Routing in Heterogeneous Wireless Ad Hoc Networks

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Abstract—Existing routing protocols for wireless ad hoc networks assume a homogeneous network with either omnidirectional antennas or smart (beamforming) antennas. However, it is possible to have a heterogeneous network with each node either using an omnidirectional antenna or a smart antenna. We investigate the routing and MAC layer issues that arise in such heterogeneous networks. We extend the expected number of transmissions (ETX) metric and propose a new power-controlled routing metric applicable for heterogeneous networks. This routing metric also serves the purpose of neighbor discovery, which now additionally involves finding the type of neighbor. We use information from the routing layer to propose changes at the MAC layer. We evaluate the performance of this new routing metric through simulations. We find that using smart antennas along with omnidirectional antennas improve the aggregate network throughput up to 200% in a random topology and up to 47% in a grid topology. We identify issues that need further consideration for improving the performance of heterogeneous networks.

I. INTRODUCTION

Heterogeneity in ad hoc networks arises from factors such as varying communication capabilities or varying transmission powers used by the nodes. In this paper, we consider the specific case of heterogeneity when the nodes in the network either use an omnidirectional antenna or a beamforming antenna.

Beamforming antennas improve the network performance through increased spatial reusability and provision of higher communication range. These antennas usually consist of arrays of antennas, whose signals are combined to achieve a better performance compared to omnidirectional antennas. We assume that a beamforming antenna is more expensive than an omnidirectional antenna. Hence, it may not be economically feasible to have a network in which every node uses a beamforming antenna. Therefore, it is possible to imagine a heterogeneous network in which a few nodes use beamforming antennas and the others use omnidirectional antennas. Henceforth, we refer to beamforming antennas as directional antennas.

Since directional antennas have a superior performance compared to omnidirectional antennas, we assume that a heterogeneous network of omnidirectional and directional antennas has a better performance than a homogeneous network of omnidirectional antennas. We study the problem of routing in such heterogeneous networks.

Most of the existing work on wireless ad hoc networks assume homogeneous networks. In homogeneous networks, a lot of research effort has been focussed on networks that use omnidirectional antennas. However, in the recent past, several MAC and a few routing approaches have been proposed for networks that use directional antennas. The bulk of the work on MAC protocols is on modifying the IEEE 802.11 DCF protocol [1] to account for directionality of the antenna. However, routing protocols and routing metrics for directional antennas haven’t received as much attention as the MAC protocols.

In this paper, we discuss routing and MAC issues that arise in a heterogeneous network consisting of omnidirectional and directional antennas. To the best of our knowledge, there is no existing work that deals with such heterogeneous networks. We propose and evaluate a novel power-controlled multiple expected number of transmissions (ETX) metric for such heterogeneous networks. The metric allows nodes to discover other nodes that are beyond the omnidirectional communication range for a given transmission power. Further, this metric also serves the purpose of discovering neighbors and their type (omnidirectional or directional). Existing work on directional antennas usually is focussed on either the MAC layer or the routing layer. We use information from the routing layer to propose a few changes at the MAC layer.

II. PRELIMINARIES

Smart or beamforming antennas are usually realized through an antenna array with beamforming technology. These anten-
One of the important issues in heterogeneous networks is the presence of asymmetric links or unidirectional links in the worst case. Consider the scenario shown in Fig. 1, where node A is an OD node and B is a D node and the distance between them is greater than O-O communication range. When A broadcasts, node B can hear as it uses directional reception. However when B broadcasts, node A cannot hear as node A is an OD node and is beyond the O-O communication range. Thus the routing metric for heterogeneous networks should consider link asymmetry into account.

Of the existing routing metrics, ETX implicitly takes the link asymmetries into account. Hence, we use ETX as the basis for designing our routing metric. Further, it is one of the best routing metrics for homogeneous networks with OD nodes, and has a better performance than the hop count metric for static ad hoc networks [4]. Moreover, neighbor discovery is straightforward with ETX as the routing metric. Since ETX has been defined for a homogeneous network having OD nodes, we extend ETX to design a routing metric that accounts for the D nodes in the network. We briefly describe how ETX works and suggest modifications to ETX for heterogeneous networks.

The ETX metric is calculated in the following manner. Nodes in the network periodically (every 1 second jittered up to 100 ms) broadcast specially designed probes. A node’s probes contain its neighbors and the number of ETX probes that this node has heard from these neighbors in the last 10 seconds. Thus when a node A receives a probe from another node B, it knows how many of its probes have reached B in the last 10 seconds. Further, node A also keeps track of the number of probes it has heard from B. The number of probes
ETX metric for the link is calculated as \( \frac{100}{d_f \times d_r} \), where \( d_f \) and \( d_r \) are the number of probes received in the last 10 seconds in the forward and reverse directions respectively. Thus ETX accounts for any link asymmetries. We make a minor addition to the ETX probes; nodes also indicate their type, i.e OD or D in their ETX probes. This way a node not only knows its neighbors, but also the type of the neighbor. With normal broadcast power, nodes can only discover their neighbors in the O-O communication range. In order to discover nodes beyond the O-O communication range, nodes have to increase the default broadcast power.

