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Ad Hoc Network Routing

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Abstract - *An ad hoc network is composed of nodes that may move arbitrarily and without the support of a stationary infrastructure. The dynamic nature of ad hoc networks makes it very challenging to realize routing and deliver data packets efficiently. This article discusses the challenges of ad hoc network routing, surveys existing routing algorithms, and provides a comparison of these algorithms.*

Keywords: ad hoc, routing, proactive, reactive, comparison.

1   Introduction

An ad hoc network, also known as a multi-hop packet radio network, is composed of nodes that may move arbitrarily and without the support of a stationary infrastructure. Research in such networks is initiated in the Defense Advanced Research Projects Agency (DARPA) packet radio network [1]. They may be used in emergency search-and-rescue operations, battle field operations and data acquisition in inhospitable terrain. This article surveys routing protocols designed for ad hoc networks and compares them.

2   Ad Hoc Network Routing

To design a good routing scheme for ad hoc networks, we must consider the following issues:

2.1   The scalability of the protocol with network size

The size of an ad hoc network may be quite large in many applications such as communications in battle fields and disaster search-and-rescue operations. As there is no wired infrastructure to serve as a backbone, the same bandwidth is used to find and maintain routes as well as to transmit data. As its size grows, the amount of information required to be transmitted and to be maintained by each node in an ad hoc network grows exponentially.

2.2   Frequent topological changes

A mobile ad hoc network is an autonomous system of nodes connected by wireless links, and nodes may move randomly and organize themselves arbitrarily. The topology of the network may change rapidly and unpredictably. When the current route is unusable, a new one must be re-established.

2.3   Unidirectional links

An ad hoc network may be composed of different kinds of devices, each with its own transmission characteristics. In addition, the same device may have different transmission ranges due to power constraints. So, if node A can transmit to node B, one can not assume that node B can transmit to node A. Interference may also introduce unidirectional links.

2.4   Power supply

As in other mobile networks, nodes in an ad hoc network are powered by battery. So power conservation and balancing should be considered in addition to traffic load balancing and transmission efficiency.

2.5   Service and quality of service (QoS) support

Key characteristics of an ad hoc network include large number of users, user mobility and the need to support multimedia communications. Frequently changing topology makes it challenging for an ad hoc network to support QoS.

Many routing protocols for ad hoc networks have been proposed. Generally, they can be categorized into three types: proactive (label switch), reactive (on demand), and intra-zone proactive with inter-zone reactive

3   Proactive Routing Protocols

Proactive routing protocols require each node to maintain one or more tables to store up-to-date routing information to every other node in the network. Examples include:

3.1   Wireless Routing Protocol (WRP)

Wireless Routing Protocol (WRP) [2] is a loop-free table-driven algorithm. In this protocol, each node in the network maintains four tables:

• Distance table
• Routing table

• Link-cost table
• Message retransmission list (MRL) table.

The distance table contains route information of each neighbor of this node, including the distance and the node at the last hop to the destination from the neighbor to each destination. The routing table is a vector with an entry for each possible destination, which specifies the distance to the destination, the predecessor of the chosen path, next hop of the chosen path, and a marker which specifies the status of the path. Nodes keep second-to-last hop information to ensure loop freedom. The link cost table lists the cost of relaying information through each neighbor. The MRL contains retransmission control entries to ensure that all update messages are received properly.

To keep routing information consistent and up-to-date, mobiles propagate update messages after processing updates from neighbors or detecting a change in a link to a neighbor. An update message is sent only between neighboring nodes and contains an update list containing updates or acknowledgments to updates as well as a response list indicating which mobiles should acknowledge (ACK) the update. An update entry in an update list specifies a destination, distance to the destination and the predecessor node to the destination.

3.2 Fisheye State Routing (FSR)

FSR [3] is a link-state scheme based on a table-driven routing algorithm. Each node keeps the following information in its routing table

• Neighbor list of the node
• Neighbor list of all possible destinations with time-stamp
• Distance and next hop to each possible destination

