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A Class of Hierarchical Routing Protocols Based on Autonomous Clustering for Large Mobile Ad Hoc Networks*

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SUMMARY Along with expansion of utilization of mobile ad hoc networks, it is expected that the network size becomes large. However, design of current typical routing protocols supposes at most several hop routes between source and destination nodes. When messages are delivered along long hop routes in the networks, such routing protocols tend to degrade performance. Previously, we have proposed an autonomous clustering scheme for constructing and maintaining hierarchical structure in mobile ad hoc networks, which are adaptive to node movement. This paper proposes a class of hierarchical routing protocols Hi-TORA, Hi-DSR and Hi-AODV, all of which are based on the autonomous clustering scheme, compares them with their corresponding flat routing protocols TORA, DSR and AODV, respectively, and shows effectiveness of these hierarchical routing protocols by simulation experiments.

key words: *ad hoc networks, clustering, hierarchical routing*

1. Introduction

Recently, the scalability issues in mobile ad hoc networks have been discussed [1], [2], [7]. Along with expansion of utilization of mobile ad hoc networks, it is expected that the network size becomes large. In wired networks, the hierarchical structure is introduced for managing the large-scale network and routing between pairs of a source node and a destination node effectively. For the same purpose, we have thus proposed an autonomous clustering scheme to introduce the hierarchical structure and shown the effectiveness of the hierarchical routing based on the autonomous clustering for large mobile ad hoc networks in [9]–[11].

The key features of the proposed clustering scheme are as follows. First, each node changes its role such as clusterhead and gateway by only local information according to its movement. In other words, each node autonomously plays the right role in the right place. Second, the number of clustermembers which each clusterhead has to manage is bounded by constants. In other words, the overhead of each clusterhead is almost equivalent. Due to these conditions and multihop property, effective clustering can be realized even when nodes move at much faster speed. We expect that thanks to introducing the proposed autonomous clustering scheme to the representative routing protocols such as TORA [5], DSR [6] and AODV [3], the corresponding new hierarchical routing protocols would have the scalability. The reasons why we consider TORA, DSR and AODV as the representative routing protocols are that AODV and DSR are standardized and being standardized in RFC documents, respectively, and these protocols have been comprehensively compared in [4] and have been installed in the network simulator ns-2 [8].

This paper proposes a class of hierarchical routing protocols: Hi-TORA, Hi-DSR and Hi-AODV, all of which are based on the proposed autonomous clustering scheme [10] and compare them with TORA, DSR and AODV, respectively. Hi-TORA, Hi-DSR and Hi-AODV apply TORA, DSR and AODV for routing among clusters, respectively. Moreover, because TORA, DSR and AODV are not designed to use for a hierarchical routing, there are some problems to apply them for it. We discuss the problems and their solutions in this paper.

The rest of the paper is organized as follows. Section 2 addresses the autonomous clustering scheme we have proposed [10]. Section 3 describes the class of hierarchical routing protocols: routing among clusters and routing within cluster. Sections 4, 5 and 6 describe the proposed hierarchical routing protocols Hi-TORA, Hi-DSR and Hi-AODV, respectively. In Sect. 7, the evaluation results on the hierarchical routing protocols are shown by simulation experiments. We discuss some related work in Sect. 8. Finally, Sect. 9 concludes this paper.

2. Autonomous Clustering Scheme [10]

We have proposed an autonomous clustering scheme for constructing and maintaining a hierarchical structure in large mobile ad hoc networks. We have also shown the proposed clustering scheme has high adaptability for highly mobile nodes in ad hoc networks [10]–[12]. This result implies that the autonomous clustering is stable, and that as a result, each cluster can provide stable subroutes of routes between a source node and a destination node in large mobile ad hoc networks. This section describes the proposed autonomous clustering scheme briefly.

2.1 Definitions

A mobile ad hoc network does not have mobile stations

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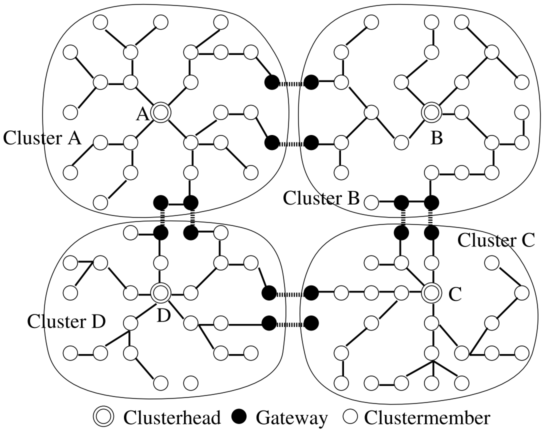


Fig. 1 Cluster formation.

and wired links and is modeled by an undirected graph $G = (V, E)$ in which a node $v_i \in V$ represents a mobile host with ID i with switching capability and an edge $(v_i, v_j) \in E$ represents a wireless link between nodes i and j. When nodes v_i and v_j are connected by a link, they are said to be neighboring with each other. Since the nodes move around in the network, as time proceeds the links are connected and disconnected among the nodes and thus the network topology always changes.

2.2 Cluster Criteria

A cluster is a set of connected nodes which consists of a clusterhead, gateways and clustermembers as shown in Fig. 1. In the proposed autonomous clustering scheme, the cluster is maintained so that the following properties are satisfied. ID of the clusterhead is ID of the cluster it manages and arbitrary nodes in the cluster are connected by a sequence of wireless links between neighboring nodes whose ID are the same as that of the clusterhead. The size of the cluster is restricted by the lower bound L and upper bound U. That is, the number of nodes $|C_i|$ in the cluster C_i must be $L \leq |C_i| \leq U$. Here, C_i denotes a cluster C whose clusterhead is v_i.

