Multi-Channel Routing Protocol (MCRP)

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Motivation

- Performance of wireless ad hoc networks degrades as the number of users increases
- One major reason: sharing of a single channel
- Single transceiver devices can only listen on one channel at a time
- Most protocols are designed to work in a one-channel environment

Motivation (cont.)

- Standards like IEEE 802.11 provide multiple non-overlapping channels
- Multiple channels would allow for simultaneous communication w/o interference
- Idea: a routing protocol to utilize multiple channels (network layer approach)

Assumptions

- Each node is equipped with a single transceiver
- Each node can switch channels (delay of ≤ 80 μs)
- IEEE 802.11 as MAC protocol remains unchanged (data link layer)
- Network layer can determine the proper channel and when to switch

Requirements

- Routing protocol must perform:
  - channel assignment
  - route discovery
  - route maintenance

Definitions

Flow:

Established connection between a source-destination pair

Route:

Path from source to destination in which

- Each node knows the next hop
- Each node knows on which channel to transmit packets to the next hop

Scenario 1

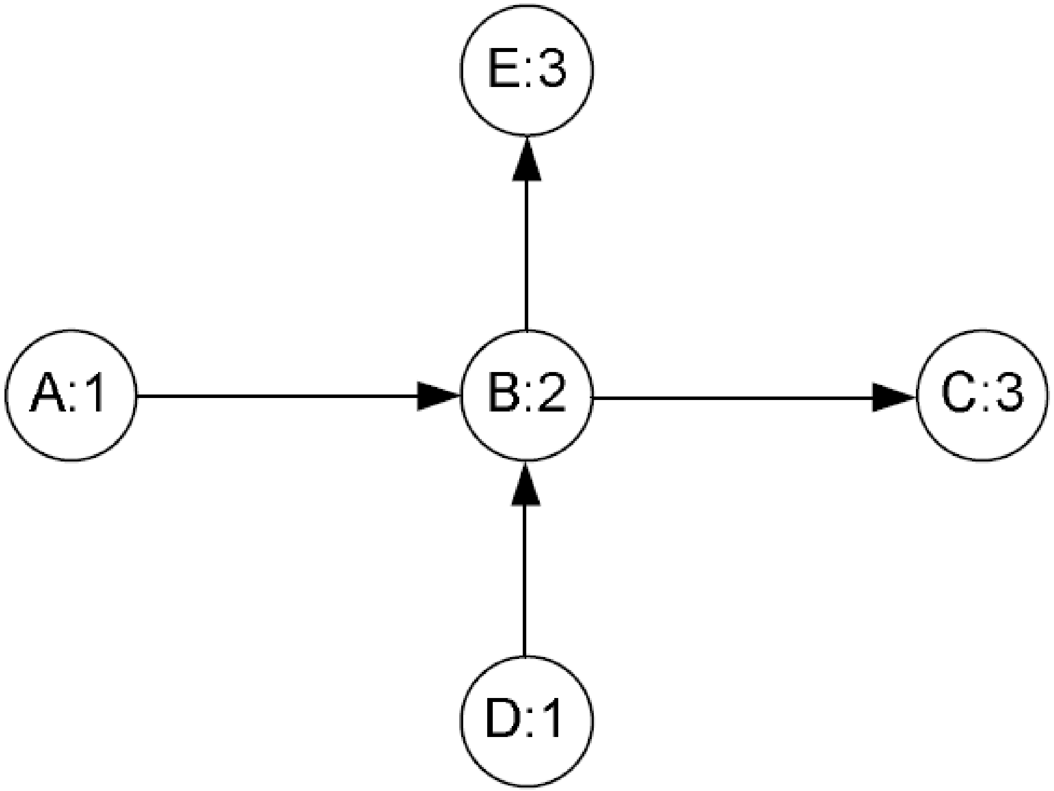


Fig. 1. An example network scenario. The label in each node indicates the node id and the channel it is listening on.

Channel Assignment (to nodes)

- Nodes are assigned channels regardless of traffic patterns
- No switch of listening channel to participate in a flow
- After establishing a route nodes switch channels to that of the receiver whenever they send packages
- Route establishment and channel assignment are separated (hence simpler)

Channel Assignment (to nodes, cont.)

Problem:

Performance degradation due to deafness:

- two nodes are on different channels and cannot communicate
- can occur when a node switches its channel for sending and another is trying to communicate with it on its normal channel

Channel Assignment (to flows)

- Channels are assigned to flows, i.e. all nodes in a route use a common channel
- Channel assignment must be coupled with route establishment
- Concept works well with on-demand routing
- Nodes do not need to switch channels when transmitting packages (avoids deafness)

Channel Assignment (to flows, cont.)

Problems:

- Intersecting flows would require all involved nodes to use the same channel
- Additional intersecting flows would require node-disjoint flows on different channels to switch to the same

Solution:

- Allow some specific nodes to switch channels
- Avoid deafness problem

Scenario 2a

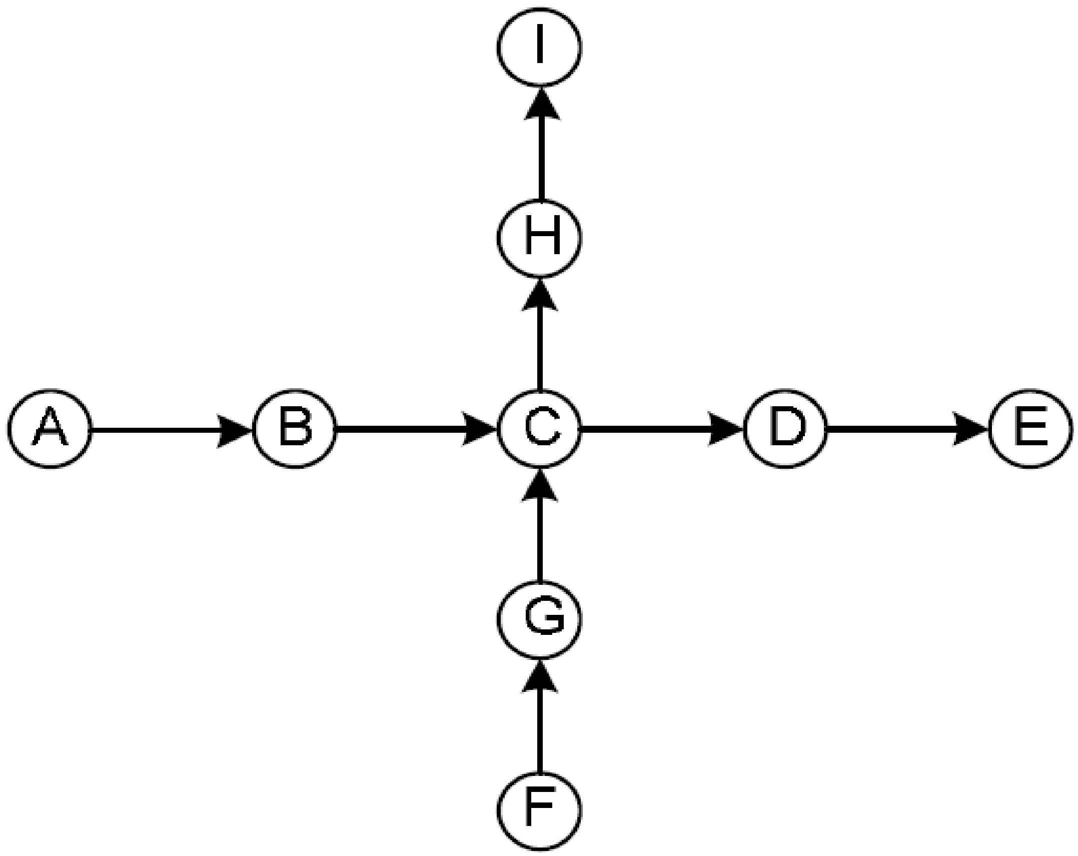


Fig. 2. An example network scenario. Two flows A-E and F-I are intersecting at node C.

Scenario 2b

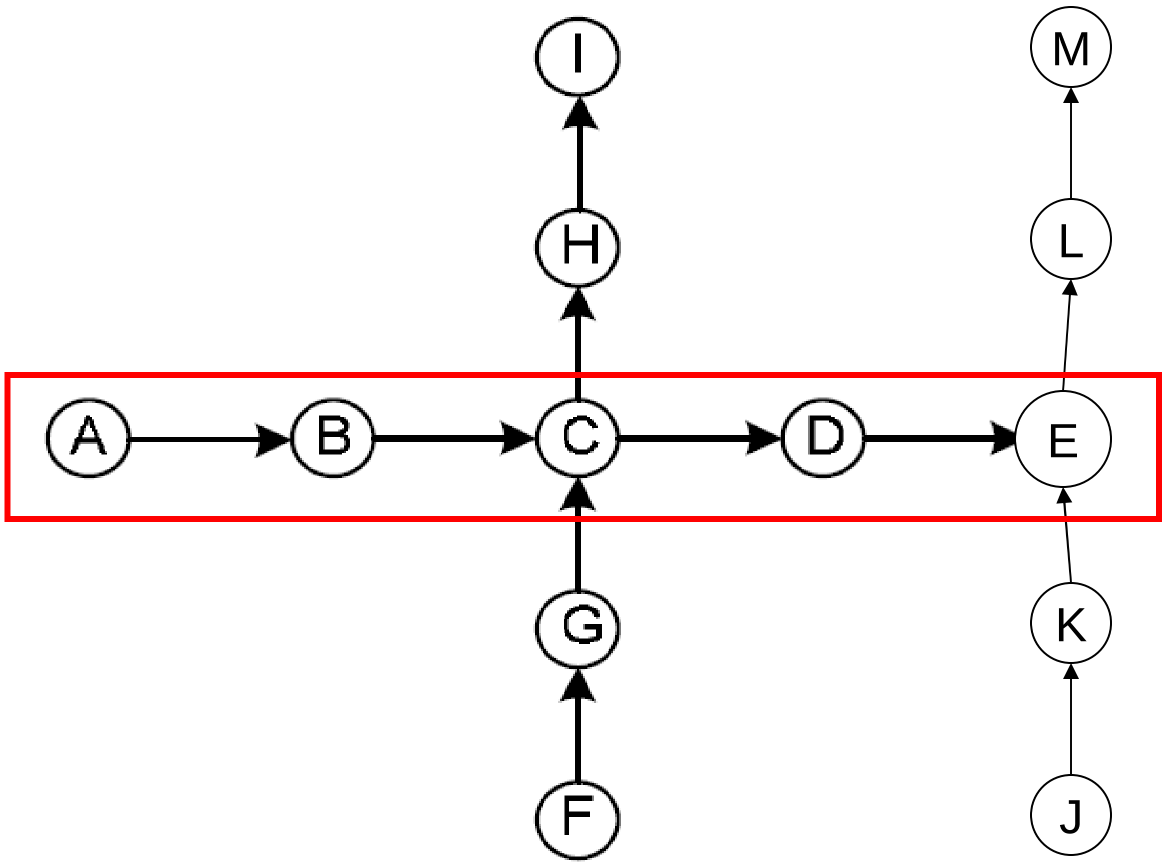


Fig. 2. An example network scenario. Two flows A-E and F-I are intersecting at node C.

Constraints (Deafness/Performance)

Deafness Avoidance:

- Two consecutive nodes on a path cannot switch channels
- When switching channels, a node must notify its neighbors on a path

Performance:

- A node can only switch between a small number of channels (here: two), though more are available
- Nodes may not switch channels too frequently, such as per-packet

Channel Selection

- Channel switching allows for more route choices
- Protocol selects route and channel

- Goal: balancing the load between available channels

➡ Need to collect information on channel load

(HELLO messages on all channels)

Scenario 3

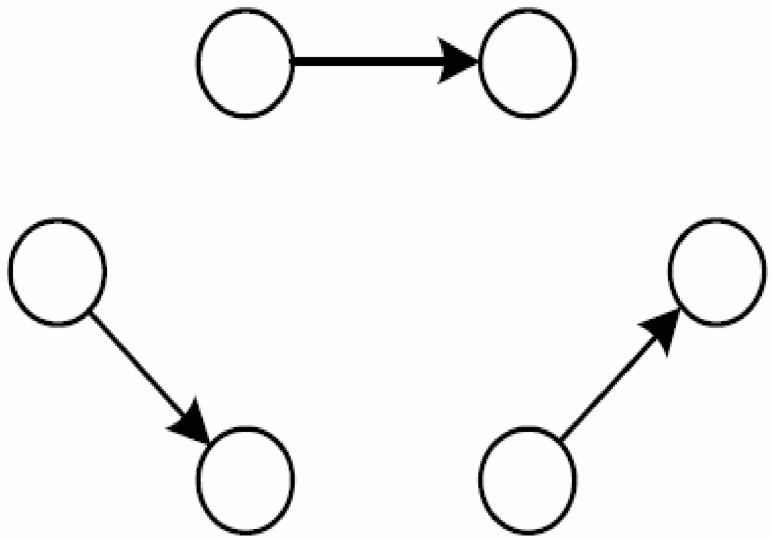


Fig. 4. An example network scenario with three node-disjoint flows. Random channel assignment may result in the same channel assigned for all flows.

