TRANSPARENT INFLUENCE OF PATH SELECTION IN HETEROGENEOUS AD HOC NETWORKS

Ian D. Chakeres[1] and Elizabeth M. Belding-Royer[2]

[1] Dept. of Electrical & Computer Engineering, University of California, Santa Barbara, USA, idc@engineering.ucsb.edu
[2] Dept. of Computer Science, University of California, Santa Barbara, USA, ebelding@cs.ucsb.edu

Abstract - In wireless ad hoc networks, heterogeneity is inherent; each node has different characteristics, resources and policies. Most current ad hoc routing protocols do not consider node heterogeneity when making routing decisions. Although existing ad hoc routing protocols can be extended to consider heterogeneity, these methods require changes to the routing protocol packets and the packet processing. We propose a simple, transparent modification during the route discovery phase of an on-demand routing protocol to select the best route considering heterogeneity. In our solution, nodes can influence their likelihood of participating in routing packets for other nodes, and there is no noticeable change to the routing protocol. To evaluate our solution, we modify an Ad hoc On-Demand Distance Vector (AODV) routing protocol implementation. Our solution's ability to influence path selection is studied in both a testbed and a network simulator. We show that using the method described in this paper, nodes that want to avoid routing packets for others are avoided when other routes exist.

I. INTRODUCTION

Present ad hoc wireless networks consist of many different types of devices. Each device in the network has its own resources, properties and policies, and it should be used accordingly. A sampling of these characteristics include:

- **Device Properties**: CPU, memory, interfaces, power.
- **Variable Resources**: Mobility, location, battery, load, disk space, memory.
- **Purpose and Policies**: Router, server, workstation, communication device, public/private use.

Ad hoc routing protocols are used in these mobile, heterogeneous networks because of their ability to easily deploy and quickly adjust to network topology changes. In current ad hoc routing protocols, all devices are considered equal when making routing decisions; in fact, the likelihood of a resource-constrained (limited) device (e.g., a battery-powered handled computer) forwarding data packets is the same as that of a resource-rich (strong) device (e.g., a fixed, powered access point). In a network of heterogeneous devices, those nodes that want to defer routing packets for others should be avoided if other willing, capable devices are available. If a limited device expends its resources, it will become unable to participate in the network, preventing its communication. If the network becomes partitioned due to the loss of a limited device, communication between other nodes in the network will also be effected. To maximize the lifetime of limited devices, it is desirable for them to defer packet forwarding to strong nodes whenever possible.

In order to prevent limited devices from being on selected paths, existing routing protocols can incorporate additional information in control packets. Extending a routing protocol by changing the protocol logic or packet fields can potentially change the routing algorithm. To avoid changing the routing protocol behavior we chose to accomplish our goal transparently, without any alteration to the routing protocol logic or packet structure. Nodes willing to route packets for others are unaware of any change to the routing protocol. To this end, we present Transparent Biased Route Discovery (TBRD), a method for nodes to influence the path selected during on-demand route discovery. We incorporate TBRD in the Ad hoc On-demand Distance Vector (AODV) routing protocol [1] to perform simulation and testbed experiments.

II. 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 and consists of a Route Request (RREQ) flood followed by a unicast Route Reply (RREP). If multiple replies are received, the route with the greatest destination sequence number and the shortest hopcount is chosen. After a route is discovered, the route table entries at all nodes on the path are maintained by forwarded data packets. If a link break is detected while data is flowing, a Route Error (RERR) is sent to the source. If the source still has data to send, it reinitiates route discovery.

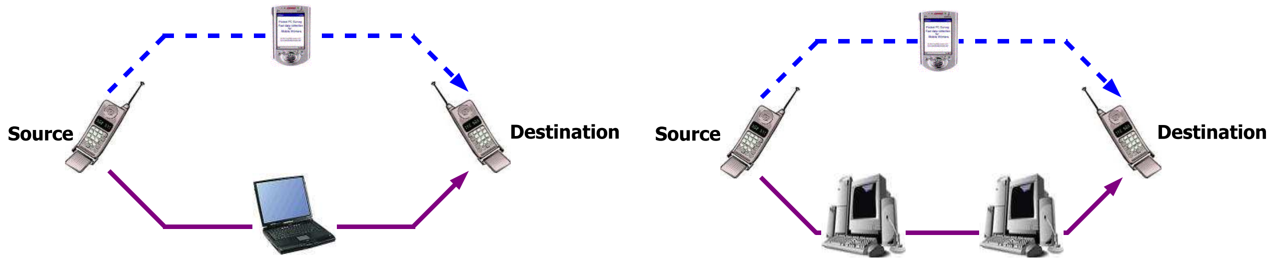
A. RREQ Destination-only Flag

The destination-only flag is an option in RREQ packets [1]. When set, it indicates that the RREQ message can only be answered by the destination; intermediate nodes cannot respond with a RREP. Because the destination only responds to the first RREQ received, an effect of this flag is that the routing metric becomes minimum-delay. Thus the source receives only one RREP, which is received over the route with minimum delay to the destination. This flag is utilized by TBRD and is discussed further in Section V.

