Hierarchical Cluster Routing in Mobile Multihop Networks

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ABSTRACT

Mobile multihop networks are collections of entirely mobile nodes that have no fixed infrastructure nor central controlling mechanism for routing or location management. In this paper, routing protocols based on a hierarchical clustering architecture are proposed. The basic idea is to partition the network into clusters and define routing mechanisms within and between clusters using a hierarchical architecture. The main advantage of this architecture is efficient routing and reduced communication and computational overhead. Simulation experiments indicated that the proposed hierarchical cluster-based routing architecture performs well in relatively low mobile networking environment.

INTRODUCTION

Mobile networks can be classified into infrastructure-based networks, such as cellular wireless networks, and infrastructure-less networks, such as multihop networks. Multihop networks are collections of mobile nodes which are capable of communicating with each other in the absence of any existing infrastructure. In this environment, all hosts can act as routers to relay packets and routes quickly adapt to changes in the topology. These networks are also known as fully mobile networks and mobile ad hoc networks, which emphasise the fact that the network is fully autonomous, all nodes can be mobile relative to each other and there is no base station to connect to a static network.

It is envisaged that multihop networks will be used in areas such as emergency operations, education, battlefield communication, home and community networking, ship-to-ship communication and remote sensing. For example, multihop networks can be used for rapid deployment in areas where wiring is not available or the infrastructure has been destroyed by natural disaster.

One of the main tasks in any network is the routing of packets. Routing protocols in traditional fixed networks are generally based on either distance vector or link state routing algorithms. These protocols are unsuitable for multihop networks [Krishna 1996, Johnson 1996, Perkins 1994]. First, these networks are subject to frequent and unpredictable topological changes, and such protocols converge slowly upon topological change. Second, the protocols place high computational overhead on mobile nodes and high communication overhead on the wireless channel. On the other hand, routing protocols based on cellular architecture are unsuitable as they rely on slowly-changing networks and fixed home agents.

Several routing protocols have been proposed for multihop networks [Chiang 1997, Das 1997a, Das 1997b, Dube 1997, Gerla 1995, Iwata 1999, Johnson 1996, Krishna 1996, Perkins 1994]. These routing protocols can be classified into three categories: Proactive routing protocols, reactive routing protocols and hybrid routing protocols. Proactive protocols maintain routes which are updated periodically (distance vector and link state are proactive); reactive protocols establish routes on demand. The hybrid protocols use features of both reactive and proactive protocols.

Routing protocols in multihop networks can also be classified into cluster-based and non-clustered routing schemes. In cluster-based routing schemes, the mobile nodes are grouped into small units known as clusters. Organising clusters improves scalability, but not all cluster-based routing organises clusters hierarchically. In the non-clustered routing schemes, there is a at architecture where each mobile node has complete routing information either by computing it or discovering it on demand. For most of these, route maintenance, computation or discovery incurs high overhead which increases considerably with increase in network size. Most proposals for multihop networks are not based on clustering architecture. However, a few routing protocols based on clustering architecture have appeared. See [Krishna 1996, Das 1997a, Das 1997b, Iwata 1999].

Krishna at al. [Krishna 1996] proposed a cluster-based routing algorithm that does not require election of a clusterhead. The protocol divides the network into overlapping small clusters. This routing protocol has

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two phases: route construction and route maintenance. In the former, routes are constructed between all pairs of nodes. In the latter, loop-free routes are maintained when the existing routes are destroyed due to topology changes. Das and Bharghavan [Das 1997a] proposed Cluster Minimum Connected Dominating Set routing algorithm. It uses a two-level hierarchical architecture with a virtual backbone. The first level clusters the network into components and the second level maintains the virtual backbone for each cluster.

Hierarchical State Routing protocol described by Iwata et al. [Iwata 1999] uses multilevel clustering and logical partitioning of mobile nodes. The network is partitioned into clusters and a clusterhead elected for each cluster. The clusterheads again organize themselves into clusters. The clusterhead summarises the cluster information and sends it to neighbouring clusterheads via gateways as it is a member of the cluster on a level higher. It then floods to the lower level the information it has learnt. The main advantage of this routing scheme is that the hierarchical architecture makes the routing table more scalable to a larger network. However, the protocol is more complex than previous proposals. For a survey of other routing protocols see [Royer 1999].

