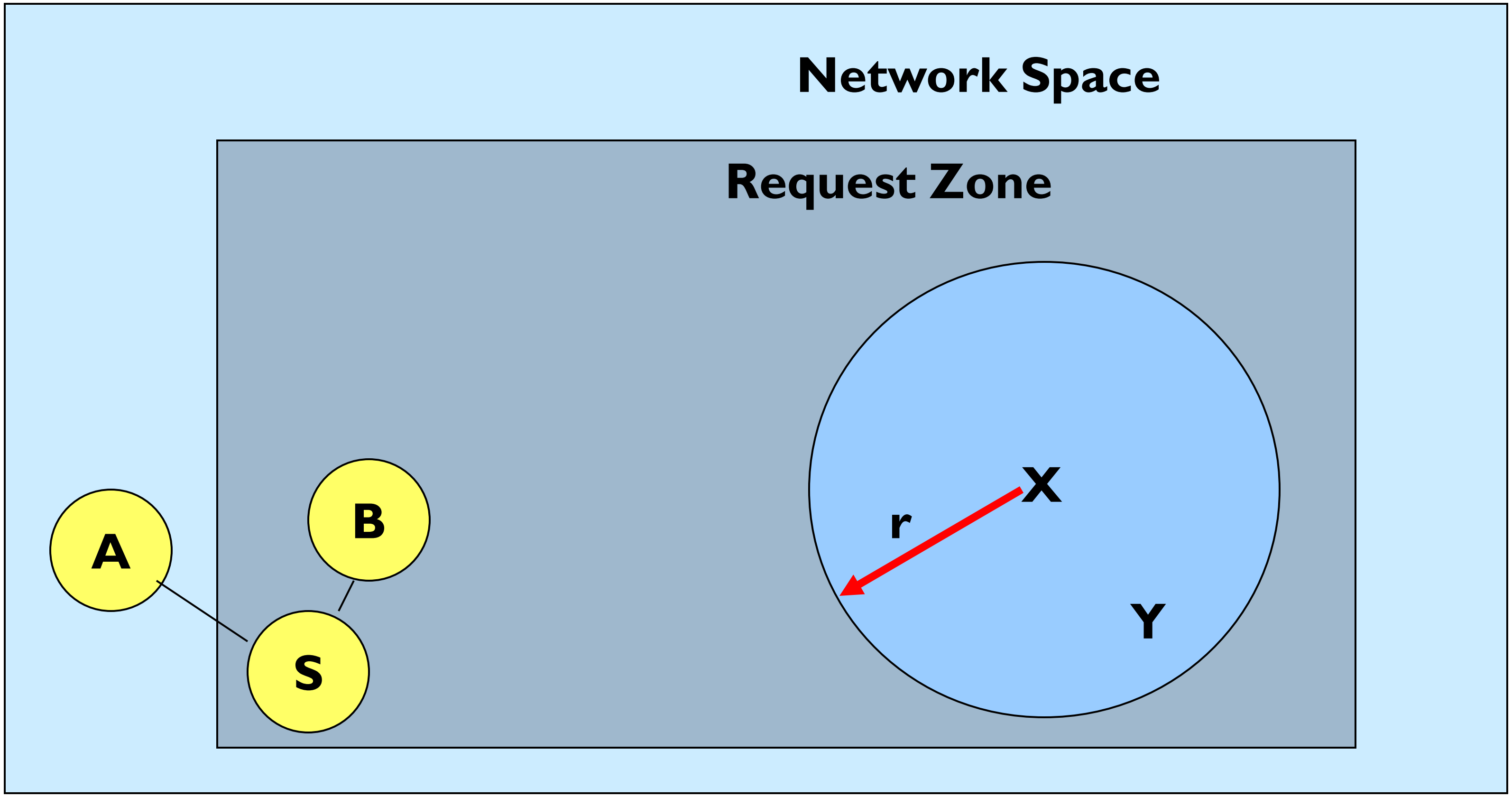
Expected Zone in LAR

- X = last known location of node D, at time t0
- Y = location of node D at current time t1, unknown to node S
- r = (t1 - t0) * estimate of D's speed



Expected Zone

Request Zone in LAR



LAR

- Zone
  - Explicitly specified in the route request
  - Each node must know its physical location to determine whether it is within the request zone
- Forwarding
  - Only nodes within the request zone forward route requests
- Failure
  - Initiate another route discovery (after a timeout) using a larger request zone
  - the larger request zone may be the entire network
- Rest of route discovery protocol similar to DSR

