Resource Biased Path Selection in Heterogeneous Mobile Networks

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***Abstract*— In wireless ad hoc networks heterogeneity is inherent; each node has different characteristics, resources and purpose. Current ad hoc routing protocols do not take node heterogeneity into account when making routing decisions; they consider each node identical in capabilities. We propose a simple way to modify the route discovery phase of an on-demand routing protocol to select the "best" route, considering heterogeneity. The Ad hoc On-Demand Distance Vector (AODV) routing protocol is modified and the performance validated in both a testbed and simulation. It is shown that by considering heterogeneity during route discovery, paths that contain more capable nodes are utilized, thereby avoiding resource-poor nodes.**

I. Introduction

Today's wireless networks consist of many different devices. With many mobile heterogeneous devices and little or no infrastructure, the network topology changes frequently. Ad hoc routing protocols will be used in these networks because of their ability to easily deploy and quickly adjust to network changes. For these reasons it is easy to imagine an ad hoc wireless network being deployed in a public place, composed of some dedicated wireless routers, desktop machines, laptops, handhelds and phones (see figure 1). Each device in the network has its own characteristics, properties and purpose and should be used accordingly. A sampling of these include:

- **Device Characteristics**: CPU, memory, interfaces, battery capacity, disk size.
- **Variable Properties**: Mobility, location, battery, load, disk, memory, interfaces available.
- **Purpose and Policy**: Router, server, workstation, communications device, shared use, private use.

In current ad hoc routing protocols, all devices are considered equal when making routing decisions. That is, the likelihood of a resource-poor (weak) device forwarding data packets is the same as that of a resource-rich (strong) device. In a heterogeneous network those nodes

Fig. 1. Example Heterogeneous Devices.

that are weak should be avoided, if stronger devices can be used instead. If weak devices expend their limited resources, they may become unable to participate, preventing themselves and others in the network from communicating. For this reason it is necessary to allow weak nodes to avoid routing packets for others. In this paper we present Heterogeneous Biased Route Discovery (HBRD), a method to bias on-demand route discovery to avoid resource-limited nodes. This protocol is suitable for collaborative networks, where all capable nodes are wiling to participate in the network.

II. Related Work

In the past few years many on-demand ad hoc routing protocols have been developed. The routing metric of a protocol determines the path that will be selected during route discovery. Some routing metrics that are used are minimum-hopcount, minimum-delay, signal strength, link stability, distance, etc.

Two of the most prominent on-demand routing protocols are AODV [1] and DSR [2]. Both protocols can use minimum delay as the routing metric; hence delay may be used to influence route selection. In the protocols PANDA-LO [3] and RDRP [4] delay is used to affect route selection during route discovery. PANDA-LO extends AODV and utilizes delay to avoid the next-

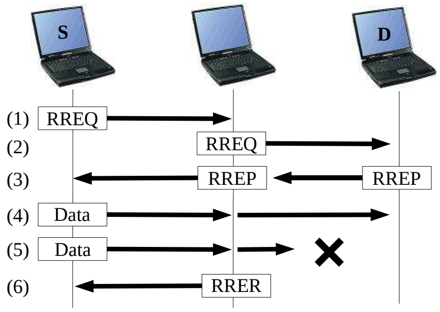

Fig. 2. AODV Operations.

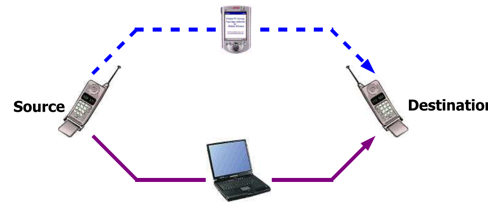

Fig. 3. Four Node Network - Scenario A.

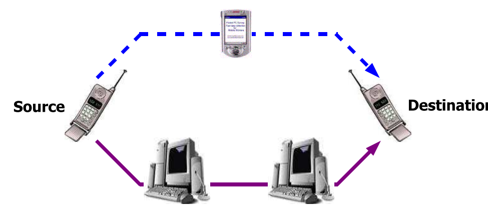

Fig. 4. Five Node Network - Scenario B.

hop racing phenomenon, which occurs when two or more nodes receive a route request at the same time and both immediately rebroadcast the request. PANDA-LO selects the delay value based on relative distance between the sending and receiving nodes to speed flooding of the request in the network. RDRP extends DSR and proposes using a delay value inversely proportional to remaining battery power to achieve balanced energy consumption. These two papers do not specify the details of implementation for proper operation or the delay value to introduce.

