Adaptive router promotion and group forming in ad-hoc networks

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Abstract: In ad-hoc networks, routing is one of the most important issues, and various protocols are proposed. However, as situations and topologies of an ad-hoc network are various and dynamic, it is difficult for a single fixed protocol to perform well for all occasions. Therefore, some dynamic and adaptive mechanism in routing protocols is necessary. In this paper, we propose an adaptive routing system for ad-hoc networks. This system begins in the same manner as a reactive protocol, and when the network situation gets unsuitable for the protocol, the system changes its manner of routing with a router-node, or a pseudo cluster-head in Cluster-based Routing, which emerges autonomously at the place of 'hot spots' in the network. Also, this system provides a protocol to organise a group around each router, or a pseudo cluster, in an autonomous decentralised manner, so that the whole network is organised in a hierarchy of routercentric subnets. This paper presents the principle and design of our system, and some preliminary experiment results.

Keywords: ad-hoc networks; adaptive routing; dynamic network grouping.

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1 Introduction

Ad-hoc networks are autonomously constructed from end-user nodes without any particular network equipments, and are expected to be used in various occasions. Among several issues to be addressed, routing is one of the most important and difficult subjects.

In a basic ad-hoc network, there is no node like a router that manages composition of the whole network and performs routing. Each node must obtain routing information by itself, and determines a route according to the information. However, this is inefficient in general, and various improvements have been devised and proposed.

Cluster-based routing is one of the improvements which are widely accepted (Jiang et al., 1998; Belding-Royer, 2003; Nieberg et al., 2003; Ibriq and Mahgoub, 2004). A network is divided into many conjunctive subnets called 'clusters'. Each cluster has a 'cluster head', and neighbouring clusters are connected by a shared 'gateway node'.

The cluster head maintains cluster membership information and member routing information. Cluster member nodes do not have routing information, and ask the cluster head whenever needed. Inter-cluster routes are transferred through the gateway node.

However, because situation and topology of an ad-hoc network changes dynamically, it is almost impossible to allocate clusters and cluster heads in an optimal manner in advance, and to fix them permanently. Clusters should be created in an autonomous and adaptive manner, and also should be reorganised whenever necessary according to the movement of nodes, the change of communication traffic, etc.

This paper proposes, first, autonomic cluster head promotion based on our previous work on adaptive router promotion (Tanaka et al., 2006), and second, autonomic cluster organisation and reorganisation around the promoted cluster. Our system changes its routing mechanism to be suitable for the network topology and situation dynamically. Its purpose is to reduce network traffic for routing, in particular by alleviating 'packet flooding'.

In the following, Section 2 summarises basic routing protocols for ad-hoc networks. Proactive ones and reactive ones are first presented, and then some improvements including cluster-based routing are described. Our solution for cluster head promotion is presented in Section 3, and incremental autonomic cluster (re-)organisation is in Section 4. Section 5 describes some simulation experiments for evaluation. Section 6 contains some concluding remarks.

2 Routing in ad-hoc networks

2.1 Basic protocols

In basic ad-hoc networks, each node must obtain necessary routing information by itself. Consequently, various routing protocols have been developed, which are primarily categorised as proactive routing protocols (OLSR (Clausen and Jacquet, 2003), TBRPF (Ogier et al., 2004), etc.) and reactive routing protocols (AODV (Perkins et al., 2003), DSR (Johnson et al., 2001), etc.) As is well known, each of the proactive and reactive protocols performs well only in a limited situation regarding operational conditions and network configurations that should be covered by ad-hoc networks. If the node mobility is higher, the possibility that the route expires immediately is also higher. Therefore, the reactive protocols which builds routes only when needed are more effective than the proactive ones. On the other hand, if the call rate is higher, the proactive protocols are more effective than the reactive ones in which a node must look for a route whenever it calls another. Regarding the node mobility and call rate, there are some network situations that neither of two basic protocols performs well.