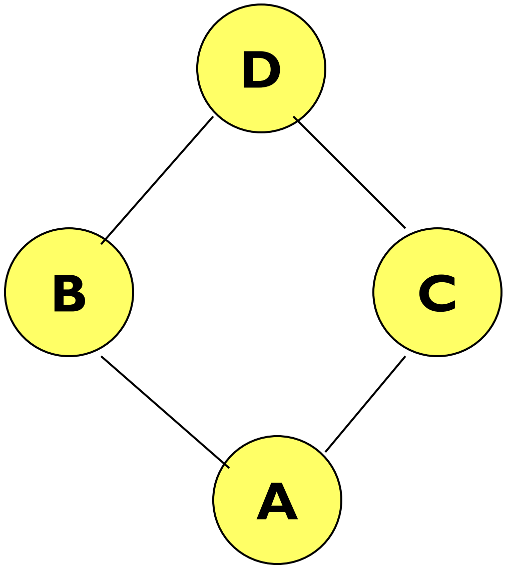
Location Aided Routing (LAR)

- 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

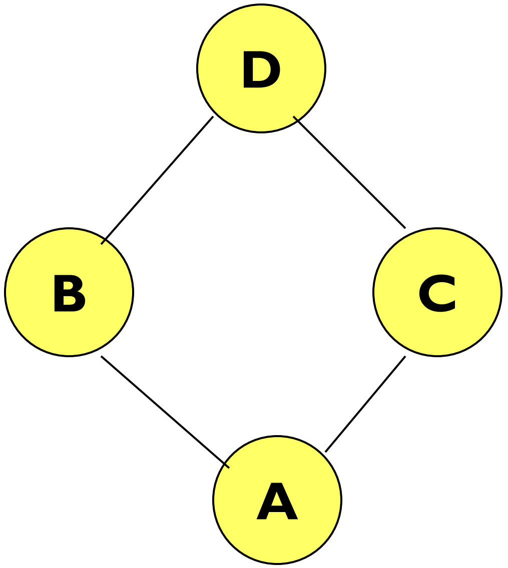
Broadcast Storm Problem

- When node A broadcasts a route query, nodes B and C both receive it
  - B and C both forward to their neighbors
  - B and C transmit at about the same time since they are reacting to receipt of the same message from A
  - This results in a high probability of collisions



Broadcast Storm Problem

- Redundancy
  - A given node may receive the same route request from too many nodes, when one copy would have sufficed
  - Node D may receive from nodes B and C



Solutions for Broadcast Storm

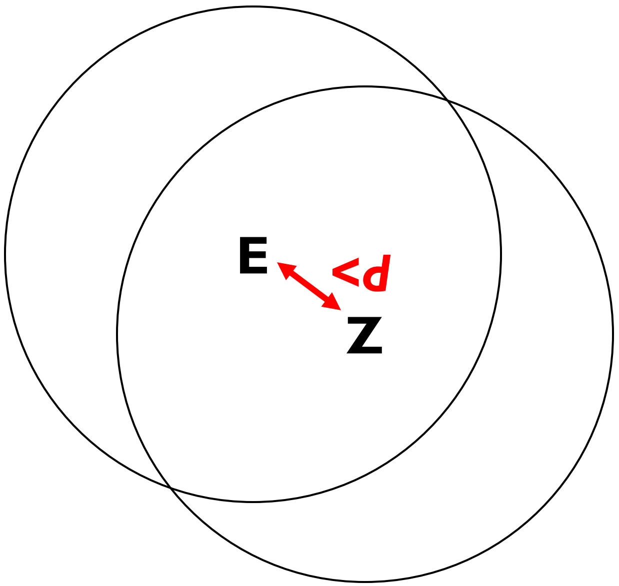
- Probabilistic scheme
  - Re-broadcast (forward) the request with probability p
  - Re-broadcasts by different nodes should be staggered by using a collision avoidance technique
  - Reduce the probability that nodes B and C would forward a packet simultaneously

Solutions for Broadcast Storm

- Counter-Based Scheme
  - If node E hears more than k neighbors broadcasting a given route request, before it can itself forward it, then node E will not forward the request
- Intuition
  - k neighbors together have probably already forwarded the request to all of E's neighbors

Solutions for Broadcast Storm

- Distance-Based Scheme
  - If node E hears RREQ broadcasted by some node Z within physical distance d, then E will not re-broadcast the request
- Intuition
  - Z and E are close, so transmission areas covered by Z and E are not very different