2.2.1 Clusterhead

A node which manages the cluster is called clusterhead. The clusterhead forms a spanning tree in the cluster to efficiently collect information on all nodes in the cluster as shown in Fig. 1. Based on the collected information, the clusterhead makes a list of nodes in the cluster. In addition, by collecting information on neighboring clusters, the clusterhead makes a list of all neighboring clusters. Using these two lists, the clusterhead adjusts the number of nodes in the cluster as follows. When it is less than L, the clusterhead checks the sizes of all the neighboring clusters and merges the cluster with one of the neighboring clusters. When it is larger than U, the clusterhead divides the cluster to two clusters. In either case, though neighboring clusters of merged or divided clusters are updated, influence of merger and division of clusters is restricted because maintenance of clusters is locally performed. Merger and Division of clusters are described in [10].

2.2.2 Gateway

Node v_i is said to be a gateway if there is a neighboring node of v_i denoted by $v_j (j \neq i)$ whose ID is different from that of node v_i. Gateway v_i can know the number of nodes in the neighboring cluster by exchanging information with the other gateways in the neighboring cluster.

2.3 Cluster Maintenance

A clusterhead periodically broadcasts “Clustermember” message within the cluster for cluster maintenance. As shown in Fig. 1, tree structure at which the clusterhead is rooted is constructed in each cluster. Leaf nodes in the cluster sends REPLY message back to the clusterhead along the tree structure. The clustermember and the gateway which received the REPLY message contains their own ID’s and the information on the neighboring clusters in it, respectively. Consequently, the clusterhead can collect information on both the clustermember in the cluster and the neighboring clusters. Each node can collect the local information because it can listen to any messages which the neighboring nodes broadcast. Each node autonomously constitutes the cluster because it changes its role in the cluster according to the local information. We describe how each node changes the role in the next subsection.

2.3.1 States and Roles

In the autonomous clustering scheme, each node has a state and play a role corresponding to the state. The roles in the following states NSN, CN, BN, BCN, ON are explained below.

Normal State Node (NSN): In this state the node does not have any special functions for maintaining clustering such as clusterheads and gateways. Control Node (CN): In this state the node plays a function of the clusterhead. Border Node (BN): In this state the node plays a function of the gateway. Border Control Node (BCN): In this state the node plays functions of the clusterhead and gateway. Orphan Node (ON): In this state the node does not have any node ID. When a node joins the network, it is in this state. The node whose state is ON periodically broadcasts “Hello” message to discover any cluster and join it.

2.3.2 State Transitions

Since even nodes which play essential roles for clustering such as clusterheads and gateways move around in the ad hoc networks, whenever they cannot play them, instead some other nodes must play them. In order to maintain clustering even when nodes move, nodes autonomously change

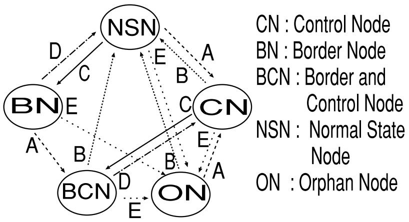


Fig. 2 State transition diagram of node v_i.

their states and play roles corresponding to the states. The state of each node is changed according to change of states of the neighboring nodes. The state changes, in other words, state transitions are represented in Fig. 2. The following five transitions A to E occur for maintenance of clustering.

A: A role of clusterhead is added to the current role of the node. B: State of the node is transitioned to state NSN and the node plays a role of ordinary node. C: A role of gateway is added to the current role of the node. D: A role of gateway is deleted to the current role of the node. E: Cluster ID of the node is deleted, state of the node is transitioned to state ON, and the node becomes an orphan node.

Since nodes always move around in mobile ad hoc networks, adaptability to node movement is one of the most important properties for clustering and routing. We have shown that the autonomous clustering scheme has a high adaptability to node movement [10], [11].

3. A Class of Hierarchical Routing Protocols

A class of hierarchical routing protocols can be designed in such a way that (1) a hierarchical structure is introduced by the autonomous clustering scheme described in Sect. 2, (2) representative routing protocols such as TORA, DSR and AODV are applied to routing among clusters, (3) a Tree-Based Routing Protocol (TBRP) is applied to routing within cluster.

3.1 Routing among Clusters

In order to describe the hierarchical routing protocols from the next section, we use the terms such as source cluster, destination cluster and intermediate cluster. The meaning of terms is as follows. A source cluster means a cluster to which a source node belongs. A destination cluster means a cluster to which a destination cluster belongs an intermediate cluster means a cluster to forward the data packets to the destination cluster.

In the hierarchical routing protocols, each cluster has a routing table, route cache and so on. Strictly speaking, the clusterhead in each cluster has all of them.

3.2 Routing within Cluster

As mentioned in Sect. 2.3, because a clusterhead periodically broadcasts "Clustermember" message within the cluster for cluster maintenance, the tree structure at which the clusterhead is rooted is constituted in each cluster as shown in Fig. 1. The data packets are forwarded along the tree. A gateway which received the data packets from the neighboring cluster forwards them to the clusterhead. In order to forward them to the neighboring cluster which is designated as the next hop cluster according to the information of the clusterhead, it sends them to the gateway which is neighboring to the next hop cluster. If a node cannot send data packets to the destined node due to node movement or cluster maintenance, it sends them back to the clusterhead and the clusterhead sends them along the updated tree again. In case that the destination node exists in the cluster, the clusterhead forwards them to it along the tree.

3.3 Routing Information of Clusterhead and Its Maintenance

A clusterhead in each cluster has the routing information for routing among clusters and routing within cluster. Concretely, in Hi-TORA, Hi-DSR and Hi-AODV, only the clusterhead has the routing information which each node has in TORA, DSR and AODV. In TORA, DSR and AODV, the node has the routing information such as the next hop node, the destination node and the ordered node list for forwarding data packets. While, in Hi-TORA, Hi-DSR and Hi-AODV, the clusterhead has the routing information such as the next hop cluster, the destination cluster and the ordered cluster list for forwarding data packets. In addition, the clusterhead has the routing information on the cluster members in its own cluster.