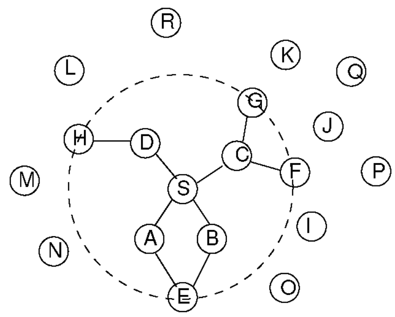
2.2 Hybrid routing

As described earlier, each basic protocol is suited for a different region of the ad-hoc network design space. In hybrid routing, each node uses different protocols by combining them into a single framework. One of the most famous hybrid routing is 'Zone Routing' (Hass et al., 2002).

In Zone Routing, a proactive protocol operates within a local area which we refer to as a routing zone (intra-zone routing), and a reactive protocol (inter-zone routing) operates outside of that. A proactive routing protocol provides a detailed and fresh view of each node's surrounding local topology, and finds a route to distant nodes reactively to reduce the overhead of route maintenance.

Figure 1 illustrates the routing zone concept with two-hop radius. The routing zone described by a dashed circle belongs to node *S*, and nodes from *A* to *H* are members of *S*'s routing zone. Note that each node maintains its own routing zone, and the zones of neighbour nodes overlap.

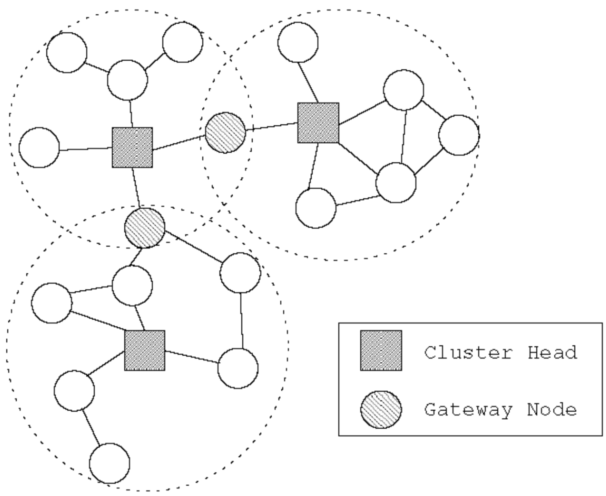
Figure 1 Zone routing with 2-hops-radius zone



2.3 Cluster-based routing

Cluster-based routing, or Clustering, is another approach to improve basic routing protocols. In cluster-based routing, all the nodes do not have routing information; instead only some nodes have. Such a node is called a cluster head, and maintains routing information of nodes surrounding it, i.e., within a cluster (Figure 2). This approach drastically decreases routing traffic. However, in the original Cluster-based routing, clusters and their heads are allocated statically, and cannot be adapted to the dynamic change of the topology and the situation.

Figure 2 Cluster-based routing

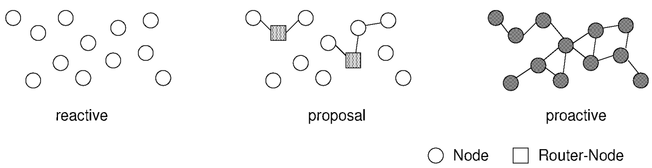


3 Adaptive cluster head promotion

The previous section describes some protocols aiming at covering the situation that neither a pure reactive nor a proactive type can work well. All the nodes keep routing information in the proactive protocols, while no node keeps routing information in the reactive ones. In this respect, these two types of the protocols stay at the opposite extremes. Therefore, it can be said that a protocol which performs well in the region between two extremes in an adaptive manner is desired for efficient maintenance of routing information.

Our protocol uses some (but not all) nodes to maintain routing information as shown in Figure 3. These nodes should be placed where they are the most effective and when they are required. Namely, each node starts in the same manner as in reactive protocols where no node has routing information, and accumulate routing information when transferring routing packets.

Figure 3 Axis of routing protocols

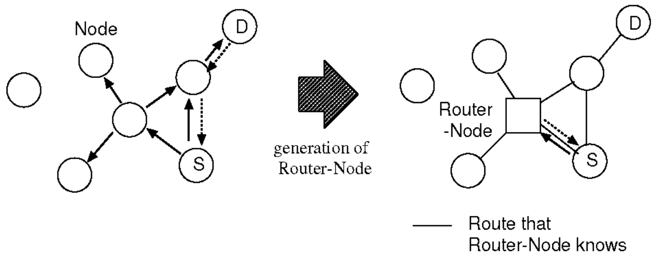


The depth of colour shows the amount of routing information.

