
Routing in Wireless Ad Hoc Networks

Mobile Ad hoc NETWORKs (MANETs)

- Autonomous system of **mobile** routers connected by wireless links, forming an arbitrary graph
- Developed within the IETF (Internet Engineering Task Force) to extend the Internet technology to mobile networks



MANETs

- Nodes are computing and communication devices, e.g laptops, PDAs, mobile phones, even sensors
 - Nodes organize and maintain the network by themselves
 - A node is both a host and a router
 - IP is used at the network layer
 - First and foremost issue: **routing**
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Problems with Routing

1. Self-organizing networks

- Need for distributed algorithms

2. Topology changes dynamically

- Mobile nodes (joining in or leaving)
- Unannounced loss of network connectivity due to the time-varying channel nature

3. Link failure / repair

- Network partitions
 - Loop formation during temporary node failures
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Problems with Routing

4. Limited bandwidth

- Protocols using flooding create high traffic and control overhead

5. New performance criteria

- Number of hops
- Available Bandwidth
- Route stability despite mobility
- Energy consumption

Routing Protocols for MANETs

- Find/maintain a route provided it exists
 - Another problem is to ensure that a route exists, e.g., through power control [Ramanathan'00, Watttnhofer'00]
- Assume that nodes are willing to cooperate

Routing Protocols for MANETs

- **Topology based routing**

- Proactive approach, e.g., DSDV, OLSR
- Reactive approach, e.g., DSR, AODV
- Hybrid approach, e.g., Cluster, ZRP

- **Position based routing**

- Location Services: e.g., DREAM, Quorum-based, GLS, Home zone etc.
- Forwarding Strategy: e.g., Greedy, GPSR, RDF, Hierarchical

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The Proactive Approach

- Based on distance vector and link-state mechanisms
- Attempts to maintain consistent, up-to-date routing information from each node to every other node in the network
 - Respond to changes by propagating updates throughout the network
 - Perfect for connection-less traffic where you may send traffic to any node at any time

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The Reactive Approach

- Routes are only created when desired by the source node
 - **Route discovery protocol**
 - Route discovery ends either when a route is discovered or all possible communication paths have been examined
- Once a route is established, it's maintained by some sort of **route maintenance protocol**

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Trade-off

	Proactive Approach	Reactive Approach
Latency	Low	High
Overhead	High	Low

- Reactive more suitable for a mobile environment with limited bandwidth
- Proactive preferred when time constraints are important

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Proactive Protocols

DV for fixed networks, DSDV for wireless networks

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Distance Vector Routing

- Route discovery algorithm used by RIP (DVR **does not address route maintenance**)
- Based on Bellman-Ford or Ford-Fulkerson algorithms but DVR **does not require an a priori knowledge of the network**

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Distance Vector Routing (1)

- Each node has a routing table where distance to all reachable destinations are recorded
 - Each node is responsible for keeping track and informing its neighbors of its distance to each destination
- A router computes its distance to a destination based on its neighbors distance to the destination

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Distance Vector Routing (2)

- Router must know its own ID and the cost of its links to each neighbor
 - The cost can be expressed in terms of number of nodes, bandwidth, latency, ...
- Initially, each node sets the cost of the link to itself to 0 and to any other node to infinity
- A router broadcasts its routing table
- A node, upon receiving information from neighbors, computes minimum path toward destination and makes changes to its routing table if needed

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Distance Vector Routing (3)

- At node i , the minimum cost path between nodes i and j is computed as

$$D^{n+1}(i, j) = \min \{D^n(i, j), \min_k \{d(i, k) + D^n(k, j)\}\}$$

where:

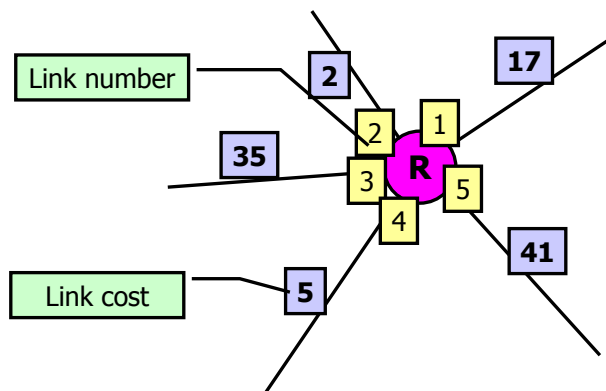
$D^n(i, j)$ is the path cost at time step n

$d(i, k)$ is the cost of the link between i and its neighbor k

- Every time a node updates its table, it broadcasts the table to neighbors. The algorithm converges by iteration

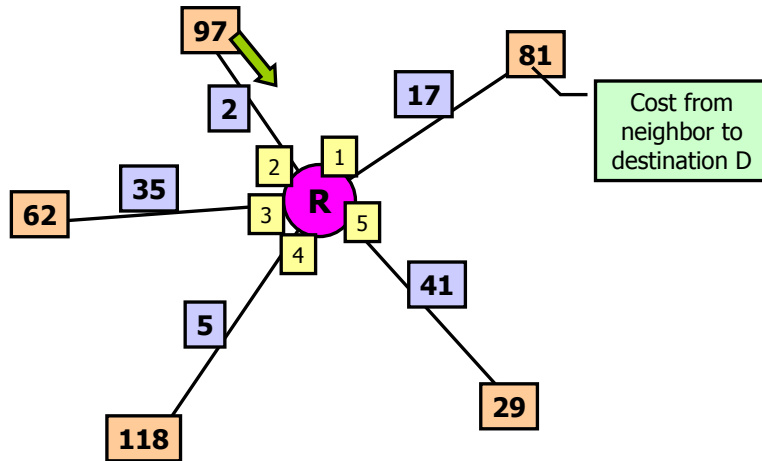
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Distance Vector Routing for Address "D"