In case that a clusterhead in a cluster moves to the outside of the cluster, any data and control packets cannot pass through the cluster because the clusterhead does not exist in it. Therefore, the rest of nodes in the cluster starts the cluster maintenance for the cluster and selects a new clusterhead for the cluster based on the proposed autonomous clustering scheme [10]. Nodes can notice that the clusterhead moves to the outside of the cluster because they cannot receive Clustermember messages for a specified period. At this time, since new clusterhead periodically sends Clustermember message to all nodes within the cluster, it has the routing information for routing within cluster while it does not have any routing information for routing among clusters. The new clusterhead in the cluster creates the routing information for routing among clusters when it receives the route discovery message or the route maintenance message from the neighboring nodes or a node in the cluster tries to send data packets.

4. Hierarchical Routing Protocol Hi-TORA

This section proposes Hi-TORA based on autonomous clustering scheme in Sect. 2 and TORA [5]. Hi-TORA applies TORA to the routing among clusters. In the routing among clusters, by regarding one cluster as one node for TORA, Hi-TORA can route data packets from the source node to the destination node to communicate with each other. Ta-

Table 1 Control packets for Hi-TORA.

Query	Used to discover a destination node
Update	Used to update hieghts of nodes
Clear	Used to clear the route

ble 1 shows control packets used for Hi-TORA. First, we explain the TORA briefly.

4.1 TORA [5]

TORA maintains a destination-oriented directed acyclic graph (DAG) for each possible destination node. In this graph structure, any node leads to the destination node according to logical direction which links have as described before. TORA uses the notation of *height* to determine the direction of each link. When a node tries to communicate with another node, all nodes in the network make use of height. Height of the source node is the largest value and height of the destination node is the smallest value. The logical links are considered to be directed from nodes with higher height towards nodes with lower height. Despite dynamic link failures, TORA attempts to maintain the DAG such that each node can reach the destination node.

TORA performs three basic functions, that is, route creation, route maintenance, and route erasure and three control packets are used by each function, that is, query (QRY), update (UPD), and clear (CLR).

4.2 Hi-TORA

4.2.1 Route Creation in Hi-TORA

We describe how to communicate between a source node and the destination node. When a source node wants to communicate with the destination node, the clusterhead in the cluster to which the source node belongs sends QRY packets toward the destination cluster. In TORA, a height is set at all nodes which received the packets. Then, the height of the source node is the largest value in the network, and the height of the destination node is the smallest one. As shown in Fig. 3, however, in Hi-TORA, a height is set at the clusterhead in each cluster. That is, the height is not set at the destination node, but is set at the clusterhead in the destination cluster. Then, the height of the source cluster is the largest value in the network, and the height of the destination cluster is the smallest one. The data packets generated by the source node are forwarded toward the cluster with the lower height like TORA.

4.2.2 Problems and Their Solutions

Hi-TORA to which TORA is applied in a straightforward way has some problems because TORA is not designed to use for a hierarchical routing. We can consider the following three cases occur.

The first case is that the source node runs away from the source cluster. Then, it does not affect anything in special in Hi-TORA. Hi-TORA takes over the idea of *DAG* from TORA. It is possible for every node to send the data packets to the destination node according to the logical link which the node has in the DAG. Therefore, if the source node moves to another cluster, the source cluster is only changed.

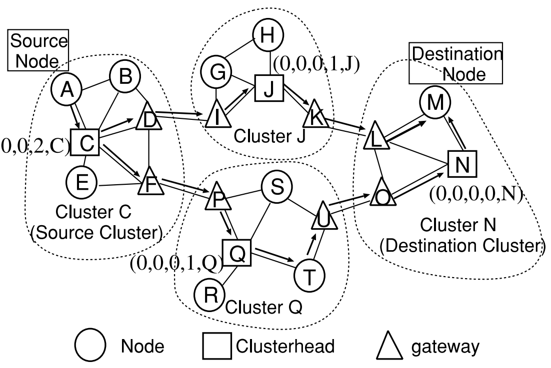


Fig. 3 Example of the routing in Hi-TORA.

The second case is that the destination node runs away from the destination cluster. The cluster which it enters is redefined as a new destination cluster. In this case, firstly, the clusterhead in the new destination cluster sets its height to *ZERO*. Then, like UPD packets of TORA it broadcasts the new height to the neighboring clusters to find a new route to the destination node in the new destination cluster.

The last case is that the cluster ID of an intermediate cluster is changed. Even if the clusterhead leaves from the cluster, data packets can be delivered to the destination cluster by reorganizing the DAG.

5. Hierarchical Routing Protocol Hi-DSR

This section proposes Hi-DSR based on autonomous clustering scheme in Sect. 2 and DSR [6]. Hi-DSR applies DSR to the routing among clusters. In the routing among clusters, by regarding one cluster as one node for DSR, Hi-DSR can route data packets from the source node to the destination node to communicate with each other. Table 2 shows control packets used for Hi-DSR. First, we explain the DSR briefly.

5.1 DSR [6]

The DSR protocol uses source routing. Each data packet includes the sequence of intermediate nodes between a source node and a destination node and is forwarded to the destination node along the sequence. The advantage of source routing is that data packets are forwarded to the destination node without exchanging the control packets among the intermediate nodes in order to maintain the route between the source node and the destination node. The DSR protocol consists of route discovery and route maintenance mechanisms.

Table 2 Control packets for Hi-DSR.

ROUTE REQUEST	Used to discover a destination node
ROUTE REPLY	Used to respond to a source node
FORWARDING ERROR	Used to send error back to a source node in case that an intermediate cluster does not forward data packet
DESTINATION ERROR	Used to send error back to a source node in case that a destination cluster does not forward data packet to the destination node

5.1.1 Route Discovery

In order to discover the route to the destination node, a source node broadcasts a ROUTE REQUEST message and receives a ROUTE REPLY message from the destination node and/or the other nodes which had already discovered a route to the same destination. Moreover, each node maintains the route cache to reduce the overhead of route discovery.

5.1.2 Route Maintenance

Route maintenance is the mechanism to detect whether the route is broken or not due to the change of the network topology and if it is broken to find a new route. A node which decides that the route information is no longer useful notifies a ROUTE ERROR message to the source node. The source node which received the ROUTE ERROR message attempts to use any other route based on its route cache or invoke route discovery to find a new route again.