In order to minimize control overhead without seriously reducing routing accuracy, sensitivity to topological changes of a node is decreased by increasing the propagation interval as the distance to the node increases. In Figure 1, we provide a simple illustration of the technique used in FSR. The areas with different gray scale levels define the fisheye scopes from the view of the center node (node 1). The scope can be defined as the set of nodes that are a given number of hops away from the center node. Nodes in different scopes propagate the change with different frequencies. When node 1 detects an update, the update message is propagated most frequently in the scope marked by the deepest gray level. In other scopes, as the number of hops to node 1 increases, the update is propagated at a lower frequency. Though routes to remote destinations are less accurate, a packet may find more accurate routes as it approaches the destination.
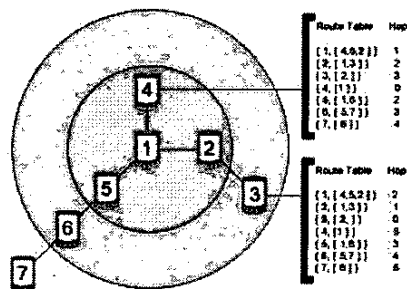

Figure 1. Scopes and routing table format in FSR

3.3 Location Aware Routing with Reduced Location Maintenance (LARRLM)

In LARRLM [4], each node knows the locations of all other nodes in the network and computes route to them. To avoid inaccurate location information, LARRLM asks each node to monitor its location and compare it with the last broadcasted location. If the difference is bigger than a predefined threshold, a beacon will be generated. Besides the beacon, there are two other types of packets, namely, routing packets and data packets. Upon receiving a beacon, each node updates its routing table accordingly. To avoid unnecessary retransmission of location information, route managers are selected. Location information included in beacons will be summarized and encapsulated by route managers into routing packets. Each non-manager node must be a neighbor of at least one route manager. We say that it is "covered" by a route manager. Route managers are interconnected to each other. Upon receiving routing packets, a node extracts all routing information included, updates its own routing table and adds up-to-date information into its own routing packet only if it is a route manager. A route manager does not broadcast all location information received. Figure 2 shows an example. A is a route manager; (bx',by') is the last re-broadcasted location of B. As B moves to (bx,by) and broadcasts its location, A divides $D_{(B'-B)}$ by $D_{(A-B)}$. The updated location (bx, by) will be encapsulated into a routing packet and also recorded as the last updated location of B if the result is bigger than a threshold.
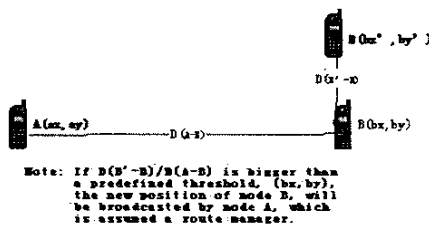

Figure 2. Illustration of location information update by the route manage

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4 Reactive Routing Protocols

A different approach from table-driven routing is on-demand routing. This type of routing creates routes only when desired by the source node.

4.1 Ad Hoc On-Demand Distance Vector Routing (AODV)

AODV [5] is an on-demand routing protocol built on the distance vector algorithm. When a source node desires to send a message to some destination node and does not already have a valid route, it initiates a *path discovery* process to erect a valid path. The source node floods a route request (RREQ) packet in the network. Each RREQ packet is identified by a combination of the source address and a broadcast ID created and maintained by the source node. A RREQ packet also contains a sequence number created by the source node, which is used to denote the "freshness" of the route. When an intermediate node receives a RREQ packet the first time, the node records in its routing table the address of the neighbor from which the packet is received and then forwards the packet. If additional copies of the same RREQ are received later, they are discarded. As the RREQ packet floods from the source to various nodes, the reverse paths from these nodes to the source node are established. The RREQ packet is forwarded till the destination or an intermediate node with a "fresh enough" route to the destination is located. Once the RREQ reaches the destination or an intermediate node with a fresh enough route, the destination (or intermediate node) responds by sending a route reply (RREP) packet back to the source along the reverse path, thus setting up a forward path to the destination. Each route entry, corresponding to both the forward and backward paths, is assigned a route timer that indicates the lifetime of the entry. If a path is not used within the specified lifetime, the corresponding route entry will be deleted from routing table. If a node along the route moves out of transmission range, its upstream neighbor notices the move and propagates a *link failure notification* message to the source node. The source node may then choose to reinitiate route discovery for that destination if a route is still desired.

4.2 Dynamic Source Routing (DSR)

Dynamic Source Routing (DSR) [6] is an on-demand routing protocol based on the concept of source routing. The protocol consists of two major phases, namely, route discovery and route maintenance. When a mobile node has a packet to send, it first consults its route cache to determine whether it already has a route to the destination. If no un-expired route can be found, the source node initiates route discovery by broadcasting a route request packet. The address of the source node, together with the address of the destination and an identification number assigned by the source node, is used to uniquely identify a route request packet. As this packet floods over the network, each intermediate node receiving the packet for the first time and not having a valid route will append its own address to the route record field of the packet and forward the packet.