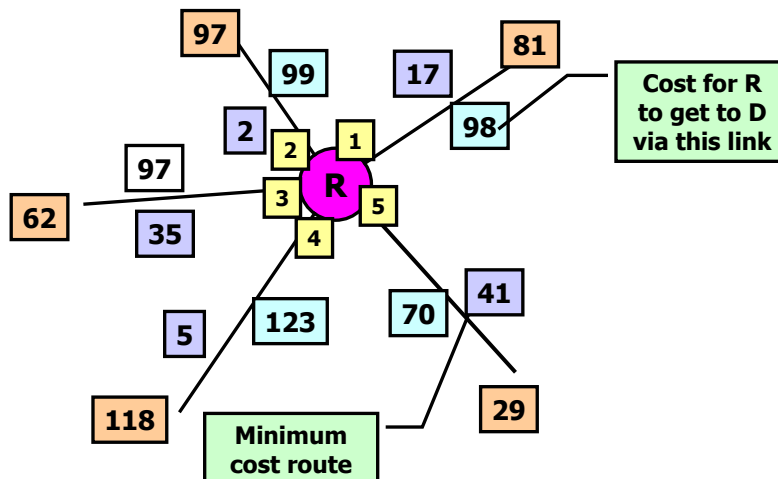
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Distance Vector Routing for Address "D"



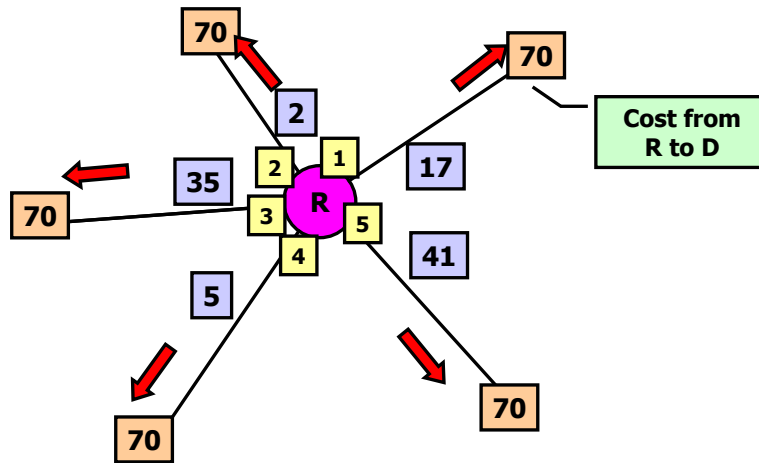
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Distance Vector Routing for Address "D"



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Distance Vector Routing for Address "D"



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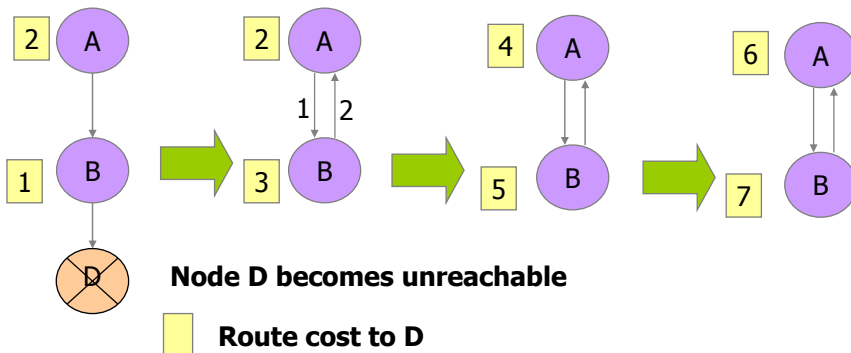
Problems with Distance Vector

- Does not scale well with the number of nodes in the network
- Slow convergence to the lowest cost route
- Slow recovery time if there are link failures, and, hence, routing problems during disruption times
 - Count-to-infinity: Router loops may take place when degradation of a link cost occurs
 - Solved only when the cost of the alternative route including a loop reaches the cost of the degraded link

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Count-to-Infinity: An Example

Cost of the link A-B and B-D equal to 1 =>
cost of the path between A and D equal to 2



It occurs only if B doesn't send its update to A first²¹

DSDV (1): Destination Sequenced Distance Vector Routing

- Proposed by Perkins ['94], based on Bellman-Ford routing mechanism
- Each node maintains routing table that records all possible destinations (Ds)
- Each table entry contains
 1. Destination node
 2. Next hop
 3. Number of hops to D
 4. A sequence number (SN) assigned by D and used to distinguish "old" vs. "new" routes and **avoid loops**

DSDV (2)

- Routing tables are **periodically** transmitted to maintain table consistency
 - A **full dump** record reports on the entire routing table. Lots of traffic, since each table is probably larger than the network protocol data unit
 - **Incremental** updates provide information on changes performed since last full dump
- A new route broadcast contains
 - The address of D
 - The number of hops to reach D
 - The SN of the route
 - SN unique to this broadcast

DSDV (3)

- Every change is communicated to the neighbors (incremental update)
- Upon reception of a route update:
 - If the node doesn't have such information, it adds an entry to its table
 - Otherwise, it checks on the SN and updates the table only in case of fresher information
- Route with most recent SN is always used
- If two routes have the same SN, the route with the smaller metric (== shorter route) is used
- When a link fails, an ∞ metric is used

DSDV (4)

- Nodes also keep track of the settling time of routes, or the weighted average time that routes to a destination will fluctuate before the route with the best metric is received
 - A broadcast of a routing table will be delayed by the length of the settling time
 - This avoids fluctuations in the table data and reduce the update packets
- If full dump updates are used, overhead grows as $O(n^2)$ thus limiting the number of nodes (n) in the network