When the amount of routing information grows, it implies that the node is at a 'crossroad' or a 'hot spot' in the network, and neighbouring nodes get benefits (from the routing standpoint of view) from the node. Therefore, it should be better to make the node as a cluster head, and make its neighbours into its cluster, so as to prevent flooding of route request packets.

In this manner, this network system transforms its way of routing from reactive to cluster-based dynamically and adaptively as shown in Figure 4.

Figure 4 Emergence of cluster head



In this system, the number of the cluster heads and their locations in the network are determined adaptively according to the network traffic in a fully decentralised manner, and clusters emerge dynamically, unlike the above mentioned original cluster based routing in which clusters are pre-defined and fixed in a static manner.

3.1 The initial state

The system performs routing using the reactive AODV protocol in the initial state. Each node sends HELLO packets periodically to confirm connectivity with neighbour nodes. RREQ (Route Request) packets are flooded to find routing information, and if the destination node or an intermediate node which caches routing information to the destination receives RREQ packet, it answers RREP (Route Reply) packet, and the route is built between two nodes.

3.2 Cache of routing information

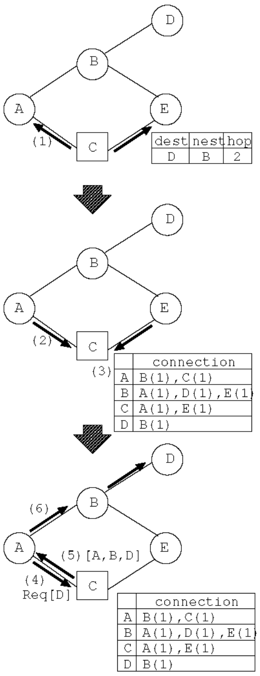
Each node caches routing information. If communication frequency goes up, and many routes are used within a short period, the amount of these caches also increases. Each node approximates the network traffic by this amount of its cache, and if this exceeds a certain pre-defined threshold, this fact implies that the node is at a place with high call rate, or a 'hot spot'. Then the node promotes itself to a cluster head. Note that every node has an option whether it can be promoted or not, according to its connectivity and capacity for example.

3.3 Promotion to cluster head

Figure 5 illustrates the process of how the node promotes itself to a cluster head, and how neighbour nodes are made to ask routing information to the cluster head directly so as to prevent the 'flooding' cost of finding routing information.

Suppose that the node *C* promotes itself to a cluster head. *C* notifies the fact to its neighbour nodes using the 'router notification' packet. Then, *C* collects routing information from its neighbour nodes. A neighbour node *E* has routing information such as "to node *D*, next hop is *B*, and hop count is 2". Therefore, *E* composes this information into a 'topology information' packet, and sends it to the cluster head *C*. *C* also receives a similar packet from the node *A*. The cluster head constructs a network topology table from the collected routing information which is specific to each original node.

Figure 5 Promotion to cluster head



When a route request arrives at the cluster head *C*, it composes routing information dynamically from this topology table using Dijkstra's shortest-path algorithm. For example, when node *A* asks *C* a route to the node *D*, *C* replies the shortest route from *A* to *D* as [A, B, D].

3.4 Search for routing information

Each node tries to get routing information in the following order: (1) check whether it has routing information, (2) ask to a known cluster head, or (3) flood RREQ packet. The cluster head does (1), and then (3); a 'plain' node (which does not know any cluster head) does (1), and then (3); and a neighbour of the cluster head does (1), and then (2). Note that when receiving an RREQ packet from another node, each node does not carry out flooding immediately, but follows the above steps.

A neighbour node which receives an RREQ from a plain node notifies the existence of the cluster head to the plain node along with a reply. The plain node becomes a new 'neighbour' node, and the router information is propagated in this manner.

3.5 Sending and forwarding

In AODV, routing is done in a 'hop-by-hop' manner. Each intermediate node has its own routing information from itself to any known destinations. On the other hand, in router-based routing, routing information is provided from the cluster head. This is a 'source route' that indicates an entire route from the source to the destination. Therefore, our system implements a switching mechanism between the two types of routings. A packet header contains a special flag, and nodes perform appropriate routing based on this flag. This is an application of Active Networks (Wetherall, 1999).