In this paper we discuss the advantages and possibilities of cluster-based routing, examine and compare several possibilities. We propose an approach called Hierarchical Cluster Routing which divides the task into three areas: Cluster formation and maintenance, intra-cluster routing and inter-cluster routing. We hope that this framework will provide the basis for further investigation of the use of clusters in routing in multihop networks. A preliminary version of this paper appeared in [Denko 1998].

MULTIHOP NETWORKS AND CLUSTERING

Characteristics of multihop networks

Multihop networks for many applications are naturally clustered by geographical or physical boundaries [Hall 1996]. Most proposed applications of multihop networks such as disaster recovery areas, people in meetings, students in classrooms, tactical military communication sites etc., can be considered as clusters. Clustering architecture can be used to improve routing performance in multihop networks.

Multihop networks have several distinguishing characteristics from other mobile networks. These are briefly described below.

*Infrastructureless operation.* There is no stable or fixed communication architecture that supports routing or mobility management.

*Relaying capability.* Nodes can communicate directly when they are in transmission range, and when outside range depend on intermediate nodes to relay packets.

*Distributed operation.* Each node performs routing and mobility management in a distributed fashion. However, a single node or subset of nodes may be used to perform route computations.

*Dynamic topology.* Multihop networks experience rapid changes in topology: nodes move unpredictably and can get disconnected from or join the network at any time.

*Limited resources.* Multihop networks have limited resources such as bandwidth and battery power.

These limitations lead to challenges in several areas of network design including network routing, mobility management, media access protocol, data management and power management.

Benefits of clustering

In infrastructure-based networks, routing information of each mobile node is maintained in a database located on the fixed network. For example, in Mobile IP, which is based on cellular wireless technology, routing information is maintained by entities known as mobility support routers which are interconnected by the wired backbone. In contrast, routers in multihop networks are mobile. The architecture of these networks is thus a hybrid of packet radio and cellular networks. Like packet radio networks it involves datagram traffic, multi-hop routing and dynamic network reconfiguration. In contrast, cluster-based network organisation, with each cluster coordinated by a clusterhead, creates an architecture similar to cellular networks. However, clusterheads in multihop networks and base stations in cellular networks are very different entities clusterheads have no special hardware and are dynamically selected.
Clustering offers several advantages in multihop networks. (a) Coordination: Clustering stabilises the network topology and provides a virtual infrastructure; the clusterhead acts as a regional coordinator. (b) Routing and mobility management: Network partitioning improves routing and mobility management and reduces signalling and control overhead and minimising congestion [Sharony 1996]. (c) Resource allocation: Clustering improves MAC resource management and provides efficient utilisation of wireless channels by assigning different codes to each cluster. It also provides power control mechanisms [Gerla 1995] as in the packet radio networks [Baker 1984].

**HIERARCHICAL CLUSTER ROUTING PROTOCOL**

Routing in a flat architecture faces scalability problems, since overhead for at routing protocols can grow faster than linearly as network size increases [Lauer 1995]. A hierarchical architecture on the multicluster infrastructure reduces traffic by hiding information about the content of a cluster, and is relatively more stable in the mobile environment. In this architecture, there is one entry per destination for nearby nodes and one entry per set of destinations which are far away. Since less information is kept about nodes far away and complete information about closer nodes, routing table length can be significantly reduced.

Motivated by the advantages of clustering and hierarchical architecture, we propose a hybrid Hierarchical Cluster-based Routing (HCR) protocol for multihop networks. HCR is a hybrid protocol because intra-cluster and inter-cluster routing may be achieved using different protocols, reactive or proactive.

**Description of HCR**

The protocol is based on a hierarchical architecture with a two-level hierarchy. The mobile nodes form the lower level whereas clusters form the higher level. Clusters can be distinct or overlapping (see Figure 1).

