48th Meeting of IFIP Working Group 10.4
Workshop “Nomadic Computing and Dependability”
Hakone, Japan – Monday July 4, 2005

Autonomous Clustering and Hierarchical Routing for Mobile Ad Hoc Networks

Yoshiaki Kakuda

Hiroshima City University

Experiences of My Research Activities on Dependability (1)

- FTCS-10, 1980, Kyoto, Japan
- FTCS-12, 1982, Santa Monica, USA
- Workshop on Responsive Computer Systems, 1992, Kamifukuoka, Japan

General Chairs: Miroslaw Malek, Tohru Kikuno

Program Chairs: Hermann Kopetz, Yoshiaki Kakuda

Experiences of My Research Activities on Dependability (2)

- Workshop on Dependability in Advanced Computing Paradigms, 1996, Hitachi, Japan

General Chairs: Jack Goldberg, Yoshihiro Tohma

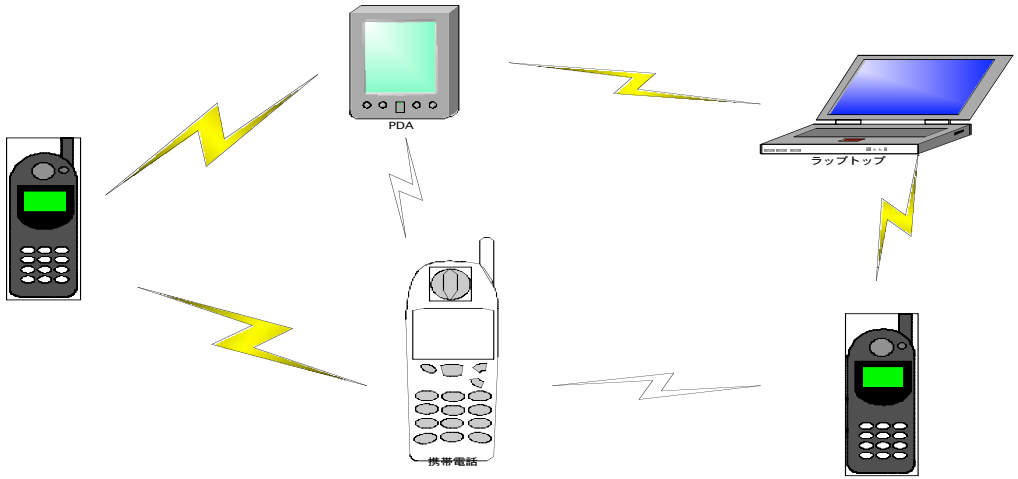
Program Chairs: Hermann Kopetz,

Richard Schlichting, Yoshiaki Kakuda

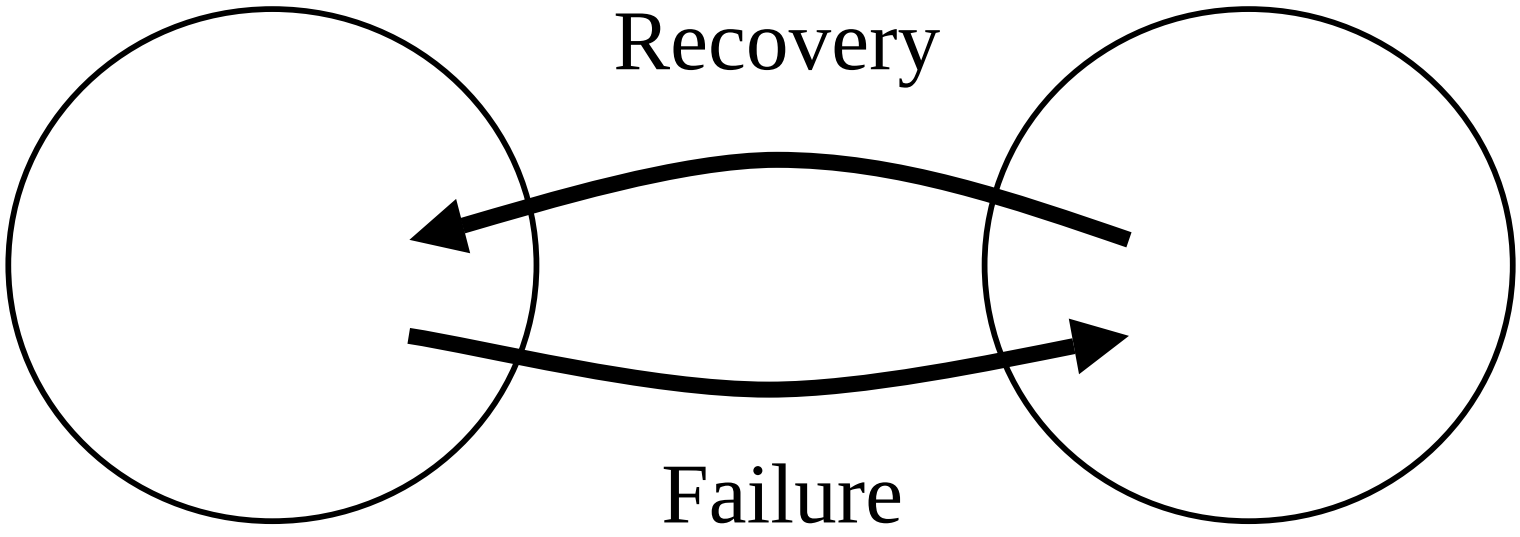
- IFIP Conference on DCCA (Dependable Computing for Critical Applications)-7, Program Committee, 1999, San Jose, USA
- DSN-2005, DCCS Program Committee, 2005, Yokohama, Japan

Mobile Ad Hoc Networks

– Wireless mobile network without the aid of any base stations
– Each mobile node has the function of router
– Each mobile node can move around the network



Characterization of Mobile Ad Hoc Networks by Dependability



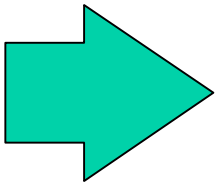
Normal system states Abnormal system states

Challenging Issues in Routing for Mobile Ad Hoc Networks

- Routing for large-scale networks
- Routing for asymmetric networks
- Location-based routing
- Energy efficient routing
- Secure routing
- QoS routing

Scalability Issue in Routing for Mobile Ad Hoc Networks

- Why does the scalability issue occur?
  - Increase of the numbers of mobile nodes and pairs of a source and a destination
  - Frequent node movement



Stable routes are required.

Research Funds from MIAC

- Ministry of Internal Affairs and Communications in Japan
- Stragetic Information and Communications R&D Promotion Programme (SCOPE)
- Research and Development Promoting Info-Communications Technology for Community Development (SCOPE-C)

Joint Project of University and Industries

- Project Title: R&D on Scalable Technology for Confirming Group Members in Mobile Ad Hoc Networks
- Project Members: Hiroshima City University, KDDI Corporation, National Institute of Advanced Industrial Science and Technology (Information Technology Research Institute), The Chugoku Electric Power Co., Inc. (Technical Research Center), Chuden Engineering Consultants

Table-Driven Routing

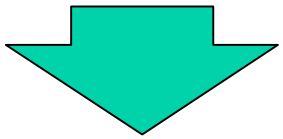
- Each node always has the routing table for the destination node because it periodically exchanges route information with each other.
- Distance-vector and link-state types
- OLSR, TBRPF, DSDV

On-demand Routing

- A route to a destination is required only when a source node wants to send data packets
- Utilizing the route cache
- Overhead to create the route is lower
- It takes longer time to start to send data packets
- TORA, DSR, AODV

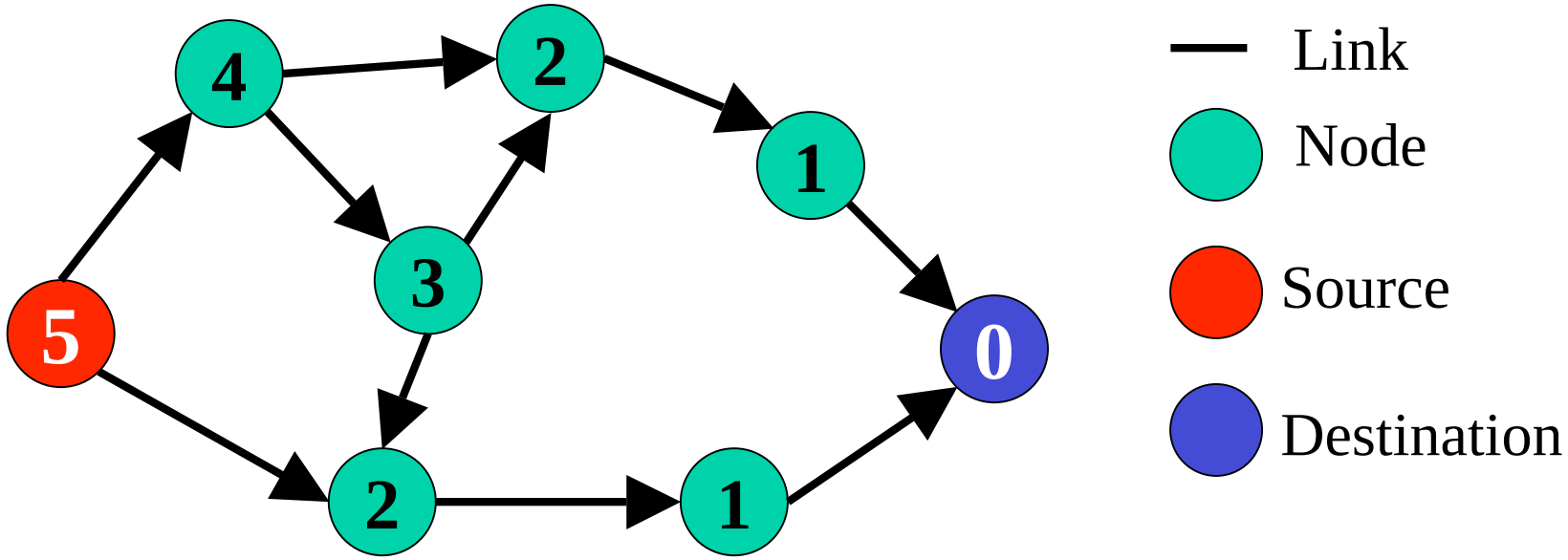
Motivation

- Ad hoc network routing protocols
  - TORA, DSR, AODV（**Flat routing**）
  - The performance becomes worse along with the increase of the network size
- Hierarchical routing protocols based on the autonomous clustering
  - Hi-TORA, Hi-DSR, Hi-AODV（Hierarchical routing）



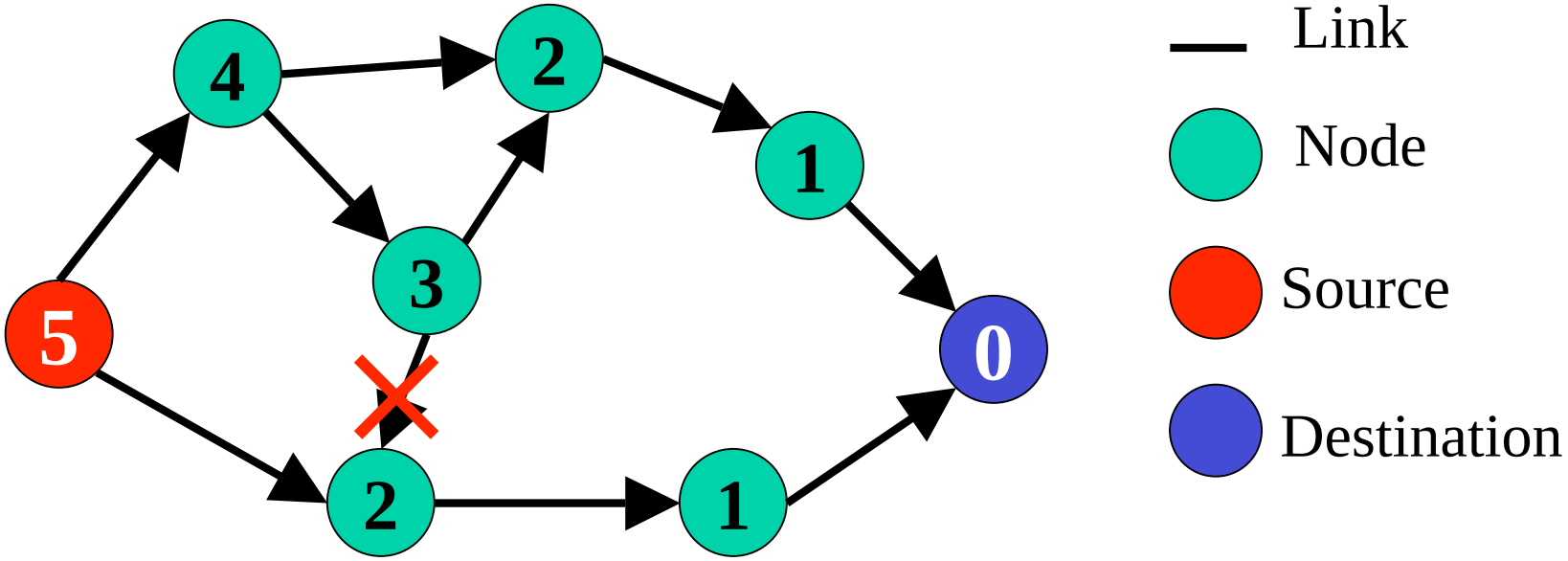
Proposal and evaluation of hierarchical routing protocols based on the autonomous clustering

Route Discovery in TORA (Temporally-Ordered Routing Algorithm)

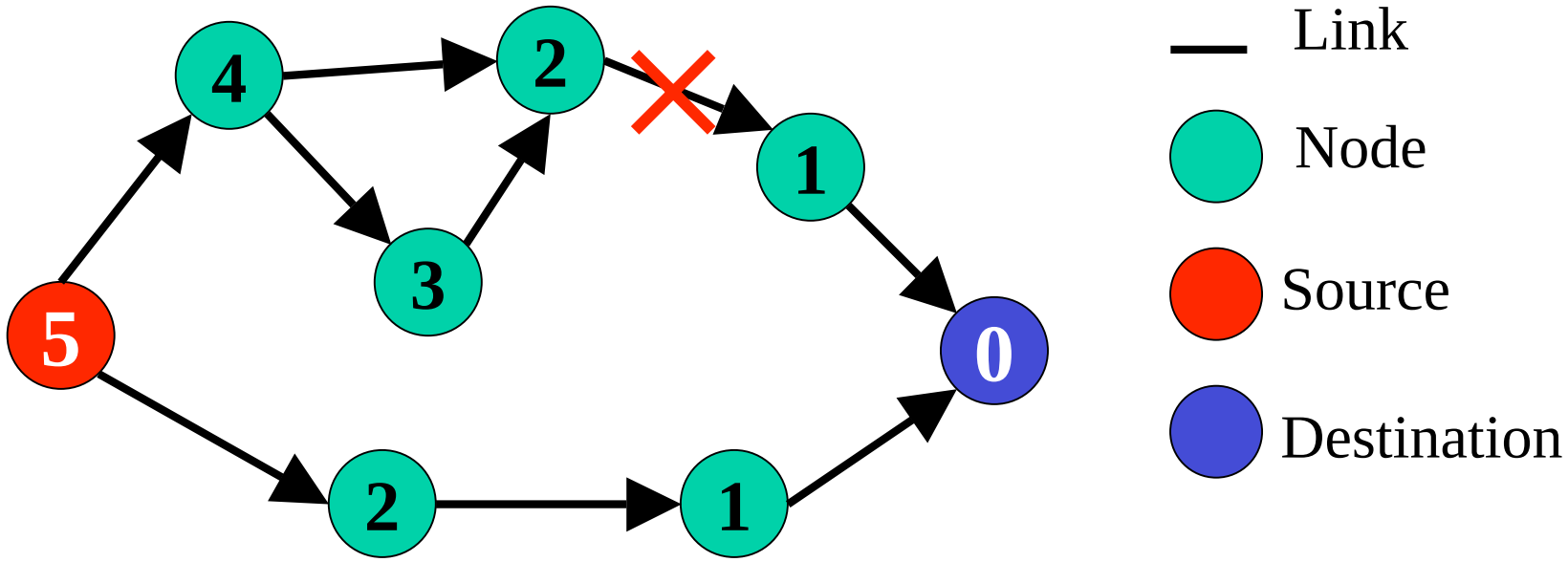


- A source node broadcasts REQUEST packets to all nodes and the notation of *height* is assigned to them to create the route.