Like these two solutions HBRD uses delay to influence route discovery. In HBRD the delay value is based on the heterogeneous properties of the node. In this paper we describe our implementation in detail, present testbed and simulation results, and describe how to determine the delay value.

III. AODV Protocol Overview

The Ad hoc On-demand Distance Vector (AODV) routing protocol [1] is a reactive protocol. Route discovery is performed to determine a route from the source to the destination. Afterward route maintenance is used to maintain the route. These AODV operations are shown in figure 2 and described in this section.

When a source has data to transmit to an unknown destination, it generates a Route Request (RREQ). The RREQ is broadcast by the source (1, in figure 2). At each intermediate node, when the RREQ is received a route to the source is created. If the receiving node has not received this RREQ before, is not the destination and does not have a current route to the destination, it rebroadcasts the RREQ (2). If a node is the destination or has a current route to the destination, it generates a Route Reply (RREP). The RREP is unicast in a hop-by-hop fashion to the source (3). As the RREP propagates, each intermediate node creates a route to the destination. When the source receives the RREP it creates a route to the destination and begins sending data (4). If multiple RREPs are received by the source, the route with the shortest hopcount is chosen.

As data flows from the source to the destination each node updates the timers associated with the routes to the source and destination, thus maintaining the routes in the routing table. If a link break is detected while data is flowing (5), a Route Error (RERR) is sent (6), in a hop-by-hop fashion, to the source of the data. As the RERR propagates to the source, each intermediate node invalidates routes to the unreachable destinations. When the source receives the RERR it invalidates the route, and reinitiates route discovery if necessary.

A. RREQ Destination-only Flag

The destination-only flag is an option in RREQ packets, specified in the AODV Internet Draft [5]. When set, it indicates that the RREQ message is to be answered only by the destination, thereby disallowing intermediate nodes from responding with a RREP. An effect of this flag is that the routing metric becomes minimum-delay. This occurs because the destination only responds to the first RREQ received. Thus the source receives only one RREP, over the route with minimum delay to the destination. This flag is utilized by HBRD and is discussed further in section VI.

IV. Problem Scenarios

For demonstrative purposes, we examine the two simple networks shown in figures 3 and 4. The first scenario is representative of a network containing two equal length routes between the source and destination. The second scenario is representative of a network containing two routes of unequal path lengths.

Consider the heterogeneous network scenario A, shown in figure 3, where AODV is being run by all the devices. If the two mobile phones are to communicate, the likelihood that the route chosen is through the laptop or through the pager are the same. The selection of the device (pager or laptop) is fairly random in this scenario. However, if heterogeneity is considered and weak devices such as the pager are avoided, traffic between the two phones should be routed through the laptop.

In many heterogeneous networks it may be appropriate for the two phones to communicate along a longer path to avoid routing data via a weak device, such as a pager, so that the battery of the weak device can be conserved. In scenario B, presented in figure 4, there are two available paths, one through the pager and the other through two desktop machines. In this scenario, using AODV, the pager is chosen as the route between the two phones. There is no way for the pager to avoid routing packets between the two phones. Because the pager is a resource-poor device, it is beneficial to route all data through the two computers. In this way the pager is spared from routing packets between the two phones. HBRD provides a simple way to bias route discovery so that the route chosen between the two phones will avoid the pager.

V. Protocol Development Requirements

There are many possible solutions for creating a routing protocol that considers heterogeneity. To focus the design it is necessary to formulate requirements and goals to restrict development.

A good solution should have the following characteristics:

- **Allow partial deployment**: Only resource-limited nodes should be required to implement additional features.
- **Allow for dynamic adjustment**: Nodes should be able to dynamically adjust their likelihood of participating based on many factor so that different heterogeneous properties, including consumable resources, may be considered.
- **Be built on a mature routing protocol**: Because ad hoc routing protocols are fairly mature, it is advantageous to build on their generous knowledge.