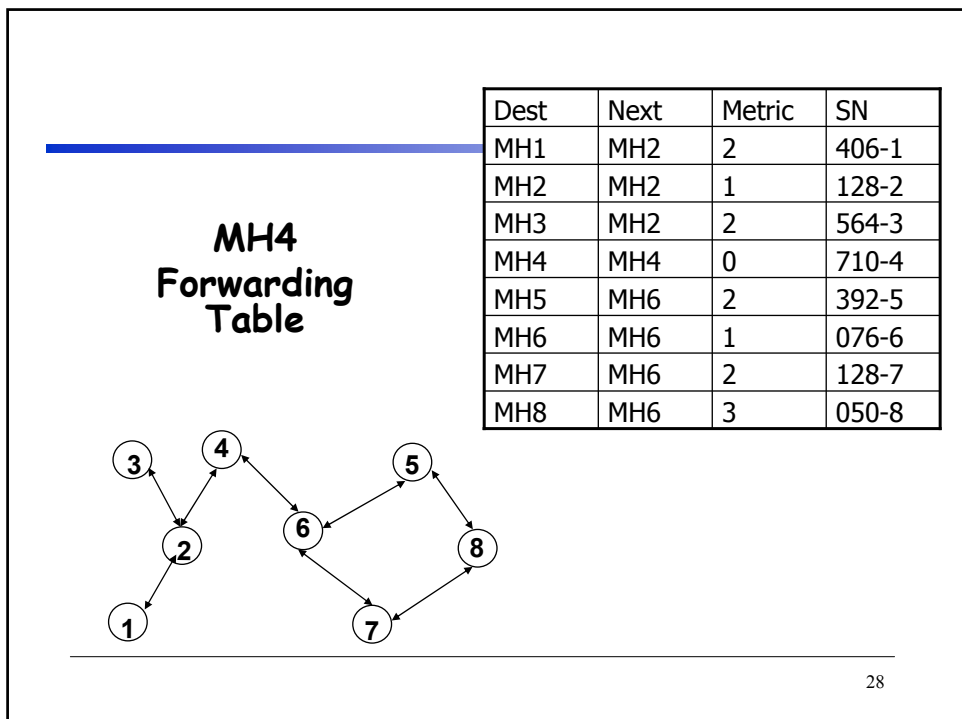
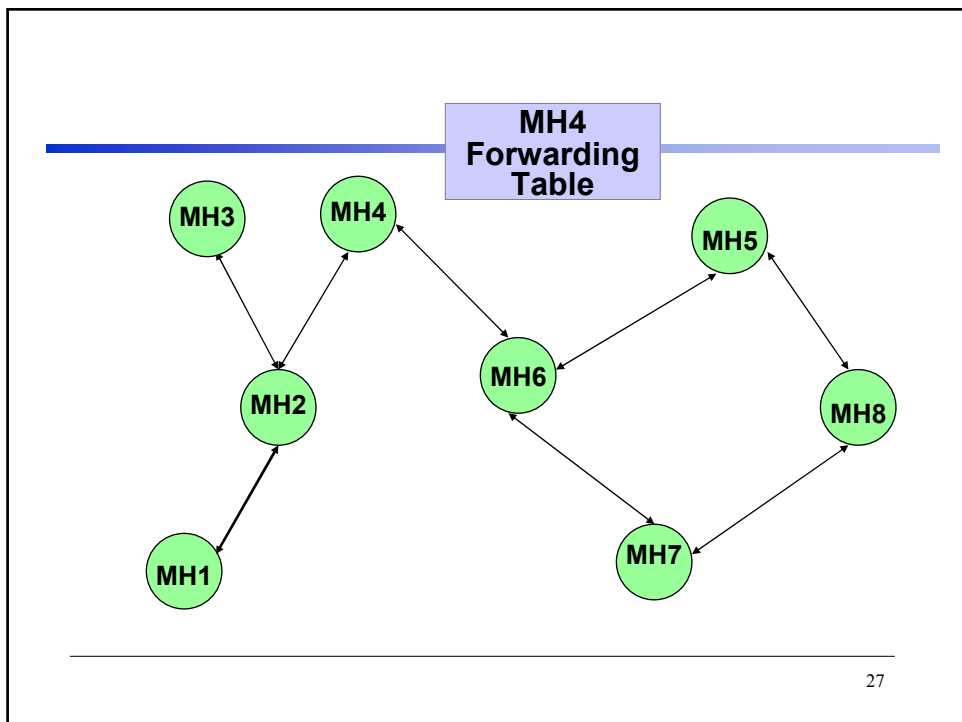
DSDV (5): Advantages and Disadvantages

Advantages

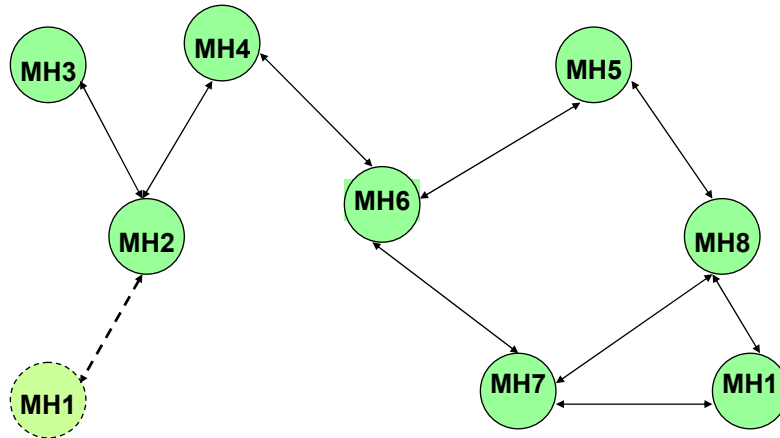
- Has moderate memory requirements
- Guarantees loop-free paths (thanks to SNs)
- Simple update coordination protocol

Disadvantages

- Provides only a single path between each given S/D pair
- Requires selection of the periodic update interval (settling time) and of the number of update intervals that should expire before a route is considered "stale", which are difficult to estimate
- Update overhead

