Mobile Ad Hoc Networks
Routing
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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 vector 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 $s$
**Dijkstra**($G, w, s$)
begin
    **Init-Single-Source**($G, w$)
    $S ← \emptyset$
    $Q ← V$
    while $Q ≠ \emptyset$ do
        $u ←$ Element aus $Q$ mit minimalen Wert $d(u)$
        $S ← S \cup \{u\}$
        $Q ← Q \setminus \{u\}$
        for all $v ∈ \text{Adj}(u)$ do
            **Relax**($u, v$)
        od
    od
end

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

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

**Relax**($u, v$)
begin
    if $d(v) > d(u) + w(u, v)$ then
        $d(v) ← d(u) + w(u, v)$
        $\pi(v) ← u$
    fi
end
Dijkstra: Example
Distance Vector Routing Protocol

- **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
The “Count to Infinity” - Problem

- **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
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
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**
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 that connected nodes are within each other's transmission range

Represents a node that has received packet P

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Flooding for Data Delivery

- Broadcast transmission

- Represents transmission of packet P

- Represents a node that receives packet P for the first time

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Flooding for Data Delivery

• Node H receives packet P from two neighbors: potential for collision
• Node C receives packet P from G and H, but does not forward it again, because node C has already forwarded packet P once.
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
• 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 the 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.
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 \textit{backward learning} the route from destination to source

\textbf{Practically: Dynamic Source Routing (DSR)}
- Use separate \textit{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

Search for route from 1 to 5

Node 5 uses route information recorded in RREQ to send back, via \textit{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

Broadcast transmission

[S]

Represents transmission of RREQ

[X,Y] Represents list of identifiers appended to RREQ
Route Discovery in DSR

- Node H receives packet RREQ from two neighbors: potential for collision
• Node C receives RREQ from G and H, but does not forward it again, because node C has \textit{already forwarded} RREQ once.
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
• 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

RREP \{S,E,F,J,D\}

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)

- 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

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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

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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 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)
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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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.
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

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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
Flooding of Control Packets

- 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

![Diagram of a network with nodes S, A, B, C, D, E, F, and H, showing the geographic distance routing.](Diagram)

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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

![Diagram showing nodes A, B, C, D, E, F, G, H, and S with green arrows indicating the route and red arrows indicating the obstruction.](http://www.crhc.uiuc.edu/wireless/talks/2006.Infocom.ppt)
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]
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]

- 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

Represents a node that has received RREQ for D from S

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Route Requests in AODV

Broadcast transmission

Represents transmission of RREQ
Route Requests in AODV

Represents links on Reverse Path

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• 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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• 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

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

 Represents a link on the forward path.
Routing table entries used to forward data packet. Route is *not* included in packet header.
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.
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

➢ 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)
Why Sequence Numbers in AODV

- Loop C-E-A-B-C
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
Thank you!