Route Maintenance in TORA

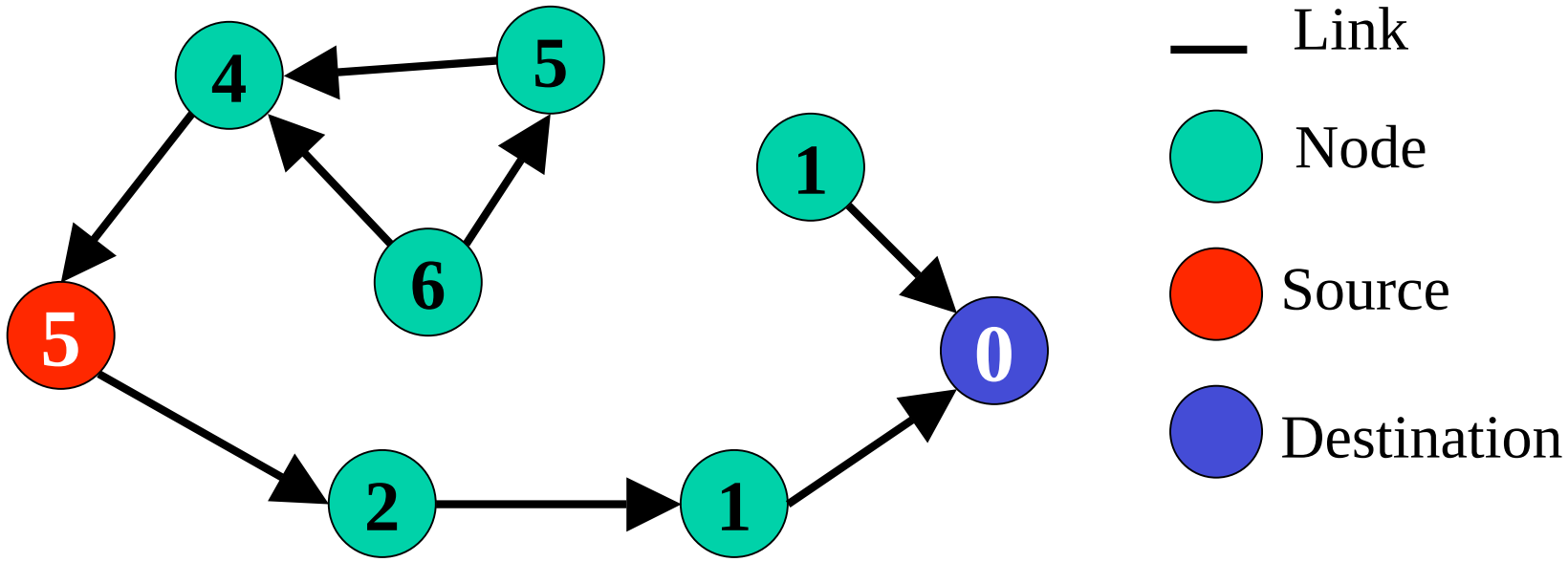


Route Maintenance in TORA



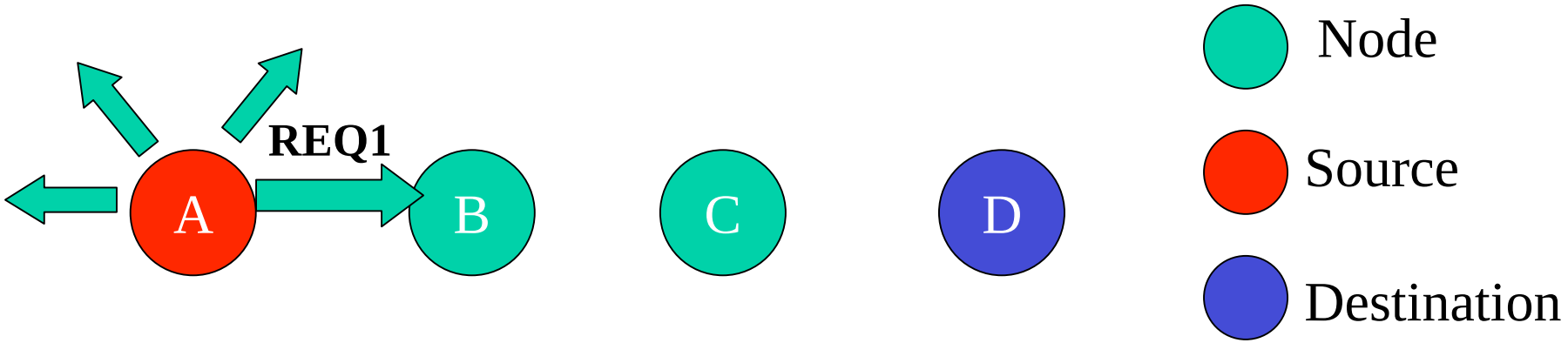
- Nothing to do because there is another route.

Route Maintenance in TORA



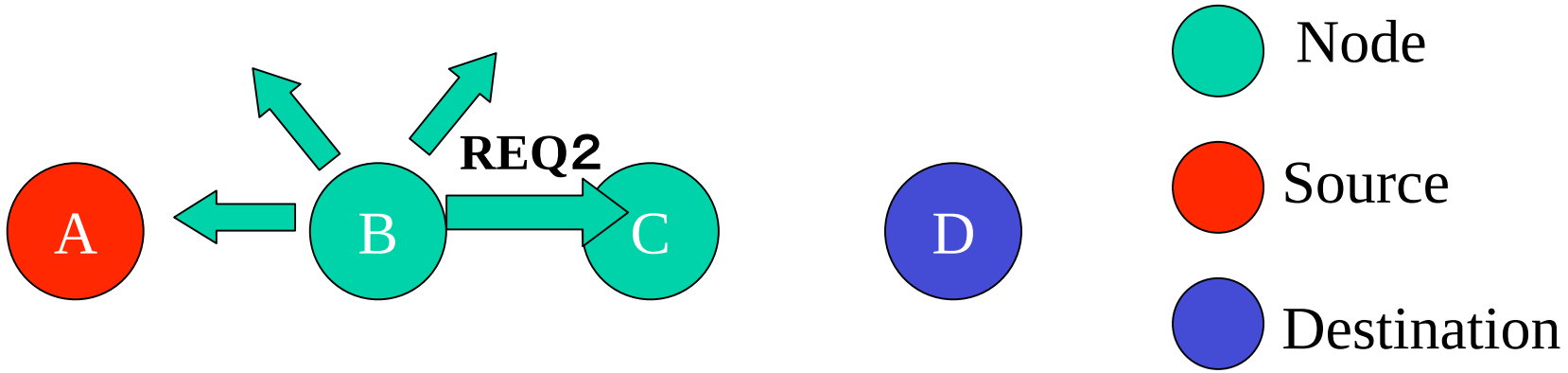
- There is possibility that the number of hops between a source node and a destination node becomes long because each node repairs the route locally.

Dynamic Source Routing(DSR)



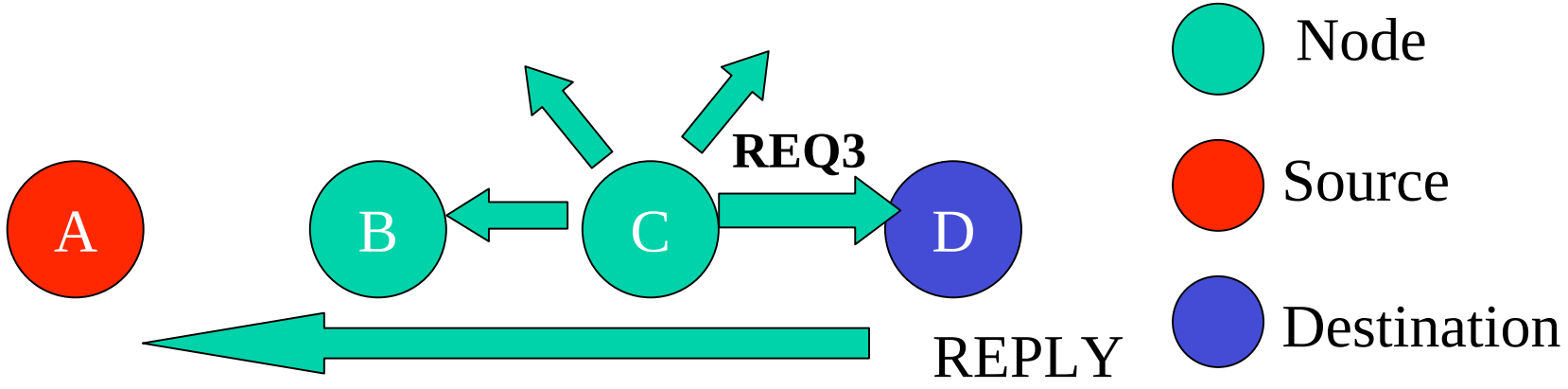
	Route Information
REQ1	A
REQ2	A→B
REQ3	A→B→C
REPLY	A→B→C→D

Dynamic Source Routing(DSR)



	Route Information
REQ1	A
REQ2	A→B
REQ3	A→B→C
REPLY	A→B→C→D

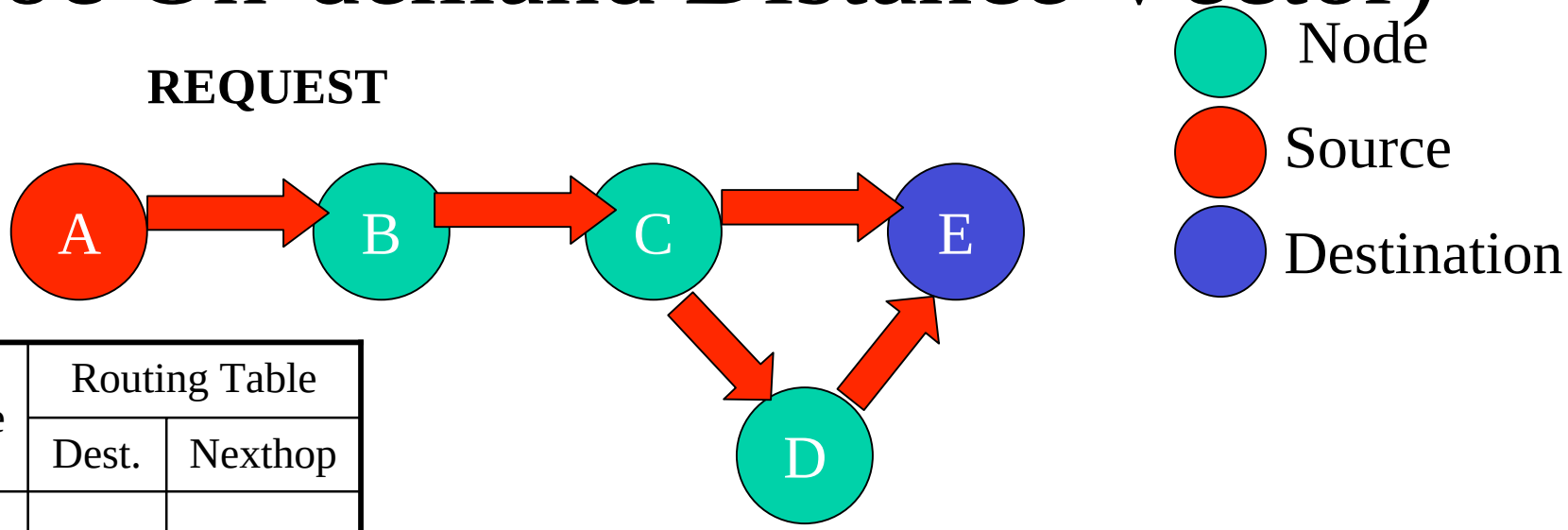
Dynamic Source Routing(DSR)



	Route Information
REQ1	A
REQ2	A→B
REQ3	A→B→C
REPLY	A→B→C→D

In DSR, if the route between the source and the destination disappeared, a source node invokes route discovery again.

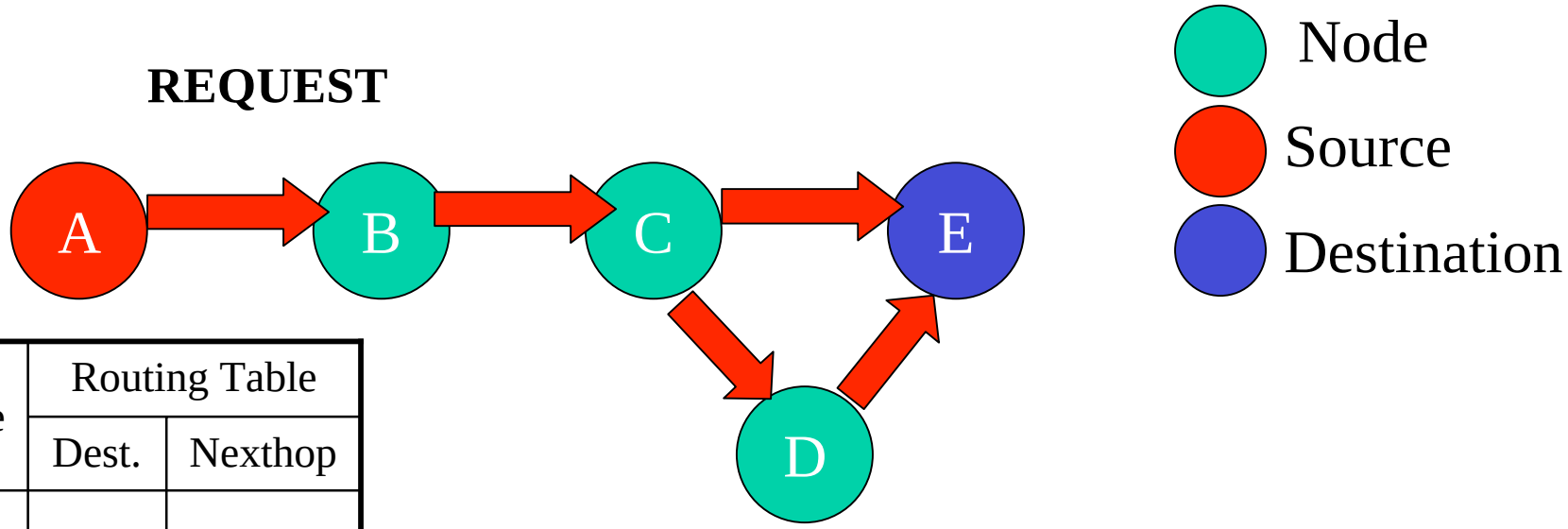
Route Discovery in AODV (Ad hoc On-demand Distance Vector)



Node	Routing Table	
	Dest.	Nexthop
A		
B		
C		
D		
E		

- Nodes which received REQUEST or REPLY packets update the routing table and forward it to the neighbors.
- Data packets are delivered along with the routing table in each node.

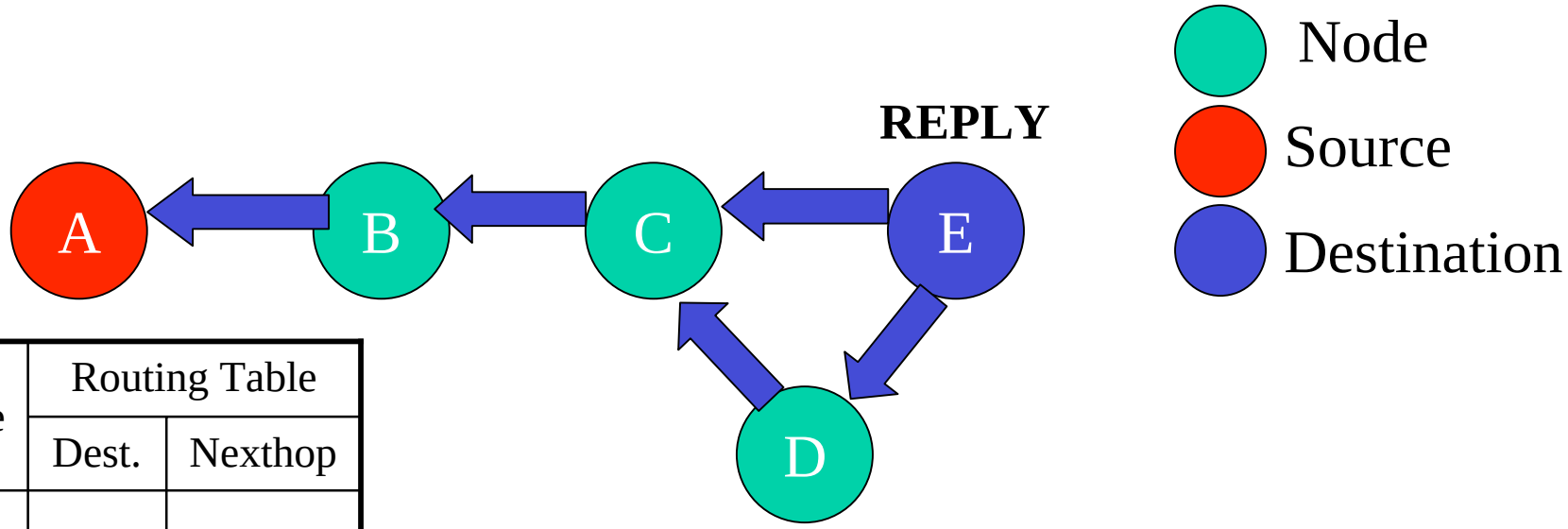
Route Discovery in AODV



Node	Routing Table	
	Dest.	Nexthop
A		
B	A	A
C	A	B
D	A	C
E	A	C

- Nodes which received REQUEST or REPLY packets update the routing table and forward it to the neighbors.
- Data packets are delivered along with the routing table in each node.