Multi-Channel Routing Protocol

- On-demand routing protocol
- Similar to Ad-hoc On-demand Distance Vector protocol, which uses a single channel (AODV)
- MCRP guarantees that a route from source to destination will be established, if one can be found in a single channel network with the same topology

MCRP (cont.)

- Assigns a common channel to all nodes in a flow
- Allows for channel-switching
- Prohibits channel-switching for two consecutive nodes in a flow
- Each node must be in one of four *feasible* states

MCRP – Feasible Node States

free:

- no flow, can freely switch to other channels

locked:

- part of a flow on a certain channel

switching:

- involved in multiple flows on different channels

hard-locked:

- has a flow on a certain channel and cannot be made a switching node

Scenario 2b

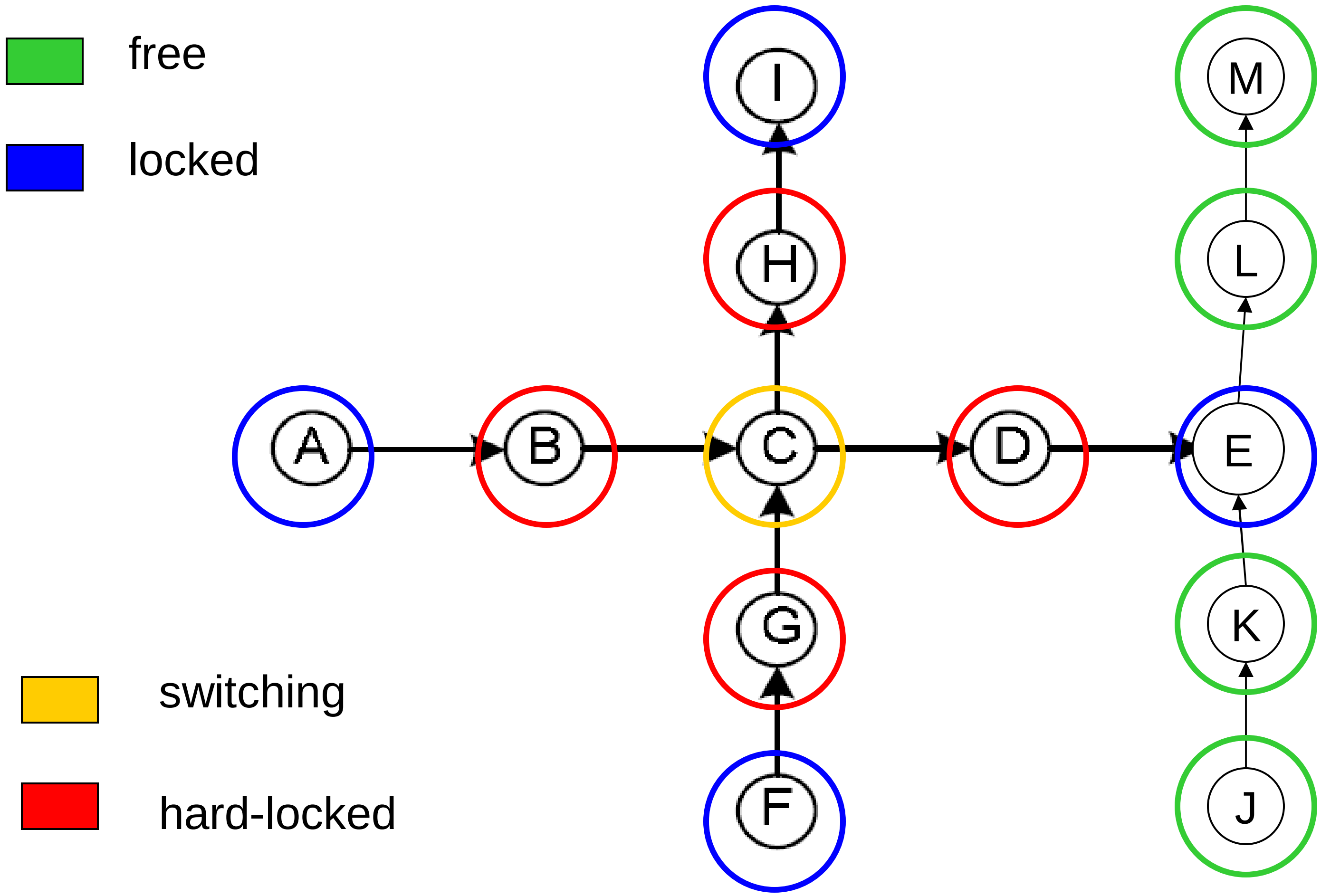


Fig. 2. An example network scenario. Two flows A-E and F-I are intersecting at node C.

MCRP - Route Discovery

- Route Request (RREQ) broadcast on all channels in rotation
- Receiving nodes also forward RREQ on all channels
- RREQ contains operating channel of the forwarding node
- Reverse path to source is set up while forwarding RREQs, using the channel information

Route Entry

dest	*seqno*	*hops*	*nexthop*
channel	*active*	*expire*	*flags*

- As in AODV, except for:
  - Channel – indicates which channel the next hop node is on
  - Active – indicates whether the next hop node is currently on the specified channel (relevant with switching nodes)

⇒ When 0, all packets on this route must be buffered

MCRP – Route Discovery (cont.)