We suggest the following mechanism for discovering nodes that are beyond the O-O communication range but also some of the nodes beyond the O-O communication range. This allows an OD node to potentially reach nodes beyond its O-O communication range. This in turn implies the destination can be reached in a fewer number of hops and hence a higher throughput can be achieved. The increased broadcast power has additional implications at the MAC layer, which we discuss in the next section. Further, we also want to to distinguish between nodes that are in the O-O communication range and those that are beyond this range so as to use transmission power in a conservative manner.

We suggest the following mechanism for discovering nodes that are beyond the O-O communication range and distinguish them from those in the O-O communication range. We do this by defining an additional ETX-like metric, ETX1. The combination of ETX and ETX1 is the new power-controlled ETX metric. ETX probes are transmitted at the default broadcast power, while ETX1 probes are transmitted at a higher power. A node either broadcasts an ETX or an ETX1 probe. It alternately broadcasts ETX and ETX1 probes every second, and hence an ETX or an ETX1 probe is broadcasted every 2 seconds. Nodes now additionally calculate the ETX1 metric between themselves and their neighbors in the same manner as they calculate ETX metric. Thus, a node B (OD node) that is beyond the O-O communication range of A (OD node) will have a finite ETX1 metric and an infinite ETX metric.

In the route discovery phase, nodes broadcast the RREQ messages at a higher power (equal to the transmission power of ETX1 probes) than the default broadcast power. Intermediate nodes add the ETX and the ETX1 values (between itself and the previous hop) in the RREQ message. If the previous hop is an OD node, the ETX values are doubled so as to penalize routes that have OD nodes. Ideally, the route should have higher D nodes so as to increase the throughput. If an intermediate node receives the RREQ message for the first time, it forwards the RREQ message.

In the actual version of DSR, intermediate nodes do not forward duplicate RREQ messages. However, with this mechanism the best routes may not be found. With metrics such as ETX [4], duplicate RREQ messages are sent if the ETX metric is better than the ETX metric of any previously forwarded RREQ message. In the current case, we have a choice between ETX, ETX1, and a linear combination of ETX and ETX1 (e.g., ETX + ETX1). Since ETX1 probes are transmitted at a higher power, nodes that are in the O-O communication range and beyond it have a finite ETX1 metric. Thus choosing ETX1 will potentially lead to a shorter route and hence a higher throughput can be achieved. Therefore, intermediate nodes use ETX1 metric for determining to forward duplicate RREQ messages or not.

When the destination receives the RREQ message, it replies to the first RREQ message. It replies to the subsequent RREQ messages only if the combined ETX and ETX1 (ETX + ETX1) metric of the route is better than that of the previously replied RREQ messages. The destination node does not use ETX1 metric because using ETX1 metric increases the chance of selecting a route that requires all the nodes in the path to use higher transmission power. Using the combined metric reduces this chance and hence allows some of the intermediate nodes to use default transmission powers, and thus conserve energy. The destination node stores the routes from the RREQ messages to which it replied in its route cache.

Once the source node receives the route reply (RREP) message(s), it stores the route in its route cache. Intermediate nodes are not allowed to cache routes from the RREP messages. The source node selects the best route and uses it to transmit data. The best route has the minimum (ETX + ETX1) metric. Since some of the nodes in the route are beyond the O-O communication range, nodes should know the power levels to reach the next hop. An intermediate node determines the power level to transmit data to the next hop as follows. It checks its neighbor table and sees if there is a finite ETX value between itself and the next hop. If so, it uses the default power level to transmit data and if not the higher power is used to transmit data.

With directional antennas, the network performance not only depends on the routing protocol but also on the MAC protocol. We study MAC layer issues that arise in a heterogeneous network in the next section.

IV. MAC LAYER ISSUES

As mentioned previously, a lot of research effort has been focussed on modifying the IEEE 802.11 DCF protocol [1] for directional antennas. This existing body of work assumes a homogeneous network and problems such as deafness and directional hidden terminal have been identified [5]. Our focus is not to design a MAC protocol for heterogeneous networks. However, we identify a few relevant issues that need to be considered at the MAC layer. We suggest a few changes to the 802.11 MAC protocol to overcome these issues. These issues are related to the handshake messages and the transmission power used by nodes.