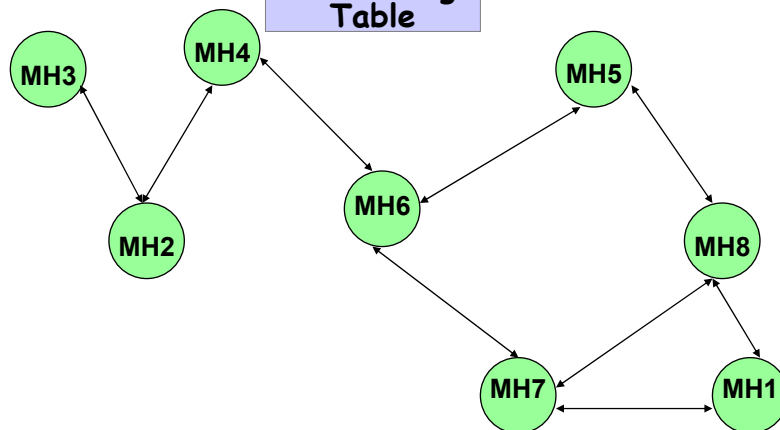


MH1 moves



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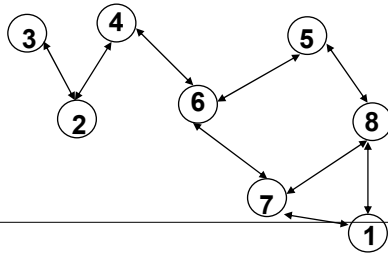
New MH4 Forwarding Table



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New MH4 Forwarding Table

Dest	Next	Metric	SN
MH1	MH6	3	516-1
MH2	MH2	1	128-2
MH3	MH2	2	564-3
MH4	MH4	0	710-4
MH5	MH6	2	392-5
MH6	MH6	1	076-6
MH7	MH6	2	128-7
MH8	MH6	3	050-8



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Reactive Protocols

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DSR

Dynamic Source Routing [Johnson'96]

- **Entirely "on demand"**: No periodic messages or advertisements at any layer
- **Dynamic**: it maintains a "soft state," i.e., all state is discovered as needed and can be easily re-discovered if needed after a failure without impacting the protocol functioning
- **Source Routing**: the source specifies in the header of each data packet the entire route, not only the next hop

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Assumptions

- The network is fairly small (up to 200 nodes, i.e., network diameter of 10-15 nodes)
- Each node maintains a cache containing all source routes of which it is aware
 - Routes in the cache are continuously updated as they are learned
 - Several routes can be cached to the same destination
- Either bi- or uni-directional links

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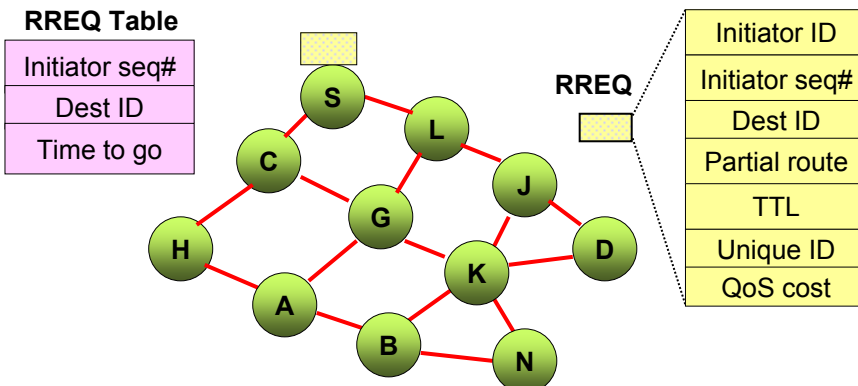
DSR

The protocol consists of two phases:

- **Route discovery:**
 - Started by **S** when **S** needs to send data to **D** and doesn't have any route to **D** in cache
- **Route Maintenance:**
 - While using a route to **D**, **S** can detect if the route is not longer valid
 - Upon route failure, **S** may use another route (if it knows it) or start a new route discovery

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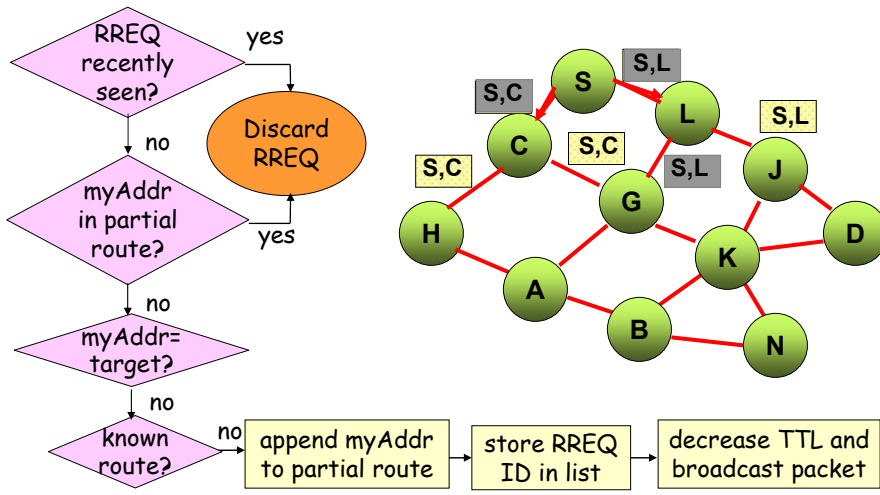
Route Discovery



If no reply by the "time to go", **S** sends a new RREQ till a max no. of attempts have been made