5.2 Hi-DSR

5.2.1 Route Discovery in Hi-DSR

We describe an example of route discovery in Hi-DSR. As shown in Fig. 4, a circle denotes a cluster and a line denotes a logical link which connects two clusters, respectively. The source node is one of clustermembers in Cluster *S* and the destination node is one of clustermembers in Cluster *D*.

First, the source cluster *S* broadcasts a ROUTE REQUEST message (we denote this as REQ in Fig. 4) to all neighboring clusters. In the ROUTE REQUEST message, the cluster ID of the source cluster is contained (Fig. 4(a)). Clusters B and C which received the ROUTE REQUEST message add its own cluster ID into it and rebroadcast it to all neighboring clusters (Fig. 4(b)). Consequently, the destination cluster *D* receives three ROUTE REQUEST messages which contain $S \rightarrow D$, $S \rightarrow B \rightarrow D$, and $S \rightarrow C \rightarrow D$. It then sends three ROUTE REPLY messages back to the source cluster based on routes contained in ROUTE REQUEST messages (Figs. 4(c) and (d)). The source cluster *S* which received the ROUTE REPLY messages stores the sequence of cluster ID to the destination cluster as the route information into the route cache (Fig. 4(e)).

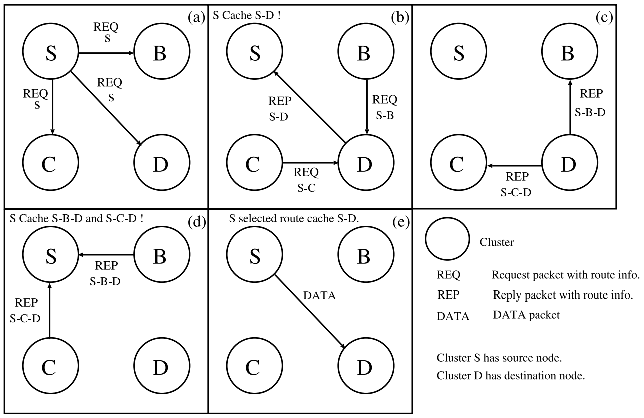


Fig. 4 Example of route discovery in Hi-DSR.

The data packets from a source node to a destination node are sent as follows. First, the source node sends them to its clusterhead in the cluster. The clusterhead forwards them to the next hop cluster based on its route cache which consists of the sequence of the cluster ID's to the destination cluster. Concretely, data packets are forwarded along two trees within the source cluster and the next hop cluster through two neighboring gateways. Then, the clusterheads in the intermediate clusters also forward them in a similar way. Finally, the destination cluster which received them from the neighboring cluster forwards them to the destination node along a tree within the destination cluster.

5.2.2 Route Maintenance in Hi-DSR

Each cluster has the list of the neighboring clusters because the autonomous clustering scheme is always working. In case that the next hop cluster to which a cluster must forward the data packet is not contained in the list, the cluster sends "FORWARDING ERROR" message back to the source cluster. The source cluster which received the FORWARDING ERROR message deletes the route information contained in the FORWARDING ERROR message from the route cache. Then, the source cluster selects the other route from the route cache. If the source cluster does not have any route cache to send the data packet to the destination cluster, it discovers a new route to the destination cluster.

In case the destination cluster received the data packet and destination node had already left from the cluster due to node movement, the destination cluster sends "DESTINATION ERROR" message back to the source cluster and invokes the route discovery to the destination node to forward the data packets which it has already received. The source cluster which received the DESTINATION ERROR message deletes all route caches of routes to the destination node and invokes the route discovery to find a new route.

6. Hierarchical Routing Protocol Hi-AODV

This section proposes Hi-AODV based on autonomous clustering scheme in Sect. 2 and AODV [3]. Hi-AODV applies AODV to the routing among clusters. In the routing among

Table 3 Control packets for Hi-AODV.

ROUTE REQUEST	Used to discover a destination node
ROUTE REPLY	Used to respond to a source node
ROUTE ERROR	Used to send error back to a source node in case that an intermediate cluster does not forward data packet

clusters, by regarding one cluster as one node for AODV, Hi-AODV can route data packets from the source node to the destination node to communicate with each other. Table 3 shows control packets used for Hi-AODV. First, we explain the AODV briefly.

6.1 AODV [3]

6.1.1 Route Discovery

When a source node seeks for the route to the destination node, it broadcasts a ROUTE REQUEST message. In case that either the destination node or the intermediate nodes which has the routing table to the destination node received the ROUTE REQUEST message, the node sends a ROUTE REPLY message back to the source node. The intermediate nodes which received the ROUTE REPLY message from the neighboring node set the neighboring node as the next hop.

6.1.2 Route Repair

In case that the link between the node and the next hop node goes down when a node received the data packets and it is about to forward them to the next hop node, the node invokes the route repair. If the number of hop counts between the node and the source node is more than the number of hop counts between the node and the destination node, the node invokes the route discovery as mentioned above. Otherwise, the node sends a ROUTE ERROR message back to the source node, and then the source node invokes the route discovery to find a new route again.

6.2 Hi-AODV

6.2.1 Route Discovery in Hi-AODV

In case of Hi-AODV, when a source node seeks for the route to the destination node, the clusterhead in the source cluster broadcasts a ROUTE REQUEST message. In case that the destination cluster received the ROUTE REQUEST message, the clusterhead sends a ROUTE REPLY message back to the source cluster. The intermediate clusters which received the ROUTE REPLY message from the neighboring cluster set the neighboring cluster as the next hop cluster.

6.2.2 Route Repair in Hi-AODV

In order to maintain the route between a source node and a destination node for data packets, Hi-AODV invokes the route repair in the following cases.

The first case is that the source node left from the current cluster and the cluster ID of the cluster which includes the source node is changed. In this case, if the clusterhead in the new source cluster has the routing table for the destination cluster, the source cluster sends the data packets according to the routing table. Otherwise, it invokes the route discovery to find out a new route.