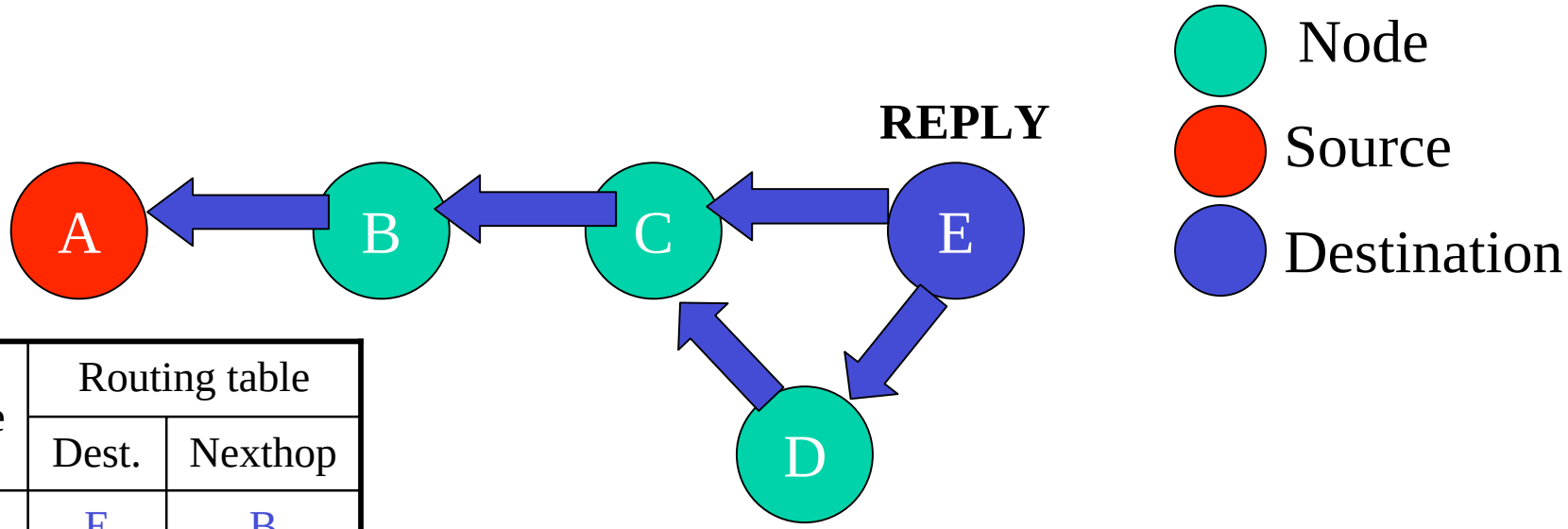
Route Discovery in AODV



Node	Routing Table	
	Dest.	Nexthop
A		
B	A	A
C	A	B
D	A	C
E	A	C

- Nodes which received REQUEST or REPLY packets update the routing table and forward it to the neighbors.
- Data packets are delivered along with the routing table in each node.

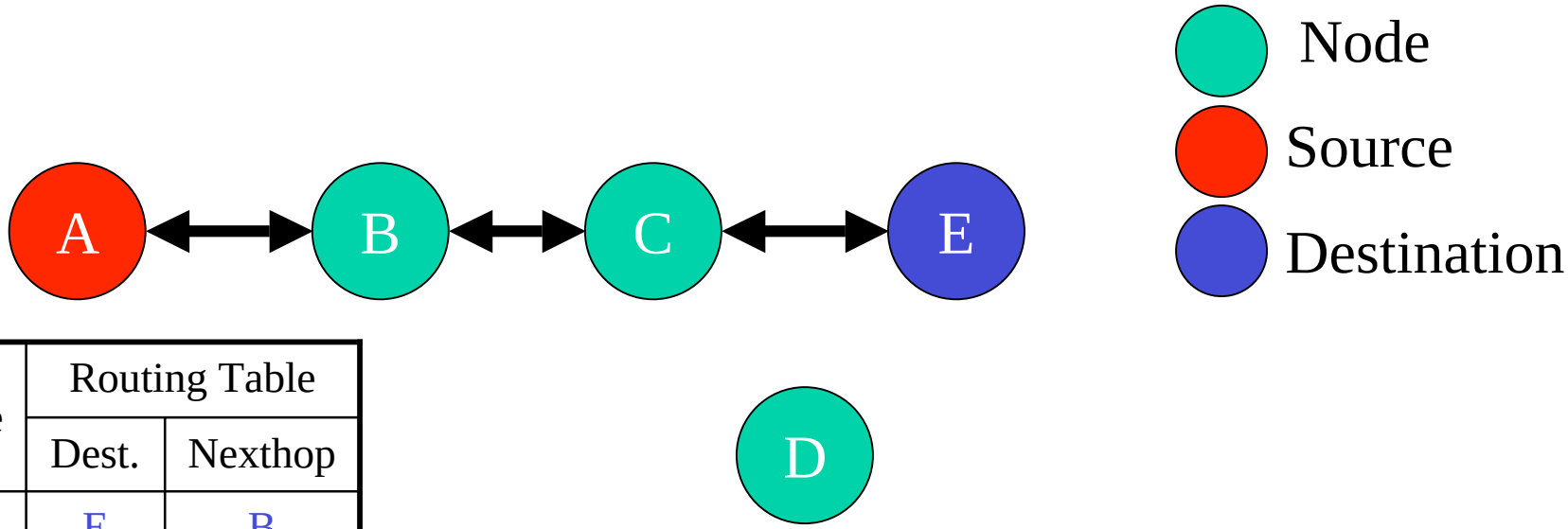
Route Discovery in AODV



Node	Routing table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	E
D	A	C
	E	E
E	A	C

- Nodes which received REQUEST or REPLY packets update the routing table and forward it to the neighbors.
- Data packets are delivered along with the routing table in each node.

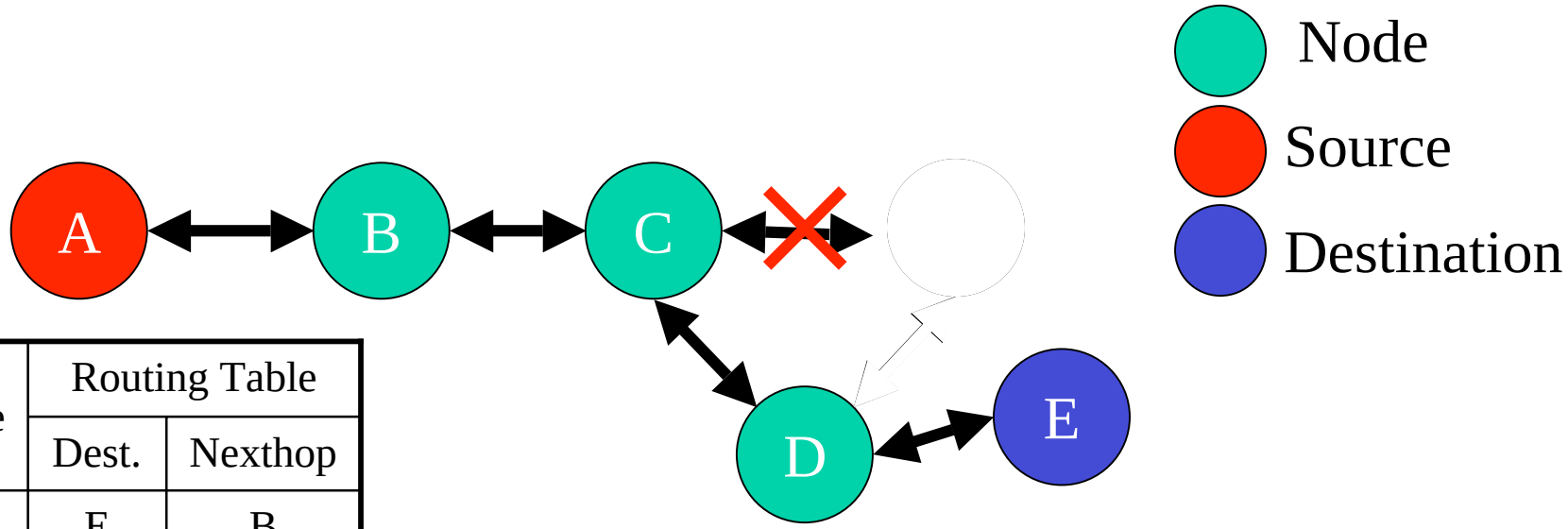
Route Discovery in AODV



Node	Routing Table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	E
D	A	C
	E	E
E	A	C

- Nodes which received REQUEST or REPLY packets update the routing table and forward it to the neighbors.
- Data packets are delivered along with the routing table in each node.

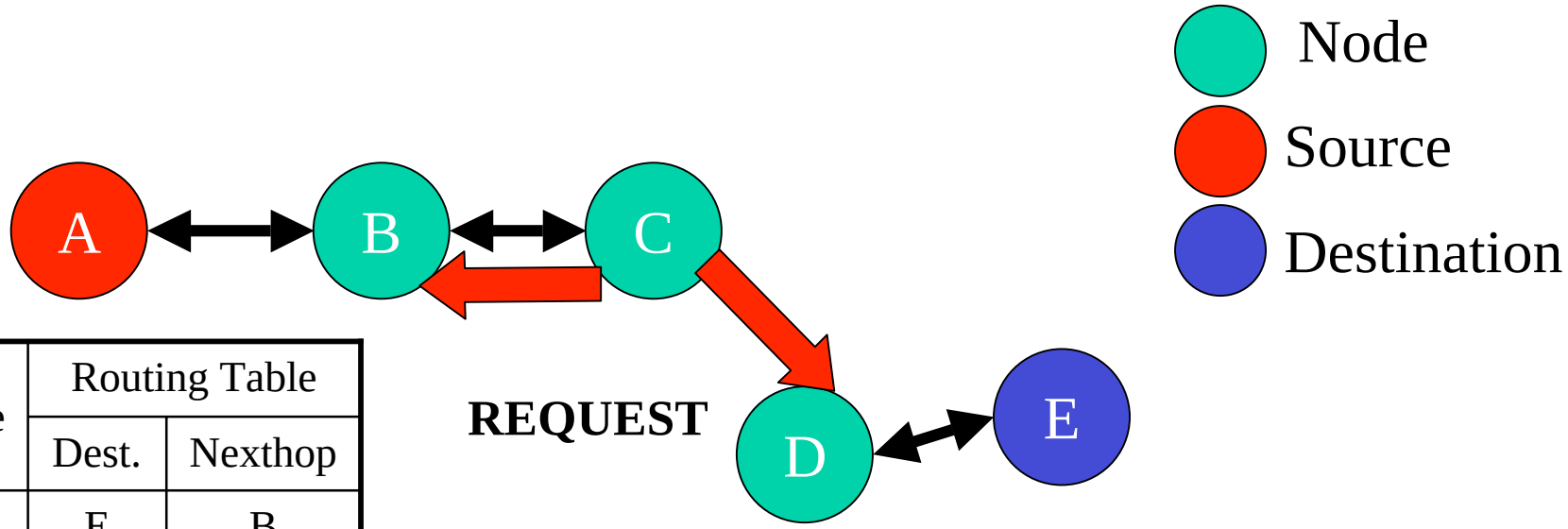
Route Maintenance in AODV



Node	Routing Table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	E
D	A	C
	E	E
E	A	C

•If a node at which the route disappeared is close to the destination node, it repairs the route locally.

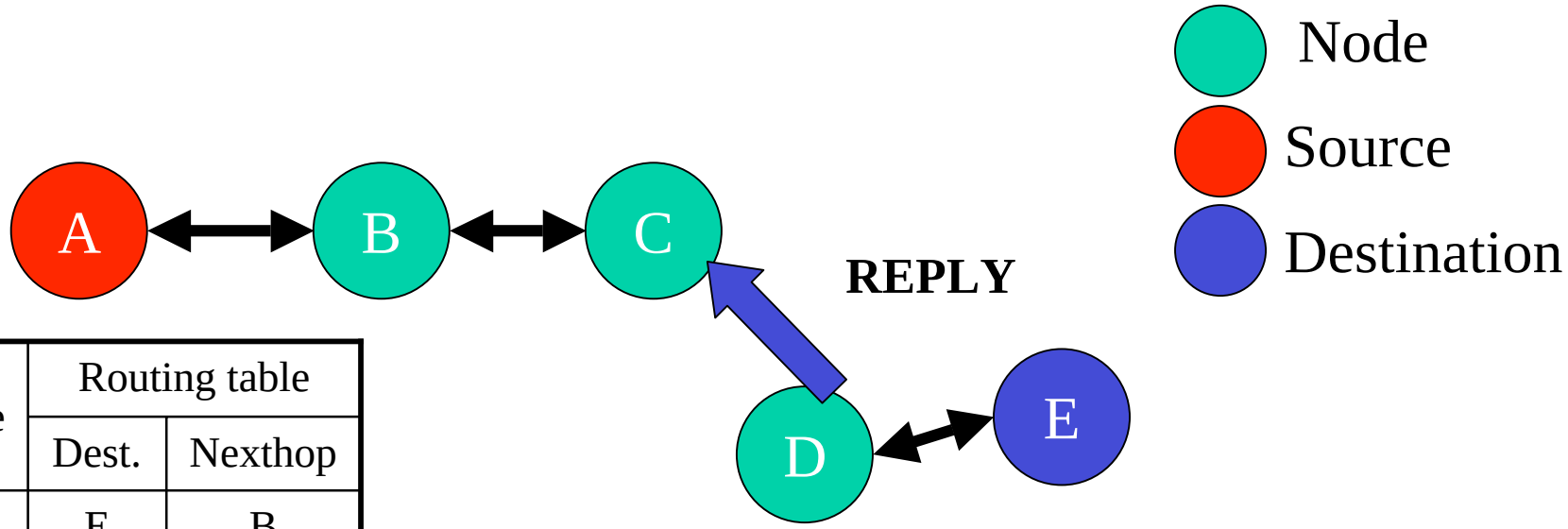
Route Maintenance in AODV



Node	Routing Table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	--
D	A	C
	E	E
E	A	C

- Node C which detected the route disappearance tries to repair the route locally.
- Node C broadcasts REQUEST packets within TTL.

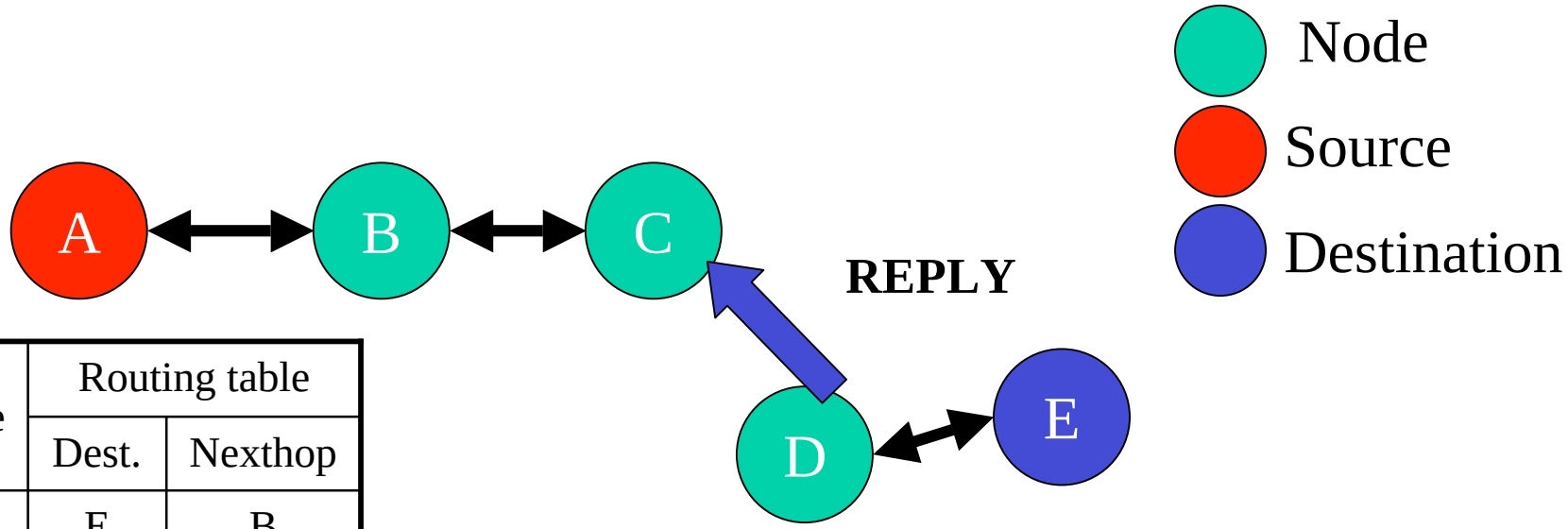
Route Maintenance in AODV



Node	Routing table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	--
D	A	C
	E	E
E	A	C

- Node C which detected the route disappearance tries to repair the route locally.
- Node C broadcasts REQUEST packets within TTL.