- Destination receives RREQ, selects a channel and sends Route Reply (RREP)
- RREP packets are dropped if a node would have to enter an *infeasible state*
  - All routes might be dropped although paths exist
  - To avoid that, a “force” mechanism can be used
- Otherwise, nodes on the return path switch channels and node states

Channel and State Switching

free:

- Becomes locked, switches to selected channel

locked:

- If locked on different channel, it becomes a switching node, else nothing happens

switching:

- If one of its channels is the selected channel, nothing changes, else RREP gets dropped (channel limit of 2)

hard-locked:

- If locked on selected channel, no change, else RREP gets dropped (cannot become a switching node)

Scenario 4

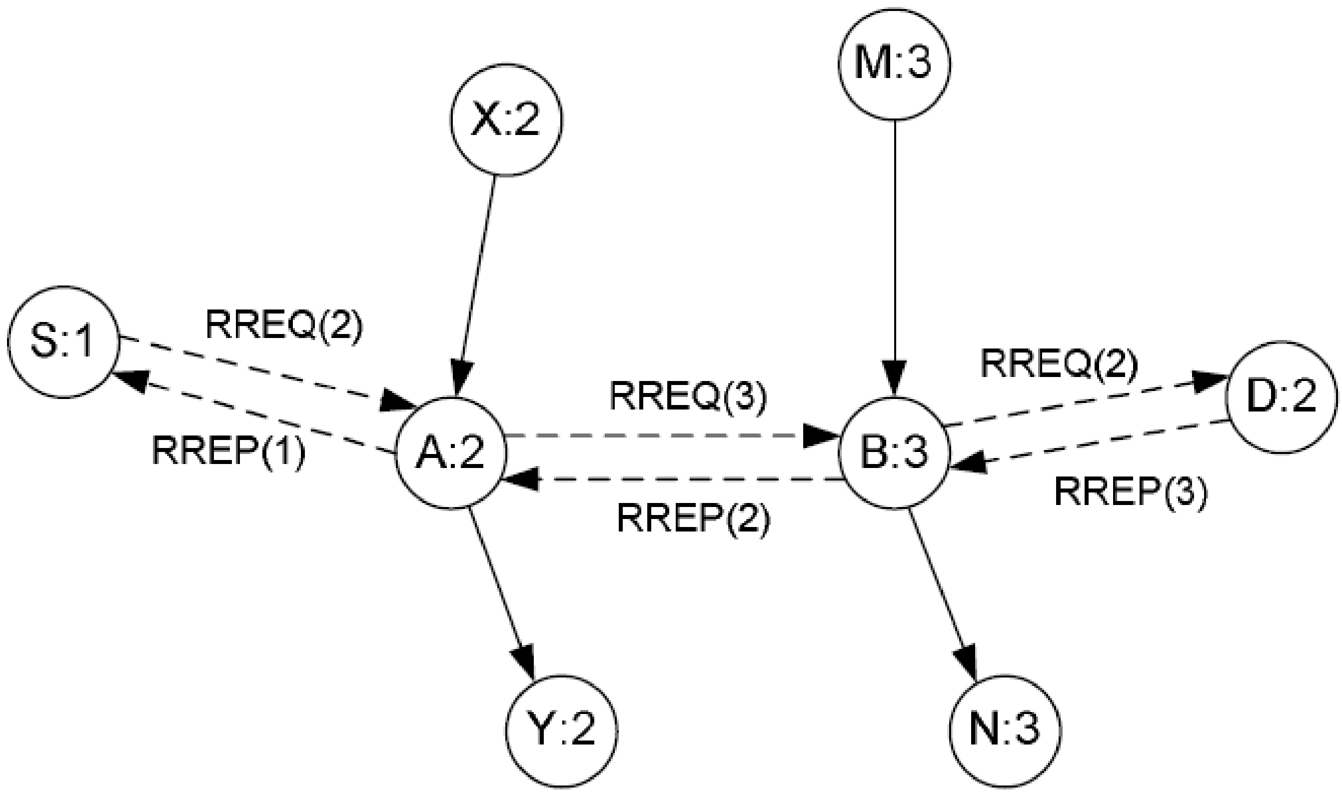


Fig. 6. A network scenario to illustrate route discovery process. The label "A:2" means that node A is on channel 2.

Channel Selection

- Two goals when choosing a channel:
  - No node on the path should go into an infeasible state ($\Rightarrow$ feasible channels)
  - Feasible channel with the lowest load should be selected for channel load balancing

- Solution: RREQ contains
  - Channel table
  - Flow table

Channel Table

ch_1	ch_2	…	ch_k

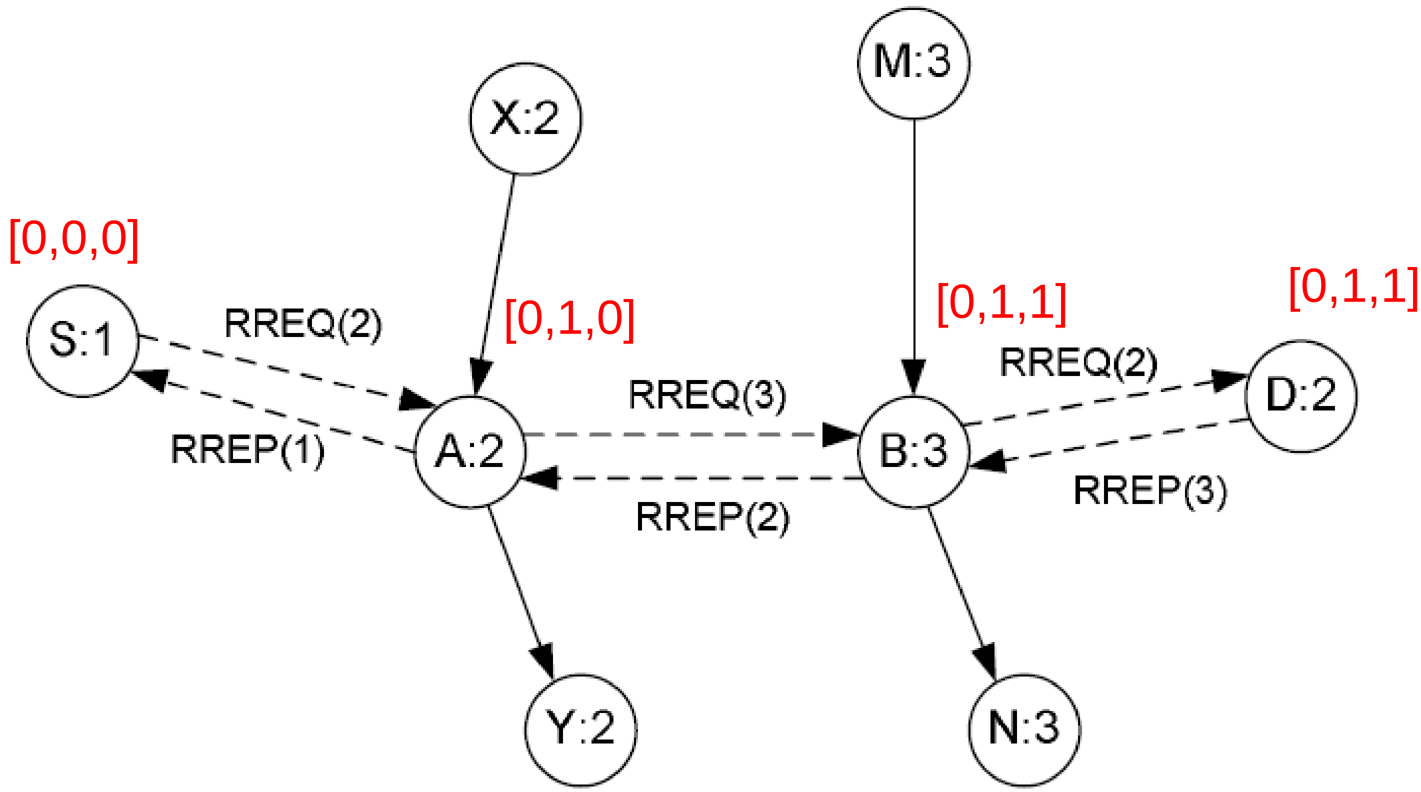
- Contains a field for each channel
- Initially all fields are zero
- Records the channel-use of nodes on the path from source to destination