The second case is that a link between an intermediate cluster and the next hop cluster to which an intermediate cluster should send the data packet goes down. Regardless of the hop count from the source node to the clusterhead in the intermediate cluster and the hop count from the destination node to the clusterhead in the intermediate cluster, the clusterhead invokes the route discovery to forward the data packets to the destination cluster in order to perform the route repair. At the same time, the clusterhead sends a ROUTE ERROR message back to the source cluster.

The third case is that the destination node left from the destination cluster which the source cluster had found out by the route discovery. The destination cluster invokes the route repair to find the new destination cluster to which the destination node currently belongs.

7. Simulation Experiments

For the evaluation purpose, the proposed hierarchical routing protocols Hi-TORA, Hi-DSR and Hi-AODV are compared to TORA, DSR and AODV through simulation experiments, respectively. This section describes the simulation model and parameters, and then, evaluates the performance of hierarchical routing protocols in terms of the number of control packets and the accuracy of packet delivery.

7.1 Simulation Model and Parameters

We used the network simulator ns-2 (version ns-2.26) [8] which models physical, data link and MAC layer except for multiple access interference. The simulation environments are shown in Table 4. We evaluated TORA, DSR and AODV using the parameters and constants which are set in ns-2 (Note that data on control packets for MAC layer of AODV are not included). Parameters and constants of the autonomous clustering used in hierarchical routing protocols Hi-TORA, Hi-DSR and Hi-AODV are shown in Table 5. The simulation experiments were performed at 5 times for combination of each parameter.

7.2 Simulation Environments for Large Mobile Ad Hoc Networks

In the previous simulations in [4], [13], assuming that the number of nodes is 50 and that the field size is $1500\,\mathrm{m} \times 300\,\mathrm{m}$, performance and overhead (that is, the packet delivery ratio and the number of control packets) for ad hoc network routings have been measured and evaluated. However, unlike the previous simulation experiments, we have conducted experiments in the simulation environments

Table 4 Parameters and constants used in the all simulation.

Field space	2000 m × 1500 m flat space
Number of nodes	150
Max node speed	1, 2, 3, 4, 5, 10, 15, 20 (m/s)
Node mobility	Random waypoint model [4]
Simulation run time	300 s
Number of source nodes	10, 20, 30
Node stop time	0 s
CBR packet delivery ratio	4/s
CBR packet size	512byte
MAC layer type	IEEE 802.11
Transmission range	250 m

Table 5 Parameters and constants used in the autonomous clustering.

Lower bound of cluster size (*L*)	20
Upper bound of cluster size (*U*)	50
Interval of clustermember message	500 ms
Interval of Hello message in case of ON state	200 ms
Lifetime on the neighboring node information in a node	1.65 s
Lifetime on the neighboring cluster information in a node	1.65 s
Lifetime on the clustermember information in a clusterhead	1.65 s
Lifetime on the child node information in a node of each cluster	1.1 s

such that the number of nodes is 150 and that the field size is 1500 m × 1000 m, which implies a relatively large mobile ad hoc networks. Since the number of nodes and the field size in our simulation environment are larger than those in the previous simulation environments, our simulation results become worse than the previous simulation results with respect to the performance and overhead concerning TORA, DSR and AODV. The large number of nodes and the large field size cause long hop paths through which data packets are delivered in the ad hoc networks. When data packets are delivered through such long hop paths, there become high possibilities that packet collision occurs. These possibilities result in degradation of performance and increase of overhead.

7.3 Results for Control Packets

Figures 5(a)–(c), 6(a)–(c) and 7(a)–(c) represent the average numbers of control packets for routings of TORA, Hi-TORA, DSR, Hi-DSR, AODV and Hi-AODV versus the maximum moving speeds of nodes for the numbers of source nodes 10, 20 and 30, respectively. In these figures, the vertical axis denotes the average number of control packets while the horizontal axis denotes the maximum number of moving speeds of nodes.

7.3.1 TORA and Hi-TORA

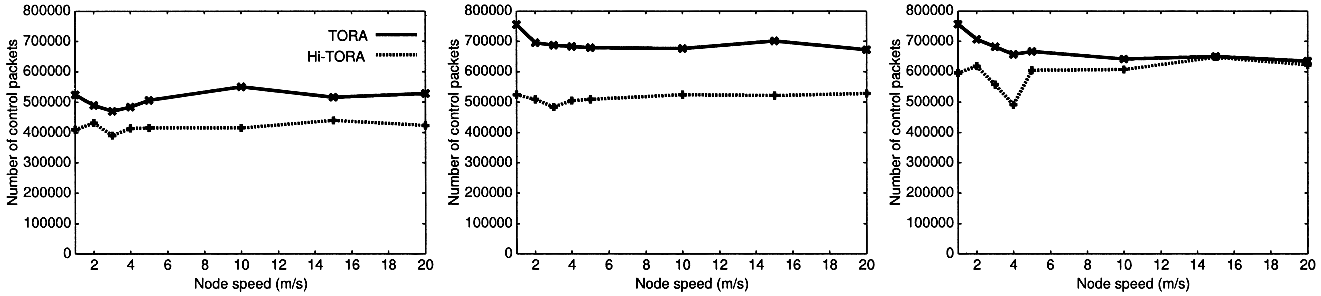
As shown in Figs. 5(a) and (b), for the number of source nodes 10 and 20, control packets of Hi-TORA are smaller than those of TORA regardless of moving speeds of nodes. Along with increase of the number of source nodes from 10 to 20, control packets of TORA and Hi-TORA increase, however, increasing ratio of Hi-TORA is smaller than that of TORA. These results are caused by the following facts. Control packets of Hi-TORA for routing is smaller than those of TORA for routing because control packets of Hi-TORA for routing in each cluster are restricted and control packets of Hi-TORA for routing among clusters are also restricted, which are considered as effects of hierarchical routing. In addition, control packets of Hi-TORA for clustering do not depend on the number of source nodes, and the clustering itself can provide stable clusters because of its adaptability to change of node movement. However, as shown in Fig. 5(c), the numbers of control packets of TORA and Hi-TORA become almost equivalent along with increase of moving speed of nodes, in other words, they are saturated. It is because control packets for routing seem to exceed the network capacity.