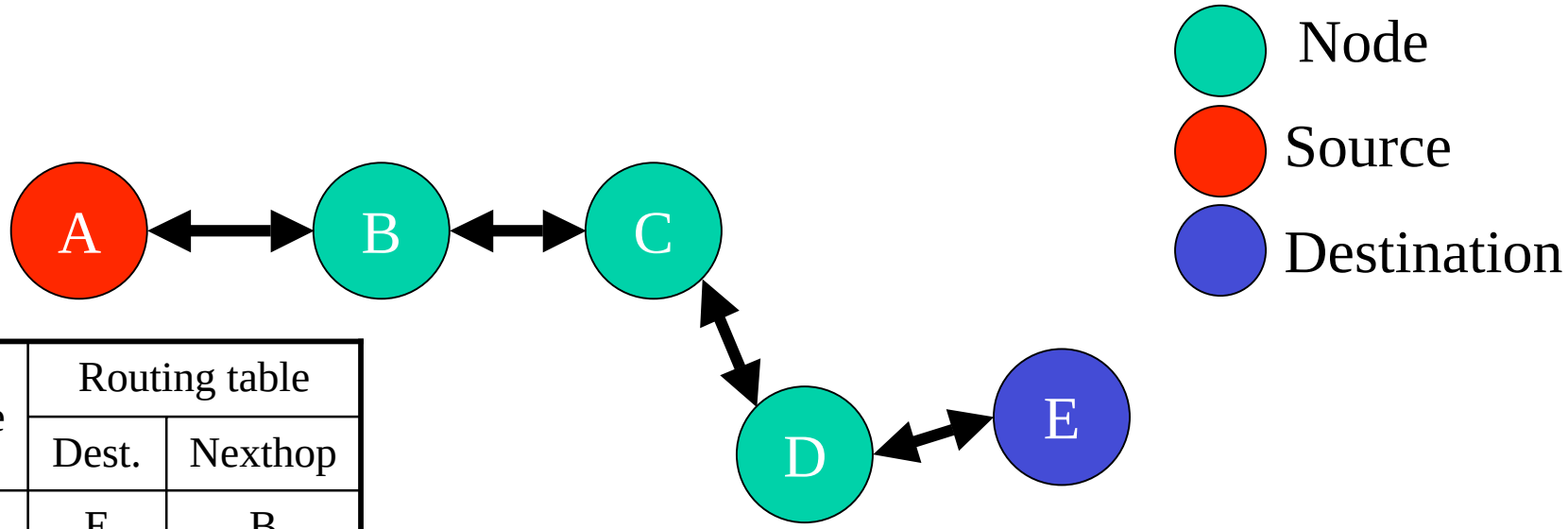
Route Maintenance in AODV



Node	Routing table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	D
D	A	C
	E	E
E	A	C

- Node C which detected the route disappearance tries to repair the route locally.
- Node C broadcasts REQUEST packets within TTL.

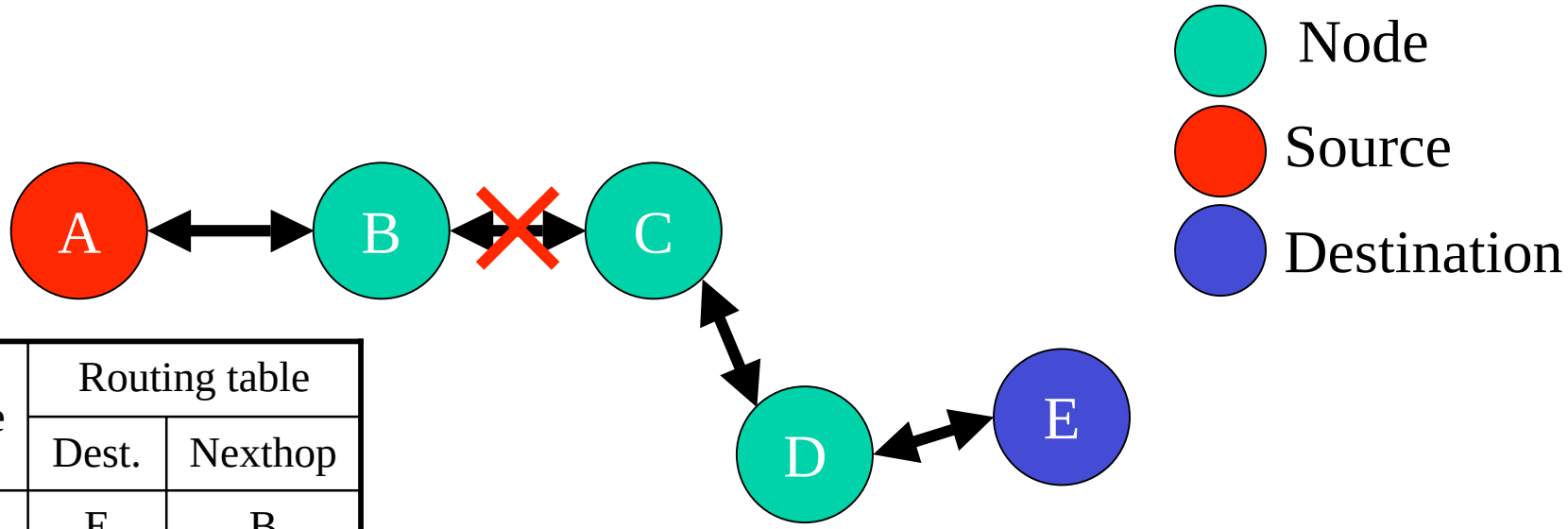
Route Maintenance in AODV



Node	Routing table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	D
D	A	C
	E	E
E	A	C

- Node C which detected the route disappearance tries to repair the route locally.
- Node C broadcasts REQUEST packets within TTL.

Route Maintenance in AODV



Node	Routing table	
	Dest.	Nexthop
A	E	B
B	A	A
	E	C
C	A	B
	E	D
D	A	C
	E	E
E	A	C

• If a node at which the route disappeared is close to the source node, it sends ERR packets back to the source node and the source node invokes route discovery again.

Problems of Flat Routing Protocols - Route Discovery -

- A source node broadcasts REQUEST packets over the entire network to create the route.
  - Due to the heavily control packets, a stable route is not provided
- TORA
  - It takes considerable control packets to create the route on all nodes and maintain it.

Problems of Flat Routing Protocols - Route Maintenance -

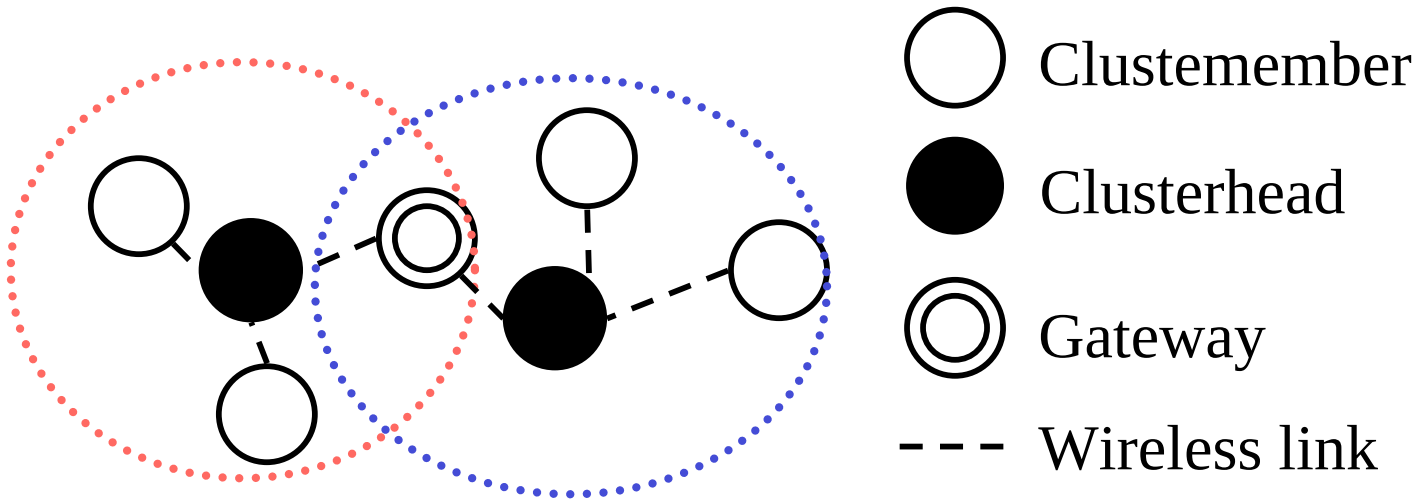
- TORA
  - The route is locally maintained while there is a possibility that the route distance becomes long.
- DSR
  - Due to node movement, the route disappearance occurs at an intermediate node and the source node invokes the route discovery again. If the route disappearance occurs frequently, the number of control packets becomes large because the source node invokes the route discovery frequently.
- AODV
  - When the route disappearance occurs near the source node, the source node invokes route discovery again.

Clustering and Hierarchical Routing

- Scalability issue
  - Hierarchical routing based on clustering (e.g. ZRP)
- Conventional clustering scheme
  - Each cluster is overlapped with each other.
- Autonomous clustering
  - True hierarchy because each cluster is not overlapped with each other.

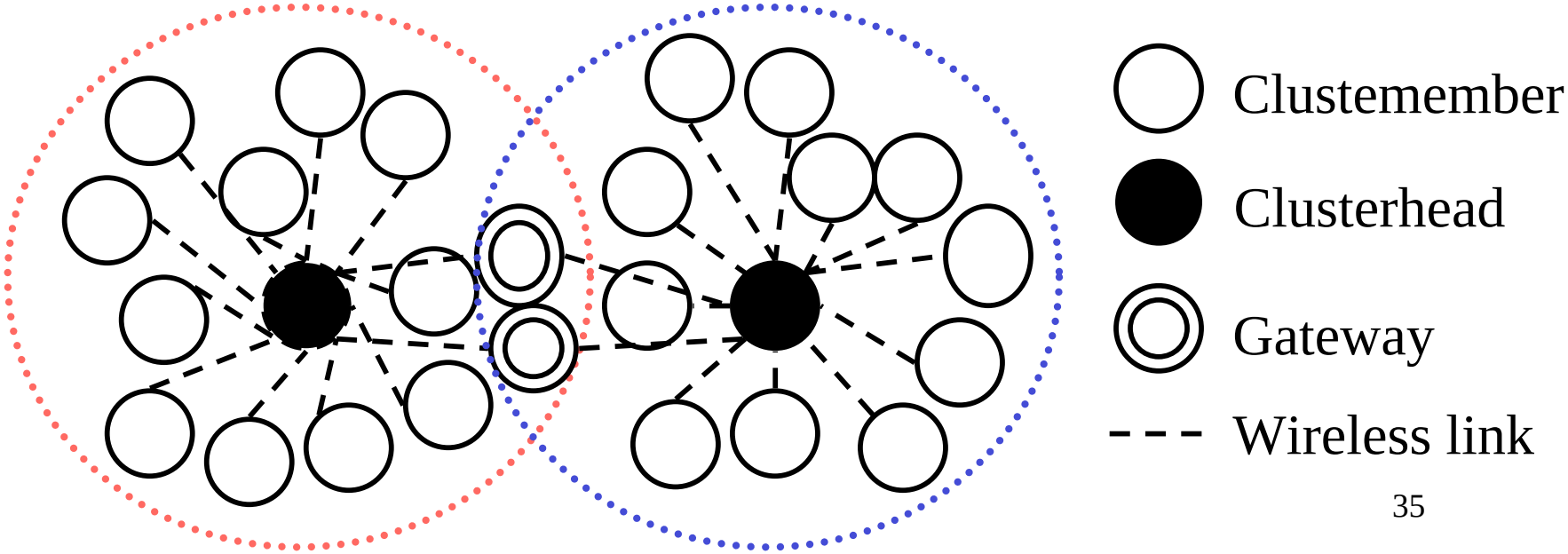
Conventional Clustering Scheme

- A cluster consists of a clusterhead and its all neighboring nodes connected by one hop number.
- A node which has neighboring different clusterheads becomes a gateway which connects them.



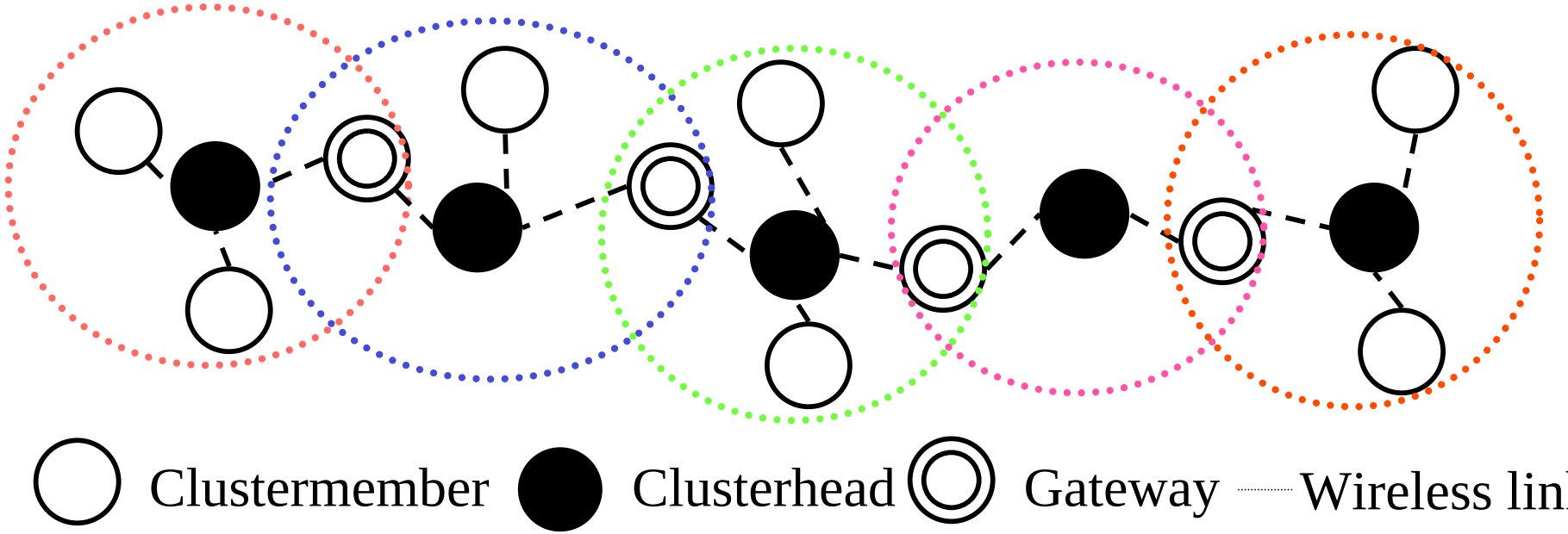
Deficiency of Conventional Scheme (1)

- Unevenly distributed node density has a big impact on network performance.
  - Too High-Density The control node has a large overhead from managing its routing table.