III. PROBLEM SCENARIOS

For demonstrative purposes, we examine the two simple networks shown in Figure 1. Scenario A is representative of a network containing two equal length routes between the source and destination, while scenario B is representative of a network containing two routes of unequal path lengths.

Consider the heterogeneous network in scenario A, where all nodes run AODV, and the two phones want to communicate. In this scenario, the laptop and handheld are equally likely to route packets, causing the selection of the intermediate node to be arbitrary. If heterogeneity is considered and handhelds are to avoid forwarding packets



(a) Four Node Network - Scenario A

(b) Five Node Network - Scenario B

Fig. 1. Testbed Network Scenarios.

for others, traffic between the two phones should be routed through the laptop.

In many heterogeneous network scenarios it may be appropriate for two devices to communicate along a path that is not the shortest path. A longer path should be used to avoid a limited device, thereby conserving its resources. In scenario B there are two available paths, one through the handheld and the other through two desktop machines. Within this context, AODV would typically select the handheld for the route between the two phones. In AODV there is no way for the handheld to avoid routing packets between the two phones. If the handheld is considered a limited device, then it is beneficial to route data through the two desktops. By avoiding the handheld its resources are conserved. TBRD provides a simple way to influence route discovery to choose routes that do not contain the handheld.

IV. PROTOCOL DEVELOPMENT REQUIREMENTS

There are many possible solutions for a routing protocol that considers heterogeneity. To focus the design it is necessary to formulate the requirements and goals of the solution. A good solution should have the following characteristics:

- **Transparent operation**: Only nodes that wish to avoid routing packets for others should be required to implement additional features. This also allows for partial deployment and backward compatibility.
- **Dynamic participation**: Nodes should be able to dynamically adjust their likelihood of participation so that different heterogeneous properties, including variable resources, may be considered.
- **Minimal routing protocol modification**: Since ad hoc routing protocols are fairly mature, it is advantageous to build on their generous knowledge and proven algorithms.

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

V. TRANSPARENT BIASED ROUTE DISCOVERY

Recall that in scenario A, shown in Figure 1(a), the handheld and laptop have the same probability of being chosen on a route between the two phones. The reason for the handheld 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.

To allow nodes to decrease their likelihood of being on a selected path, we propose the introduction of additional delay during the propagation of the RREQ through nodes that wish to avoid routing packets for others. Therefore, RREQs along routes without delay reach the destination first. This results in the avoidance of limited devices. The RREQ delay introduced by a limited node should be inversely proportional to its willingness to participate; the more adverse a node is to being on the chosen route, the larger the delay it should utilize.

For example, in scenario A, if the handheld delays the rebroadcast of the RREQ, the destination receives the RREQ from the laptop first. Therefore the route through the laptop is chosen and the handheld does not participate 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 based on the minimum delay, but instead on the hopcount and the destination sequence number. Using AODV with the destination-only flag fulfills the above requirements.

During route discovery, it is possible for packets to collide or be dropped. If this occurs, then the route discovery procedure will still select the most resourceful discovered route.

A. *Determining the Introduced Delay*

The amount of introduced delay impacts the probability of a node 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 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 an AODV network, where 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

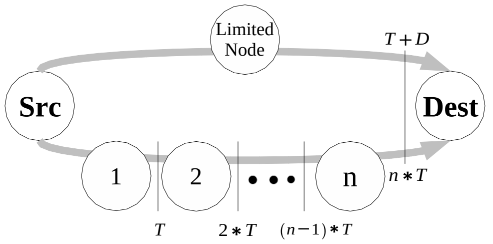


Fig. 2. Introduced Delay Calculation.

Table 1
EXPERIMENTAL RESULTS.

Scenario	Route Discovery Protocol	Handheld Chosen	Handheld Not Chosen
A	AODV	50%	50%
A	TBRD	0%	100%
B	AODV	100%	0%
B	TBRD	0%	100%

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 after reception at the first intermediate node.