7.3.2 DSR and Hi-DSR

As shown in Figs. 6(a)–(c), control packets of DSR are almost same in all cases. These results indicate that even when the number of source nodes is 10, control packets of DSR become saturated. Such fast saturation is caused by explosive propagation of the ROUTE REQUEST message (we denote this as REQ) for route discovery and frequent occurrences of ROUTE ERROR messages (we denote this as ERR) for route maintenance. Concerning the REQ, since route information is stored in REQs, not only the number of the REQs but also the size of the REQs becomes large. Concerning the ERRs, there are high possibilities that the ERRs occur in the large networks, in which the hop counts of routes between pairs of a source node and a destination node tend to be long. Similar reasons why control packets of Hi-TORA is smaller than those of TORA as described in Sect. 7.3.1 hold for Hi-DSR and DSR. However, the number of control packets of Hi-DSR is a little larger than that of Hi-TORA. These results are caused by differences of routing among clusters between Hi-DSR and Hi-TORA.

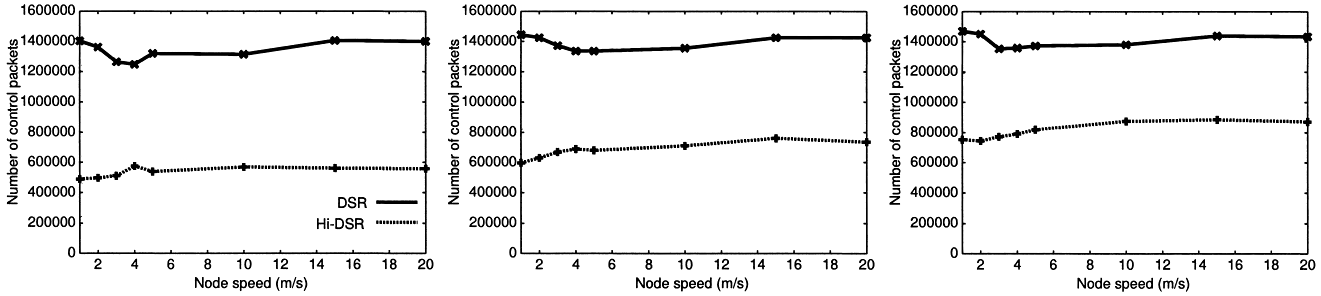
7.3.3 AODV and Hi-AODV

For fair consideration on control packets, Hi-AODV and AODV both of which do not include the number of control packets for MAC layer are compared. We denote these routing protocols as *Hi-AODV and *AODV. As shown in Figs. 7(a)–(c), control packets of *Hi-AODV are almost same in all cases. However, control packets of *AODV increase along with increase of the number of the source nodes. In case that the numbers of source nodes are 20 and 30, control packets of *Hi-AODV are smaller than that of *AODV. The increase of the number of control packets of *AODV is caused by the route repair. In case of AODV, intermediate nodes broadcast a ROUTE REQUEST message (we denote this as REQ) to all nodes within the range of TTL which is calculated to find a new route from the intermediate node to the destination node.



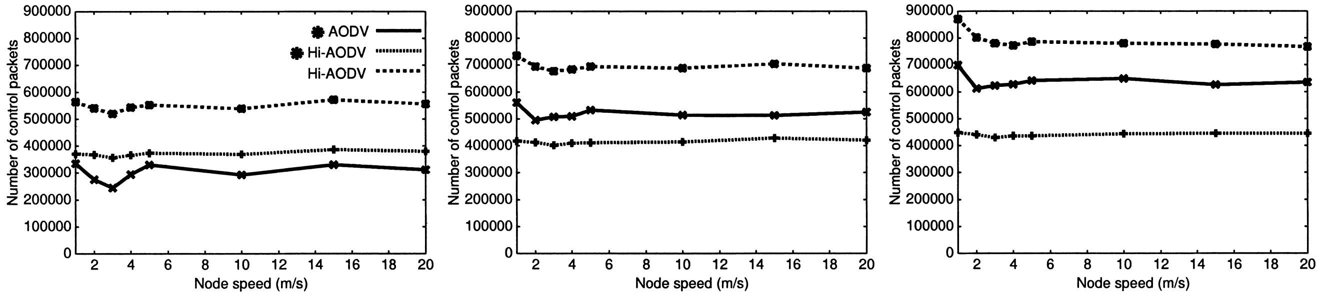
(a) Number of Source nodes = 10 (b) Number of Source nodes = 20 (c) Number of Source nodes = 30

Fig. 5 The number of control packets of TORA and Hi-TORA.



(a) Number of Source nodes = 10 (b) Number of Source nodes = 20 (c) Number of Source nodes = 30

Fig. 6 The number of control packets of DSR and Hi-DSR.



(a) Number of Source nodes = 10 (b) Number of Source nodes = 20 (c) Number of Source nodes = 30

Fig. 7 The number of control packets of AODV and Hi-AODV (Note that *AODV and *Hi-AODV do not include the number of control packets for MAC layer).