Summary: Broadcast Storm Problem

- Flooding is used in many protocols, such as Dynamic Source Routing (DSR)
- Problems associated with flooding
  - Collisions
    - May be reduced by "jittering" (waiting for a random interval before propagating the flood)
  - Redundancy
    - May be reduced by selectively re-broadcasting packets from only a subset of the nodes

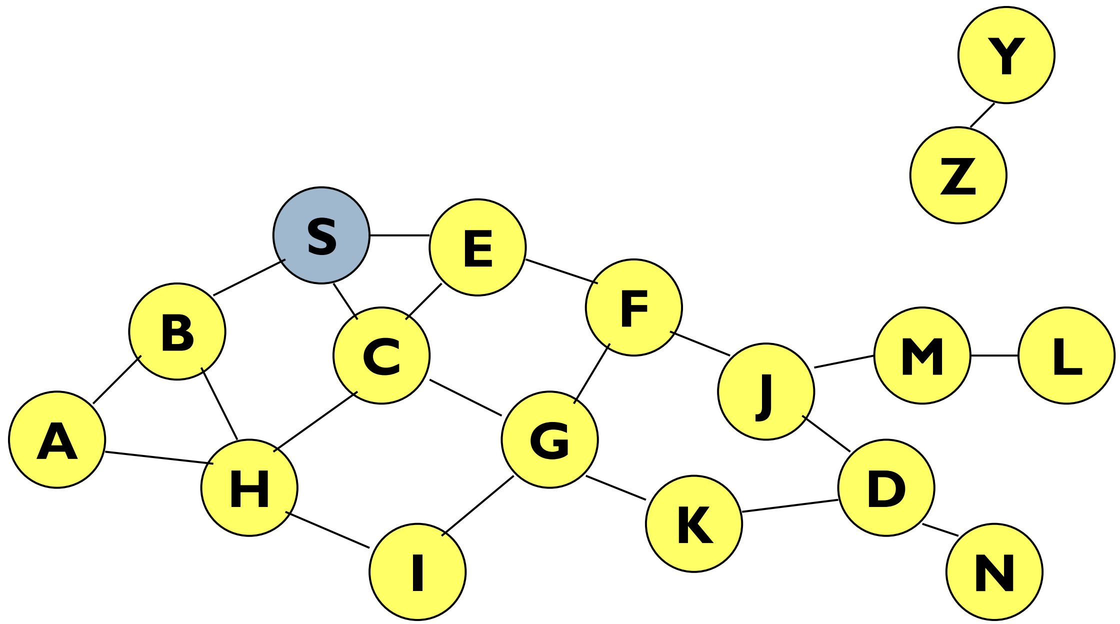
Ad Hoc On-Demand Distance Vector Routing (AODV)

- Source routing
  - Large headers
  - Particularly when data contents of a packet are small
- AODV
  - Maintaining routing tables at the nodes
  - Routes are maintained only between nodes which need to communicate