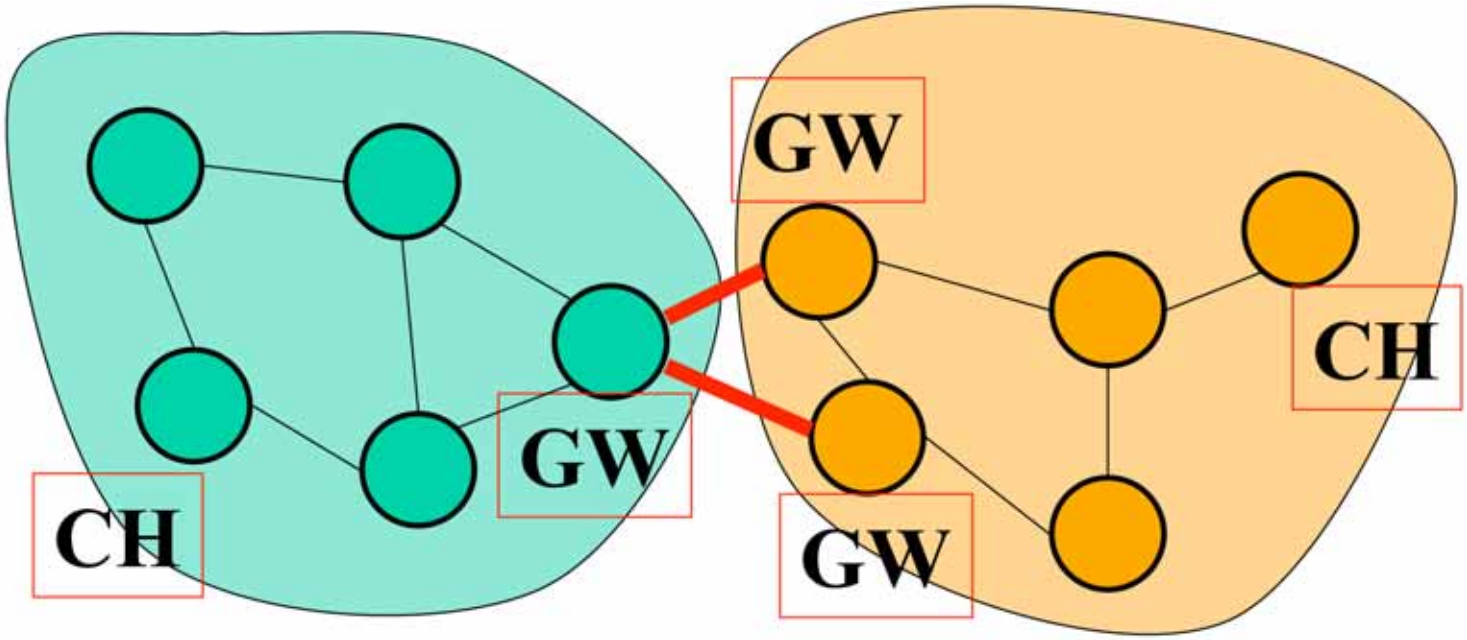


Deficiency of Conventional Scheme (2)

– Too Low-Density The benefits of a hierarchical structure are not apparent, because there are many small clusters in the network.

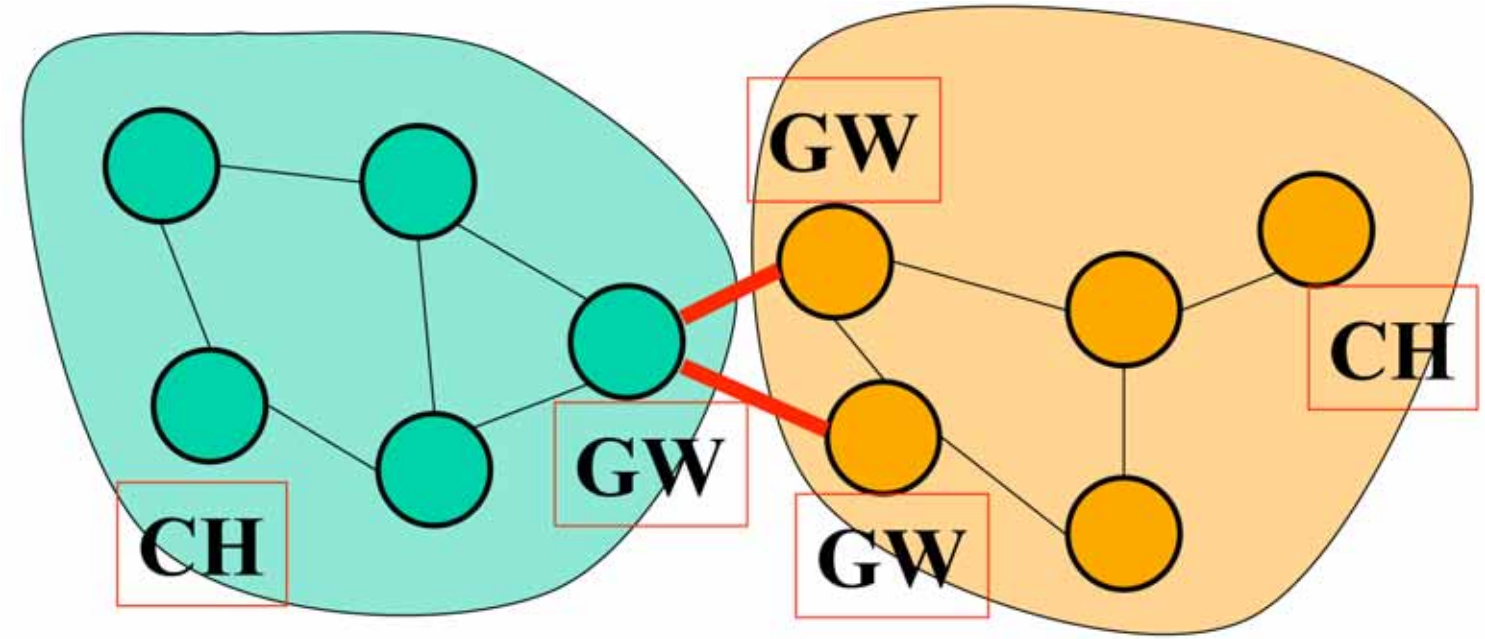


Proposed Clustering Scheme (1)



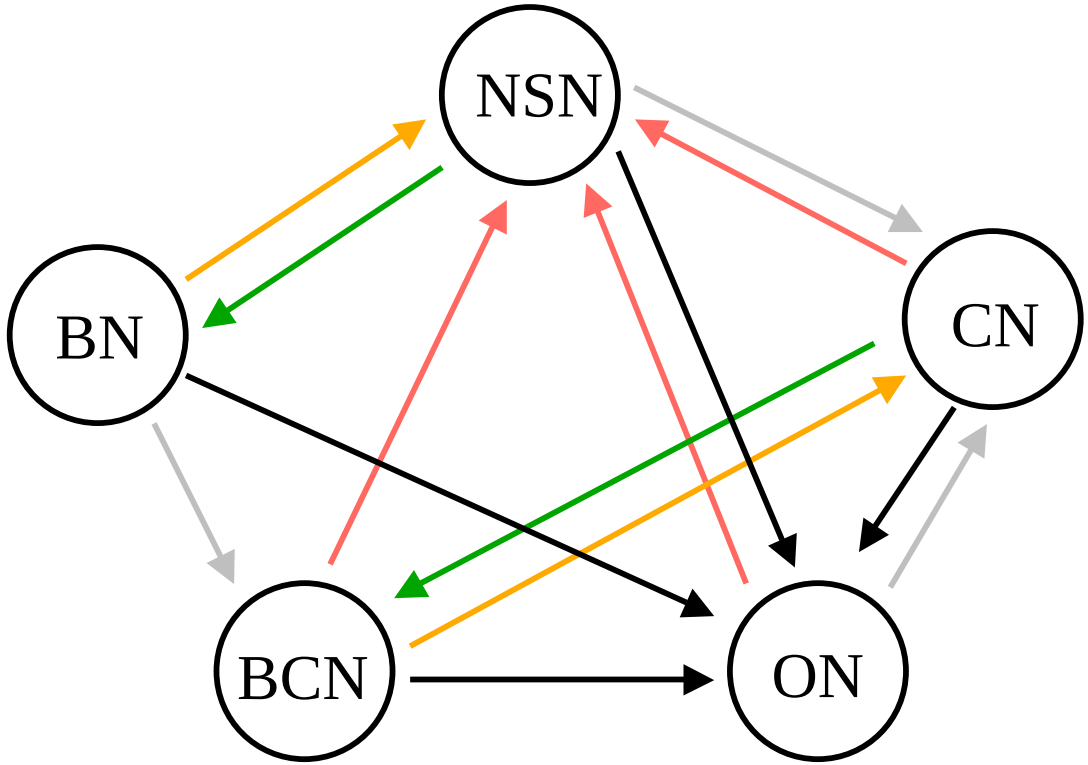
- The cluster consists of one clusterhead (CH), one or more gateways (GW), and clustermembers.
- When a node in a cluster communicates with a node in its neighboring cluster, packets are forwarded through only the GWs.

Proposed Clustering Scheme (2)



- Clusterhead works to manage the cluster.
- Gateway works to get the information of a neighboring cluster.

State Transition Diagram in Each Node



Transition A : Add the role of a gateway to a node.

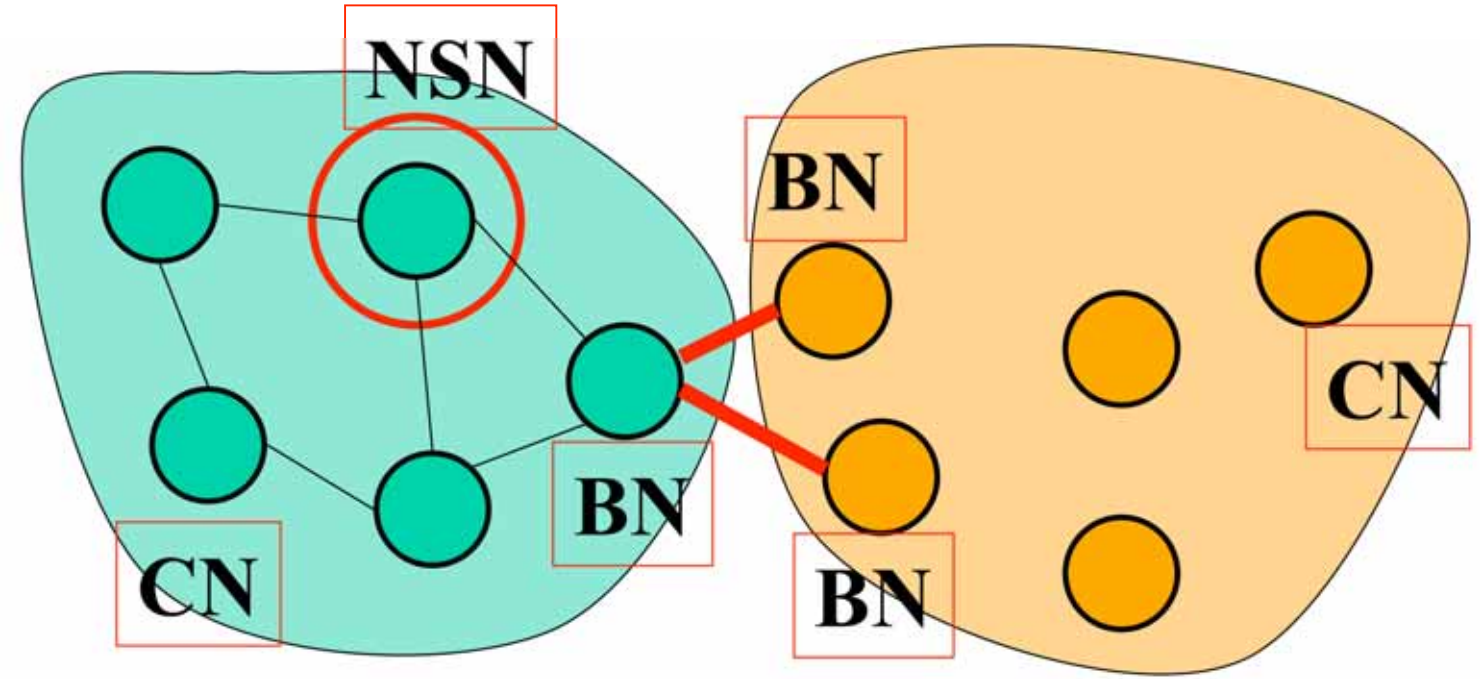
Transition B : Change to a clustermember.

Transition C : Add the role of a gateway to a node.

Transition D : Delete the role of a gateway from a node.

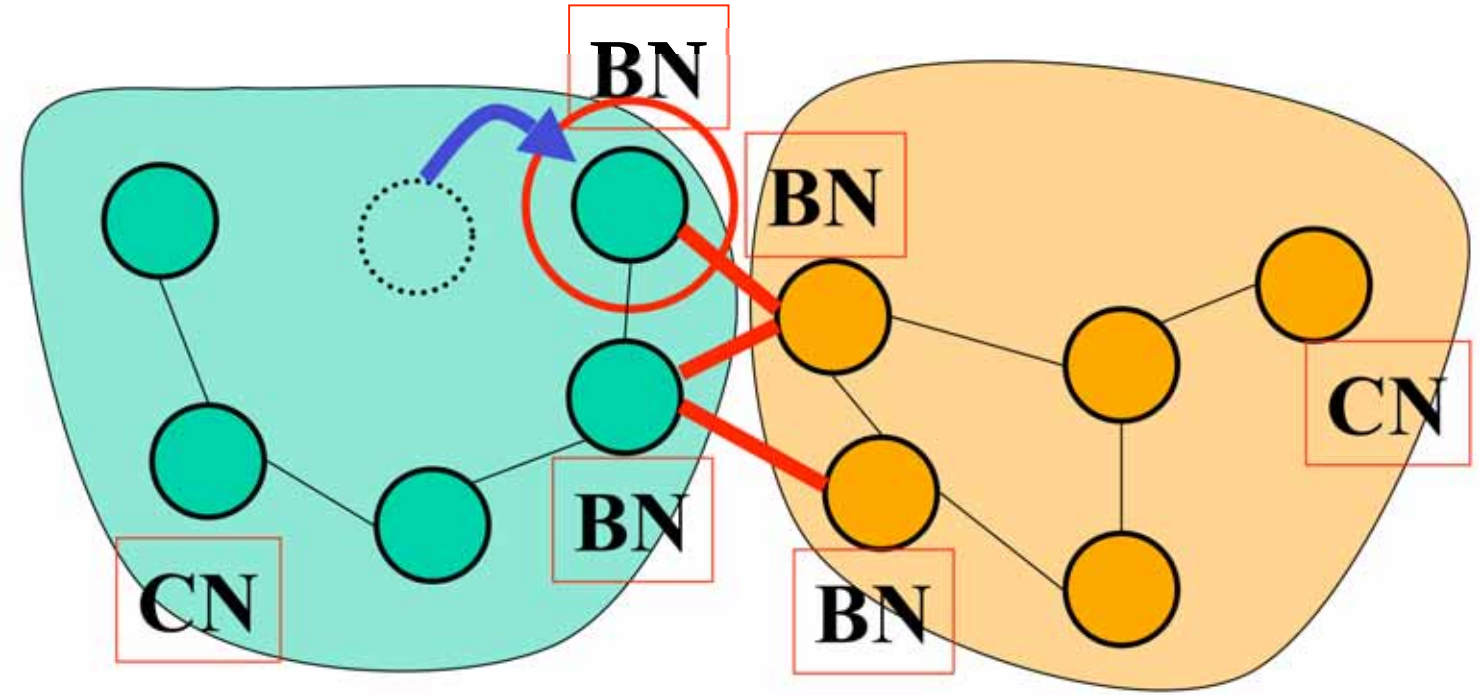
Transition E : Change to Orphan Node.

Example of Maintenance (1)



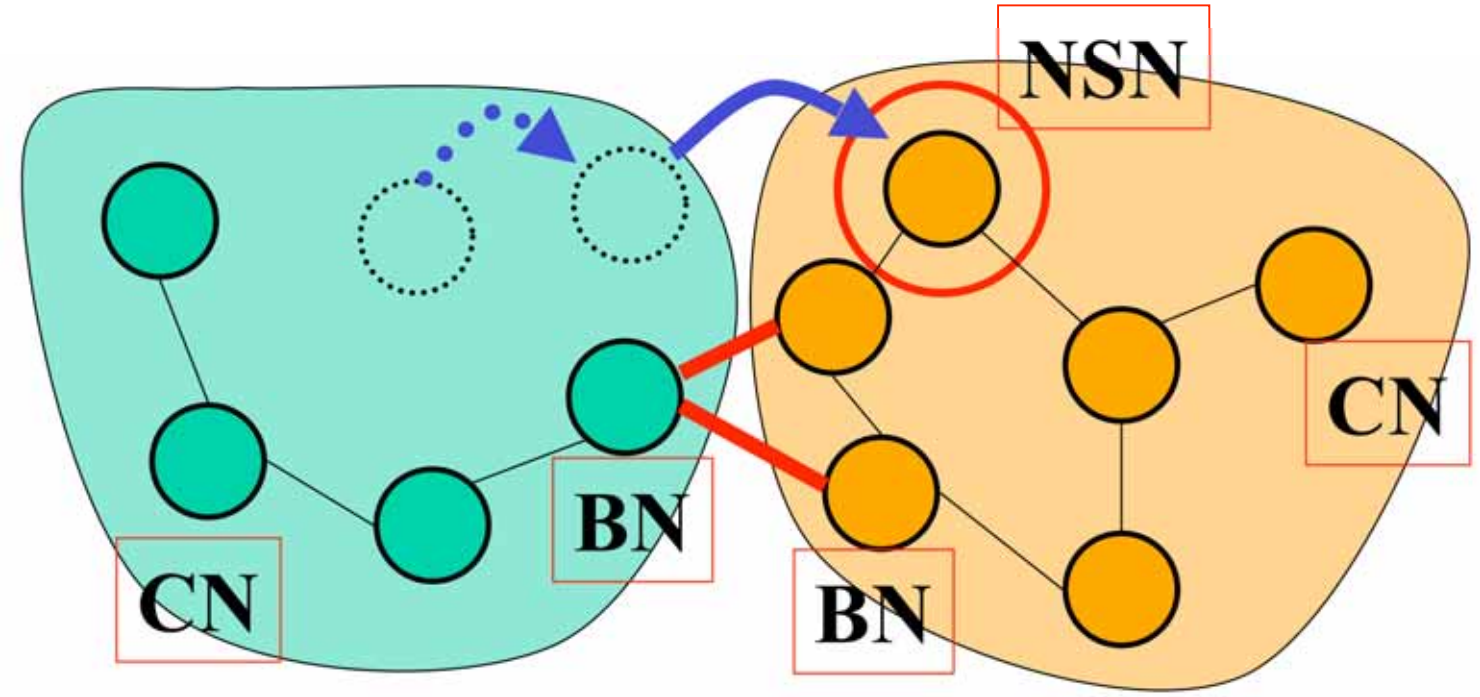
- The current state of  is NSN because the node has neighboring nodes all of which belong to green cluster.