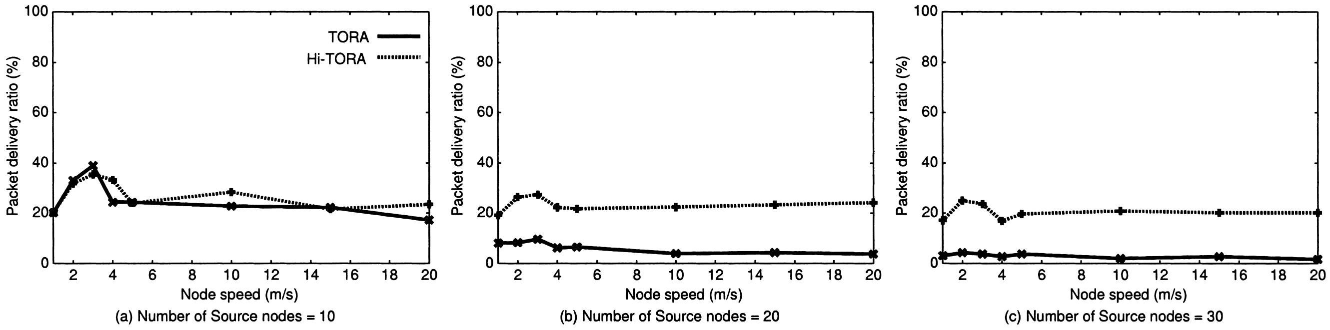
On the other hand, in case of *Hi-AODV, if the TTL is less than hop counts from a clusterhead to any gateway in the cluster, the destination node could be in the cluster, the clusterhead sends a data packet to the destination node and it is thus unnecessary to broadcast a REQ in the cluster. If hop count from a clusterhead to a gateway in the cluster is longer than TTL, the following cases are considered. If the destination node is within the cluster, the clusterhead sends a data packet to the destination node. Otherwise, the clusterhead has only to broadcast a REQ to gateways to which hop count from the clusterhead is longer than TTL. In this case, it is unnecessary to broadcast the REQ to not all nodes in the cluster. Consequently, the more the number of source nodes increases, the more the effect of the autonomous clustering scheme for reducing control packets is seen.

7.4 Results for Delivered Packets

Figures 8(a)–(c), 9(a)–(c) and 10(a)–(c) represent the average numbers of data packets which have been delivered from source nodes to destination nodes by routings of TORA, Hi-TORA, DSR, Hi-DSR, AODV and Hi-AODV versus the maximum moving speeds of nodes for the numbers of source nodes 10, 20 and 30, respectively. In these figures, the vertical axis denotes the average number of delivered data packets while the horizontal axis denotes the maximum number of moving speeds of nodes.

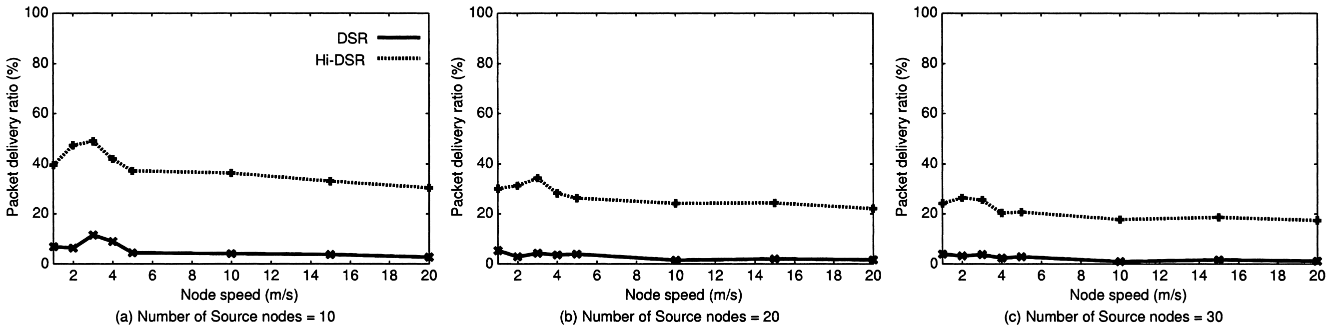
7.4.1 TORA and Hi-TORA

As shown in Fig. 8(a), when the number of source nodes is 10, the number of delivered data packets of Hi-TORA is



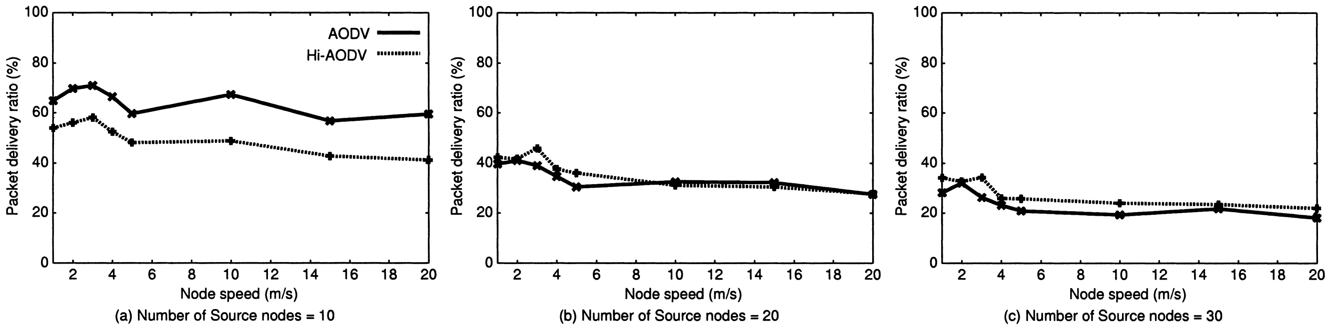
(a) Number of Source nodes = 10 (b) Number of Source nodes = 20 (c) Number of Source nodes = 30

Fig. 8 The number of delivered data packets of TORA and Hi-TORA.



(a) Number of Source nodes = 10 (b) Number of Source nodes = 20 (c) Number of Source nodes = 30

Fig. 9 The number of delivered data packets of DSR and Hi-DSR.



(a) Number of Source nodes = 10 (b) Number of Source nodes = 20 (c) Number of Source nodes = 30

Fig. 10 The number of delivered data packets of AODV and Hi-AODV.

a little larger than that of TORA. Along with increase of the number of source nodes, the number of delivered data packets of Hi-TORA increases. On the contrary, the number of delivered data packets of TORA rapidly decreases. The reason for such decrease is that the number of control packets of TORA reached a congestion state corresponding to the network capacity. As a result, TORA cannot provide stable routes between source nodes and destination nodes. This can be proved by an evidence that hop counts of routes through which data packets have been delivered from source nodes to destination nodes are one or two in the simulation environments of Figs. 8(b) and (c). The Hi-TORA restrains the number of control packets for routing and clustering. As a result, the number of delivered data packets can grow until the number of control packets reaches the congestion state.