In most of the existing MAC protocols for directional antennas, nodes use a directional handshake to improve the spatial reusability. However in a heterogeneous network, a D node is likely to have OD neighbors and using a directional handshake can aggravate the deafness problem. To avoid
this issue, all D nodes transmit RTS/CTS messages omnidirectionally. However, nodes use directional transmissions for transmitting the data and the acknowledgment frames. As mentioned in the previous section, nodes determine the power levels for transmitting data frames using the neighbor information. Nodes try to avoid using a high transmit power so as to reduce the power consumption and the interference levels at neighboring nodes. We use the same power levels for transmitting RTS/CTS messages.

Increasing the transmission power is not a good idea for the following reasons. Devices might be running on batteries or limited power supplies. Therefore, devices need to conserve energy so as to prolong the lifetime of the network and hence using a high transmission power is not suggested. Increasing the transmission power also increases the interference levels at the neighboring nodes or nearby communicating devices. However increasing the transmission power enables nodes to find shorter routes and improve the reliability of the message delivery (as the SINR increases at the receiver).

In heterogeneous networks, asymmetric links are created due to the difference in gain between an OD node and a D node. This problem is analogous to the directional hidden terminal problem with directional antennas [2]. In homogeneous networks with directional antennas, nodes use directional transmissions to overcome the difference in gains in the OM and D mode. However in heterogeneous networks, D nodes need to use a higher transmission power to overcome this issue. It is known that using different power levels among different nodes in a homogeneous network causes asymmetric links [6]. Thus, in heterogeneous networks using variable power levels creates more asymmetric links than in a homogeneous network. However using ETX as the routing metric should avoid these asymmetric links while finding the routes. We evaluate this aspect the Section V.

To summarize, we use the 802.11 MAC protocol with the following features. OD nodes use the standard 802.11 MAC DCF protocol, while D nodes use a modified version of the 802.11 MAC protocol [7]. Further, D nodes use omnidirectional handshake messages and use the directional mode for data and acknowledgment frames. The power level for the handshake messages and the transmit messages is determined from the neighbor information.

Interested readers are referred to [2] and [8] for a complete discussion on the MAC layer issues in using directional antennas. We discuss simulations in the next section.

V. SIMULATIONS

We use Qualnet (ver 3.9) [9] simulator for our simulations. Nodes use 802.11 b radios with a fixed transmission rate of 11Mbps. The O-O communication range is nearly 250 m and the O-D communication range is nearly 500m when using the default transmission power of 15 dB. In all our simulations, we use the first 100 seconds of simulation time for neighbor discovery using ETX probes. Once the discovery process is done, we use dummy traffic to find routes between the nodes. Once routes are found, we use those routes for simulating the actual traffic. We simulate the actual traffic for 200 s. We report the aggregate throughput achieved in the network. All the points in the subsequent graphs correspond to an average of 5 runs.

The objectives of our simulations are as follows: to compare the performance of a heterogeneous network that consists of omnidirectional antennas and directional antennas with that of a homogeneous networks, to evaluate the performance of the power-controlled routing metric and compare it with the performance of the ETX metric for heterogeneous networks, and to evaluate the levels of asymmetry in the routes chosen by the power-controlled ETX metric and ETX metric for heterogeneous networks.

![Fig. 2. Grid topology for simulations](image-url)
ETX metric. However at a traffic rate of beyond 100 packets per second, the power-controlled ETX metric has a better performance and improves the performance up to 11% over the ETX metric. The improved performance at higher rates with the power-controlled ETX metric can be attributed to the improved SINR at the receivers.

We next consider a random topology of 50 nodes of which 10 nodes use directional antennas. We randomly select 10 pairs of flows to evaluate the network performance. We initially evaluate the performance with the homogeneous case of OD nodes to get a lower bound on the aggregate throughput. Fig 4 shows the network performance for the three cases. We observe that the heterogeneous case has a far superior performance than the homogeneous case. The ETX metric (heterogeneous case) improves the performance up to 189% over the OD case, and the power-controlled ETX metric improves the performance up to 200% over the OD case. Further, the power-controlled ETX metric has a better performance than the ETX metric and provides an improvement in throughput up to 8%. The network is not well connected in the homogeneous case and hence the achieved aggregate throughput is low. Using directional antennas improves the connectivity of the network and hence a higher throughput is achieved. The throughput increases with an increase in the transmission power (power-controlled ETX metric case) as the connectivity is increased further and the improved SINR at the receivers.

In the previous section, we have mentioned that heterogeneous networks consisting of OD and D nodes that use variable transmission power levels will have higher asymmetric links than a homogeneous network. We now evaluate the asymmetric nature of the routes chosen by ETX and the power-controlled ETX for heterogeneous networks. We initially use 100 seconds of simulation time for neighbor discovery and then use dummy traffic to find the routes. We then use the next 100 seconds for simulating the traffic in the forward direction and then use the next 100 seconds for simulating the traffic in the opposite direction. We define the asymmetry ratio for characterizing the asymmetric nature of the routes.