Either the destination itself, or an intermediate node which contains a valid route to the destination in its routing cache, will generate a route reply packet when it receives the routing request packet and tunnel it back to the source.

Route maintenance is accomplished through the use of route receipt confirmation and error packets. To ensure the validity of links of a path, receipt confirmation is needed when a node forwards a packet. If a node can not receive any receipt confirmation from the next hop after the maximum number of allowable retransmissions, it concludes that there is a fatal transmission problem and generates *route error* packets. When a route error packet is received, the hop in error is removed from the node's route cache and all routes containing the hop are truncated at that point.

4.3 Associativity-Based Routing (ABR)

Associativity-Based Routing (ABR) [7] is another on-demand routing protocol. To minimize control overhead caused by node mobility, ABR tries to choose strong links on the path. It evaluates the stability of each link from its *associativity*. Each node needs to locally broadcast beacons periodically. Associativity is the recorded number of beacons from a neighbor. Nodes with high associativity are likely to be in stable state.

During the route discovery phase, besides the address of each node along the route, associativity to upstream node, route relaying load, signal strength, forward delay, power life, and other information needed are added into the broadcast query (BQ) packet for route selection. Based on the information included, the route with the biggest aggregate degree of association stability and the minimum number of hops is selected by the route selection algorithm. Information included in each BQ packet is summarized and included in a reply control packet. ABR adopts partial route discovery in the route reconstruction phase. When there is a broken link along the route, the upstream node erases its route and divides its number of hops to the destination by that of the source node. If the ratio is less than 0.5, it sends localized query LQ[H], where H is the maximum hops this LQ packet will be re-broadcasted, to find a valid partial route to the destination if it is an intermediate node. Otherwise, it sends a route erase packet to the source node to invoke the BQ process. The downstream node sends a route erase message toward the destination to erase invalid route if it is not the destination itself.

5 Intra-Zone Proactive with Inter-Zone Reactive Routing Protocol

An intra-zone proactive with inter-zone reactive routing protocol can be seen as a hybrid of proactive routing and reactive routing. The network is clustered into several zones and nodes in the same zone maintain routing information to each other. Nodes need to find a route reactively when they want to communicate with nodes in a different zone..

5.1 Zone Routing Protocol (ZRP)

Zone Routing Protocol (ZRP) [8] is a hybrid of proactive routing and reactive routing. Instead of keeping routes to all possible destinations or searching for routes only when needed, each node keeps the routing to every other node within its local routing zone centered at itself. When the node has to send a packet to a destination outside the range of its routing zone, it will find routes on an on-demand basis.
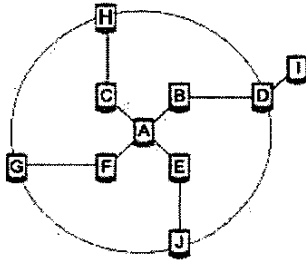

Figure 3. An example of local zones.

A routing zone can be seen as a collection of nodes whose distance (hop account) to the center node is no greater than a parameter called zone radius. The routing zones may overlap substantially, making the routing extremely robust. Robust routing means less path failures and less route rediscovering. Fig. 3 gives an example of a routing zone whose zone radius is two. Nodes inside the circle form a routing zone centered at node A. Nodes lying on the edge of the circle (nodes H, G, J, and D) are called peripheral nodes. Nodes of the routing zone keep the topology of the zone (typically, one node belongs to multiple routing zones) through a proactive algorithm. If a node wants to communicate with a destination out of its routing zone, it initiates a route discovery process by broadcasting a query to its peripheral nodes. Each peripheral node appends its own identity to the query message. In order to limit the volume of query messages and reduce the cost of the route finding process, a parameter hop_{max} is set, which is the maximum number of times a request message can be forwarded. An interesting feature of ZRP is that by changing the zone radius, ZRP may have different routing robustness.