![Figure 1. Network Architecture](image)

Nodes with links to other clusters, or in multiple clusters, are called border nodes. A shared border node is a node that is a member of more than one cluster. It can fully hear both clusters and exists in overlapping clusters. A distributed border node is a node that is a member of one cluster but can communicate with a node that is in another neighbouring cluster.

Each cluster is coordinated by a clusterhead which can directly or indirectly communicate with every other node in the cluster. A clusterhead is the unique leader and is elected by a clustering algorithm during cluster formation or re-elected upon the original clusterhead failure. The clusterheads cannot directly communicate with each other; their communication is through one or more nodes or clusters. Some dynamic clustering algorithm is used to select the clusterhead, but the clusterhead performs extra work. Among these, the clusterhead enables inter-cluster communication and facilitates local resource coordination.

The generic algorithm for cluster-based routing can be summarised as follows.
1. Choose a clustering and cluster maintenance strategy.
2. Choose a routing strategy for intra-cluster routing.
3. Choose a routing strategy for inter-cluster routing.

Our high-level routing rules for steps 2 and 3 are:
(a) Routing within each cluster is flat and is performed in one of three methods: proactively maintained either at each node or at the clusterhead or reactively discovered on demand. These alternatives are discussed below.

(b) Routing to other clusters is performed reactively using route discovery. It involves first routing from source node to clusterhead or border node and second, routing from clusterhead or border node to the destination cluster. Within the destination cluster, routing is done as in (a) above.

Assumptions

The basic assumptions about the underlying link layer, physical layer as well as node and network conditions for the proposed routing protocol are: (a) All hosts use a common wireless channel for communication and the communication links are bi-directional. (b) The underlying data link layer protocol ensures distributed knowledge of the connectivity changes. (c) Communication is more frequent within cluster and less frequent between clusters. Also, nodes do not move so fast as to make flooding the only appropriate routing protocol. (d) All hosts wishing to communicate are willing to forward packets to other hosts within or between clusters. (e) Every node has a unique ID and knows the identity of its neighbours. The network topology does not change during the execution of the clustering algorithm.

Frequent communication between nodes and low mobility rate is assumed for the protocols based on route computations whereas infrequent communication and relatively low mobility rate is assumed for protocols based on route discovery. The efficiency of the proactive or reactive protocol for intra-cluster and inter-cluster routing depends on the number of hops used for node-to-node or node-to-clusterhead communication. When one uses a small hop length, most routing is between clusters. On the other hand, when a hop length is large, most routing is carried out within clusters. Thus, as the number of hops along which a node and clusterhead communicate increases, the efficiency of intra-cluster routing may decrease while that of inter-cluster routing increases.

The main operations of the protocol

The main routing requirements in multihop networks are to avoid the creation of loops, to avoid congestion and to enable fast convergence of the routes upon topology changes. The main components of the protocols are cluster formation, cluster management and packet routing. In routing, the operations common to all protocols are route generation, packet forwarding and route updates or maintenance. We briefly describe these mechanisms below.

Route generation and packet forwarding

Multihop routing algorithms must rapidly react either to compute and maintain current routes and topology tables using proactive protocols, or to discover up-to-date routes using reactive protocols. In the former, all pairs shortest paths are computed, whereas in the latter, route caches store necessary route information after learning routes through a route discovery mechanism.

Both route discovery packets and data packets are forwarded in the routing process. A packet is delivered to the destination node if the destination is a neighbour; otherwise it is forwarded to the next node. While a route discovery packet traverses through the network as a broadcast, a data packet follows
an explicit path since routes are pre-determined and can be carried out based on source routing or on a hop-by-hop basis. Generally, packets may be dropped when the destination node is in motion, a wireless link is not available or congestion occurs. The higher layer protocols are assumed to react to this problem.

**Route updates and packet formats**

Changes in network topology are caused by node mobility or link failures. Changes may result in neighbourhood change, cluster membership alteration or network partition. Hence route updates are performed after a new route discovery or after a route computation. Nodes can be classified by type (ordinary, border or clusterhead) or by role (source, destination or intermediate). A route update depends on the type and role of nodes involved in the mobility. For example, movement of an ordinary node does not have the same impact as that of a border node or clusterhead: ordinary node mobility within a cluster a single cluster, that of the border node affects at least two clusters, whereas clusterhead mobility may affect other clusters. Also the impact of movement of the source node is not the same as that of an intermediate or destination node.