It is defined as the ratio of difference in throughput (absolute value) between the forward and reverse directions over the average throughput in both the directions. A more asymmetric route would have a higher asymmetric ratio. Fig 5 shows the asymmetry ratios for the two metrics. We observe that ETX metric chooses lower asymmetric routes than the power-controlled metric. However the asymmetry ratios for the routes for both the metrics are below 30 % and hence we conclude that both the metrics choose non-asymmetric routes.

To summarize our results, heterogeneous networks with directional antennas and omnidirectional antennas have a better performance than a homogeneous network of omnidirectional antennas. We find that the aggregate throughput can be improved up to 200 % in a random topology and up to 47% in a grid topology. The routes chosen by ETX and power-controlled ETX are not-asymmetric and the asymmetry ratios are below 30 %.

VI. RELEVANT WORK

Roy et al [10] compare the performance of multipath routing with omnidirectional and directional antennas in homoge-
neous networks. They hypothesize that “route coupling” is minimized when directional antennas are used, and hence a higher throughput is achieved using directional antennas than with using omnidirectional antennas. Roy Choudhury et al [5] evaluate the performance of dynamic source routing (DSR) using directional antennas. They suggest a “delayed route reply optimization” mechanism that allows better routes to be discovered. Roy Choudhury [8] propose a capture aware routing protocol for multi-beam smart antennas that minimizes the effect of MAC layer capture thus improving the performance of the network. A weighted metric of hop count, capture-awareness, and node-sharing is used for choosing the routes. Recently, Cheekiralla et al [11] compared the performance of a queue-length based routing metric with the hop count metric and found that the queue length-based metric performs better than the hop count metric.

Sundaresan and Sivakumar [12] propose a MAC and routing protocol for heterogeneous networks that includes omnidirectional antennas, fixed beam antennas, adaptive array antennas, and Multiple-Input, Multiple-Output (MIMO) antennas. A heterogeneous routing protocol similar to DSR is described. This protocol uses a three-tuple routing metric of which the first two components capture the spatial reusability of the network and the third component captures the link rate. However, they assume the same transmission range for all the links on the network. Thus, the advantage of increased range that is possible by using a smart antenna is lost. We would like to distinguish our work from theirs as we consider a more specific case of heterogeneous network and our focus is on designing and evaluating a routing metric for this specific case. Further in our work, the higher communication range of directional antennas is not sacrificed.

Yarvis et al [13] use a resource aware routing and MAC protocol for exploiting the heterogeneity in the network. Heterogeneity is considered from an energy and link perspective. They evaluate the quantity and placement of the heterogeneous nodes in the network through analysis, simulation, and deployment. They find that using a modest amount of line-powered nodes and long-range back haul links improves the network life time. Fujii et al [6] describe a MAC protocol for heterogeneous ad hoc networks where nodes use different transmission powers. They propose using additional handshake messages that allow lower powered nodes to communicate effectively in the presence of higher-powered nodes. We realize that these works are complimentary to ours.

VII. CONCLUSIONS

In this paper, we presented a novel routing metric (power-controlled ETX metric) for routing in heterogeneous networks that consist of directional and omnidirectional antennas. We compared the performance of this metric with the standard ETX metric in homogeneous and heterogeneous networks by performing simulations of grid and random topologies. The homogeneous network consisting of omnidirectional nodes gave a lower bound on the performance of the routing metrics. Specifically, we observed improvements up to 200% in a random topology and up to 47% in grid topologies with heterogeneous networks.

We observed that heterogeneous networks consisting of directional and omnidirectional antennas have asymmetric links and these links increase with the power-controlled ETX metric. Since ETX inherently accounts for link asymmetries, we find that using ETX and the power-controlled ETX metric keep the asymmetry ratios of the routes below 30%.

Note that in the grid topology considered, the source and destination were omnidirectional nodes and the intermediate nodes were directional nodes. Such a topology would be useful in disaster management or providing Internet connectivity, where the omnidirectional nodes are the edge nodes and the intermediate directional nodes provide shorter and better links for higher throughput. Work is currently in progress to evaluate the impact of number of directional antennas and their placement on the network performance.

In the future, we plan to address the various MAC layer issues in heterogeneous networks in greater detail. Specifically, we plan to use neighbor information from the routing layer to design the features for MAC protocol. For example, these could be adaptive usage of power and omnidirectional and directional transmission of control messages. We also plan to study the impact of increasing the power in a greater detail as part of our future work.

REFERENCES