3.6 Update of routing information

The routing information in the cluster head does not expire unless it is reported obsolete. If the cluster head itself or any of its neighbours finds a change in network connectivity, the routing information is updated. Any new routes will possibly be reported to the cluster head as well.

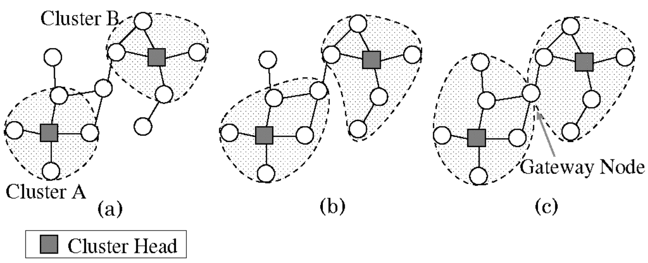
3.7 Demotion of cluster heads

A cluster head monitors accesses to itself, and when the access rate decreases under a certain threshold, it demotes itself to a plain node. It still keeps all the routing information, and replies when asked just like the (volatile) cache in a plain node. Its neighbours stop asking routing information to it directly, and go back to use the reactive protocol. The threshold for demotion is set much lower when compared with the promotion threshold so as to prevent racing (or thrashing).

4 Dynamic clustering

The earlier mechanism, if applied alone, would make a group of the neighbouring nodes, or a cluster, around the cluster head to grow larger eventually up to the whole network. It must be accompanied by any mechanism of dynamic cluster organisation. The mechanism presented here is to make a cluster stop growing when the cluster reaches any neighbouring cluster as shown in Figure 6.

Figure 6 Dynamic clustering



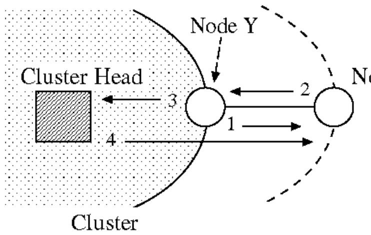
4.1 Cluster creation

When a node promotes itself and a cluster head emerges, the node notifies the fact of promotion to its neighbour nodes within one-hop radius by a message of the cluster head ID. If a node receiving this notification has not belonged to any other cluster yet, the node becomes a member of the new cluster around the head. Route information for the member nodes are stored in the cluster head.

4.2 Cluster growth

Suppose, as shown in Figure 7, that the node *X*, which is located one hop away from a cluster broadcasts route request packets to search a route, and the node *Y* which is at the edge of the cluster and also a neighbour of *X*, receives this route request packet.

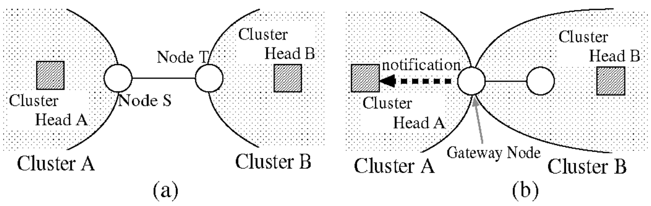
Figure 7 Cluster growth



Then, *Y* notifies to *X* the cluster head information (1 in Figure 7). If *X* has not belonged to any other cluster yet, *X* accepts the information (2), and becomes a member of the cluster (3), so that the cluster is enlarged one-hop further. The head replies route information, if it can, to *X* through *Y* (4). The cluster grows one by one, including surrounding nodes in this incremental manner.

There is a case that a growing cluster comes adjacent to any neighbouring cluster, as shown in Figure 8. If the node *S* in the cluster of the head *A* carries out the same procedure as of the node *X* in Figure 7, then the cluster of the head *B* tries to include *S*. Then, *S* notifies ID of the head *B* to *A*, as well as the head *B* gets to know ID of *A*. *S* becomes the gateway node of *A*'s cluster and *B*'s cluster in this manner.