7.4.2 DSR and Hi-DSR

Since control packets of DSR explosively increase, they prevent to generate or maintain routes between source nodes and destination nodes. As shown in Figs. 9(a)–(c), the number of delivered data packets of DSR remains small even when the number of source nodes is 10. On the contrary, for the similar reasons of the Hi-TORA described in Sect. 7.4.1, the number of delivered data packets increases along with increase of the number of source nodes. As an effect of adoption of DSR to routing among clusters in Hi-DSR, increasing ratio of the number of delivered packets of Hi-DSR is higher than that of Hi-TORA. However, increase of the number of delivered data packets stops when the number of control packets reaches the congestion state in a similar way of Hi-TORA.

7.4.3 AODV and Hi-AODV

As shown in Fig. 10(a), when the number of source nodes is 10, the number of delivered data packets of Hi-AODV is smaller than that of AODV. Along with increase of the number of source nodes, the number of delivered data packets of Hi-AODV increases. In case that the number of source nodes is 20 and 30, the number of data packets of Hi-AODV is a little larger than that of AODV. In addition, as mentioned in Sect. 7.3.3, the number of control packets of Hi-AODV is much smaller than that of AODV. This implies that Hi-AODV has data packet delivery performance almost equivalent to AODV with lower overhead.

8. Related Work

Zone Routing Protocol (ZRP) [14] uses IntrAzone Routing Protocol (IARP) for routing within cluster and IntErzone Routing Protocol (IERP) for routing among clusters, respectively. Note that ZRP uses the term 'zone' instead of the term 'cluster.' IARP is derived from Link State routing protocols. The base protocol is modified that the scope of the route updates is restricted to the radius of the node's routing zone. In IERP, a source node broadcasts a route query packet to all the peripheral nodes to discover a destination node. When a node sends any packets to the outside of the zone, it can send them along the shortest path within the zone because IARP works in the zone. Therefore, ZRP broadcasts and sends any packets much efficient. However, it is expected that ZRP has high overhead for IARP although IARP is used only in the zone.

Clusterhead-Gateway Switch Routing (CGSR) [15] uses Least Clusterhead Change (LCC) [17] for introducing the hierarchical structure and routing on the top of LCC. CGSR uses as a basis the Destination Sequenced Distance Vector (DSDV) [18] and improved that any packets are forced to pass through the clusterhead. CGSR does not need to use the routing within cluster because a cluster consists of a clusterhead and the neighboring nodes in LCC. Since the size of each cluster in CGSR is much smaller than that in ZRP, CGSR do not reduce the control packets globally. Especially, in case that the network size becomes large, it is expected that the performance degrades significantly.

In Wireless HIerarchical Routing protocoL (WHIRL) [16], the entire network is divided into logical subnets. Each logical subnet has one primary Home Agent (HA) based on the Mobile IP concept. A subnet consists of some physical clusters which are constructed by LCC. Each clusterhead in each physical cluster broadcasts its neighbor clusterhead list to all the other clusterheads periodically for physical routing. HA maintains the physical clustering information of its logical subnet members. The source node sends data packets to the HA and then, the HA forwards them to the destination node according to the subnet member list table. WHIRL is designed for group mobility model in which motions are dependent between mobility epochs. Therefore, it is expected that WHIRL has heavy overhead to maintain the physical routing and the subnet member list table in a HA in random way point model.

Table 6 Comparison of hierarchical routing protocols.

Protocol	Routing within cluster	Routing among clusters
ZRP	IARP	IERP
CGSR	-	CGSR
Hi-TORA	TBRP	TORA
Hi-DSR	TBRP	DSR
Hi-AODV	TBRP	AODV

Since LCC which is used for CGSR and WHIRL is not adaptive to node movement, the numbers of changes of clusterheads and cluster IDs are large when nodes move frequently. Consequently, it cannot provide the stable hierarchical routing in comparison with the proposed autonomous clustering [10].

Hi-TORA, Hi-DSR and Hi-AODV use Tree-Based Routing Protocol (TBRP) for routing within cluster. In TBRP, the tree structure at which the clusterhead is rooted is constituted in each cluster. The overhead of routing within cluster in Hi-TORA, Hi-DSR and Hi-AODV can reduce significantly in comparison with ZRP. However, in Hi-TORA, Hi-DSR and Hi-AODV, any packets which pass through cluster need longer hops than that in ZRP. Moreover, in the routing among clusters because each cluster which is constructed by the proposed autonomous clustering does not overlap with each other, by regarding one cluster as one node for TORA, DSR and AODV, Hi-TORA, Hi-DSR and Hi-AODV can route data packets from the source node to the destination node to communicate with each other. Hi-TORA is designed to provide multiple route to a destination node and minimize communication overhead by localizing algorithmic reaction to the change of network topology like TORA. The key advantage of Hi-DSR is that intermediate clusters do not need to maintain update routing information in order to route data packets they forward like DSR. Hi-AODV relies on dynamically establishing route table entries at intermediate clusters, and it thus uses bandwidth efficiently by minimizing the overhead for control packets and is responsive to the change of the network topology link AODV.

We summarize the comparison of hierarchical routing protocols in Table 6. In Table 6, WHIRL is not included because it is the hierarchical routing protocol used for group mobility model.

9. Conclusion

This paper has proposed a class of hierarchical routing protocols for large mobile ad hoc networks based on both the autonomous clustering scheme and the representative flat routing protocols such as TORA, DSR and AODV. It has shown that thanks to the proposed autonomous clustering scheme the proposed hierarchical routing protocols are much effective and robust for large mobile ad hoc networks from view points of control packets overhead and data packet delivery performance compared to the representative flat routing protocols.

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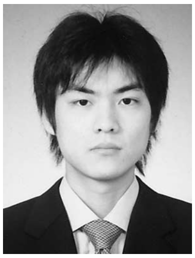

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