Channel Table (cont.)

Rules for updating (depending on node states):

- *free*:
  - no changes in the table
- *locked*:
  - increments ch_i if node is on channel i
- *switching*:
  - increments ch_m and ch_n if node switches between channels m and n
- *hard-locked*:
  - increment ch_i by *two* if node is on channel i

Scenario 4



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Flow Table

F_1	F_2	$\ldots$	F_k

F_c - number of flows on channel c

- Used to determine the interference level of each channel used in the path (could be done with a different metric)
- Each node:
  - transmits HELLO messages periodically, which contain the node's channel and its flow state
  - builds up its *own* flow table by recording the number of flows on each channel for itself and its neighbors
- RREQ flow table:
  - If F_c(node) > F_c the update F_c := F_c(node)

Scenario 4

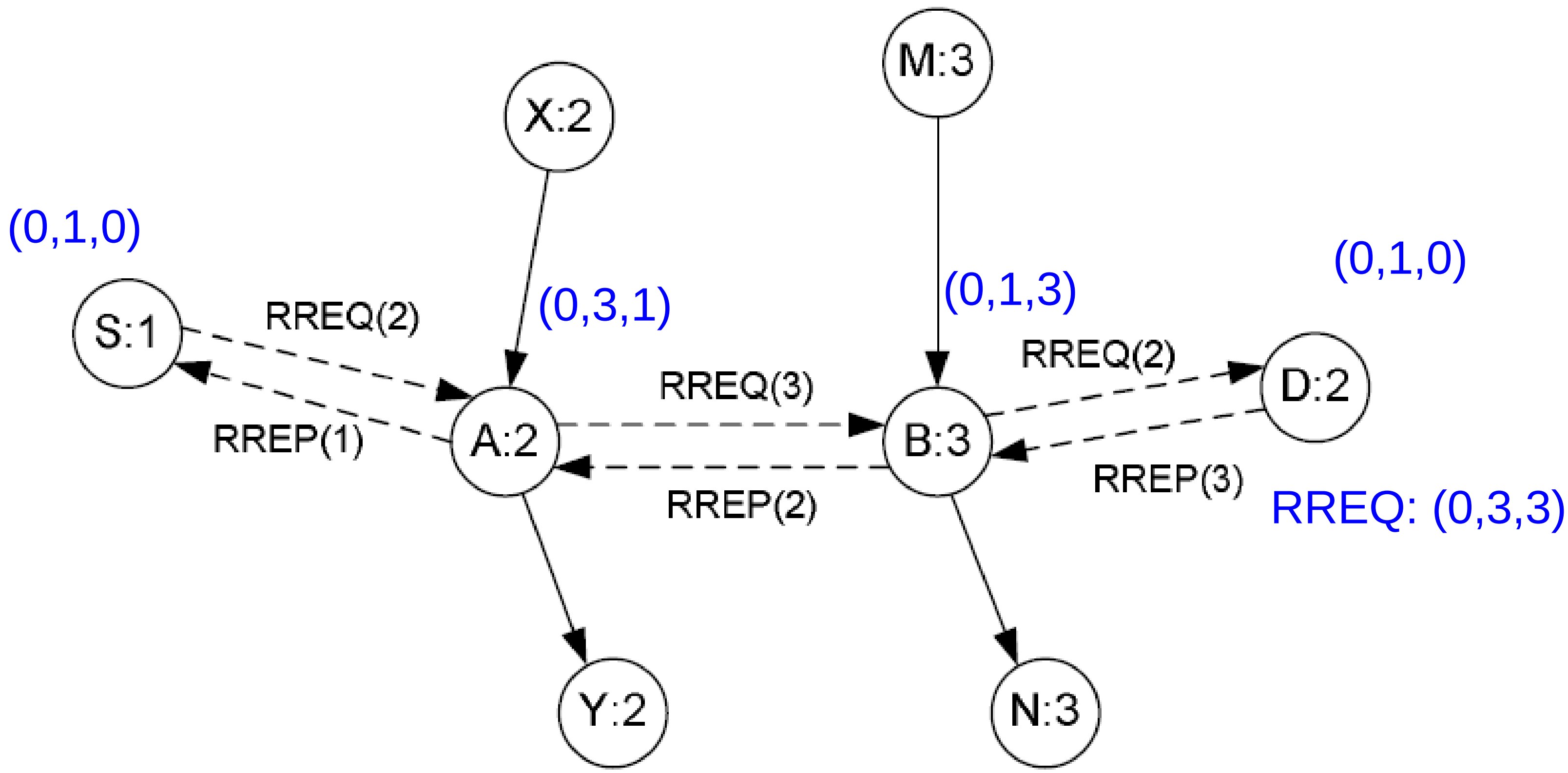

Fig. 6. A network scenario to illustrate route discovery process. The label "A:2" means that node A is on channel 2.

Channel Selection Algorithm

- Route feasibility

  (infeasible if consecutive switching nodes or more than two channels assigned to a node)
- Test with channel table:
  - Multiple channels have values ≥ 2
  - More than two channels have values ≥ 1
- If any of these conditions are met, route is either dropped or used with “force”

Channel Selection Algorithm (cont.)