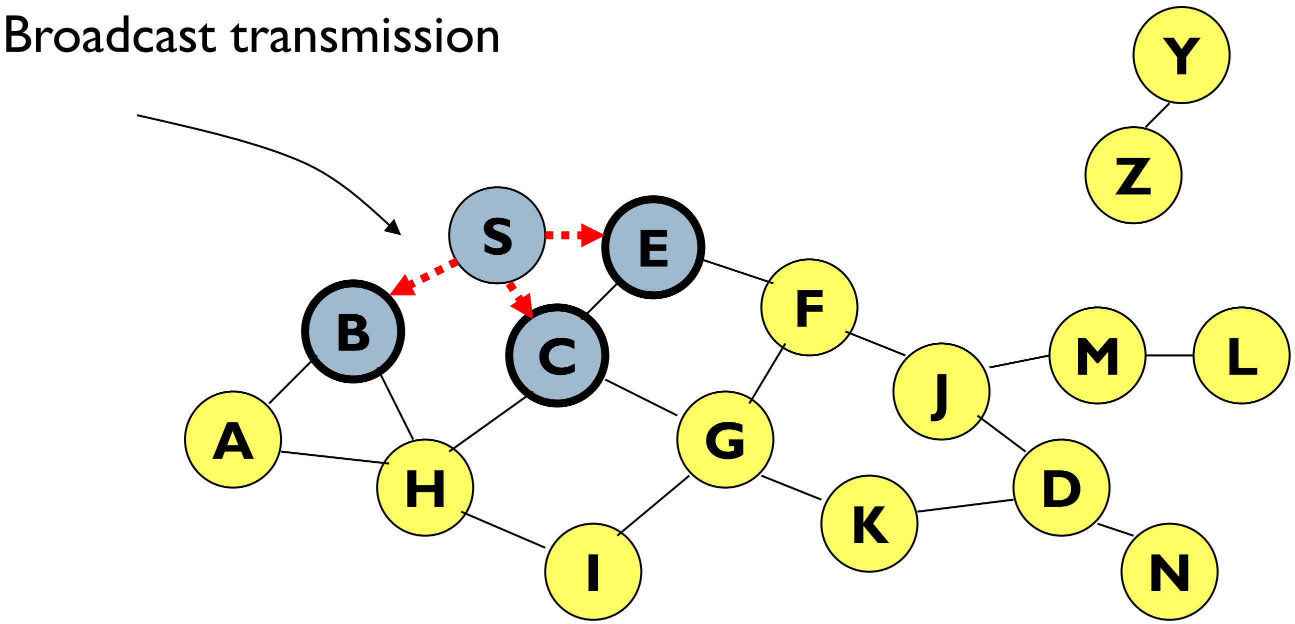
AODV

- Route Requests (RREQ)
  - Forwarded in a manner similar to DSR
- Routes
  - When a node re-broadcasts a Route Request, it sets up a reverse path pointing towards the source
  - AODV assumes symmetric (bi-directional) links
- Destination
  - Destination replies to Route Request with a Route Reply
- Route Reply
  - Follows reverse path set-up by Route Request