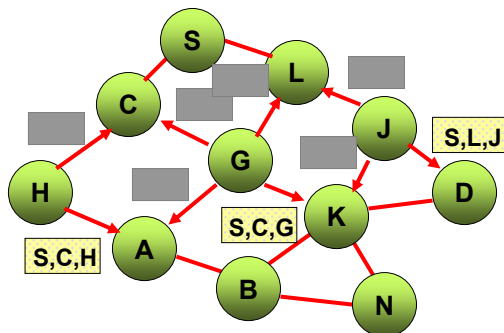
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Route Discovery



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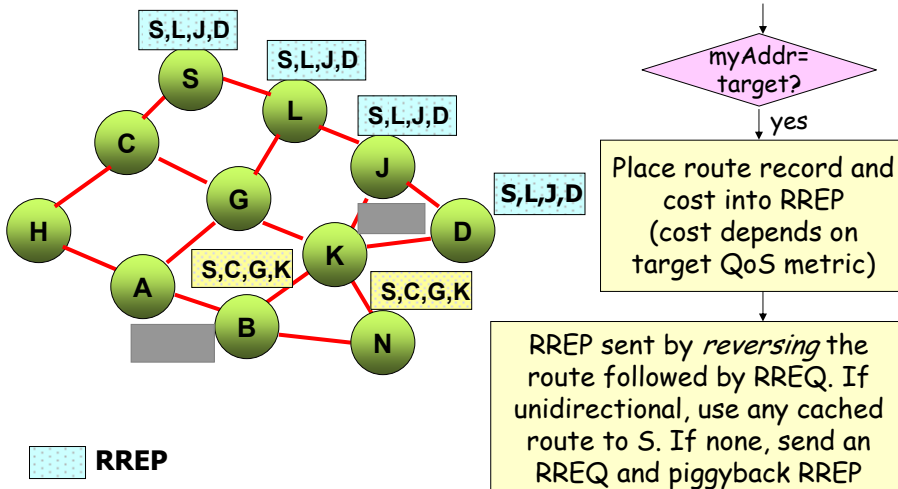
Route Discovery



Route discovery succeeded !

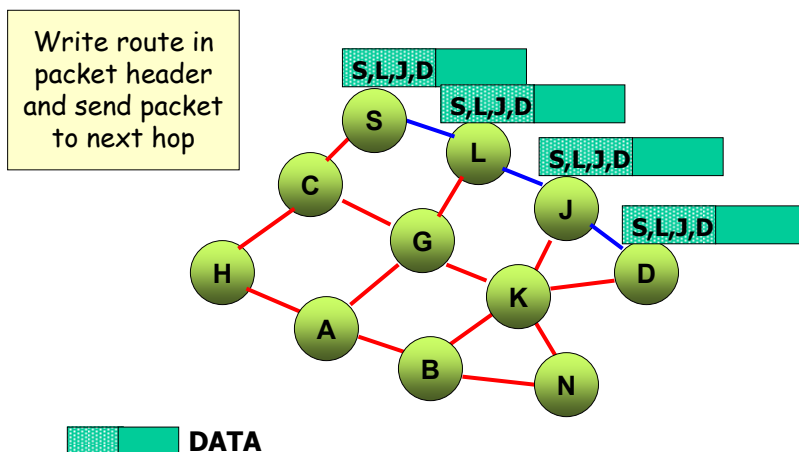
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Route Reply



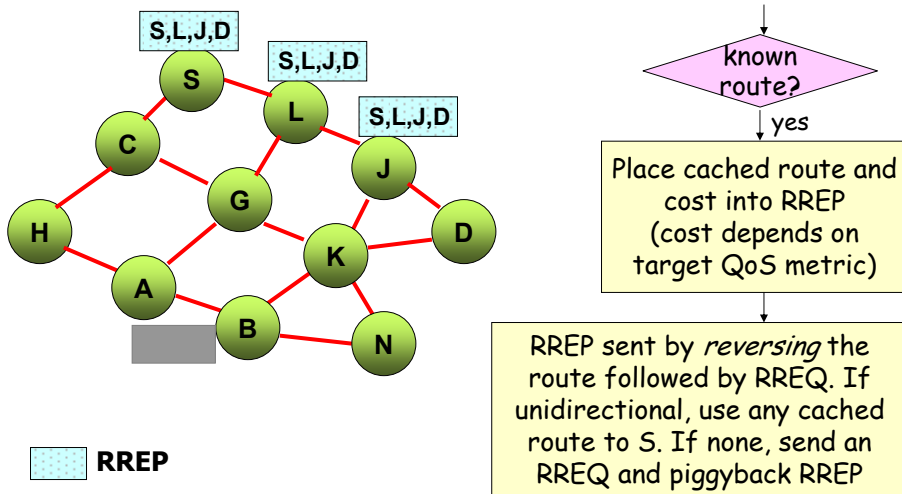
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Data Delivery



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Route Caching



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Route Caching

- Advantages of route caching
 - Speeds up routing
 - Reduces propagation of route requests
- **S** caches the route to **D** contained in the RREP
 - For each **D**, more than one route can be cached, thus **S** can perform traffic routing over several possible routes

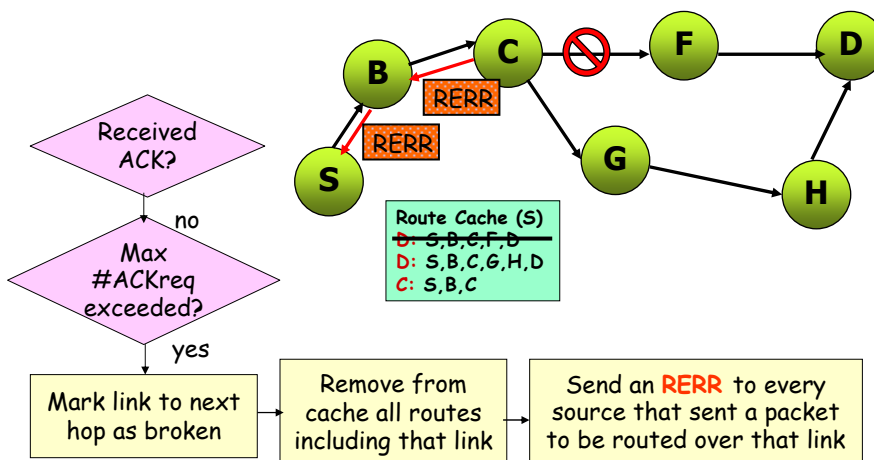
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Route Maintenance