- If route is feasible, select channel according to channel table:
  - If channel value ≥ 2, the channel has to be selected
  - If two channels have value 1, one of these channels with minimum interference is selected
  - If only one channel has value 1 and others 0, then select any channel with minimum interference
- For interference level use flow table

Scenario 4

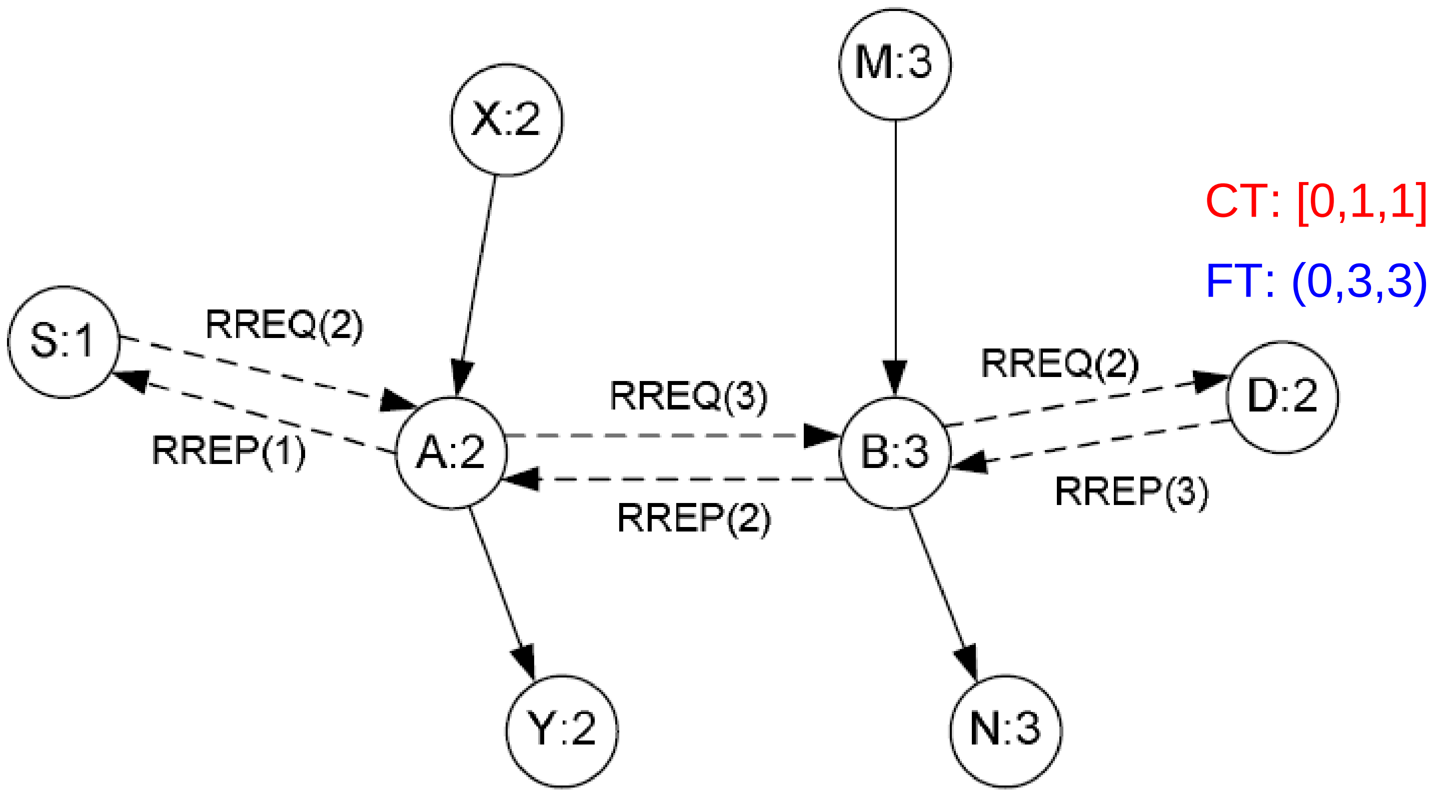

Fig. 6. A network scenario to illustrate route discovery process. The label "A:2" means that node A is on channel 2.

Delayed Reply

- MCRP makes use of delayed reply
  - When destination first receives a RREQ, it sets a timer and waits for more RREQs to arrive
- Intermediate nodes forward RREQs after the first one (if the route is *feasible* and has *lower path interference* level)
- If destination receives multiple RREQs it chooses one where the selected channel has minimum interference level

Forwarding & Channel Switching

- Common channel with all nodes in a flow
- Communication with a switching node requires buffering and signal messages
  - LEAVE / JOIN messages to neighbors on the respective channels
  - Neighbors set the ‘active’ flag in route entries
  - Need to buffer packets till they receive a JOIN
  - Packets in the buffer are then sent with higher priority
- Duration in channels should be handled intelligently according to traffic load (here: fixed 50 ms)

Force Mechanism

- Destination receives RREQ(s) but all routes are infeasible
- Avoid connection failure despite existence of a source-destination path

  ⇨ set “force” flag in RREP
- Guarantees that a route can be found if there is a path
- Nodes receiving RREP with “force” channel *x* must switch channel

Force Mechanism (cont.)

- *free*:
  - Becomes locked on channel *x*
- *locked or hard-locked*:
  - If locked on a different channel, send RERR to flows on the other channel, else stay in channel *x;*
  - Node state remains unchanged
- *switching*:
  - If locked on different channels, choose one and send RERR for those flows
  - Replace that channel with channel *x* as operating channel
  - Node state remains unchanged

Force Mechanism (cont.)

- Locked nodes are not allowed to change state to avoid two consecutive switching nodes
- At least one flow loses the route
- Its source needs to perform route discovery
- To avoid oscillation nodes caused by two flows, “forced” nodes temporarily do not accept another RREP with “force” set

Route Maintenance

- Timer, which is refreshed each time the route is used
- When considered to be stale it is deleted from the routing table
- If MAC layer finds broken links: send RERR
- *Precursor list* on the path, RERR only transmitted when a node has a precursor for the broken route

Maintenance & State Changes

When routes are removed, node states can change:

- *locked, hard-locked, switching*:
  - If all routes are removed, it becomes a free node
- *hard-locked*:
  - If all routes with a switching node as next hop are removed, the node becomes locked
- *switching:*
  - If all routes in one channel are removed, it becomes a locked node

Performance Simulation

- Simulations with ns-2
- Metric: throughput over all flows
- MCRP with 2,3,4 channels + AODV for comparison
- Network area: 1000m x 1000m
- Random node distribution
- Node transmission range of about 250m
- Channel bit rate 11Mbps