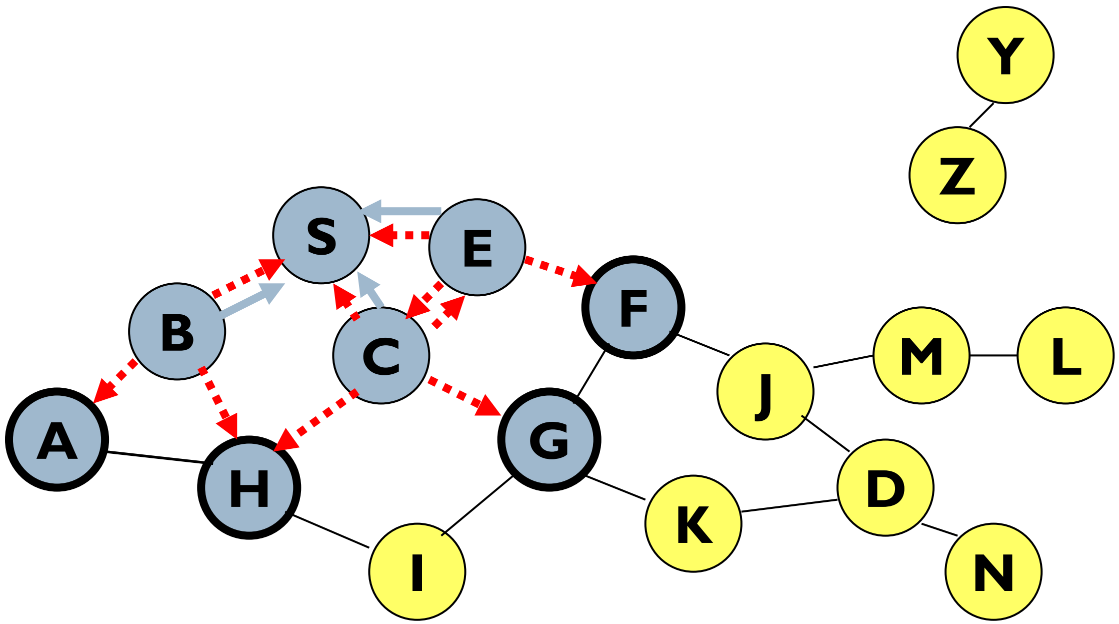
Route Requests in AODV



Route Requests in AODV

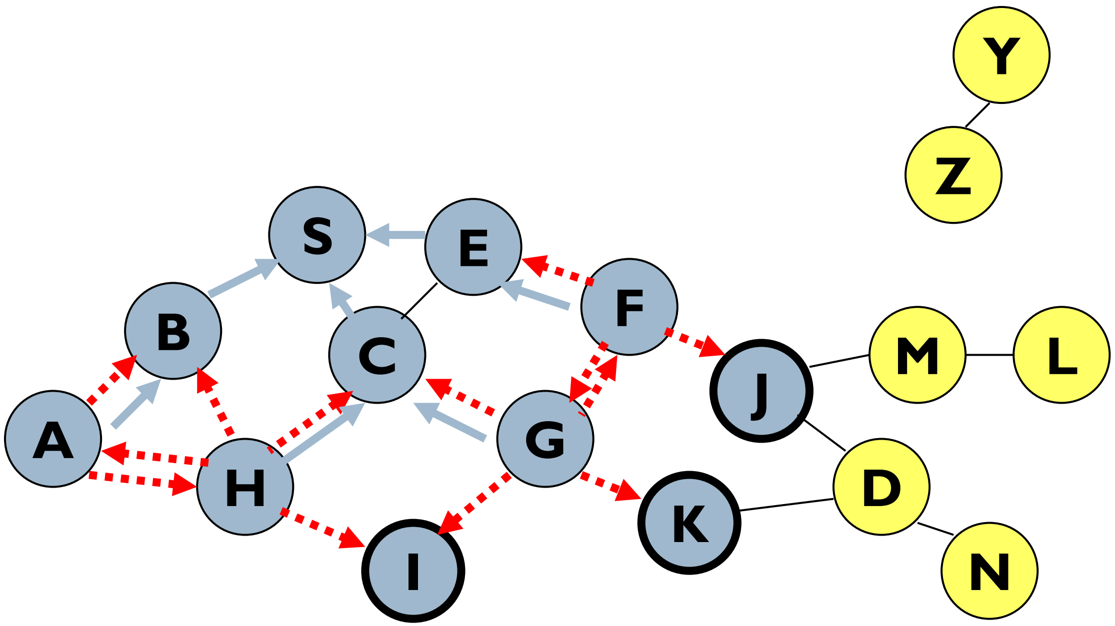


Route Requests in AODV

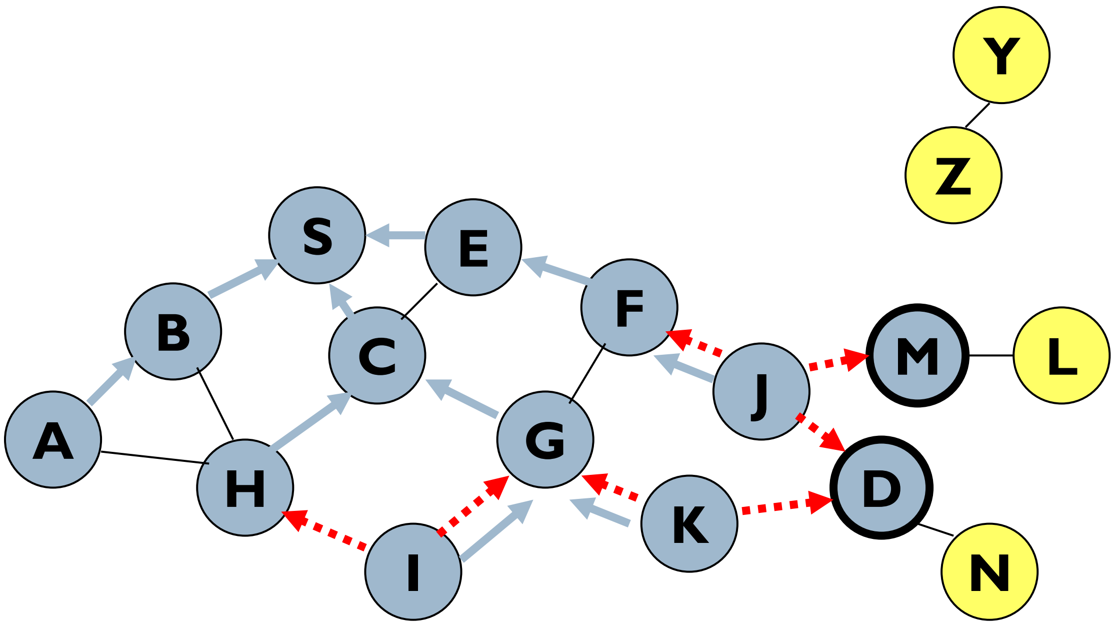


Reverse Path Setup in AODV

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

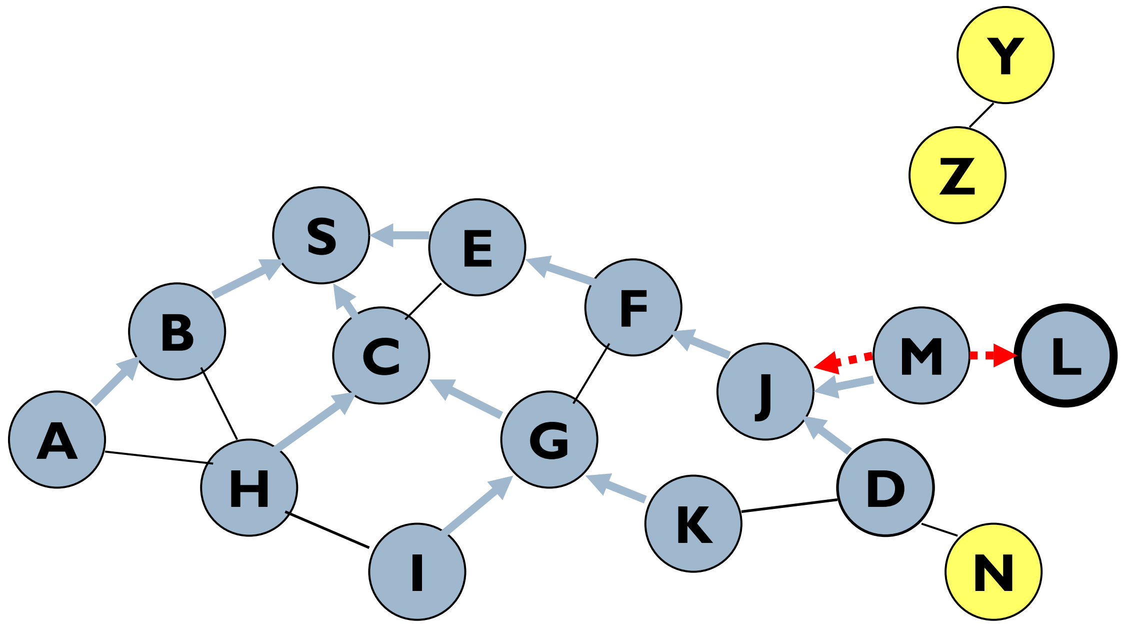


