Adaptive Multiple Metrics Routing Protocols for Heterogeneous Multi-Hop Wireless Networks

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***Abstract*— The calculation of path cost is a critical component of route discovery for network routing. The criteria used to represent path cost guides resource consumption in the network. In this paper, we describe our approach, a set of protocols based on our Multiple Metrics Routing Protocol (MMRP) for integrating hop count, energy consumption, and traffic load into the path cost calculation for ad hoc or multihop-cellular networks. Our initial aim is to select among multiple disjoint routes in order to maintain a low path cost, in terms of energy consumption and delay, without depleting resources at popular intermediate nodes. One extension of MMRP removes the constraint that only disjoint paths are considered and enables discovery of more optimal routes. A second extension includes adaptive adjustment of cost metrics to support device classification (e.g., energy capacity, bandwidth) in heterogenous networks. We illustrate our approach with a simple example, followed by extensive simulation analysis. Results indicate that proper combination of multiple metrics for calculating path costs results in improved performance and lower overall system resource consumption as compared to AODV or energy efficient routing protocols.**

I. Introduction

The calculation of path cost is a critical component of routing for multi-hop networks, including ad hoc and sensor networks, as well as multi-hop access networks for hybrid and mesh systems. Path cost is typically determined during the route discovery phase wherein some form of flooding is used to disseminate route request messages from a source, and a route reply is forwarded by the destination to identify the "least-cost" path found. The path cost is usually determined by accumulating one or more cost metrics at each intermediate node as the route request propagates from the source to the destination.

Prior work on multi-hop network routing protocols relies largely on the use of path cost metrics commonly used in reactive ad hoc routing protocols. These metrics include the number of hops in a path [1], [2], the energy consumed along a path [3]–[5], the energy remaining after using a path [6], or the load carried by nodes along a path [7]–[10]. The aim is to guide path selection to favor the least-cost path, where the path cost metric reflects the criteria that is to be minimized.

A side-effect of this approach is the limitation of a single metric to guide path selection, which could overload or deplete resources along preferred paths. To mitigate this, routing protocols combining multiple metrics have been proposed recently, such as [6], [11]. In this paper, we describe our Multiple Metrics Routing Protocol (MMRP) which combines multiple metrics (initially hop count, energy cost and traffic load). Our initial version of MMRP improves upon the performance of the popular AODV routing protocol, but considers only disjoint paths between a source and destination. Therefore, we introduce an extended version of MMRP (MMRP-I) that removes the constraint that only disjoint paths are considered to enable discovery of a greater number of path choices, guided by the metrics in use. This is implemented, in part, by enabling intermediate nodes to forward updated route requests.

Development in new radio access and wireless communication technologies is driving the deployment of a wide array of various wireless devices to form heterogenous or hybrid networks. Routing protocols that assume that all network devices are identical, do not fit well in such networks. As such, we take advantage of the flexibility of combining multiple metrics in MMRP, and extend it to a new method (MMRP-A) for heterogenous or hybrid networks. In MMRP-A, based on the device classification, the routing protocol can adaptively adjust the parameters at each device used to weigh the combining of multiple metrics that comprise the path cost. For example, for wireless devices with fixed power supply, MMRP-A will not consider the energy metrics.

Our simulations illustrate that the use of multiple metrics path cost, during the route discovery phase, can provide greater control over how network resources are allocated, and thereby result in improved performance and reduced resource consumption. In addition, simulations in heterogenous networks also indicate that the adaptive method performs better than other methods in such networks.

In summary, the contributions of this paper are: (1) we propose a general framework (MMRP) to combine multiple different cost metrics, instead of just power related metrics as in [6] and [11]; (2) to accommodate heterogeneous devices, we further propose MMRP-A protocol which adaptively assigns coefficients in the combined metric based on device classification; (3) we conduct a series of simulations to evaluate the performance of our proposed methods.

II. Related Work on Multihop Routing

Multihop routing protocols using different cost metrics have been proposed in related work, such as shortest-path routing, energy efficient routing, load-aware routing and so on.