Assume there are two paths, as shown in Figure 2, one through a limited node implementing TBRD that does not want to be chosen and another through multiple unmodified (normal) AODV nodes. The node running TBRD must introduce delay, D, such that the RREQ propagates along the other route with less delay. Given that the RREQ propagation time along the route containing the TBRD node is $T + D$, and that the time on the route containing normal nodes takes $n{*}T$, the introduced delay, D, 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 various path lengths the delay value may be static or adjusted dynamically. To determine a static delay value the willingness of a limited node may be set equivalent to a threshold of n hops. Suppose n is 2 hops and there are two routes, one through a limited node and the other through two normal nodes. In this case the two hop route through the normal nodes will be chosen. On the other hand, given a choice between two routes, one through a limited node and the other through four normal nodes, the one hop route through the limited node will be chosen. In this way, a limited 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 than some threshold. When variable resources are considered, a range of different delay values or hopcount thresholds may be used. By utilizing a range of values a node can correlate its participation with its resources.

In the testbed experiments in Section VI-A, an experimentally determined value of T is used. During simulation, as described in Section VI-B, the effect of changing the delay value is examined.

VI. EVALUATION

To fully evaluate TBRD, testbed experiments and simulations were performed. The testbed experiment results provide verification that the delay influences path selection, as expected. In Section VI-A, testbed results of scenarios A and B, shown in Figure 1, are given. Simulation results for larger networks are discussed in Section VI-B. Using simulation we also examine the impact of the introduced delay and verify that TBRD does not negatively impact performance when compared with AODV.

A. Testbed Validation

To perform the evaluation we modified an existing AODV implementation [2] to include TBRD. This AODV implementation allowed us to run experiments in a testbed with off-the-shelf hardware, as well as simulations to examine the effectiveness of TBRD. The testbed results prove that TBRD does indeed avoid routes containing limited nodes.

In our experimental testbed all the nodes were Pentium III laptops running Linux 2.4. Each was equipped with a Lucent Orinoco IEEE 802.11b wireless card that was set to communicate at 2 Mbps. The laptops were located on the same desk and connectivity was controlled using the MAC layer filtering program *iptables*. Each test was run 10 times.

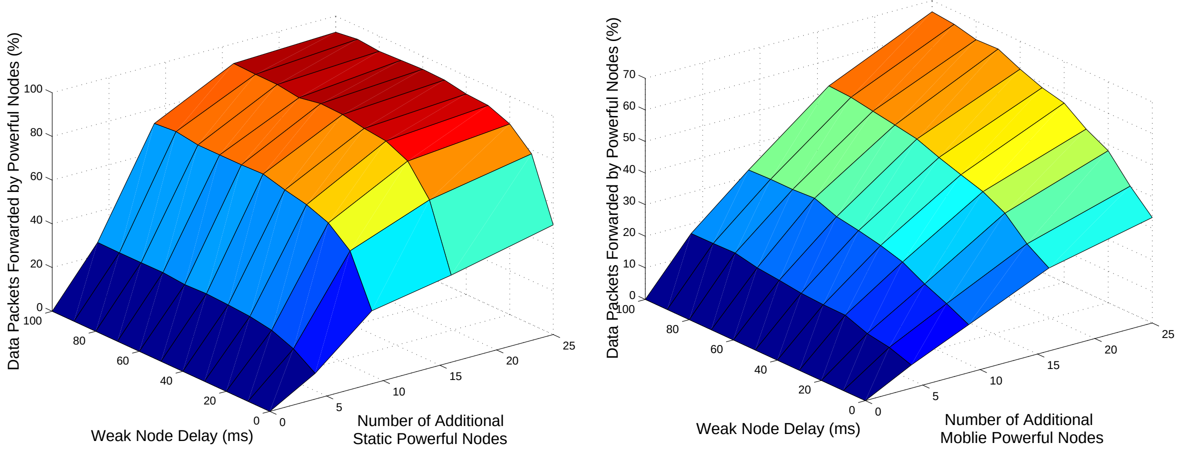
Testbed experiments with the same configuration as Figures 1(a) and 1(b) were run. Though all the devices here were identical, each device could be configured with a delay value. The laptop representing the handheld was given a delay value greater than the traversal time of two hops. Through experiments 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 limited node during route discovery. No other devices introduced delay.

When route discovery occurs, the RREQ in the laptop representing the handheld is delayed. The introduced delay causes the RREQ rebroadcast by the other route to be received by the destination before the RREQ rebroadcast by the handheld. Because the destination only responds to the first RREQ received, the route with the handheld is avoided and the other route is chosen. The results in Table 1 verify that in scenario A without TBRD, the route through the handheld and laptop are chosen equally. The results also show that when TBRD is used the handheld is avoided.

Examining scenario B with five nodes as shown in Figure 1(b), the route through the handheld is always chosen when AODV is unmodified. However, as Table 1 shows, with TBRD the route through the two nodes is chosen and the handheld is avoided.