Performance Simulation 1

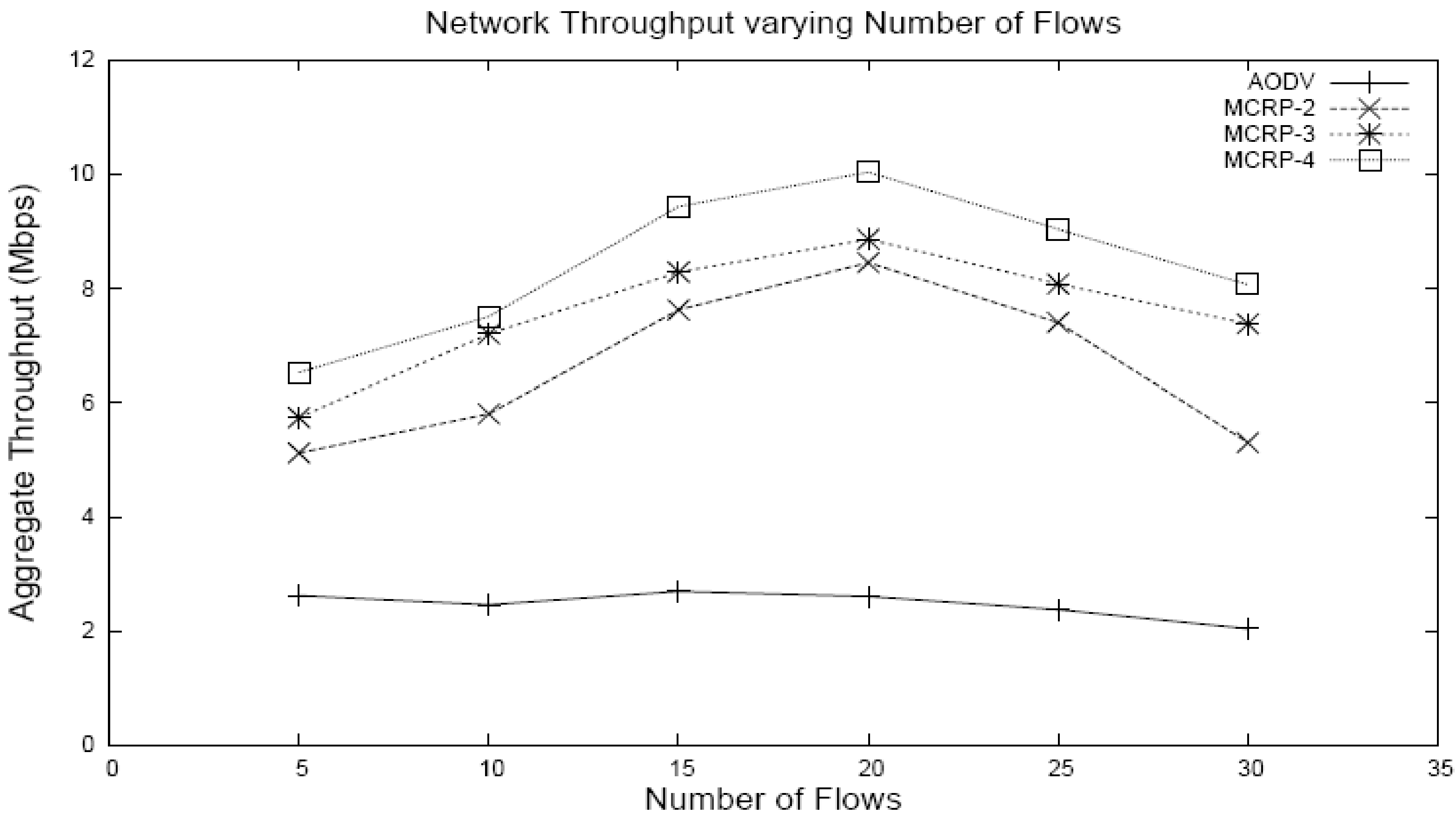

Fig. 9. Network Throughput varying Number of Flows

Performance Simulation 1 (cont.)

- Varied number of flows
- MCRP can sometimes improve throughput by factor 4 with 4 channels
- Overhead and flow-level channel allocation prevent a factor of *k (the number of channels)*
- Contention is better distributed over channels and collision rate is thus reduced
  - ➡ Sometimes with *k* channels more than *k* times the throughput of AODV