Example of Maintenance (2)



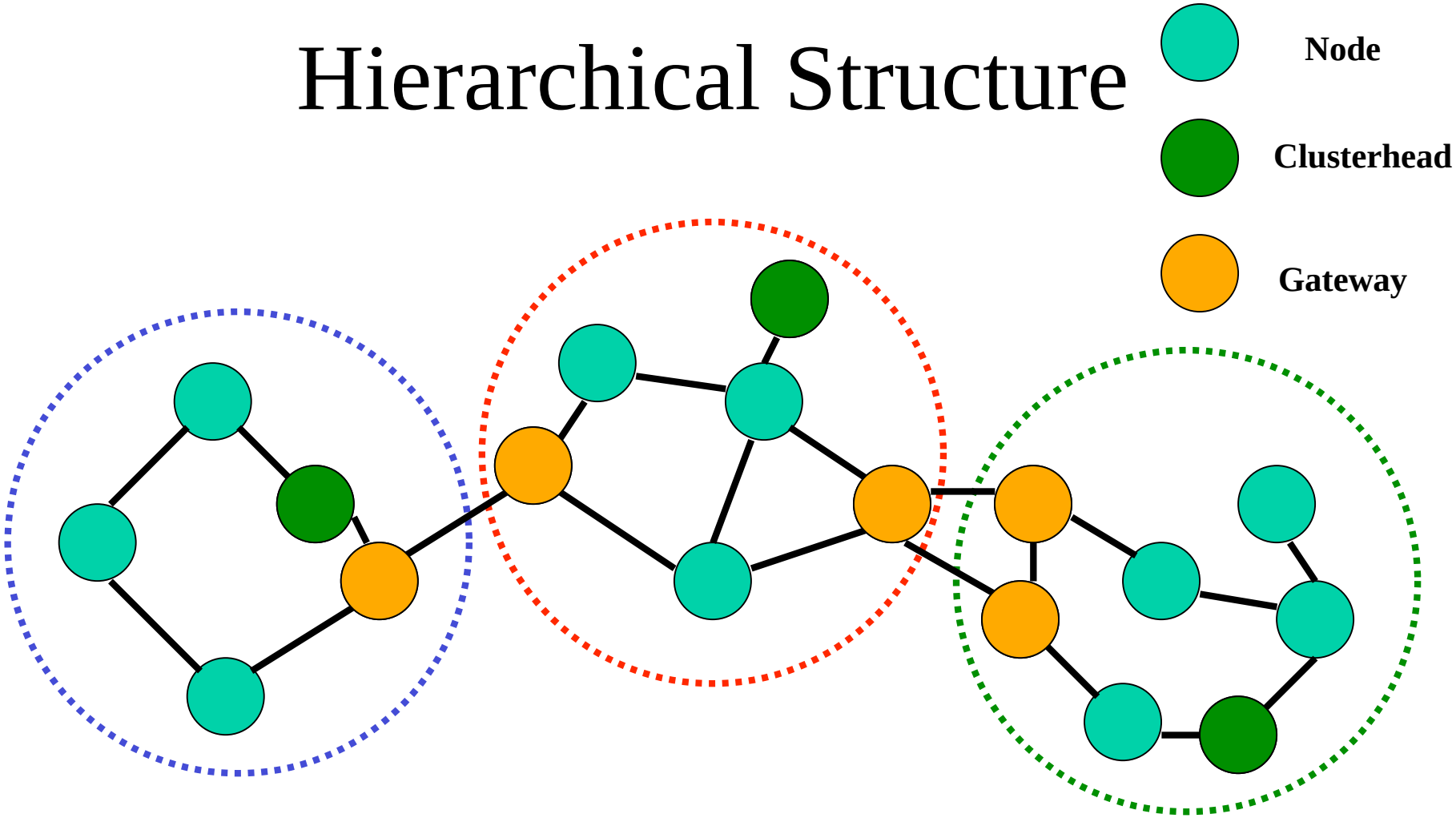
- The node changes the state to the border node because the node has some neighboring nodes which belong to orange cluster.
- It works to get the information of the neighboring cluster represented by orange.

Example of Maintenance (3)



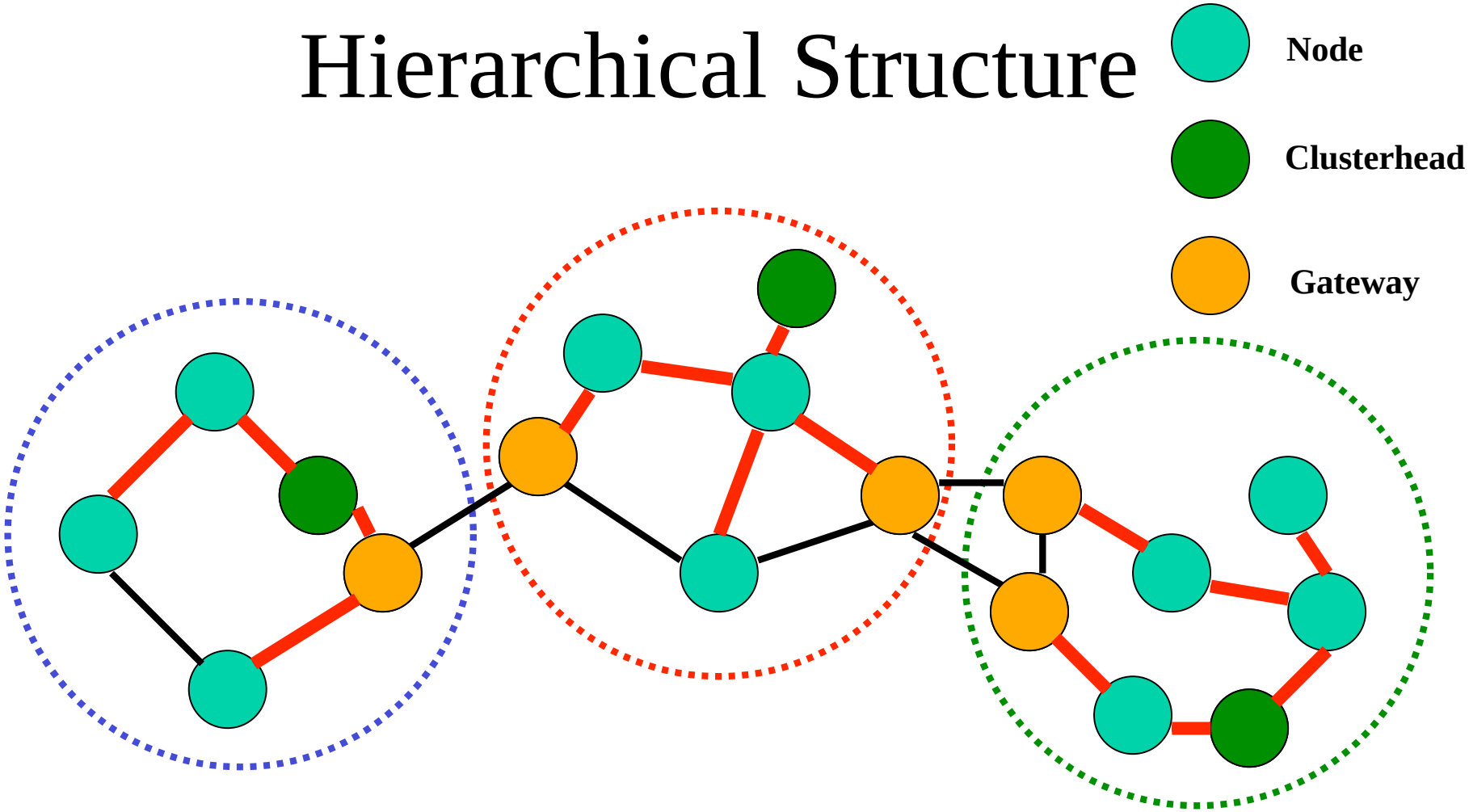
- The node changes the cluster ID to orange cluster because the node has neighboring nodes all of which belong to orange cluster.

Hierarchical Structure



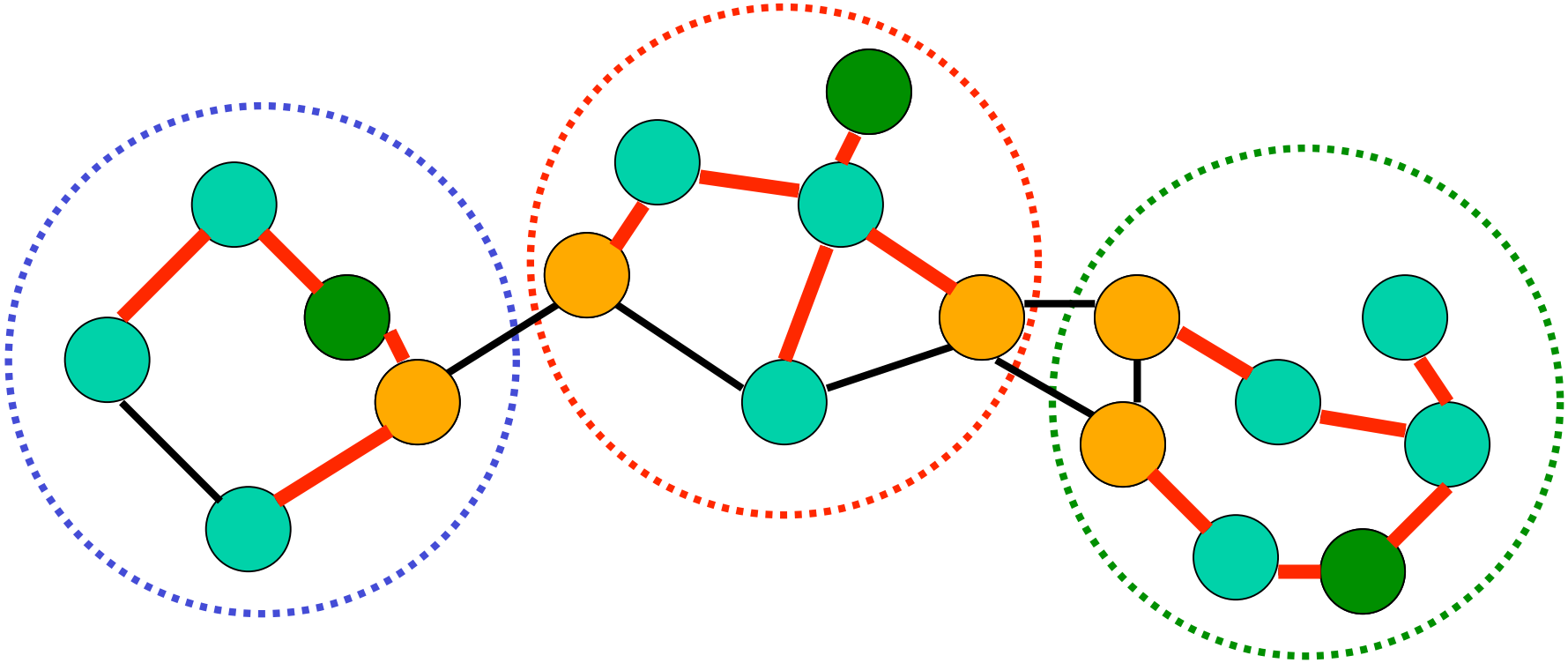
- The entire network is divided into multiple clusters.
- The cluster size is managed by the number of nodes in the cluster (Upper bound and Lower bound).

Hierarchical Structure



- A spanning tree at which the clusterhead is rooted is constructed.

Hierarchical Routing Protocol Based on Autonomous Clustering



- By regarding each cluster as one node, the route are constructed.
  - Within cluster ･･･ Spanning tree is used.
  - Among clusters ･･･ TORA, DSR, or AODV is used.

Effect of Autonomous Clustering Scheme

- Among clusters
  - By regarding each cluster as a virtual node, the routing protocol works just like in the small network.
- Within cluster
  - The route within cluster is stable because the clustering is provided by the autonomous clustering scheme and the proper cluster size.

Evaluation Purpose

- In large mobile ad hoc network environment, we compare proposed hierarchical routing protocols with conventional flat routing protocols.
  - Overhead
    - Measuring the number of control packets to maintain the route between a source node and a destination node.
  - Stability of route
    - Measuring the number of data packets which destination nodes could receive.

Node Mobility Model

- Random waypoint model
  1. A node moves at a specified speed to a position which is selected randomly.
  2. At the position, the node stays for a specified period (which is called “pause time”).
  3. Return 1.

  Pause time is 0 in our simulation.

Simulation Models

- Conventional simulation models
  - Field size ･･･ 1200m×300m
  - Number of nodes ･･･ 50
- Our simulation model
  - Field size ･･･ 2000m×1500m（8.3 times）
  - Number of nodes ･･･ 150（3 times）

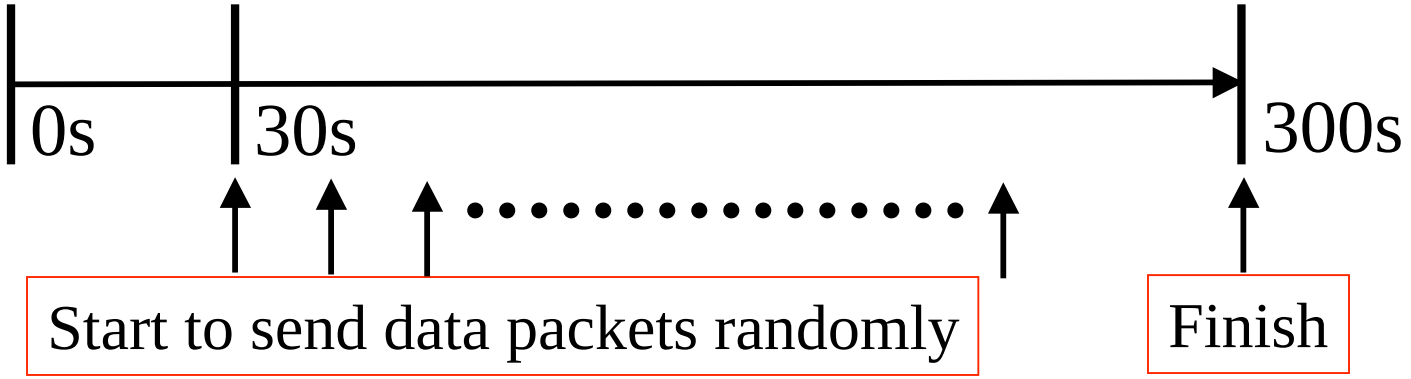
Simulation Method

- Number of nodes ・・・150
- Movement model・・・Random waypoint model
- Field size・・・2000m x 1500m
- Range of wireless link ・・・ 250m
- Cluster size・・・Upper 50, Lower 20

In comparison with conventional simulation models, the field size is 8.3 times and the number of nodes is 3 times.