- Along a source route, each node transmitting a packet is responsible for correct transmission confirmation
- An ACK is needed for confirmation
 - MAC or link-layer ACKs can be used
 - Overhearing next node forwarding the packet (**passive ACK**: A hears B sending to C)
 - Use of DSR-ACKs: the node transmitting the packet can require an ACK (which may follow a different route back)

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Route Maintenance



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Route Maintenance

- Nodes overhearing RERR remove from their cache all routes including the broken link
- **S** uses another route from its cache, if it has any; otherwise it starts a new route discovery
- The transport layer (e.g., TCP) should take care of data retransmissions

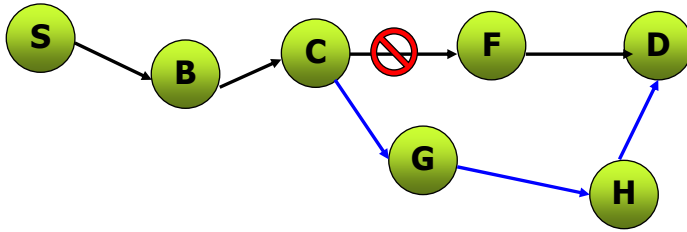
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Optimizations

- **Promiscuous mode:** listening to arbitrary routes in use (A hears B sending to C)
 - Replace with shorter routes / Store new routes
 - But promiscuous mode takes energy
- **Packet salvaging**
 - Upon link failure
 - If intermediate node has another route to **D**, it replaces the original source

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Packet Salvaging: An Example



- C has another route cached to D (C-G-H-D)
- C can salvage the packet by replacing the original route (S-B-C-F-D) in the packet with the new route (C-G-H-D)

Caution: No double salvage allowed !!!

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DSR: Advantages

- Entirely reactive
- "Soft state" and support of unidirectional links
- Source routing
 - No need of routing decisions by intermediate nodes
 - Nodes can learn new routes from relayed packets
 - Guarantee that routes are loop-free
- Caching
 - Reduced route discovery overhead
 - One route discovery may yield many routes to D, due to intermediate nodes replying from local caches

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DSR: Disadvantages

- * RREQ flooding may be huge
 - * Possible collisions between RREQs propagated by neighboring nodes
 - * Contention between RREPs come back due to use of local caches (RREP *Storm* problem)
- * Packet delays/jitters due to on-demand routing
- * Headers may become too long with respect to data payloads -> suitable for small networks
- * Cached routes may become invalid; stale caches can adversely affect performance

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AODV

Ad-Hoc On Demand Distance Vector [Perkins'99]

- Builds routes *on demand*
- Attempts to improve DSR by using **routing tables** at the nodes so that packets do not have to include routes
- Avoids loop formation by using sequence numbers
- Similar procedures of route discovery and route maintenance as in DSR

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Assumptions

Each node maintains:

- A routing table
- A sequence no. for each destination route (DSN)
 - DSN is assigned to the route by the destination
- A broadcast ID to be used for RREQs
 - Broadcast ID is incremented for each RREQ
 - Combination of the node IP address & broadcast ID uniquely identifies an RREQ

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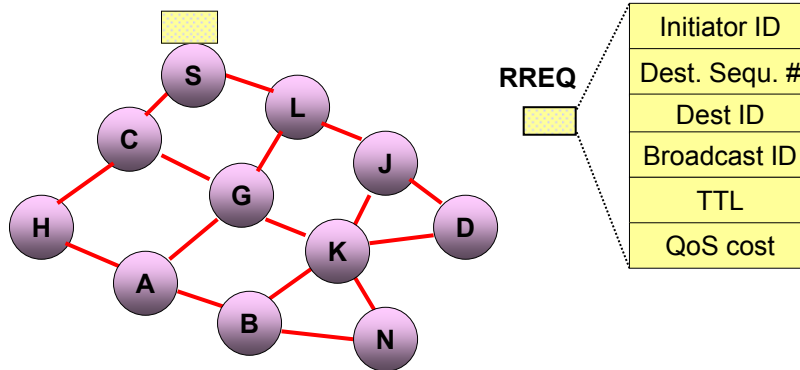
Routing Table

A routing table entry includes:

- Destination IP address
- Sequence number assigned to the path by the destination
- Hop count
- Next hop
- List of nodes from which RREP msgs may be received and from which RREQ msgs are received
- Active route timeout (lifetime)
- Routing flag indicating whether the path is active

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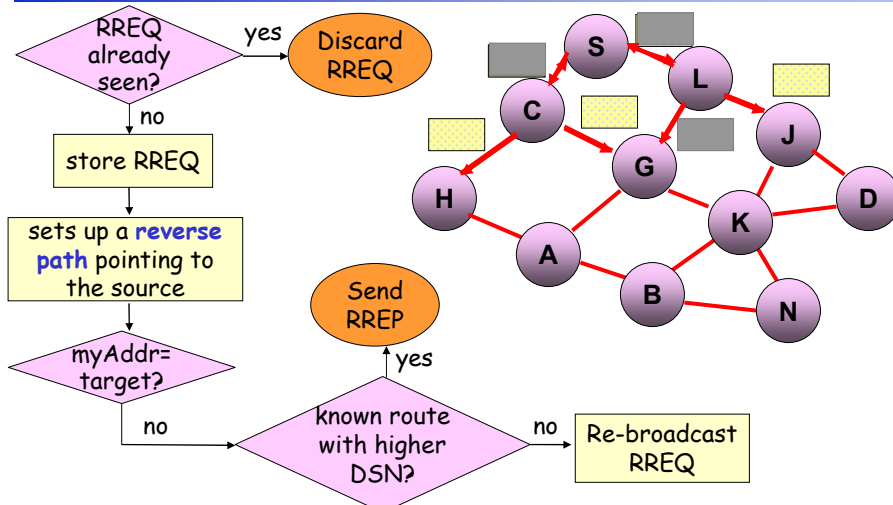
Route Discovery