The route discovery and reply packets contain fields for gathering information along all the paths that the packet traverses. For route query within clusters, the query packet only propagates within a single cluster. The border nodes do not process such packets. The query packet consists of source and destination ID, sequence number and a route cache to accumulate information on link and node qualities. The reply packet consists of source and destination ID, sequence numbers, intermediate node IDs, and information on link and node qualities. In order to collect link and node status information, reply packets from the destination node are preferred.

For route query between clusters, query packets propagate in at least two clusters. The query packet consists of source and destination ID, sequence numbers and destination clusterhead. A route reply packet consists of IDs for source and destination nodes, intermediate nodes (border or ordinary), clusterheads, sequence numbers and information on node and link qualities.

**DETAILED ROUTING MECHANISMS**

**Intra-cluster Routing**

We have proposed a two-level routing mechanism for constructing and maintaining routes in multihop networks. The intra-cluster routing uses one of three possibilities: route computation at nodes, route computation at clusterheads and routing on demand.

**Route computation at nodes**

In this method, each node participates in route computation and route maintenance. A source node that wishes to send data uses the routes from its routing table. Note that even if every node is in direct contact with the clusterhead, as in some clustering mechanisms, this approach is reasonable as it reduces load on the clusterhead.

A modified link state algorithm or the link vector algorithm [Behrens 1997, Gracia-Luna-Aceves 1995] can be adapted for route computation at each node. For multihop routing this routing algorithm has two advantages. First, a node maintains only a subset of the topology information unlike link state algorithms which maintain the entire topology map. Second, the use of diffusing computation for information dissemination, unlike flooding in the link state algorithm, reduces communication overhead. The algorithm can be modified to make it more suitable to multihop networks. For example, constructing routes only when a route is needed (not whenever topology changes) can reduce the overhead. Route maintenance is invoked when the node itself notices the change or is noticed by other nodes. Node mobility may affect all routes that pass through it.
Route computation at clusterheads

In this, only the clusterheads compute and maintain the routes to nodes within their clusters. Each node keeps route(s) to the clusterhead. The advantage is reduced computation and communication overhead. In order to further reduce communication overhead, the link layer protocol is assumed to use the clustering architecture for resource scheduling and channel access. A backup node can be used to reduce the risk of data loss.

The clusterhead performs route computation in a manner similar to the link state routing algorithm restricted to the clusterhead. The link state packet formation can be periodic or event-driven, depending on the dynamics of the network topology. The clusterhead requests topology information periodically from all nodes in its cluster through broadcast query. Each node replies by appending its identity to the reply packet. Then, routing tables for all nodes within the cluster are computed. Once computed, the routes are stored at the clusterhead. These routing paths are obtained on demand from the clusterhead.

There are several reasons for choosing link state type algorithm for route generation. These include: low overhead (as only cluster knowledge is required); compatibility with the Internet; possibility of maintaining multiple routes to a destination; and support of Quality Of Services (QOS) routing. Moreover, we argue that node and link status information is much more useful for routing than distance characteristics in multihop networks. Topology change such as link down and link up or node up and node down may cause complete partition of the network or connection via a distributed border node. Route changes are made when the changes are detected by the clusterhead or an update message is received from another node or clusterhead. Suppose that a node is added or deleted from the cluster. The clusterhead updates the route as follows. First, addition or deletion of a node is detected by absence or presence of a beacon from it. Second, the neighbour nodes notice the change and update their entries. Third, each neighbour node notice changes to the clusterhead.

Routing on demand

The third routing mechanism for intra-cluster routing is based on routing on demand and is similar to the protocol proposed by Johnson and Waltz [Johnson 1996].