Figure 8 Cluster adjacent to another



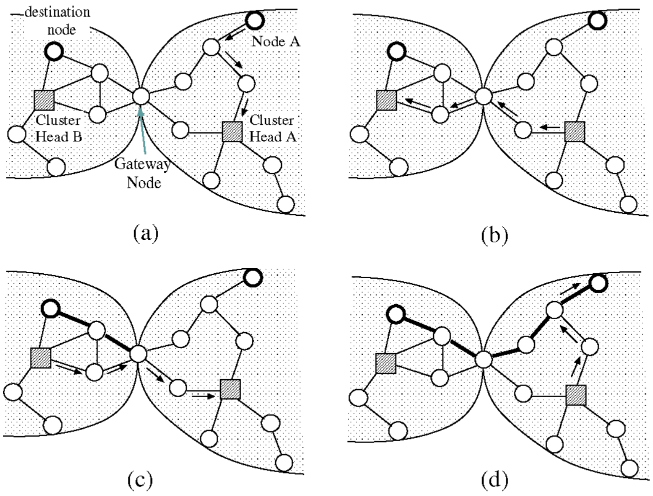
4.3 Interaction between clusters

When a single cluster cannot resolve routing, it must interact with any neighbouring cluster through its gateway node, as shown in Figure 9.

If a node in *A*'s cluster wants to send a message to some destination, and the head *A* does not have any route information, it means that the destination node is outside the cluster. Then the head *A* multicasts route request messages to all the neighbouring clusters through gateway nodes.

If the head *B* knows the destination node, it constructs a route information from the gateway to the destination, and send the information to *A* through the gateway, so that a route from the sender and the destination is established. Otherwise, *B* multicasts the route request messages to all the *B*'s neighbours except for *A*'s cluster in a recursive manner.

Figure 9 Communication with other clusters



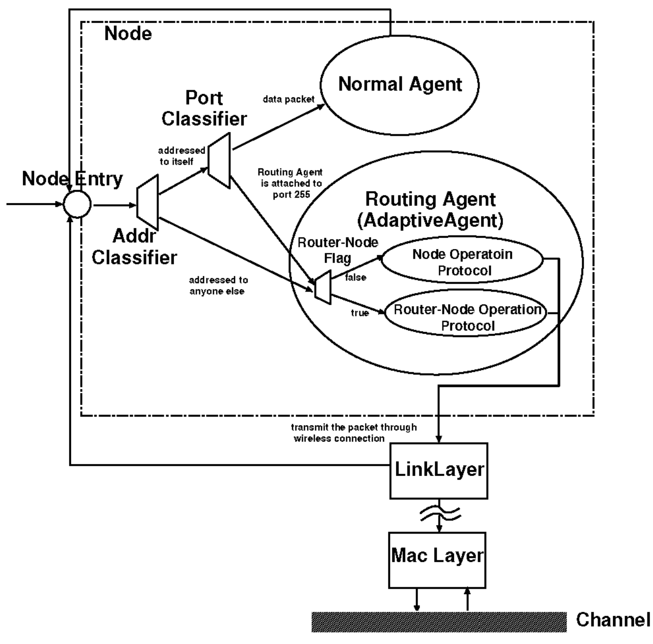
4.4 Adaptation to dynamic topology changes

Each node in a cluster exchanges a Hello packet occasionally to detect and reflect change in the network topology. A node detecting any change notifies the fact to its cluster head, so that the head updates route information.

5 Simulation experiments

We have implemented a simulator of our protocol system for design verification and preliminary performance evaluation. It is implemented in Java. The schematic outline of the node implementation is shown in Figure 10. Each node has two modes of operations: 'Normal Agent' and 'Routing Agent'. The former implements protocols for the plain node operations, and the latter for the cluster head operations.

Figure 10 Outline of node implementation

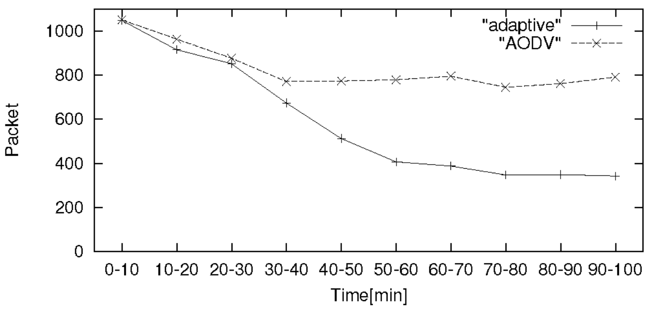


Because of the limit of the space, here we present a few results out of experiments performed on the simulator.