In the next section we describe HBRD, a protocol that fulfills these requirements.

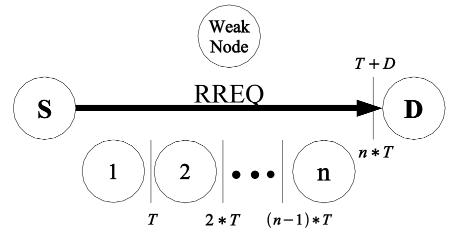

Fig. 5. Introduced Delay Calculation.

VI. Heterogeneous Biased Route Discovery

Recall in scenario A, the pager and laptop have the same probability of being chosen on a route between the two phones. The reason for the pager and laptop having the same probability of being on the route selected by AODV is because the propagation time of the RREQ, from the source to destination, is nearly equal along the two paths. We propose introducing additional delay during the propagation of the RREQ through weak nodes. Therefore, RREQs in routes without delay reach the destination first and routes with weak nodes are avoided. The RREQ delay introduced by a weak node should be inversely proportional to its willingness to participate; the more adverse a weak node is being on the chosen route, the larger the delay it should utilize.

For instance in scenario A, if the pager delays the rebroadcast of the RREQ, the destination will receive the RREQ from the laptop first. Therefore the route through the laptop will be chosen and the pager is spared from participating on this route.

For this technique to function properly the destination must use minimum-delay as the routing metric for RREQs. Also the destination must be the only node to respond to the RREQ and must respond only to the first RREQ it receives. Otherwise, if multiple RREPs are received by the source then the route selection is not be based on the minimum delay, but instead on the minimum hopcount. Using AODV with the destination-only flag fulfills the above requirements.

It is possible for packets to collide or be dropped during route discovery. If this occurs, route discovery selects the most resourceful discovered route.

A. Determining the Introduced Delay

The introduced delay in nodes implementing HBRD impacts their probability of being on the route selected between the source and destination. The longer the accumulated delay of a route, in relation to other routes, the less likely that route is to be chosen. It is necessary for nodes that do not want to route packets for others to determine the delay needed to avoid being on the chosen route.

Consider a network running AODV where all nodes participate equally. The RREQ propagation time is a function of the number of hops (n) and the time incurred during each hop. Let the maximum time it takes to traverse one hop be T, where T includes the processing, propagation, transmission and queuing time. Then, given T and n, the RREQ takes $n * T$ time to reach the destination, from reception at the first intermediate node.

Assume there are two paths as shown in figure 5, one through a node implementing HBRD that does not want to be chosen and another through multiple strong nodes. The node running HBRD must introduce delay, D, such that the RREQ propagates along the other route more quickly. Given the RREQ propagation along the route containing the HBRD node is $T+D$, and that the time on the route containing strong forwarding nodes takes $n*T$, the introduced delay must be greater than $(n-1)*T$ to avoid being chosen. In other words,

$$D > (n-1) * t \tag{1}$$

The calculation for the introduced delay is simple when n and T are known. For arbitrary networks with varying n the delay value may be static or adjusted dynamically. To determine a static delay value the willingness of a weak node may be set equivalent to a threshold of n hops. Suppose n is 2 hops, and there are two routes, one through a weak node and the other through two strong nodes. In this case the two hop route through the strong nodes will be chosen. On the other hand, given a choice between two routes, one through a weak node and the other through four strong nodes, the one hop route through the weak node will be chosen. In this way a weak node decreases its likelihood of routing packets for others, but may still be on the chosen route if alternative routes to the destination are longer. In section VII-A an experimentally determined value of T is used. In section VII-B the effect of changing the delay value is examined.

VII. Evaluation

To fully evaluate HBRD, testbed experiments and simulations were performed. Testbed experiments provide validation that the protocol functions as expected. In section VII-A testbed results of scenarios A and B, shown in figures 3 and 4, are given. Testbed experiments may be run on small specific network topologies, but are difficult for larger experiments. In section VII-B simulation results for larger networks are discussed. Using simulation we also verify that HBRD does not negatively impact performance, when compared with AODV, and examine the impact of the introduced delay.