If a node has a route to the destination in its route cache, it uses this route. If the route is stale, a new route discovery is made. Route discovery also occurs when the source node encounters failure of data transmission when a data packet is sent. A node initiating route discovery can carry on doing other tasks while the route discovery process is in progress. Route discovery packets are forwarded to the next node until the desired target is reached. During the route discovery process, all nodes that hear can update their entries. The route reply packet is a unicast sent directly to the source node following the path in the discovery packet. Data packets are forwarded along the path that was found.

Inter-cluster routing

Either clusterheads or designated border nodes are responsible for inter-cluster communication. This can be performed in one of three different ways: (a) making external route discovery when the route is needed; (b) maintaining complete external route information; or (c) sending data using explicit path or forwarding packets to other clusters with a single-hop knowledge. We assume that communication within clusters is more frequent than communication between clusters. Hence, only a few source destination pairs will be sending packets across clusters. In such environments, computing and keeping routes at each node or clusterhead may be inefficient. Therefore, in our proposal inter-cluster routing is carried out using demand-based routing.

A clusterhead communicates with other clusters through a designated border node or any border node along the path to the target destination cluster. To facilitate routing, the border node may store additional information such as list of border nodes in neighbouring clusters or list of all border nodes, etc. Alternatively, it may request this information from the clusterheads if this can be maintained at the clusterhead. A node that wishes to send to a destination outside its cluster, forwards the packet to a clusterhead or border node which checks whether it has routes in its route cache. If so, it forwards the packet to the destination clusterhead using the route. If the destination is not in the neighbour cluster, the
packet is forwarded to the next cluster via the neighbour cluster. The process continues until the packet is finally delivered. If a clusterhead does not have a route to the required destination, it uses a route discovery procedure to get another route.

**Route discovery**

Depending on how intra-cluster routing is done, inter-cluster route discovery is performed in our proposal as follows:

(a) If intra-cluster routing uses route computation at each node, a route to the desired destination is first sought in the node's routing table. If not found, the node sends a message to the clusterhead, which sends a route request broadcast message to the other clusterheads. Alternatively a node can send a packet directly to the border node. The route reply packet is sent via the clusterhead back to the source node which adds the entry into its routing table. In this approach the clusterhead maintains a list of the clusterheads and border nodes.

(b) If intra-cluster routing uses route computation at clusterheads, a route to the desired destination is first searched in the clusterhead's routing table. If the destination is not found, the clusterhead initiates a route discovery process by sending a broadcast message to the other clusterheads. When the destination is found, the route reply packet is sent back to the clusterhead which records the route in its routing table. The clusterhead maintains a list of the clusterheads, intra-cluster routing table and designated border nodes and those in the adjacent clusters.

(c) If intra-cluster routing is on-demand, a route to the destination is first sought within the cluster. If this fails, the node initiates an external route discovery process by sending a message to the clusterhead. When the destination is found, the route reply packet is sent back and recorded. The clusterhead maintains a list of the clusterheads, border nodes and route cache. After the route reply is obtained, route information is cached in the clusterhead for future use

**Packet forwarding**

For routing packets across clusters, the following mechanisms can be used: routing through clusterheads; routing through border nodes; or a combination of these. If routing is via a clusterhead, then the source node always sends its packet to the clusterhead. The clusterhead can choose any border node across which it forwards the packet. If routing is via a border node, then the source node forwards the packet to the border node which relays the packet to the neighbouring cluster's border node. Packets are forwarded via border nodes but the border node may rely on the clusterhead for information on the destination cluster. Figure 2 shows one scenario of a packet forwarding mechanisms.

![Cluster border-node-routing](image)

Figure 2: Cluster border-node-routing
Clustering algorithms

In order to implement the above, we need finally a suitable clustering algorithm. Several clustering algorithms have been proposed for multihop networks in recent years. Some of these algorithms create clusters with more than two-hops [Krishna 1996, Ramanthan 1998]. This may cause communication delay and makes cluster maintenance more complex. Like Gerla and Tsai [Gerla 1995], we suggest two-hop clustering. In this, each node is a neighbour of the clusterhead and at most two hops away from the other members of the cluster. The advantage is effective communication and low routing and clustering overhead.

