Routing Protocols for Wireless Ad Hoc Networks
Hybrid routing protocols

Theofanis Kilinkaridis
tkilinka@cc.hut.fi

Abstract
This paper presents a particular group of routing protocols that aim to combine the advantages of proactive and reactive protocols. Hybrid protocols try to exploit the advantages of both these schemes and to provide better routing solutions for mobile ad hoc networks. The particular paper is more focused on their main concepts as well as on their performance. It analyzes five hybrid protocols and presents their advantages and disadvantages.

1. Introduction

Routing protocols generally fall in two categories: Proactive protocols and Reactive protocols. Proactive protocols establish network route regardless of the demand for such routes. While these protocols periodically exchange routing information, they can provide routes quickly after source's request. Reactive protocols, on the other hand, discover routes only when it's needed. While this on-demand operation may result in route discovery delay, the protocol overhead is much lower.

An optimal routing protocol depends on network characteristics which may change dynamically. A static network where routes to all nodes are equal is more suitable for a proactive protocol. A dynamic network however, where a few mobile nodes are the most popular destinations might use a reactive protocol. Hybrid routing protocols find the optimal mix of proactive route dissemination and reactive route discovery.

2. Hybrid Routing Protocols

Usually in hybrid protocols nodes are grouped into zones, based on their location in the network. Inside these zones, proactive scheme is used for routing while the reactive one is used for the communication between zones. In this paper the following protocols are presented: Core Extraction Distributed Ad Hoc Routing Protocol(CEDAR), Zone Routing Protocol(ZRP), Zone-based Hierarchical Link State Routing Protocol(ZHLS), Preferred Link-based Routing Protocol(PLBR) and Optimized Link State Routing Protocol(OSLR).

2.1 Core Extraction Distributed Ad Hoc Routing Protocol

Core Extraction Distributed Ad Hoc Routing(CEDAR) protocol [1] [2] establishes a core of the network which is used for efficient delivery of the transmitted packets. Route establishment uses reactive routing scheme and is performed by core nodes. CEDAR consists of three main phases: Core extraction, link state propagation and route computation. During the core extraction a set of nodes is dynamically elected to form the core of the network. During the link state propagation the bandwidth availability information of stable high bandwidth links is propagated to core nodes, while information regarding low bandwidth and unstable links is kept local. Finally, during the last phase, the core path is used to establish a route from the source to the destination.

In CEDAR there is at least on core node every three hops. The path between two core nodes is called virtual path. Here, the selection of core nodes is done by distributed algorithm. Core nodes are used to perform the packet transmission over the network in unicast mode. In order to achieve this transmissions efficiently, each core node has to know its neighboring core nodes. If the core node moves away, all the nodes that were attached to it have to find a new core node. Also in CEDAR, every node picks up a node within a distance not greater than one hop from it, as its dominator.

During the route establishment, a core path has to be found from the source to the destination and then QoS requirements have to be satisfied for the selection of the path. First the source checks the local topology whether the destination is in the local topology table of source's core node. If it is, the path is established directly. If it's not, the source initiates a RouteRequest message which is broadcasted to all the core nodes of the network. Each of the core nodes that receive the message forwards it to its neighboring core nodes if the destination is not among its core members. If it is among one of its core members, this core node originates a reply message to the source core node. So the core path is established.

Let's see the Figure 1, where the source is the node 1 and the destination is the node 15. The core nodes are 3, 5, 11, 12 and 13. Node 5 is the dominator of nodes 1 and 6 and node 12 is the dominator of node 15. The abovementioned procedure is followed till one core node finds the destination node among its core members. In this case, core node 12 finds it and replies to the core node 5. Once the path between the nodes is established the last one to be checked is whether the required bandwidth for the transmission is available on this path. If its not available, the core path will be rejected.

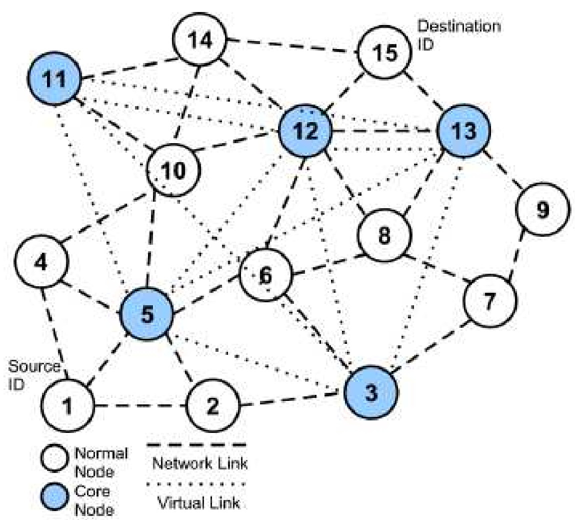

Figure 1: Route establishment in CEDAR

As for the link break case, CEDAR deals with it quite efficiently. When a link break occurs, the node after which the break occurred(on the path from source to destination) sends a notification of failure and begins to find a new path from it to the destination. The particular node rejects every received packet till the moment it finds a new path to the destination. Meanwhile, as the source receives the notification message, it stops to transmit and tries to find a new route to the destination. If the new route is found by either of these two nodes, a new path from the source to the destination is established.