Reverse Path Setup in AODV

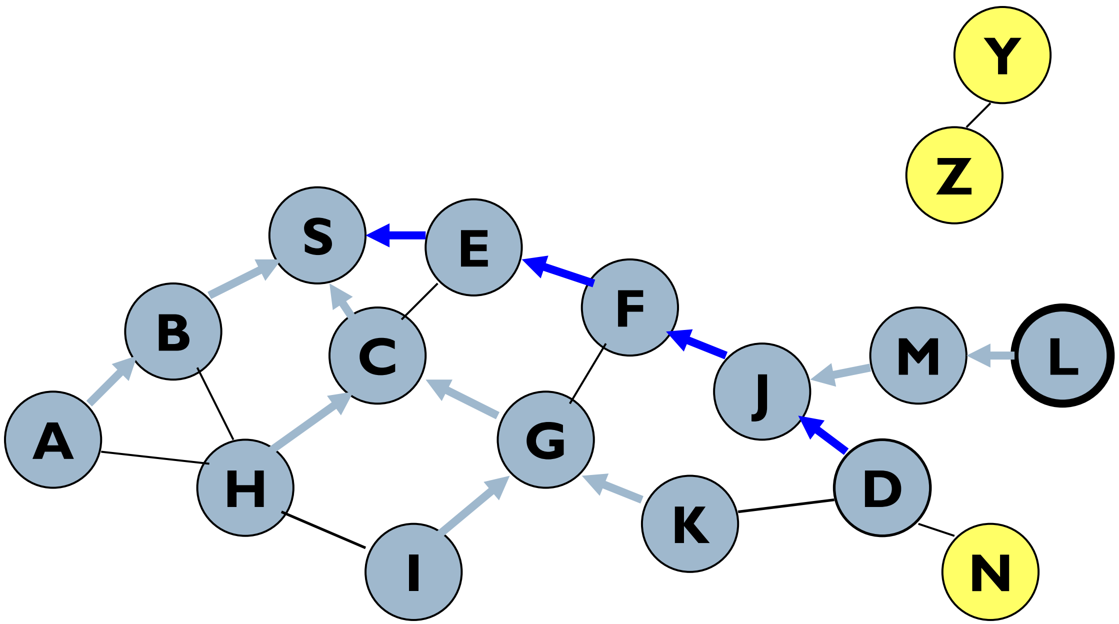


Reverse Path Setup in AODV

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



Route Reply in AODV

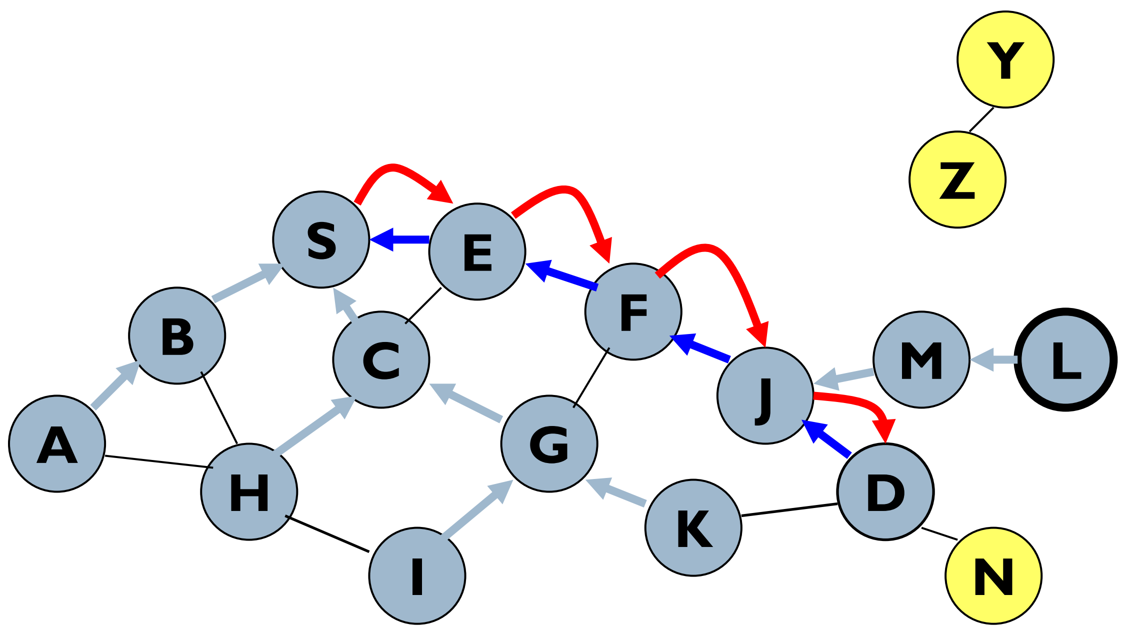


Route Reply in AODV

- Intermediate node reply
  - Send a Route Reply (RREP) if it knows a more recent path than the one previously known to sender
- Sequence Numbers
  - Destination sequence numbers are used to determine age
- Fewer intermediate replies than DSR
  - A new Route Request for a destination is assigned a higher destination sequence number
  - An intermediate node that knows a route with a smaller sequence number cannot send Route Reply