A new RREQ by node S for a destination is assigned a higher DSN

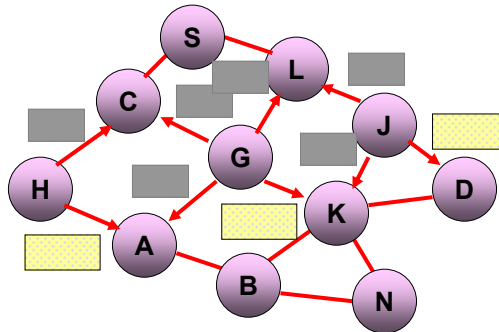
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Route Discovery



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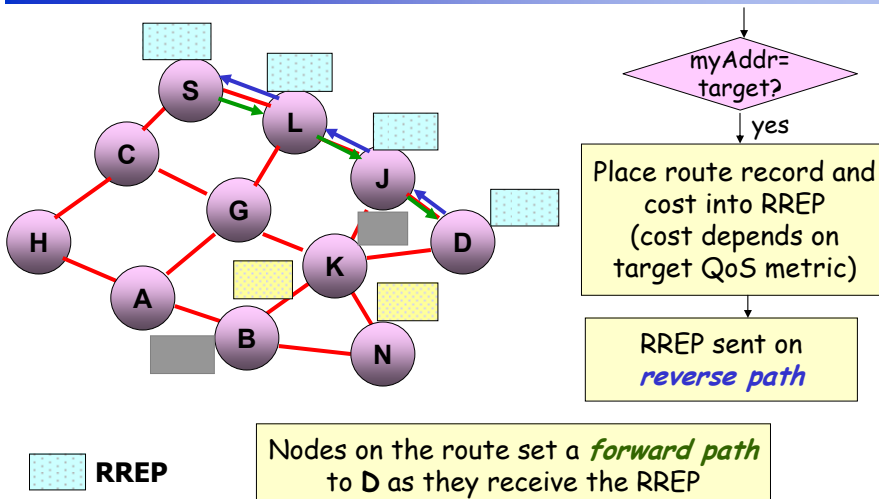
Route Discovery



Route discovery succeeded !

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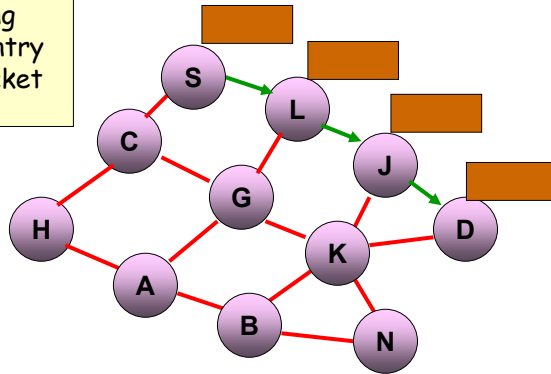
Route Reply



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Data Delivery

Send data packet to next hop using routing table entry (no route in packet header)



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Remarks

- D replies to the first arrived RREQ thus AODV favors the least congested route (that is not always the shortest one)
- Only supports symmetric links!
 - RREP forwarded along the route followed by the RREQ

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Timeouts

- A routing table entry maintaining a **reverse** path is purged after a timeout interval long enough to let the RREP come back to the source
- A routing table entry maintaining a **forward** path is purged if not used for an **active_route_timeout** interval

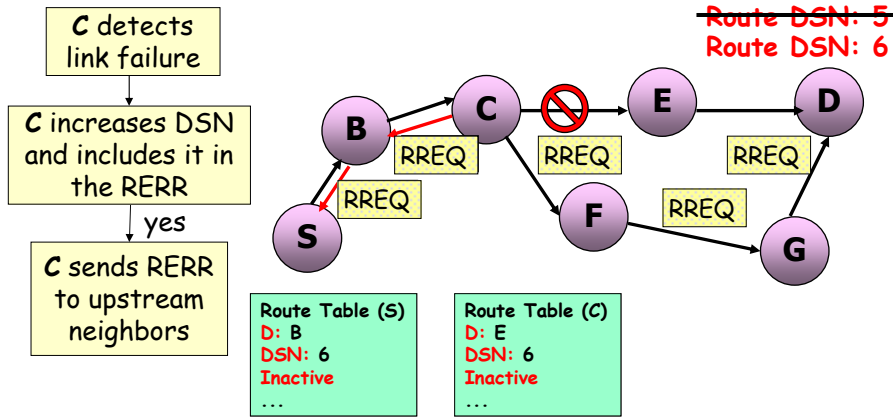
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Route Maintenance

- **HELLO** messages are periodically exchanged among neighboring nodes to maintain local connectivity
 - Absence of hello messages is used as an indication of link failure
 - Hello messages can also contain the ID of the neighbors from which a node has heard
- A node can also use packet retransmissions done by a neighbor to check on the next hop reachability or MAC acknowledgements

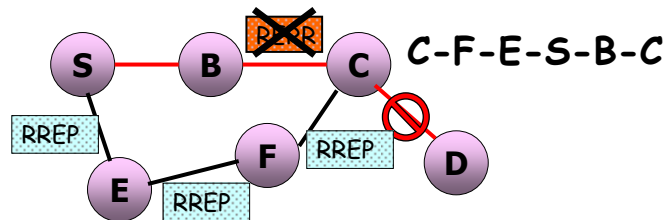
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Link Failure



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Link Failure: A Remark



- Loop formation avoided thanks to DSN!