5.2 Zone-based Hierarchical Link State Routing (ZHLS)

In ZHLS [9], each node can determine its own zone ID by mapping its location to the zone map. There is no cluster head in a zone. The zone level topology is distributed to all nodes. This peer-to-peer feature avoids traffic bottlenecks, enhances the stability of routes and simplifies mobility management. As each node keeps node-level topology of its own zone and zone-level topology, a packet can be forwarded to a node if its node ID and zone ID are given. If a node has a packet to send and does not know the zone ID of the destination, it initiates a location request process by sending a message to every other zone. A gateway node replies with a location response message if it receives a location request message and finds the destination in its intra-zone table. After identifying the destination zone ID, the source node can route data packets to the zone of the destination according to the inter-zone routing table. Packets can be forwarded to the destination when they are received by the gateway node of the zone of the destination.

6 Comparisons and discussions

Nodes running WRP keep an additional matrix that contains distance value to each possible destination through each neighbor. This incurs substantial memory requirements when the number of nodes in the network is large. WRP avoids the problem of creating routing loops by verifying predecessor information. As all nodes keep the most up-to-date route information, the control overhead of WRP is $O(P \times N_{link} \times X)$, where P, the probability of link failure, is related to node mobility and N_{link} is the number of links in the network. The parameter X denotes the number of nodes which may be affected by a link failure. N_{link}, together with X, are related to network size.

In FSR, topology information is exchanged between nodes in larger time intervals when nodes are farther away from where the topology change occurs. The control overhead of FSR is $O(P \times N_{node}^2 \times \alpha)$, $1 > \alpha > (I_{core}/I_{edge})$, where N_{node} is the number of nodes in the network, I_{core} is the exchange interval of nodes adjacent to the topology change, I_{edge} is the exchange interval between nodes with the biggest hop count from where topology change occurs. α becomes smaller as network size grows because I_{edge} increases with the hop count.

LARRLM is a location aware proactive routing protocol. One advantage of using location information is that it can adopt movement-triggered updates. Nodes with high mobility incur location updates frequently while nodes with low mobility incur less location updates to reduce unnecessary control overhead. Only route managers need to summarize updated information and rebroadcast it. Location updates are exchanged between

nodes less frequently when nodes are farther away from where the location update is triggered. So, the control overhead of LARRLM is $O(V_{avg} \times N_{node} \times N_{r\_node} \times \alpha)$, $1 > \alpha > (Mt_{core}/Mt_{edge})$, where V_{avg} is the average speed of nodes, N_{node} is the number of nodes in the network, N_{r_node} is the number of route managers, Mt_{core} is the movement threshold for a node to trigger location update, Mt_{edge} is the movement threshold of the node with the biggest distance for a route manager to rebroadcast location update. The maximum number of router managers (N_{r_node}) is determined by the service area of the nodes. α becomes smaller as the network size grows.

AODV needs intermediate nodes to keep a record of RREQ and RREP packets in their routing caches. When path break occurs, AODV needs to rebuild a valid route by initializing another route finding process. This route rebuilding process typically incurs $O(2L)$ delay in data transmission. The control overhead needed for route initializing and maintaining is composed of two parts: route finding and broken route rebuilding. Therefore, the control overhead of AODV is $O(P_{SYNC} \times Tr \times N_{node})$, where P_{SYNC} is the probability a route is broken for a connection, and is related to node mobility, and Tr is the traffic load of the network. As RREP packets need to be sent back to the source via the reverse path erected by RREQ, AODV requires symmetric links between nodes, as opposed to DSR which works with asymmetric links.

DSR is a source-initiated on-demand routing protocol that includes route information in packets. Compared to other protocols described so far, DSR has larger overhead. But DSR can reduce overall control overhead efficiently as it eliminates periodic beacons needed for route maintenance. An additional advantage of DSR over AODV is that it allows nodes to keep multiple routes to a destination. As DSR is also an on-demand routing protocol, it has similar performance in transmission delay and control overhead as AODV. Notably, the probability of route break is smaller than that of AODV.

ABR tries to utilize "stable" links to form its routes. It evaluates links based on its existence duration and tries to select a route with the biggest aggregate associativity and the minimum number of hops. As a result, routes selected tend to be more stable compared to those of DSR and AODV, thus reducing the need for route reconstruction.