TABLE I
Experimental Results.

Scenario	Route Discovery Protocol	Pager Chosen	Pager Not Chosen
A	AODV	50%	50%
A	HBRD	0%	100%
B	AODV	100%	0%
B	HBRD	0%	100%

A. Testbed Validation

To perform the evaluation we modified an existing AODV implementation [6] to include HBRD. This implementation allowed us to run experiments in a testbed with off the shelf hardware as well as simulations examining the effectiveness of HBRD. The results verify that HBRD does indeed bias routes toward more capable nodes, with minimal impact to performance metrics.

In our experimental testbed all the nodes were Pentium III laptops running Linux 2.4. Each was equipped with a Lucent Orinoco wireless card set to communicate at 2 Mbps. They were all located on the same desk and connectivity was controlled using the MAC layer filtering program *iptables*. Each test was run 10 times.

Testbed experiments with the same configuration as figures 3 and 4 were run. Though all the devices here were identical, each device could be configured with a delay value. The laptop representing the pager was given a delay value greater than the traversal time of two hops. Through experiments using the laptops with unmodified AODV, the time for a route request to traverse one hop was found to be less than 25 ms. For this reason a delay of 50 ms was introduced by the weak node during route discovery. No other devices introduced delay.

When route discovery occurs, the RREQ in the laptop representing the pager is delayed. This causes the RREQ rebroadcast by the other route to be received by the destination before the RREQ rebroadcast by the pager. Because the destination only responds to the first RREQ received, the laptop representing the pager is avoided and the other route is chosen. The results in table I verify that in scenario A without HBRD, the route through the pager and laptop are chosen equally. The results also validate that when HBRD is used the pager is avoided.

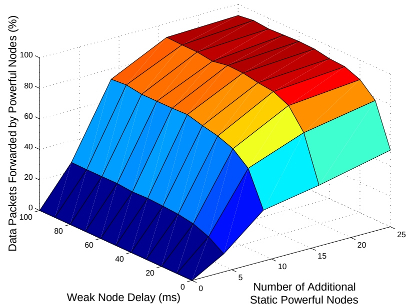

Fig. 6. Effect of Increasing Static Well Placed Powerful Nodes and Delay.

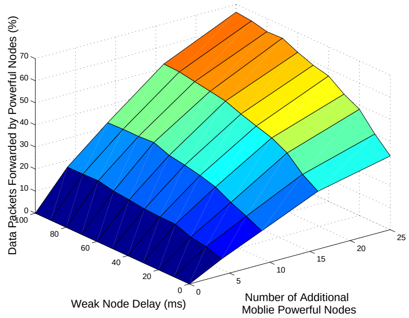

Fig. 7. Effect of Increasing Mobile Powerful Nodes and Delay.

Now examining scenario B with five nodes as shown in figure 4, with unmodified AODV the route through the pager is always chosen. However, as table I shows, with HBRD the route through the two computers is chosen.

These results verify that HBRD performs as predicted. HBRD biases route discovery such that the heterogeneity of the different nodes is considered. Using HBRD the resource-rich route is chosen to forward data packets.

B. Simulation

To perform larger simulations, compare performance with AODV and vary the delay value, the NS-2 simulator was utilized. The size of the simulated area is a 1000x1000 meter square. The mobility model utilized was the random waypoint model with speeds uniformly distributed between 0 and 10 m/s with no pause time. There were ten source-destination pairs, each sending four 512-byte packets per second. Each source sent 200 packets and started five seconds after the prior source. Each simulation was run for 300 seconds and ten runs were performed for each scenario. Each node uses 802.11 with a 250m transmission radius; link layer feedback was utilized.

In these simulations there are three node types:

- **Powerful Nodes**: Nodes that are powerful and willing to forward packets for others. These nodes introduce no delay during route discovery, and function as though running unmodified AODV.
- **Limited Nodes**: Nodes with limited resources, that want to defer forwarding traffic to more powerful nodes. These nodes introduce delay in proportion to their willingness to forward packets for others. In the simulations, the delay introduced by these nodes increases as remaining battery power decreases.
- **Weak Nodes**: Nodes that do not want to participate in routing packets for others, but may if no other routes exist. These nodes introduce a large delay to RREQ messages.