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Advantages & Disadvantages

Advantages

- No need to include route in the packet header
- Nodes maintain routing tables containing entries only for routes in use
- DSNs allow nodes to avoid invalid/broken routes
- DSNs prevent formation of loops

Disadvantages

- * Unused routes expire even if topology is unchanged
- * Multiple routes for each pair S-D are not supported
- * Need for symmetrical links

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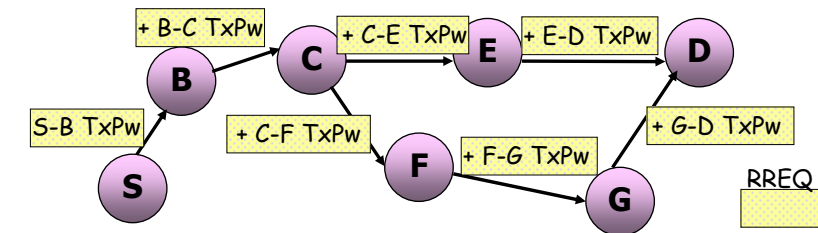
Routing Performance

- Several performance comparisons
[Broch98Mobicom,Johansson99Mobicom,
Das00Infocom,Important03Infocom]

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QoS Routing

- Associate each link with a *cost*
 - E.g., transmission power, transmitter's residual energy, traffic load, available bandwidth
- RREQs used to collect the cost (or minimum cost) of all traversed links along a route



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QoS Routing

- Destination responds with a Route Reply to a RREQ if
 - it is the first RREQ with a given ("current") sequence number, or
 - the route cost is smaller than all other routes cost received with the current sequence number
- Possible modifications to routing protocols, such as DSR, to make them QoS-aware

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QoS Routing

- Optimal routing decision requires constant updates on link state information (e.g., delay, bandwidth, loss rate, link stability) resulting in large overhead
- Dynamic nature of ad hoc networks makes maintaining the precise link state information very hard
- Even after resource reservation, QoS still cannot be guaranteed due to the frequent topology changes

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Nodes Cooperation

- Routing-forwarding misbehaviors can be caused by nodes that are malicious or selfish
- A malicious node misbehaves because it intends to damage network functioning
- Selfish nodes may refuse to relay other nodes' traffic in order to save energy
 - e.g., WLAN stations at an airport hall: if the average number of hops from source to destination is ~5, ~80 % of the energy will be devoted to packet forwarding

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Nodes Cooperation

- No cooperation leads to zero throughput, thus nodes **must be stimulated to cooperate...**
 - ... however, complete cooperation leads to unfairness and short nodes lifetime
- ➔ Two issues:
1. **How much should nodes cooperate**
 2. **How can they achieve a level of cooperation**

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Mitigating Routing Misbehavior [Marti00]

- Improve network throughput in presence of misbehaving nodes
- Misbehaving nodes are those who agree to relay packets but refuse to do so
- Solution based on an extension to DSR
 - *Watchdog* runs on every node and keeps track of how the other nodes behave
 - *Pathrater* calculates the route with the highest reliability and isolates misbehaving nodes
- Throughput increase of 17% with 40% misbehaving nodes; overhead increase: 9 to 7%

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The Terminodes Project

[Buttyn00]

- An ad hoc network of terminodes
- Nodes must be encouraged to relay packets and discouraged from overloading the network
- Pricing is a natural strategy
- Use of virtual currency: nuglets

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Packet Purse Model

- Each packet is loaded with nuglets by the source node
- Each relay node consumes or charges a certain number of nuglets from the packet before forwarding it
- Discourages sources from flooding the network
- Source needs to keep track of exactly how many nuglets to include in the packet

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Packet Trade Model

- Each packet is bought instead of sold
- A relay node will buy a packet in the hope that a downstream node will buy the packet from it
- The destination node ends up paying for the packet
- No need to keep track of required nuglets
- No incentive for a source to not flood the network

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A Game Theory Approach

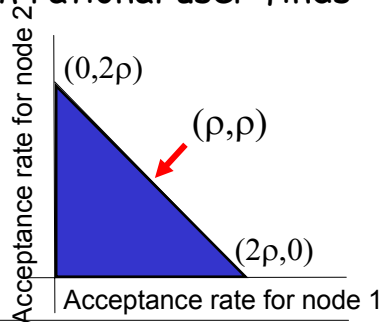
[Srinivasan03]

- Assumptions
 - Classes of nodes based on their average rate of energy consumption (ρ), i.e., energy level and lifetime expectation
 - Nodes are rational and self-interested
 - As a session is started, the source asks the nodes along the route to relay traffic. Relay nodes may either accept or reject
- What's the optimal network performance?
- Which algorithm achieves it?

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Optimal Network Performance

- There are infinite operating points for the network
- An operating point is defined as optimal if it is **Pareto optimal** and each rational user finds it **fair** to himself
- Ex.: 2 users with equal $\rho=0.5$
- A rate vector (r_1^*, r_2^*) is Pareto-optimal if there is no other feasible vector (r_1, r_2) such that: $r_1 > r_1^*$ and $r_2 > r_2^*$



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How to Achieve the Optimal?

- No guarantee that nodes will follow a given strategy unless they cannot do better by following any other strategy
- In game theoretic terms: we need a strategy which constitutes a Nash equilibrium
- Distributed acceptance algorithm:
 - Given the target operating point (acceptance rate), τ
 - Define: ψ as the help given to others and ϕ as the help received from others
 - Reject if $\psi > \tau$ or $\phi < \psi - \epsilon$
 - Accept else

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