B. Simulation

We use the NS-2 simulator [3] to study large networks and parameter variation. The size of the simulation area



(a) Static Well-placed Powerful Nodes

(b) Mobile Powerful Nodes

Fig. 3. Effect of Increasing Powerful Nodes and Delay.

is 1000m x 1000m. The mobility model is the random waypoint model [4] with speeds uniformly distributed between 0 and 10 m/s with no pause time. There are 10 source-destination pairs, each sending four 512-byte packets per second. Each source sends 200 packets and starts five seconds after the prior source. Each simulation is run for 300 seconds and 10 runs are performed for each scenario. The nodes use IEEE 802.11 with link layer feedback and a 250m transmission radius.

In our 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. Each limited node starts with the same amount of energy. The energy consumed by each node is determined by its idle time, as well as the time spent transmitting and receiving packets.
- **Weak Nodes**: Nodes that do not want to participate in routing packets for others, but may if no other route exists. These nodes introduce a large delay to RREQ messages.

In the first two scenarios there are 50 weak nodes, and a variable number of powerful nodes (running unmodified AODV) are added. In Figure 3, the x-axis varies according to the number of additional powerful nodes added (0, 4, 9, 16, 25) to the simulation. The weak nodes introduce delay varied from 0 to 100 ms, as shown along the y-axis. The z-axis shows the percentage of data packets that are forwarded by powerful nodes.

In the first scenario the powerful nodes added to the simulation are statically placed. They are positioned in a grid within the simulation area to maximize their coverage. Figure 3(a) shows that as the number of powerful nodes increases, the amount of traffic they forward also increases because there are more powerful nodes available. Also, as the weak node delay increases, the amount of traffic forwarded by the powerful nodes increases. Routes that contain weak nodes become less likely of being chosen because these RREQs are delayed whereas RREQs through powerful nodes are not.

In the second scenario the powerful nodes added to the simulation are randomly placed and mobile. The trends in Figure 3(b) are similar to those in Figure 3(a), 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 static nodes can significantly improve the ability of powerful nodes to alleviate the amount of forwarding done by weak nodes.

To further test the impact of TBRD and its ability to influence route selection, 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 is 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. The weak nodes introduce 100 ms delay because limited and powerful nodes should be favored over weak nodes.

The results in Table 2 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 can impact the amount of data packets it forwards for others.

Table 2
TBRD AVOIDANCE OF WEAK NODES.

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

To verify that TBRD does not degrade performance, a comparison with unmodified AODV was performed. In the TBRD 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 3. TBRD resulted in a positive increase in all performance metrics. The delay introduced by weak nodes leads to less contention, fewer packet collisions along the best routes and shorter end-to-end delay.

The simulation results verify that TBRD can be used to avoid limited nodes. The effectiveness of static, well-placed powerful nodes using TBRD is more significant than when the powerful nodes are mobile, but both are beneficial. An additional benefit is that TBRD exhibits a small improvement in most performance metrics when compared to AODV.

VII. 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 used to forward data packets. Some routing metrics that are used are hopcount [1, 5], delay [1], signal strength [6], and link stability [7]. Routing protocols that control path selection by using additional control fields or altered routing protocol logic are not discussed in this paper.

Two of the most widely researched on-demand routing protocols are AODV [1] and DSR [5]. The PANDA-LO [8] and RDRP [9] protocols modify AODV and DSR, respectively, to use delay to affect route selection during route discovery. PANDA-LO extends AODV and utilizes delay to avoid the next-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 more rapidly flood the request in the network. RDRP extends DSR and proposes using a delay value inversely proportional to the remaining battery power to achieve homogeneous energy consumption. The details of implementation for proper operation and the delay value to introduce are not specified in either of these publications. Further, neither PANDA-LO or RDRP has been tested using an actual implementation.

VIII. CONCLUSION

In this paper we present TBRD, a simple method to transparently bias on-demand route discovery to avoid resource limited nodes by using delay during route discovery. Testbed experiments and simulation results demonstrate that TBRD does not negatively impact overall performance. In addition, we show that using TBRD, well-placed static powerful nodes perform the majority of packet forwarding. This shows promise for campus-wide ad hoc networks, where static nodes can be placed to assist in the formation of ad hoc networks.

Table 3
COMPARISON OF TBRD AND AODV.

Metric	AODV	TBRD
% Packets Delivered	92.88	93.77
Route Discovery Latency (sec)	0.1926	0.1888
Path Length	3.472	3.433
% Packets Forwarded by Powerful Nodes	42.0	88.7

The development of TBRD has introduced many new questions. One of the topics left is the mechanism to choose the proper delay value given an unknown network. This is a difficult problem because the delay introduced may be related to the willingness of other nodes to forward packets. It may be possible to determine the delay introduced by other nodes by monitoring the interval at which neighboring nodes rebroadcast RREQs. However, we believe in most common deployments statically configured delay values or ranges will suffice.

ACKNOWLEDGMENTS

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