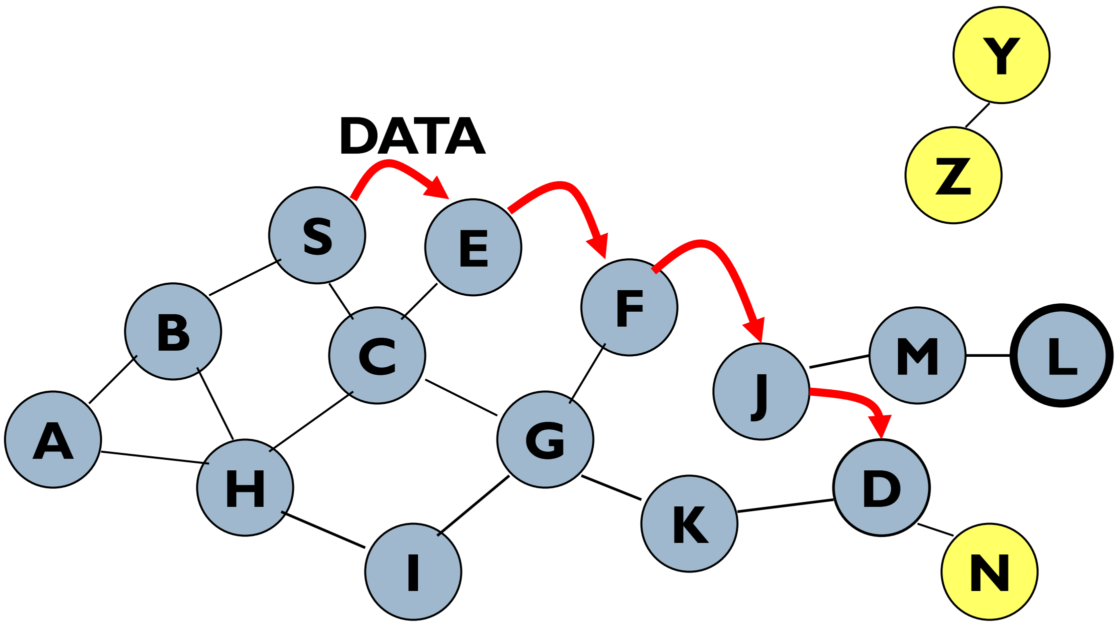
Forward Path Setup in AODV

- Forward links are setup when RREP travels along the reverse path



Data Delivery in AODV

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



Timeouts

- Routing table entries
  - Reverse Paths
    - Purged after a timeout interval
    - Timeout should be long enough to allow RREP to come back
  - Forward Paths
    - If no is data being sent using a particular routing table entry
      - Entry is deleted from the routing table (even if the route may actually still be valid)

Link Failure Reporting

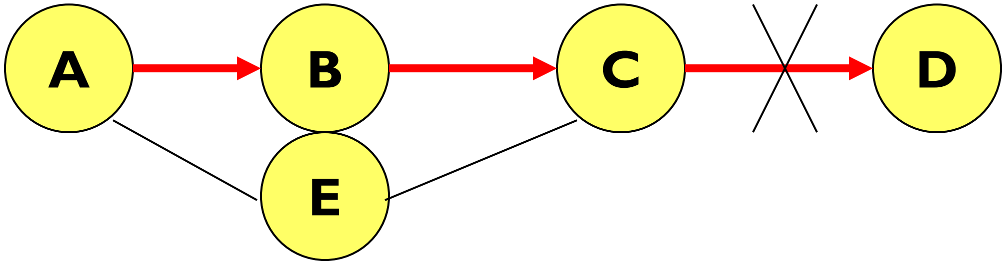
- Link Failure
  - When the next hop link in a routing table entry breaks, all active neighbors are informed
  - Active neighbors
    - Any neighbor that sent a packet within active_route_timeout interval which was forwarded using that entry
- Link failures
  - Propagated by means of Route Error messages
  - Also update destination sequence numbers

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

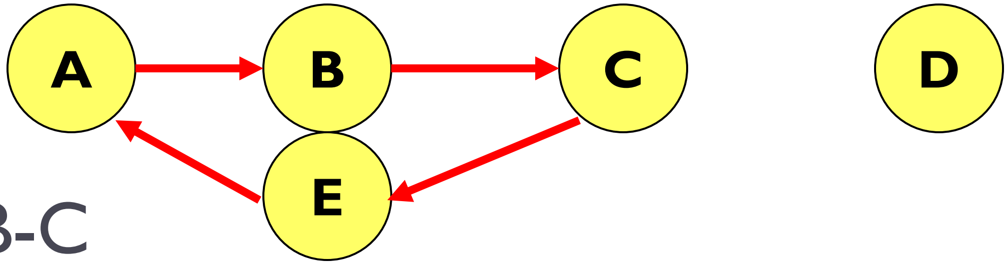
Why Sequence Numbers in AODV

- To avoid using old/broken routes
  - To determine which route is newer
- To prevent formation of loops



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

Why Sequence Numbers in AODV



- Loop C-E-A-B-C

Optimization: Expanding Ring Search

- Route Requests
  - Initially sent with small Time-to-Live (TTL) field, to limit propagation
  - DSR also includes a similar optimization
- If no Route Reply is received
  - Larger TTL

Summary: AODV

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

Some Variations

Power-Aware Routing

- Define optimization criteria as a function of energy consumption
- Examples
  - Minimize energy consumed per packet
  - Minimize time to network partition due to energy depletion
  - Maximize duration before a node fails due to energy depletion

Power-Aware Routing

- Assign a weight to each link

- Weight of a link may be a function of
  - Energy consumed when transmitting a packet
  - Residual energy level
  - Low residual energy level may correspond to a high cost

- Prefer a route with the smallest aggregate weight

Link Stability-Based Routing

- Idea
  - A node X re-broadcasts a Route Request received from Y only if the (X,Y) link is deemed to have a strong signal stability
- Signal stability
  - Evaluated as a moving average of the signal strength of packets received on the link in recent past
- Alternative approach
  - Assign a cost as a function of signal stability

Connection Stability-Based Routing

- Only utilize links that have been stable for some minimum duration
  - If a link has been stable beyond some minimum threshold
    - It is likely to be stable for a longer interval
  - If it has not been stable longer than the threshold
    - It may soon break (could be a transient link)
- Prefer paths with high aggregate stability