The main advantage of the CEDAR is that it utilizes the use of core nodes to satisfy both routing establishment and QoS path computation. It is also very flexible in case of link break restoring the connectivity of the network quickly and efficiently. Its main disadvantage however, is that the route establishment and computation is relied on core nodes. Due to the mobility of ad hoc networks, core nodes may move. This movement affects the performance of the protocol.

2.2 Zone Routing Protocol

As we know both proactive and reactive protocols have their advantages and disadvantages. Zone Routing Protocol (ZRP) [1] [3] is a protocol which combines the advantages of both approaches into a hybrid scheme. Its key feature is that it uses proactive routing scheme within a node's local neighborhood and reactive scheme for communication between these neighborhoods. These local neighborhoods are called *zones*. An intra-zone routing protocol (IARP) is used in the zone, where a particular node establishes a proactive routing. However, routing beyond the zone is managed by a reactive protocol called inter-zone routing protocol (IERP).

Each zone of a given node is a subset of the network. Each node may be in more than one zone and each zone may be of a different size. The size of the zone is determined by the zone radius r, where r is the number of hops to the perimeter of the zone. Figure 2 shows an example of routing zone with r = 2.

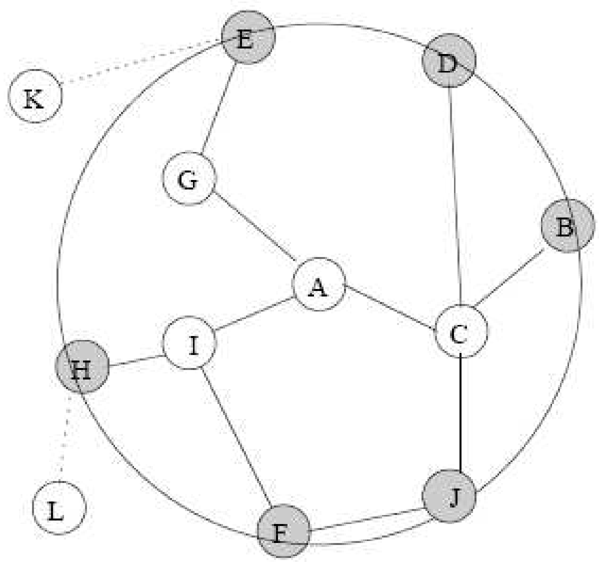

Figure 2: routing zone of the node A with r = 2.

With zone radius = 2, the nodes B, C, D, E, F, G, H, I and J comprise A's zone. Nodes C, G and I are interior nodes, while nodes B, D, E, F, H and J are called peripheral nodes. Each node maintains the information about the routes to its zone nodes using proactive routing scheme by exchanging periodic route update packets.

IARP is used for communication between a node and its zone's nodes. Since the local neighborhood is dynamic with a lot of topology changes, the IARP, as mentioned above, is a proactive, table-driven protocol. Due to its proactive nature, the route selection within the zone is very efficient by having available all the possible routes to the local destinations(zone nodes). IERP however, is responsible for route discovery to the nodes which are not within the routing zone. In other words, IERP takes advantage of the known local topology of a node's zone and using a reactive routing scheme, establishes communication with nodes in other zones.

When a node s wants to send a packet to the node d, it first checks whether the destination node is within its zone. If it is, the source node delivers the packet directly to it. Otherwise, it bordercasts the RouteRequest to its peripheral nodes. More particularly, this procedure is held by a protocol called the Bordercast Resolution Protocol (BRP) which is used for optimizing the efficiency of the in-zone communication. BRP is responsible for sending the RouteRequest message to all the peripheral nodes. Unlike IARP and IERP, BRP is more like a packet delivery service and not a routing protocol. If any of these peripheral nodes finds the destination node in its own routing zone, it sends a RouteReply back to the source node s indicating the path. Otherwise, it bordercasts the RouteRequest to the peripheral nodes of its zone. This process is continued till the destination node d is located. The nodes that find the destination node in their routing zone, initiate the sending of the RouteReply packets to the source. During the spread of the RouteRequest message, each node appends its address to it which can be used later for establishing the path for RouteReply message, sent back to the source.