Performance Simulation 2

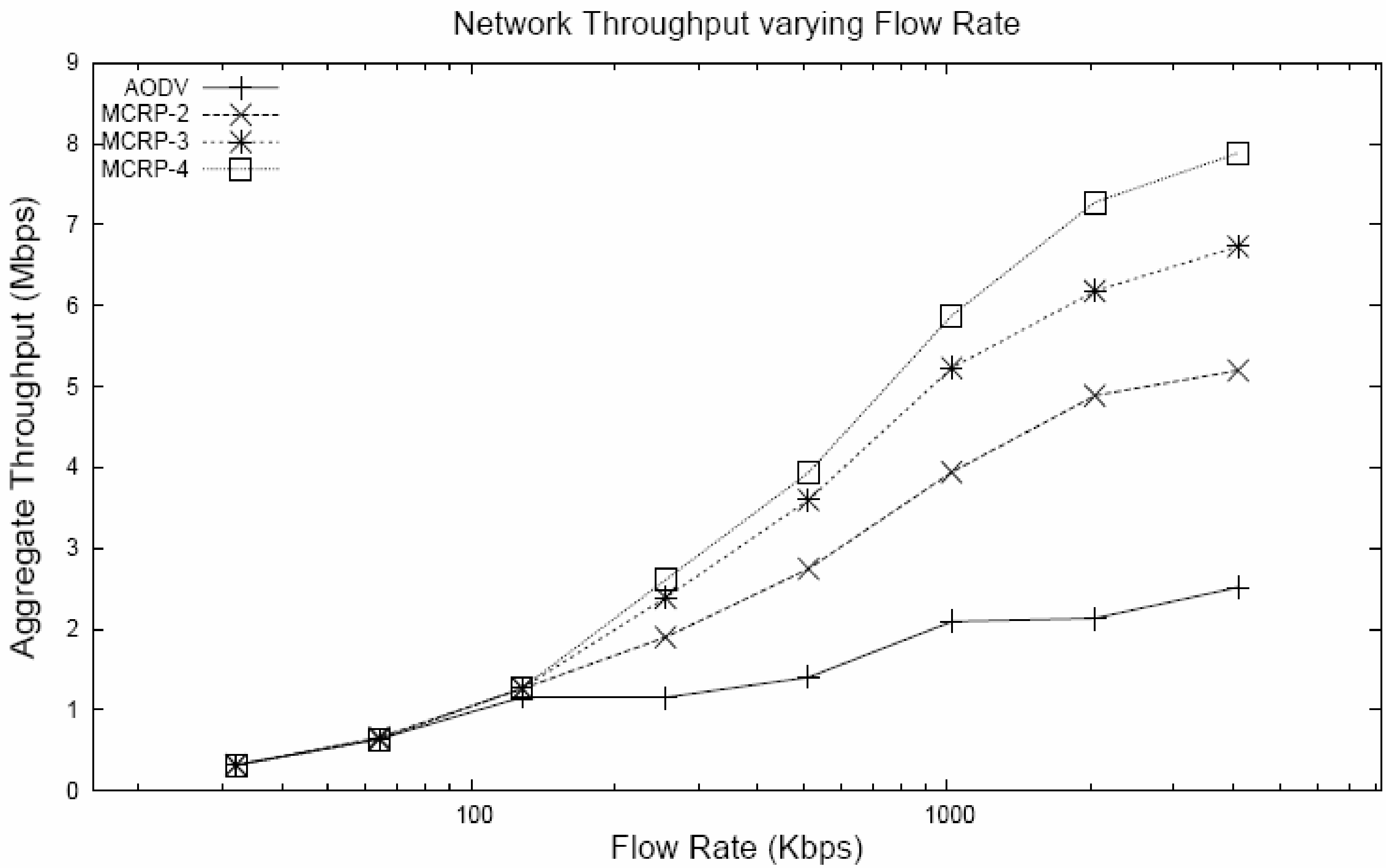

Fig. 10. Network Throughput varying Flow Rate

Performance Simulation 2 (cont.)

- Varied traffic of each flow, 10 flows from 32Kbps to 4096Kbps
- Low traffic: AODV slightly better (less overhead)
- Increased traffic: MCRP is a dramatic improvement over AODV

Performance Simulation 3

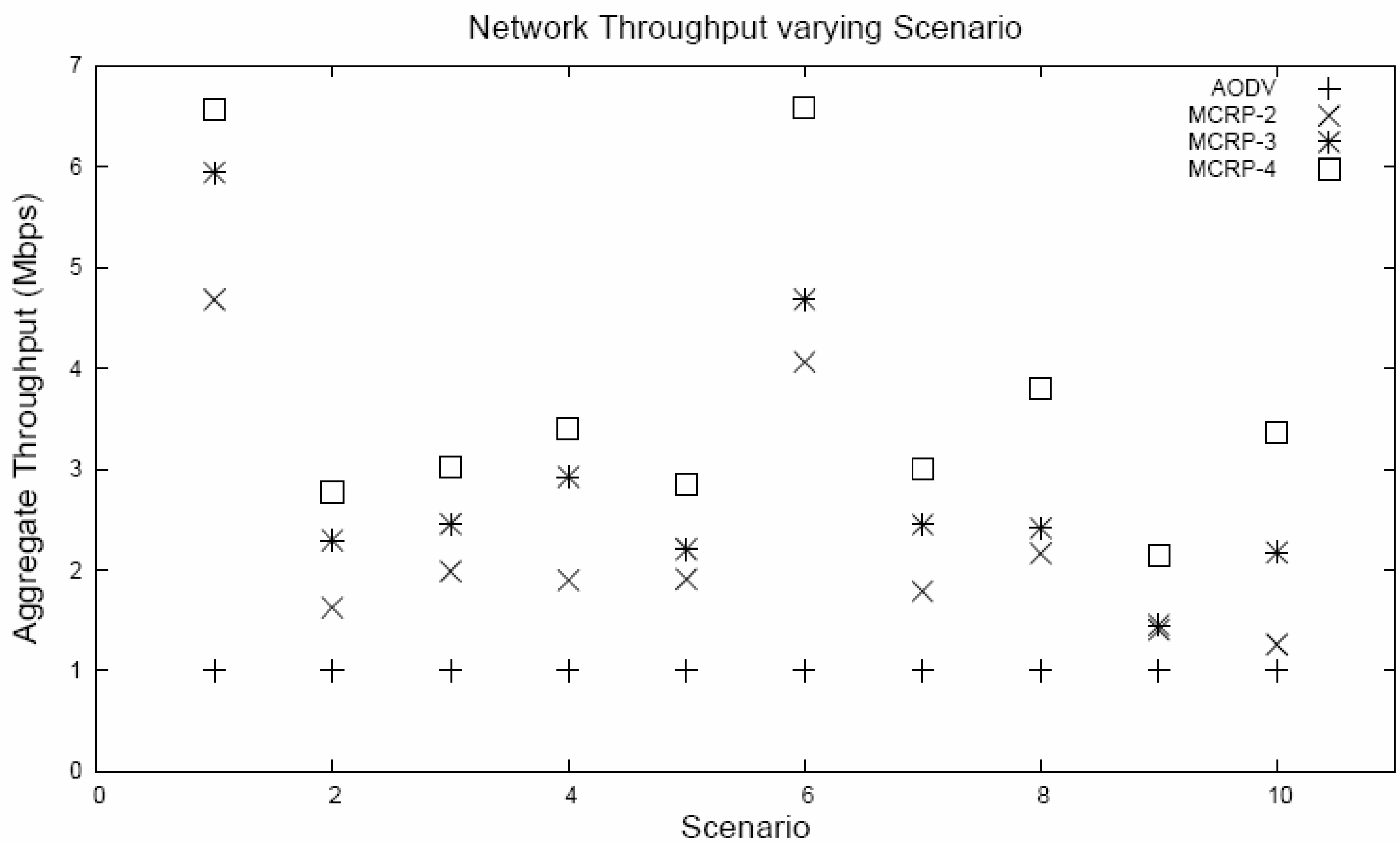

Fig. 11. Network Throughput varying Scenario

Performance Simulation 3 (cont.)

- 10 different scenarios with 50 randomly placed nodes
- Mostly improvement over AODV is a little less than factor *k*
- Sometimes it can be more than factor *k* due to fewer collisions as a result of channel distribution

Conclusion

- Some points still need to be tweaked
  - Metrics for route selection
  - Clever channel switching
- Even with standard equipment a dramatic improvement in network throughput is possible by utilizing multiple channels