In the first two scenarios there are 50 weak nodes, and an additional number of powerful nodes (unmodified AODV nodes) are added. In figures 6 and 7, the x-axis varies according to the number of additional mobile powerful nodes added (0, 4, 9, 16, 25) to the simulation. The delay introduced by weak nodes is varied from 0 to 100 milliseconds, along the y-axis. The z-axis shows the percentage of data packets that are routed by powerful nodes.

In the first scenario the powerful nodes added to the simulation are statically placed. They are placed in a grid within the simulation area to maximize their coverage. Figure 6 shows that as the number of powerful nodes increases so does the amount of traffic they forward, because there are more powerful nodes available. Also, as the weak node delay increases so does the amount of traffic forwarded by the powerful nodes. Routes that contain weak nodes become less likely of being chosen because the RREQs are delayed by weak nodes.

In the second scenario the powerful nodes added to the simulation are mobile and randomly placed. The trends in figure 7 are similar to those in figure 6, though less pronounced. When the static and mobile scenarios are compared the percentage of packets forwarded by the static powerful nodes is much higher for fewer nodes and lower weak node delay. Well placed nodes can significantly improve the ability of powerful nodes to alleviate the amount of forwarding done by weak nodes, when compared with mobile powerful nodes.

To further test the impact of HBRD and its ability to bias routes, an additional test was run with 25 weak nodes, 25 mobile limited nodes and 25 statically placed powerful nodes. The delay value for the limited nodes ranged from 25 to 50 ms. The delay introduced at each node was inversely proportional to its remaining battery power. This delay range was chosen because it caused most packets to be forwarded by powerful nodes in the first two simulation scenarios. Because weak nodes

TABLE II

HBRD EFFECTIVENESS TO AVOID RESOURCE-POOR NODES.

Metric	Powerful Nodes	Limited Nodes	Weak Nodes
% Packets Forwarded	91.9	6.0	2.1

TABLE III

COMPARISON OF HBRD AND AODV.

Metric	AODV	HBRD	Impact
% Packets Delivered	92.88	93.77	+
Delay (seconds)	0.1926	0.1888	+
Path Length	3.472	3.433	+
% Packets Forwarded by Powerful Nodes	42.0	88.7	+

should be avoided more than limited nodes, these nodes introduced 100 ms delay.

The results in table II show most of the traffic is routed through the powerful nodes. Only a small portion is forwarded through the mobile limited nodes and almost no traffic is forwarded by weak nodes. These results verify that by introducing different amounts of delay a node may impact the amount of data packets it forwards for others.

To verify that HBRD does not degrade performance, a comparison with unmodified AODV was performed. In the HBRD test runs there were 25 powerful nodes, and 50 weak nodes. The weak nodes introduced 50 ms delay. In the AODV test runs there were 75 nodes and no delay was introduced. The results are shown in table III. The final column indicates whether HBRD had a positive (+) or negative (-) impact on the performance when compared to AODV. HBRD resulted in a slight positive increase in all these performance metrics. This is primarily due to decreased congestion during route discovery. Because weak nodes introduce delay they postpone their rebroadcast of the RREQ. This leads to less contention and congestion along the best routes, and therefore shorter delay.

The simulation results verify that HBRD can be used to maximize use of resource-rich nodes and avoid weak nodes. The effectiveness of static, well-placed powerful nodes while using HBRD is large when compared with mobile powerful nodes, but both are beneficial. HBRD exhibits a small improvement in most performance metrics when compared to AODV.

VIII. CONCLUSION

In this paper we presented HBRD, a simple method to bias on-demand route discovery toward resource-rich routes by using delay during route discovery. Testbed experiments and simulation results were presented that show HBRD selects routes according to node resources without negatively impacting performance.

The development of HBRD has introduced many new questions. One of the main questions left open is how to choose the proper delay value given an unknown network. This is a difficult problem because the delay introduced must be decided in proportion to the willingness of other nodes to forward packets for others. It may be possible to determine the delay introduced by others by monitoring RREQ reception times. However, we believe in many common situations statically configured delay values (or ranges) will suffice.

ACKNOWLEDGMENTS

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