When an intermediate node, detects a broken link in the path, it chooses another alternative path to bypass the broken link. This process is called local path reconfiguration and during it, a path update message is sent to the sender to inform it about the link failure. After that a new, sub-optimal path is established between the source and the destination nodes. In order to establish an optimal path, the source node reinitiates the path finding process.

Generally, combining the advantages of both proactive and reactive routing schemes, ZRP provides better solutions than both of them. Compared to them, it reduces the control traffic produced by periodic flooding of routing information packets(proactive scheme). It also reduces the wastage of bandwidth and control overhead compared to reactive schemes where RouteRequest flooding mechanisms are used. The main disadvantage however of ZRP, is the large overlapping of routing zones.

2.3 Zone-based Hierarchical Link State Routing Protocol

Zone-based Hierarchical Link State (ZHLS) [1] [4], is a hybrid hierarchical routing protocol that uses the geographical location information of the nodes to divide the network into non-overlapping zones. ZHLS is based on node ID and zone ID approach whereas each node knows only the node connectivity within its zone and the zone connectivity of the whole network. A low level, within a zone, connectivity is called node-level topology while the high level zone connectivity is called zone-level topology. The node-level topological information is distributed only to the nodes of a particular zone while the zone-level information is distributed to all nodes of the network. No cluster heads are defined in this protocol. Routing is established based on zone ID and node ID of the destination. No path containing the nodes between the source and the destination is required. Therefore, no link break could cause any problem to the delivery of the information.

In ZHLS, a node knows its physical location(node ID) by location techniques like GPS. Using this information it can determine its zone ID by mapping its node ID to zone map. The zone map is done during the network design phase. Two types of link state packets(LSP) are defined in ZHLS. A node LSP of a particular node contains a list of its connected neighbors. A zone LSP contains a list of its connected zones. At this point, having its node ID and zone ID, each node can start the intra-zone clustering and then the inter-zone clustering procedures to build its routing tables.

In intra-zone clustering, each node broadcasts a link request. The nodes reply with a link response that contains their node ID and their zone ID. After all link responses, every node generates a node LSP that contains the node IDs of its neighbors of the same zone, and the zone IDs of its neighbors of different zones.

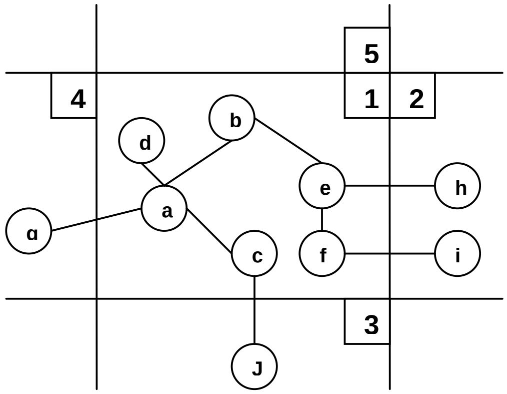

Figure 3**:** Node-level topology

Source	Node LSP
a	**b,c,d,4**
b	**a,e**
c	**a,3**
d	**a**
e	**b,f,2**
f	**e,2**

Figure 4: Node LSPs in zone 1

Then, every node broadcasts its LSP to the nodes all over its zone. As a result, a list of node LSPs like in Figure 4 can be generated in every node and each node knows now the node-level topology of its zone. The Shortest Path algorithm is used now for building intra-zone routing tables. Figure 5 shows the intra-zone routing table of node a.

Destination	Next node
b	**b**
c	**c**
d	**d**
e	**b**
f	**b**
2	**b**
3	**c**
4	**g**

Figure 5: Intra-zone routing table of node a.

After the initial broadcast of a link request from every node, some nodes receive also responses from nodes whose location is in neighbor zones. These nodes are called gateway nodes through which the communication with the neighbor zones can be established. As it is mentioned above, node LSPs contain the zone IDs of the neighboring zones. So each node knows which zones are connected to its zone. Just after receiving all nodes' LSPs, each node of the same zone generates the same zone LSP. Then the gateway nodes broadcast the zone LSP all over the network. As a result a list of zone LSPs is maintained by every node which now knows the zone-level topology of the network. Finally the inter-zone routing tables are built in every node.