Figure 11 shows transition of the total amount of packets in the network. Some parameters for the experiment are: the number of nodes is 50, the number of node connection is between 1 and 4 randomly, and the threshold of the cache amount for promoting to a cluster head is 15. The simulator generates request packets from a randomly-chosen source to a randomly-chosen destination.

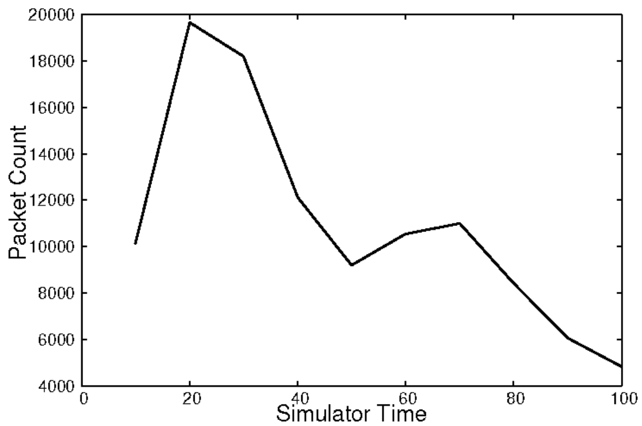
The solid line is of our system, while the dotted line is of a typical reactive protocol AODV. The amount of packets, or network traffic, in our system drastically reduces from the moment of '20–30 (virtual) min', while the traffic in AODV stays high. Some cluster heads emerge at the same moment as '20–30 min', so the reduction of traffic is considered to be brought by the cluster heads. We also observed that the number of emerging route nodes is 2–4, which is sufficiently fewer than the number of all nodes (50).

Figure 11 Transition of traffic by head promotion



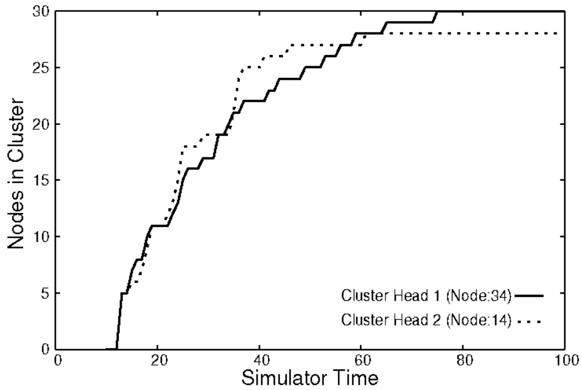
Next, Figure 12 shows transition of the number of all the packets in the network according to the cluster growth. Some principal parameters are: the number of cluster heads = 2, and the maximum number of nodes in a cluster = 30. During 1000 cycles, each node emits routing requests to random destinations at the probability of 0.2 at each cycle until 950th cycle. Two cluster heads emerge at the 10th cycle.

Figure 12 Transition of traffic by cluster growth



There is a peak at the 10th cycle when the two cluster heads emerge. Thereafter, the network traffic reduces gradually until approximately 100th cycle, and becomes stable. Figure 13 shows transition of the number of nodes in clusters. The number of packets decreases as the number of nodes in clusters increases.

Figure 13 Transition of cluster sizes



6 Conclusions

There have already been some proposals for dynamic cluster organisation, for example, Safari Project (PalChaudhuri et al., 2005; Du et al., 2004). Compared with those related studies, our proposal has a simpler protocol system, which implies faster execution and easier deployments.

Although our simulation-based preliminary experiments show effectiveness of our proposal, we are still at the starting point in our research project, and we must conduct much more rigorous investigations and evaluations as further studies.

One of the most important issues to address next is collaboration of several cluster heads. We are now investigating, and the following shows an outline of the design idea. To collaborate, each cluster head must first know other cluster heads. Any node that gets to know more than one cluster heads during its routing notifies all the cluster heads. The cluster heads get to know the others, and also routes to them in this manner. When a cluster head receives an RREQ packet to an unknown node, it forwards the packet to other routers for inter-cluster routing. We may consider emergence of any super cluster head among cluster heads, similar to IXs in the internet routing.

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