Simulation Method（cont.）

- Simulation time：300 sec.
- # of SD pairs：10, 20, 30



- Maximum Node Moving Speed
  - **1m/s (3.6km/h), 2m/s (7.2km/h), 3m/s (10.8km/h), 4m/s (14.4km/h), 5m/s (18.0km/h), 10m/s (36.0km/h), 15m/s (54.0km/h), 20m/s (72.0km/h)**

About Data Packets

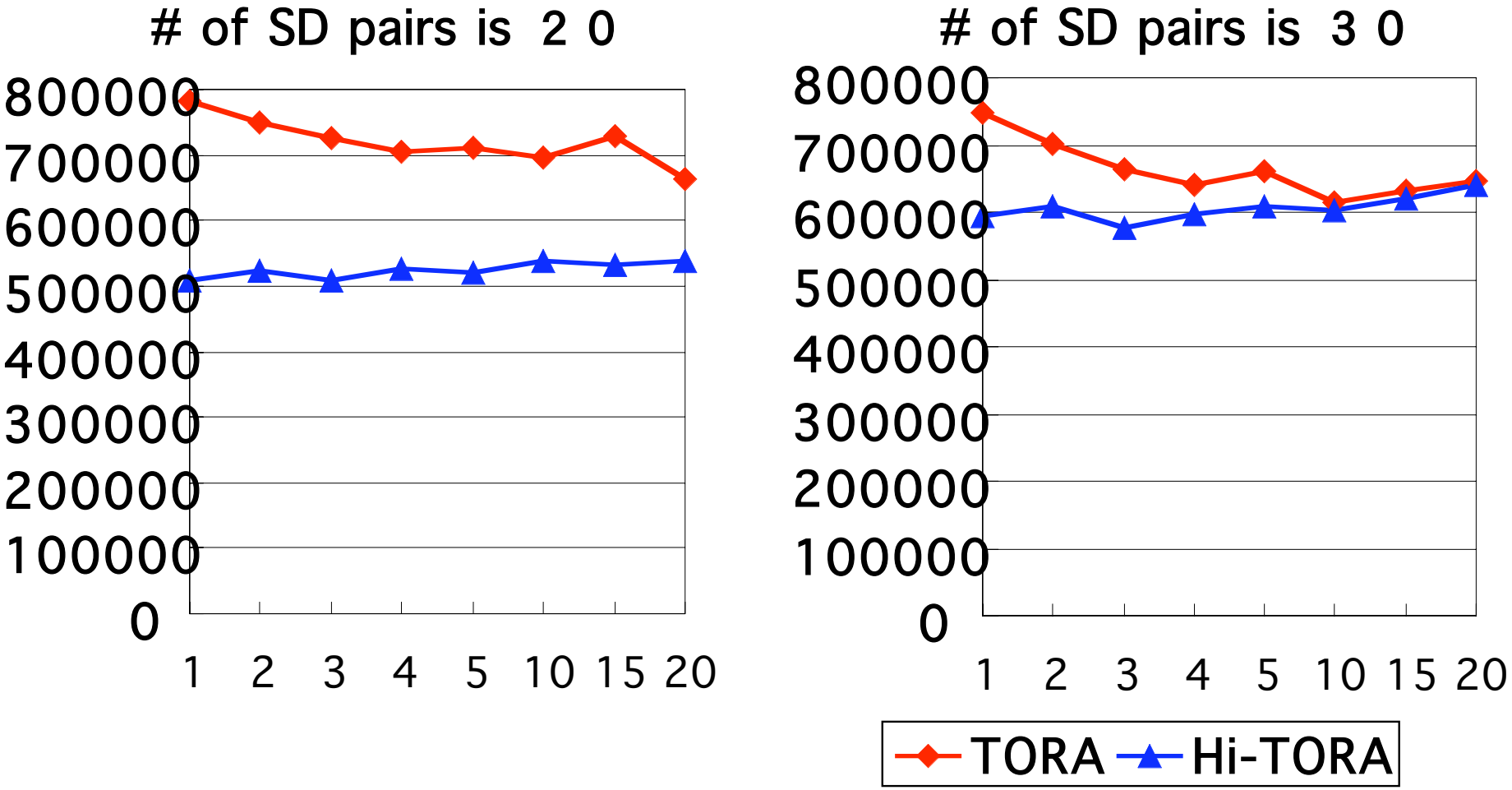
- Total number of data packets which source nodes send
  - Packet size･･･512byte
  - # of SD pair is 10 ･･･about 9000
  - # of SD pair is 20 ･･･about 18000
  - # of SD pair is 30 ･･･about 27000

  Interval of sending : 250msec

Simulation Experiment 1

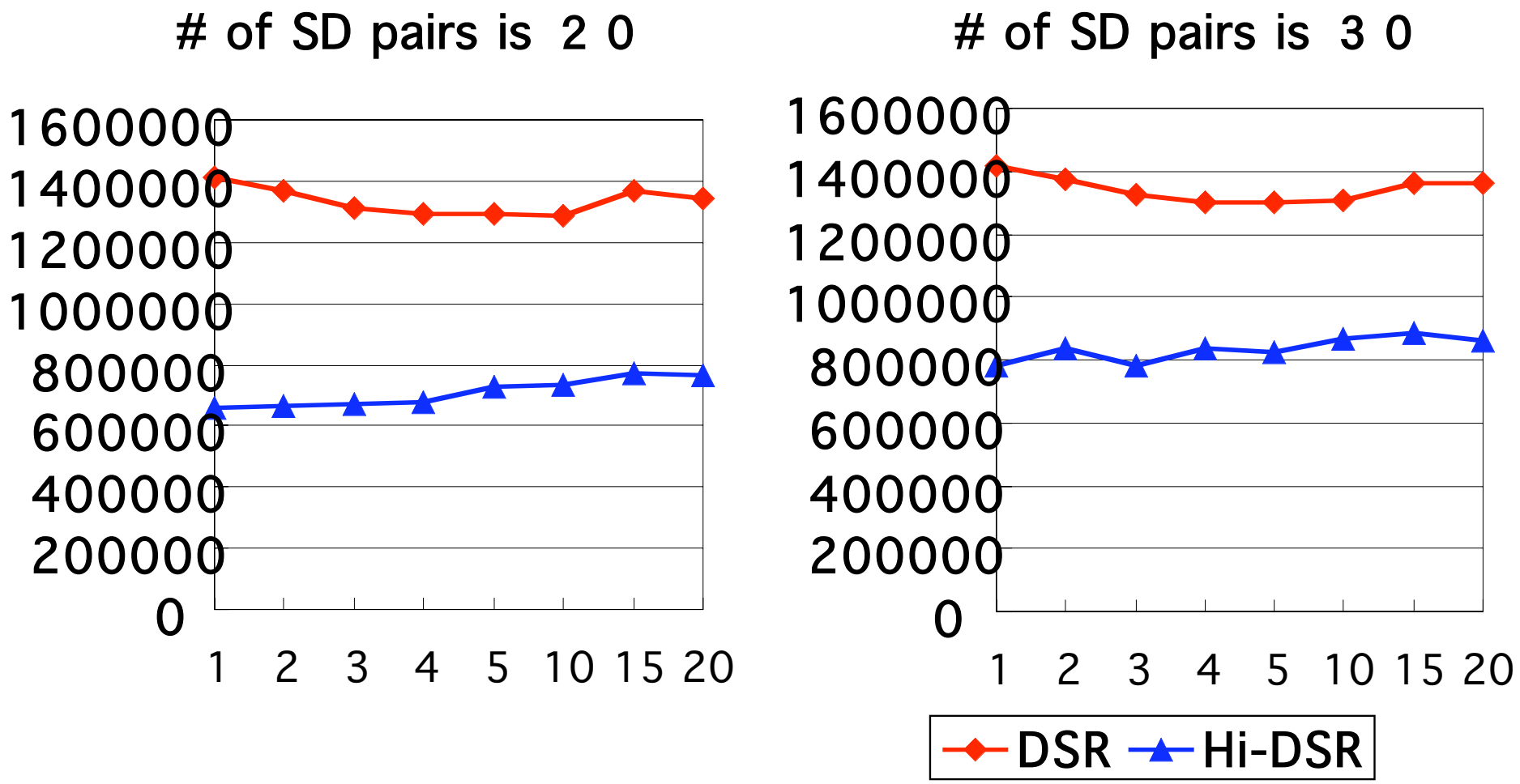
- We evaluated the total number of control packets.
- Types of control packet
  - Control packets for autonomous clustering
  - Control packets for routing

Number of Control Packets
TORA vs. Hi-TORA



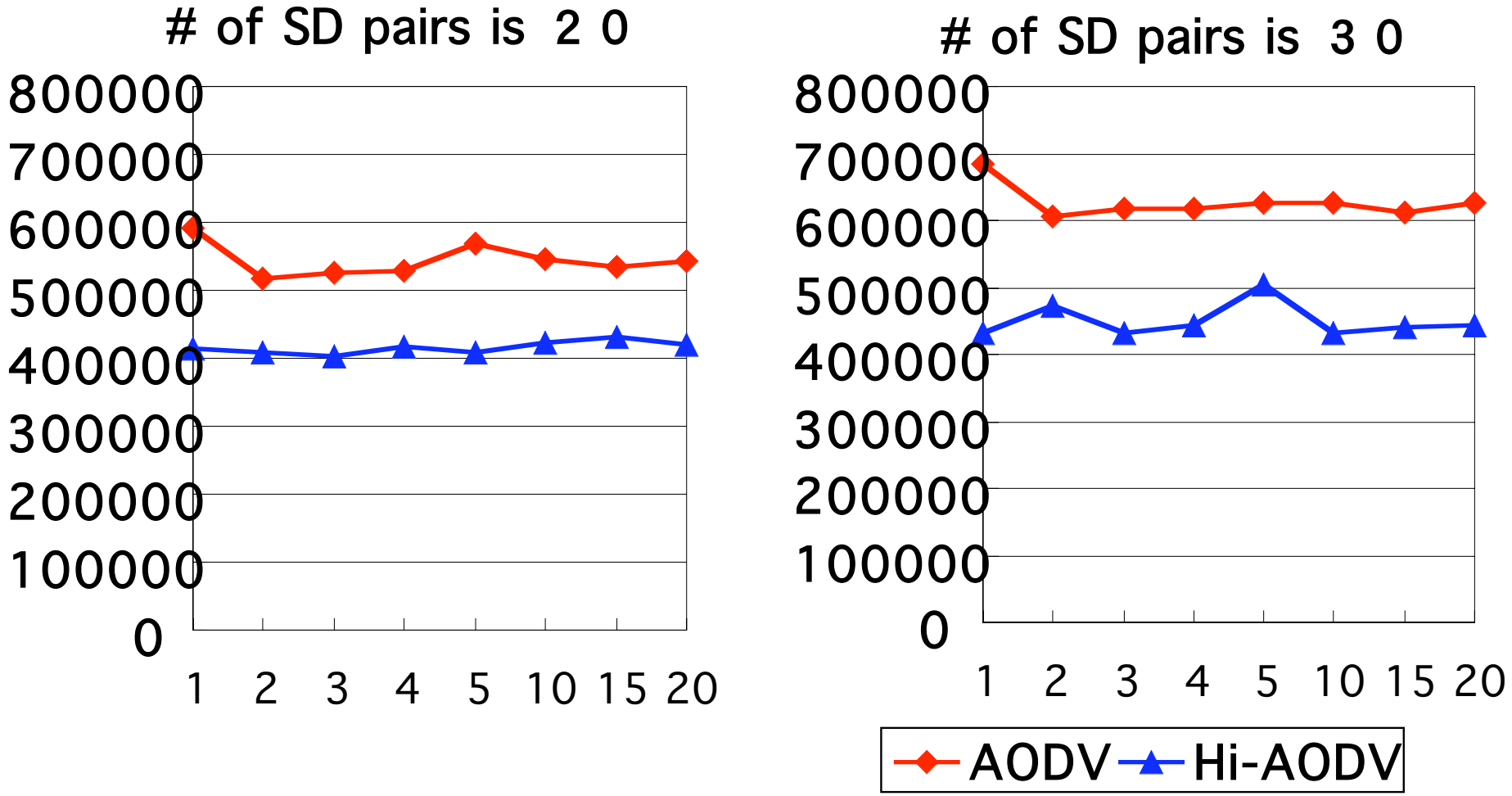
X-axis:Node moving speed (m/s) Y-axis:# of control packets