If a source node s wants to communicate with the destination node d, s checks whether d is located in its zone. If it is, the packet is sent to the destination node based on intra-zone routing table. If it is not, then s initiates a location request packet which contains source's and destination's information. The location request packet is sent to every zone. A gateway node of each zone will receive the packet and check whether the requested node belongs to its zone. The gateway node to which zone the destination node belongs will initiate a location response packet indicating the zone information of d. After knowing the d's zone ID, node s will communicate with node d, based on its inter-zone routing table.

The main advantage of ZHLS against ZRP is that it does not have any overlapping zones. Also the fact that the zone-level topology information is distributed to all nodes and that there is no cluster head, reduces the traffic and avoids single point of failure. The main disadvantage of the protocol is additional traffic produced by the creation and maintaining of the zone-level topology.

3. Routing Protocols with Efficient Flooding Mechanisms

The main mechanism of reactive protocols is flooding the network with RouteRequest packets in order to establish a path from the source node to the destination. These on-demand protocols increase the traffic overhead and decrease the already limited, available bandwidth. A provision of efficient flooding mechanisms however, could reduce the overhead caused by different routing schemes. Two protocols will be discussed further: Preferred Link-based Routing Protocol(PLBR) and Optimized Link State routing protocol(OLSR).

3.1 Preferred Link-based Routing Protocol

The Preferred Link-based Routing(PLBR) [1] [5] is a reactive routing protocol which applies particular mechanisms to avoid just flooding the network with RouteRequest packets. It provides a mechanism where not all the nodes are allowed to forward the received RouteRequest packet. Hence, it reduces the control overhead. Here, every node maintains a table if its neighbors(NT) and of its neighbor's neighbors(NNT). A node selects always a subset of nodes from its neighbor list(NL). This subset is called the preferred list(PL). The determination of the PL is based on nodes' or links' characteristics and will be discussed later. The RouteRequest packet contains the PL of the sender and is broadcasted to its neighbors. The ones that are in the PL will forward the RouteRequest packet. The others will discard it. The size of the PL is K, where K is the maximum number of nodes comprising the PL. PL is always a subset of PLT where PLT is the preferred list table maintained by every node and which contains all neighbor nodes in order of preference. Any change in neighbors' topology is maintained by sending a beacon that updates the tables. PLBR consists of three different phases: route establishment, route selection and route maintenance.

During the first phase of route establishment, the source node s is trying to establish a route to the destination node d. If the node d is in source's NNT, the route is established directly and the information is forwarded to the destination. If it is not, the source initiates a RouteRequest packet which contains:

- Source node's address: SourceID
- Destination node's address: DestinationID
- Unique sequence number: SeqNum, which prevents the forwarding of multiple copies of the same RouteRequest packet received from different neighbors.
- Traversed Path: TP, which indicates the nodes that have been visited so far by the packet.
- Preferred List: PL which, as already mentioned, is list of nodes determined by the sender node as eligible to forward the RouteRequest packet.
- Time to Live(TTL) field: a decreasing value which determines the allowed duration of packet existence in the network.

Every time, before forwarding the RouteRequest packet, the node that receives the RouteRequest packet updates its PLT and inserts in the PL field of the packet its own PL(which contains the first K nodes from its PLT). The PL of the received packet is always replaced by the one of the receiver.

The RouteRequest packet is always broadcasted to all node's neighbors. However, not all these nodes are considered to be eligible to forward the packet further. In order to be eligible a receiver node has to be in the PL of the received packet, not to have forwarded the same packet again and the TTL value must be greater than zero. If the node satisfies all these requirements, it can forward the packet to all its neighbor nodes. Before broadcasting the packer however, the node checks whether the destination node is in its NT or NTT. If it is, it unicasts the packet directly to the neighbor which can be the destination node or can just have the destination node as a neighbor in its NT. Otherwise, the packet will be broadcasted with new PL and new parameters.

As soon as the destination node is detected, the route selection procedure is followed. As it is obvious multiple RouteRequest packets can reach the destination node. The best route is selected based on the shortest path, the least delay path or the most stable path. After receiving the first RouteRequest packet, the destination node starts a timer which indicates for how long it will be receiving RouteRequest packets from the network. After the expiration of the timer, no more RouteRequest packets are received by the destination node and the route selection phase can start. Finally in order to deal with link breaks, PLBR uses a particular mechanism to achieve optimal route maintenance. PLBR uses a quick route repair mechanism to bypass the broken link using information about the next two hops from NNT.

But how the preferred list(PL) is constructed? Every time the node receives RouteRequest packet, it has to determine its own preferred list of eligible nodes and to replace the received with the new one. Two different algorithms have been proposed for the selection of eligible nodes. The first one is called Neighbor Degree-based Preferred Link Algorithm and is based on neighbor nodes' degree information. The second one is called Weight-based Preferred Link algorithm. Here, the preferred list is calculated based on the stability of the links indicated by the weight.