Nodes in ZRP need to keep routing information of nodes in its local zone. Inter-zone routes are found by the reactive method. Compared to proactive routing algorithms, ZRP needs only keep the routing information of a small number of nodes. At the same time, connections between source/destination pairs in ZRP are more stable due to the overlap between local zones. The control overhead of ZRP is a combination of intra-zone route

maintenance and inter-zone reactive route building and re-establishment. Given the number of nodes in a local zone $N_{Local\text{-}zone}$ and P_{zone}, the probability of a node on the path moving out of the local zone of its upstream/downstream link, the control overhead of ZRP is $O(P \times N_{node} \times N_{Local\text{-}zone} + P_{zone} \times Tr \times N_{node})$. The transmission delay of ZRP when there is a route failure is also $O(2L)$. When the local zone is small, the cost of route maintenance of the local zone is small, but the chance of link failure increases as the overlap between zones is also small. On the contrary, large zone radius incurs larger overhead in proactive route maintenance but improves the stability of connection between source/destination pairs. To reduce control overhead, ZRP uses a set of peripheral nodes to denote a route. The zone radius may adapt to the node mobility to draw a balance between control overhead and route stability.

ZHLS is another intra-zone proactive and inter-zone reactive routing algorithm. Nodes can map themselves into a zone map and get their own zone IDs. By maintaining route information within a zone, the chance of path break is greatly reduced, especially when the zone size is large. This algorithm also simplifies the process of route maintenance and location management. The main constraint of this algorithm is that, for ZHLS to work, nodes need to know their locations and zone maps to determine their zone IDs. This means ZHLS can only work in a predefined area.

Table 1 gives a rough comparison of the algorithms discussed. Each algorithm is characterized by its scalability, transmission latency, and usability with unidirectional links. In general, nodes in proactive routing algorithms keep route information to all possible destinations regardless of when and how frequently such routes are desired. This causes unnecessary control overhead. But as all possible routes are stored, alternate routes can be erected quickly when link failure occurs. This feature of proactive routing allows it to enjoy shorter transmission delays, which is important in real time communications. On the contrary, nodes in reactive routing algorithms only need to find a valid route when needed. This can reduce control overhead, especially in a low mobility and low traffic load environment. Reactive routing algorithms outperform proactive routing algorithms in a network with a small number of low mobility nodes that can reach each other within a small hop count. Intra-zone proactive and inter-zone reactive algorithms try to find a balance between proactive and reactive algorithms. They typically maintain less routing information than proactive algorithms and suffer smaller transmission delays than reactive algorithms

7 Conclusions

In this article we survey routing algorithms proposed for ad hoc networks. We also present a comparison of

these algorithms, highlighting their key features and characteristics. Each algorithm has its own advantage and disadvantage, and is most suited for certain environments. Though ad hoc network still faces many challenges, it will be used widely due to its flexibility.

Acknowledgment

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	Routing philosophy	Connection stability enhanced	Control overhead	Transmission delay^^^	Critical parameters	Symmetric link required
WRP	Flat	Na $^\wedge$	$O(P \times N_{link} \times X)$	Na	. Network size . Nodes' mobility	No
FSR	Flat	Na $^\wedge$	$O(P \times N_{node}^2 \times \alpha)$	Na	. Network size . Nodes' mobility	No
LARRLM	Flat	Na $^\wedge$	$O(V_{avg} \times N_{node} \times N_{r\_node} \times \alpha)$	Na	. Nodes' mobility	No
AODV	Flat	No	$O(P_{SYNC} \times Tr \times N_{node})$	$O(2L)$	. Network size . Traffic load . Nodes' mobility	Yes
DSR	Flat	No	$O(P_{SYNC} \times Tr \times N_{node})$	$O(2L)$.	. Network size . Traffic load . Nodes' mobility	No
TORA	Flat	Yes	$O(P_{SYNC} \times Tr \times N_{node})$	$O(2L)$	. Network size . Traffic load . Nodes' mobility	Yes
ABR	Flat	Yes	$O(P_{SYNC} \times Tr \times N_{node})$	$O(2L)$	. Network size . Traffic load . Nodes' mobility	No
ZRP	Hierarchical	Yes $^{\wedge\wedge}$	$O(P \times N_{node} \times N_{Local-zone} + P_{zone} \times Tr \times N_{node})$	$O(2L)$	. Network size . Traffic load . Nodes' mobility	No
ZHLS	Hierarchical	Yes $^{\wedge\wedge}$	$O(P \times N_{node} \times N_{Local-zone} + P_{zone} \times Tr \times N_{node})$	$O(2L)$	. Network size . Traffic load . Nodes' mobility	No

$^\wedge$ Proactive routing algorithms provide strong connections between nodes.
$^{\wedge\wedge}$ The stability of connections depends on the size of the zone.
$^{\wedge\wedge\wedge}$It is the time needed to erect a new valid route.

Table I Comparison of ad hoc routing algorithms