To improve stability, we use the Node Mobility-based Clustering (NMC) proposed in [Denko 2001] (and shown to be better in some respects). In this clustering algorithm, information on node mobility is used for cluster formation. Each node broadcasts the list of nodes that it can hear from, its own ID and mobility rate to all its neighbours. The mobility rate measures the relative mobility of a node with respect to its neighbours and it is maintained at each node based on mean clusterhead and cluster membership changes. A node can become a clusterhead only if its mobility rate is below a certain threshold and no member of its neighbourhood is already a clusterhead. A mobility threshold is the mean node mobility determined through simulation experiments. In case of a tie, a node with the lowest ID is chosen. Thus our proposal suggests that a node should not be elected as a clusterhead if it is highly mobile relative to its neighbours since reclustering algorithm may be invoked frequently.

The details of a simulation of clustering algorithms are to be found in [Denko 2001].

The clustering process proceeds as follows. Initially, nodes communicate asynchronously while in the transmission range of each other. Each node broadcasts its neighbour table information periodically in a Hello message. A node collects complete neighbour topology information from these message which it uses for cluster formation. After clustering, each node will be grouped into a cluster with a clusterhead, and each node is either a clusterhead, border node or ordinary node.

On clusterhead failure or movement out of range, the clusterhead failure is detected by members of the cluster through neighbourhood information exchange. A new clusterhead is then elected to replace the old one or to coordinate a newly formed cluster. To improve clustering performance, the clusterhead can be chosen among the most stable nodes in the network. A designated backup node may be used during clusterhead failure. For this, either the information is maintained at both clusterhead and backup node or such information is forwarded by the clusterhead upon request.

PERFORMANCE EVALUATION

We evaluated the performance of our routing protocol by using a proactive mechanism for intra-cluster routing and a demand-driven mechanism for inter-cluster routing. Routes were computed at clusterheads for intra-cluster routing. The three important parameters used as performance metrics were moving probability, number of clusters and radio transmission range. We used PARallel Simulation Environment for Complex systems (PARSEC) [Bagrodia 1998] for simulation of our routing protocol. PARSEC is a C-based simulation language developed at UCLA for discrete-event simulation.

In our simulation experiments, 25 mobile nodes were placed within the simulation environment of 100 X 100 units square according to uniform distribution. The radio transmission range between 20 and 70 units and the moving probability levels between 0.10 and 0.50 were used. The channel capacity was 1Mbps and each simulation was run for 1000 simulation time. In the simulation, a total of 20,000 packets were randomly generated and transmitted to random destinations. Packet interarrival time was drawn from exponential distribution. For each performance metric, the packet delivery status was investigated. Figures 3-5 show the averaged results of these simulation experiments. As figure 3 shows the packet delivery increases with increase in transmission range. Little is gained by increasing transmission range beyond 60 units. As figure 4 shows the packet delivery decreases with increase in moving probability. A good packet delivery is observed at lower moving probabilities. But with increase in mobility the routing algorithm becomes less robust resulting in increasing number of dropped packets. Figure 5 shows that the packet delivery decreases with increase in the number of clusters. This decrease indicates that new cluster formation causes route changes resulting in unreachable destination and the loss of packets.
CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a class of hierarchical cluster-based routing protocols for multihop networks. The advantages and possible alternatives as well as optimisation mechanisms have been proposed. We analysed intra-cluster routing by maintaining routes proactively. Inter-cluster routing employs routing on demand and hence uses route query and reply mechanisms. The Node Mobility-based Clustering (NMC) algorithm was used for cluster formation. For this purpose, information on node mobility was used for clustering the mobile nodes into multihop networks. The results of the simulation experiments indicated that packet delivery increases with increase in the radio transmission range while increase in moving probability and number of clusters increase the number of dropped packets. For low mobility environment, the Hierarchical Cluster Routing protocol (HCR) shows a good performance with relatively high rate of packet delivery and hence it is suitable for routing in multihop networks.
Further research may be carried out in many directions. Some of the current research activities in this area are: (a) investigating the scalability to large networks and (b) comparison with other hierarchical and cluster-based routing protocols.

REFERENCES