Neighbor Degree-based Preferred Link Algorithm is based on neighbor nodes' degree. Degree of a node is the number of its neighbors. The algorithm is executed for one node and takes under consideration parameters that have to do with the degree of its neighbor nodes. After the execution of the algorithm, two lists are created: INL and EXL The Include List(INL) contains a set of neighbor nodes which are considered as reachable for forwarding the RouteRequest packet. EXL is the Exclude List which contains the set of neighbor nodes which are considered as unreachable. On the other hand, Weight-based Preferred Link algorithm is based on the weight given to a node, which in turn is based on its neighbors' temporal and spatial stability. Temporal stability has to do with a particular time period in which it is communicating with its neighbors, while spatial stability has to do with the distance estimated from the strength of the signals received from its neighbors. In both algorithms a preferred list table PLT is created with nodes being set in order of preference. After this step, a node can choose K first nodes from PLT and to create its preferred list.

The efficient flooding mechanism used in both PLBR and WBPL reduces the routing control overhead and provides better solutions than the other reactive protocols. A flooding efficient protocol has higher scalability and decreases the network collisions. However, both PLBR and WBPL are much more computationally complex than the other reactive protocols.

3.2 Optimized Link State Routing Protocol

The Optimized Link State Routing (OLSR) protocol [1] [6] is a proactive routing protocol and is based on the link state algorithm. It employs periodic information exchange keeping every node updated about the topology of the network. OLSR is an optimization of a pure link state protocol as it reduces the size of information messages and the number of retransmissions of these messages throughout the network. Its basic concept is the use of multipoint relaying technique to flood the network with control messages. It can provide routes to the destination nodes in an efficient and quick manner. The particular protocol is more efficient in large and dense ad hoc networks.

The idea of the multipoint relay is to reduce the retransmissions and generally minimize packets flooding in the network. Each node in the network selects a set of its neighbors which are supposed to retransmit the packets received from it. This set of selected nodes, which is subset of node's neighbors, is called the multipoint relays(MPR) of that node. Any neighbor that is not in node's MPR, receives the packet but does not retransmit it. Similarly, each node maintains a subset of its neighbors which is called the MRP Selectors of the node. MRP Selectors is the set of node's neighbors that have selected the node as a multipoint relay. Thus, every broadcast message that is coming from the MRP Selectors is supposed to be retransmitted by receiver node.

Each node selects its own set of multipoint relays. Node's MPRset has to be configured in such way to contain the minimal subset of neighbor nodes though which the node can obtain access to all of its two-hop neighbors. Since each node selects its MPRset independently, it knows the topology of its two-hop neighborhood. The MPRset is re-calculated only when a change is detected in the neighborhood: bidirectional link break or bidirectional link appearance. Also, the MPRset is recalculated when a change in the two-hop neighbor set is detected.

Multipoint relays are selected among the one hop neighbors with a bidirectional link.
In order to decide which neighbor nodes can be in the MPRset, each node broadcasts periodically HELLO messages which contain the information about its neighbors and their link status. These HELLO messages are received by all one-hop neighbor nodes but are not retransmitted to other nodes. A HELLO message originated from one node contains a list of neighbors with which the node has bidirectional link and a list of neighbors from which the node has received HELLO message but their link is not yet confirmed as bidirectional. OLSR supposes bi-directional links and so the connectivity must be checked in both directions.

Every node maintains a topology table about the network topology in order to establish routes to destination nodes. That's why every node broadcasts topology control (TC) messages that contain topology information. Every TC message contains the MPRSelector set of every node. A node records information about the multipoint relays of other nodes in this topology table. An entry in the topology table consists of an address of a potential destination node which is the MPRSelector and the address of a last-hop, which is the node that originated the TC message. So using the topology table a node can reach every other node in the network.

The main advantage of OSLR against other proactive protocols is the reduced number of broadcasts, due to the use of MPRs, which leads to reduced control overhead. One of its main disadvantages is the overlapping MPRsets and MPRSelectors which leads to duplicate messages.

Conclusion

In this paper few hybrid routing protocols were presented. In most of the cases, hybrid solutions provide reduced control traffic overhead and reduced routing message size. Hybrid protocols provide flexible mechanisms for handling link breaks and restore quickly the connectivity of the network. However, they have quite few disadvantages. Some of them are subject to single point of failure, while others require additional traffic for creation and maintaining of their topology information. Sometimes they are just very complex computationally.

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