Number of Control Packets
DSR vs. Hi-DSR



X-axis:Node moving speed (m/s) Y-axis:# of control packets

Number of Control Packets
Hi-AODV vs. AODV

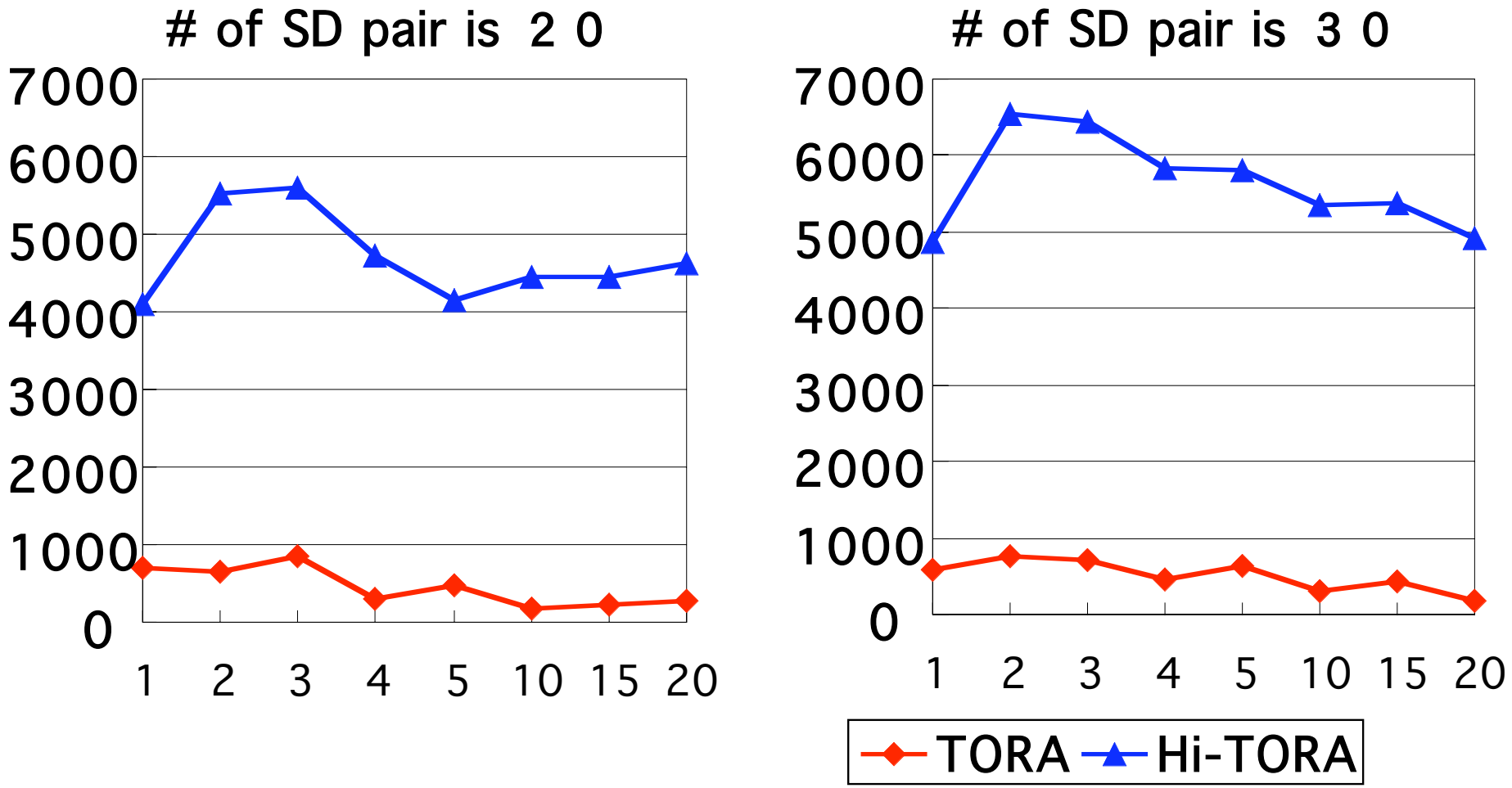


X-axis:Node moving speed (m/s) Y-axis:# of control packets

Simulation Experiment 2

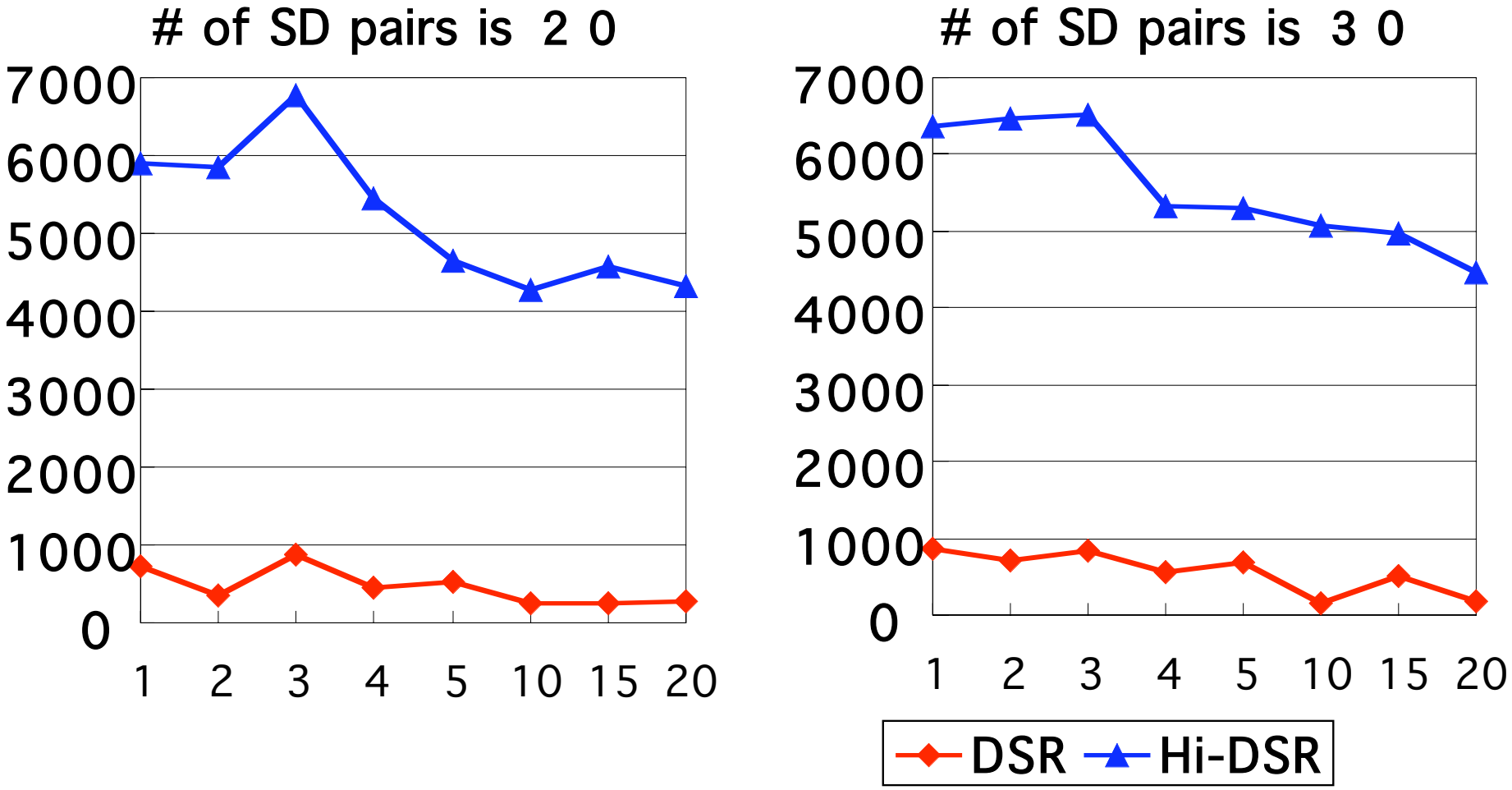
- We evaluated the number of delivered data packets.

Number of Delivered Data Packets
TORA vs. Hi-TORA



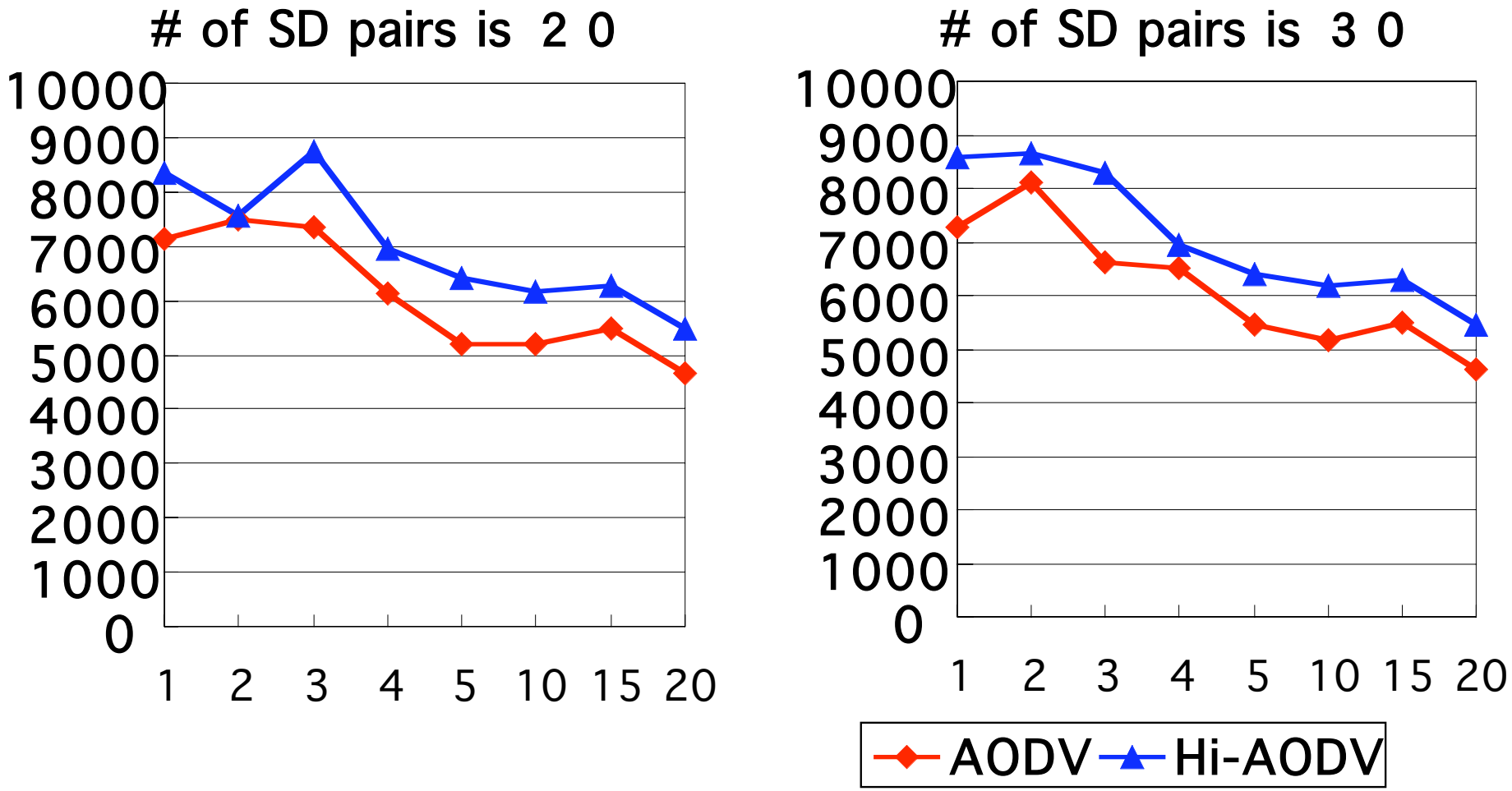
X-axis:Node moving speed (m/s) Y-axis:# of delivered data packets

Number of Delivered Data Packets
DSR vs. Hi-DSR



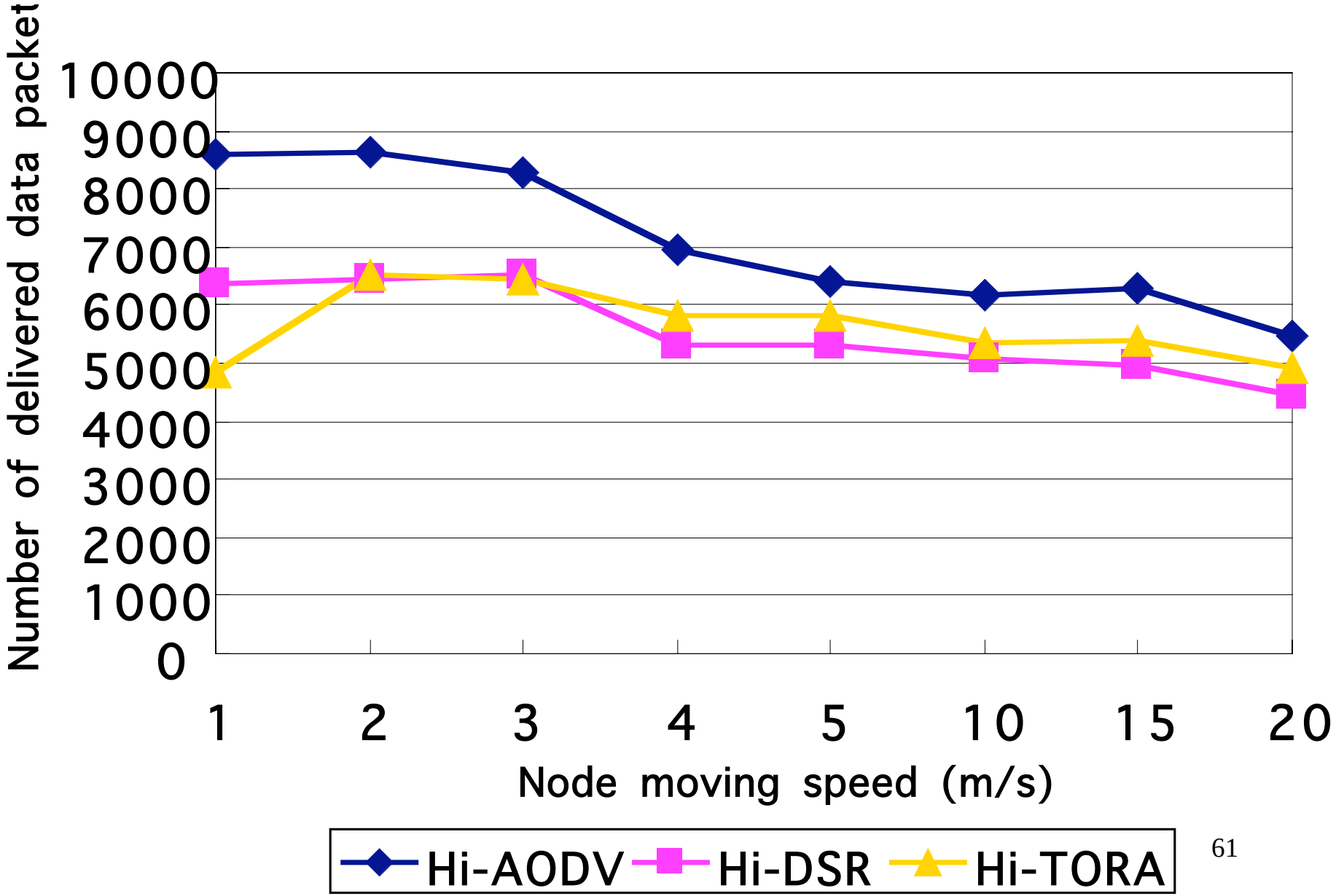
X-axis:Node moving speed (m/s) Y-axis:# of delivered data packets

Number of Delivered Data Packets
AODV vs. Hi-AODV

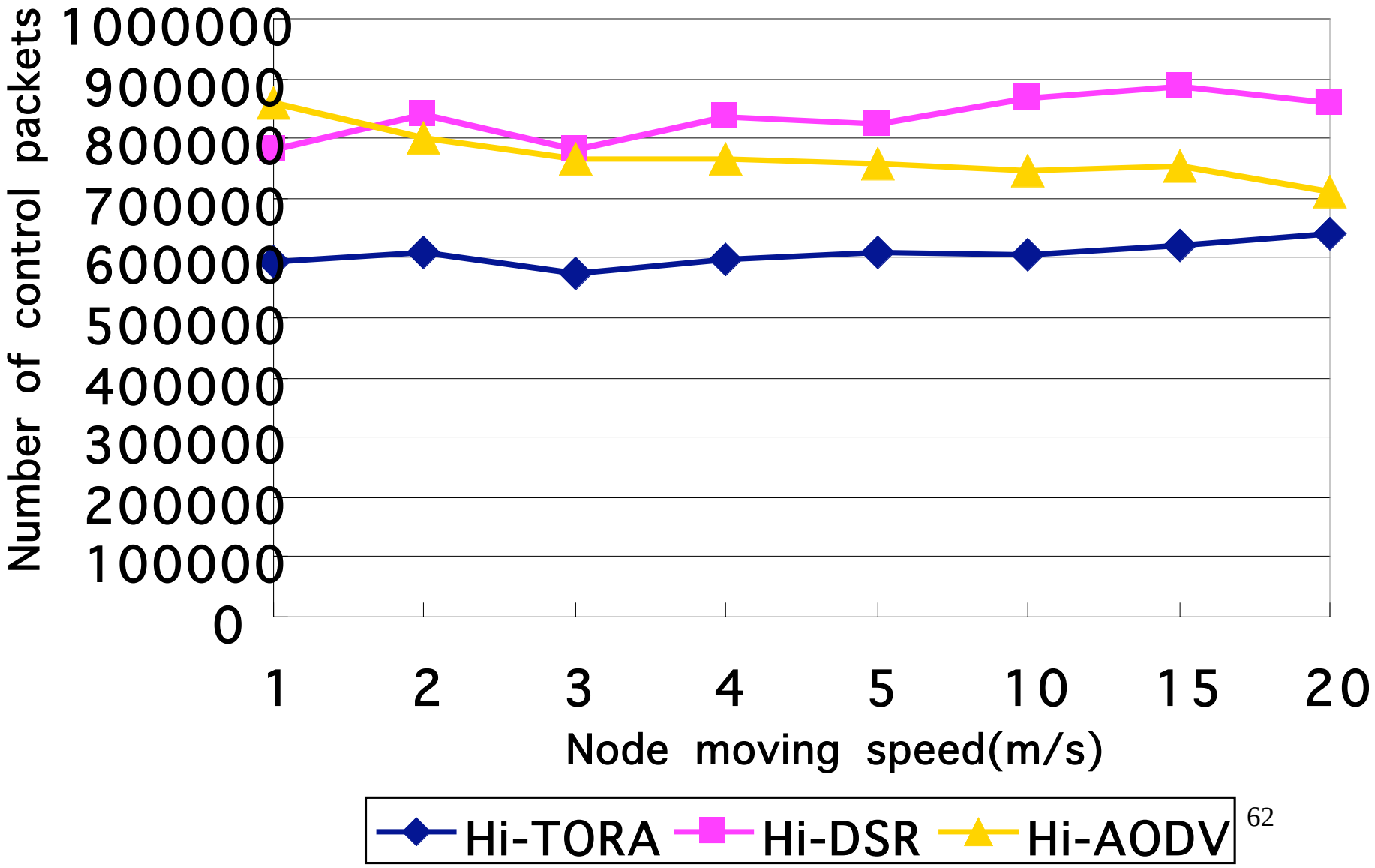


X-axis:Node moving speed (m/s) Y-axis:# of delivered data packets

Number of Delivered Data Packets



Number of Control Packets



Observation - Hierarchical Routing -

- Effect of autonomous clustering
  - By regarding each cluster as one node, the routing protocol works just like in the small network.
  - The route within cluster is stable because the clustering is provided by the autonomous clustering scheme and the proper cluster size.

Observations - Hi-AODV -

- Hi-AODV is the best hierarchical routing protocol as shown in the result of delivered data packets
  - Effect of autonomous clustering
  - Different from Hi-TORA and Hi-DSR, when the route disappeared in an intermediate cluster, the overhead becomes low because the intermediate cluster repairs the route locally. As a result, Hi-AODV provides the most stable routes.

Evaluation of Hierarchical Routing Protocols (Control packets)

	Hi-TORA	TORA	Hi-DSR	DSR	Hi-AODV	AODV
Node Moving Speed	○	×	○	×	○	○
# of SD	○	×	○	×	○	△
Decreasing Rate	20%	—	50%	—	20%	—

Evaluation of Hierarchical Routing Protocols (Data packets)

	Hi-TORA	TORA	Hi-DSR	DSR	Hi-AODV	AODV
Node Moving Speed	○	×	○	×	○	△
# of SD	○	×	○	×	○	△
Increasing Rate	50%	—	50%	—	10%	—

Conclusion and Future Work

- Conclusion
  - Hierarchical routing protocols based on the autonomous clustering scheme provide the stable route in comparison with flat routing protocols.
  - We have applied for a patent on the autonomous clustering.

- Future Work
  - Developing a framework of hierarchical routing protocol based on the autonomous clustering scheme.

Challenging Issues in Routing for Mobile Ad Hoc Networks

- Routing for large-scale networks
- Routing for asymmetric networks
- Location-based routing
- Energy efficient routing
- Secure routing
- QoS routing