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Shortest-path routing, which aims to find the route with the minimum hop count value, has been widely used in both wired and wireless networks. The most important feature of the shortest path is that it usually has the minimum delay and is easily implemented. For ad hoc networks, shortest path routing protocols have been proposed in early research, such as classical DSDV [2] and AODV [1]. However, always using the minimum hop count for path cost is not perfect. Research shows that this group of protocols degrade network performance in some situations due to congestion and power depletion on those nodes along the minimum hop path.

In order to solve such problems, load-aware routing and energy efficient routing have been proposed. In [7]–[10], authors proposed load-aware routing protocols to discover routes with the minimum traffic load. These load-aware routing protocols use different cost metrics to measure traffic load of a route. For example, in [7], the authors used the number of packets buffered at intermediate nodes along the route as a route selection metric. Thus, load-aware routing protocols can avoid congestion by detouring around nodes with high traffic load.

Energy is an important resource for ad hoc networks, since every node is powered on battery. Energy efficient routing protocols are mainly divided into three categories. Protocols in the first category aim to minimize the total power consumption, for example, the minimum total transmission power routing (MTPR) proposed in [4], which selects the route with the minimum total transmission power. Protocols in the second category aim to maximize the lifetime of every node in the network. Minimum Battery Cost Routing (MBCR) and Min-Max Battery Cost Routing (MMBCR) in [6] use remaining battery capacity as cost metric and aim to find the route with maximum battery capacity. In [5], the authors proposed a protocol which used the remaining node lifetime as cost metric and selected the path with maximum lifetime. In order to achieve a tradeoff between minimizing the total transmission energy and maximizing the lifetime of each node, protocols in the third category combine these two aspects during route discovery, i.e., Conditional Max-Min Battery Capacity Routing (CMMBCR) [6] and Power-Aware On-Demand Routing [11].

III. Multiple Metrics Routing Protocols (MMRP)

A. Multiple Metrics Path Cost

Since different routing metrics play certain importance in the multihop routing, we propose to simultaneously consider them to determine the path cost. MMRP uses a simple linear combination of different routing metrics. Here, we use three routing metrics as a case study: hop count, energy cost and traffic load. The combined cost $cost$ is computed using the following equation:

$$cost = cost' + \alpha_1 \times 1 + \alpha_2 \times load + \alpha_3 \times energy\_cost \quad (1)$$

Here, "1" is hop count, $cost'$ is the accumulated cost of previous nodes in the path; $load$ represents the traffic load at the current node; and $energy\_cost$ denotes the energy cost for the link from the previous hop to the current node. α_1 , α_2 and α_3 are three weighted factors (or called coefficients) to calculate the cost. By varying these three weighted factors, we can change the importance of the three cost metrics during route discovery. For example, we can set $(\alpha_1, \alpha_2, \alpha_3) = (1, 0, 0)$, which means we only consider hop count. Hence, we can scale these factors to easily change our route selection scheme.

B. Routing Protocols

MMRP is an on-demand routing protocol modified from the classical AODV routing and using the cost definition in the previous section.

Whenever a source node requires communicating with another node for which it does not have a route, it initiates the route discovery phase by broadcasting a Route Request (RREQ) packet to all its neighbors. The RREQ contains the following fields: <source_addr, source_sequence_no, broadcast_id, dest_addr, dest_sequence_no, hop_count, cost>. The cost field is initialized to zero and is updated by intermediate nodes involved in route discovery, as follows. Upon receiving the RREQ, an intermediate node first checks whether it has received this RREQ before. If yes, it drops the RREQ. Otherwise, it updates the hop_count entry by adding one, and updates the cost field with Equation (1). The intermediate node then creates a new entry in its routing table to record the previous hop and rebroadcasts the RREQ.

After the destination node receives the first RREQ, it starts to wait for a period of time to receive enough RREQs. Then it selects the route with the smallest cost value and sends back a Route Reply (RREP) to the source node via the selected route. Upon receiving the RREP, an intermediate node records the previous hop and relays the packet to the next hop. A key feature of this protocol is that the destination does not react to the first route request, which likely is received via the shortest path. Rather, the destination waits for additional route choices to arrive that may exhibit a more favorable cost when energy and congestion are also considered, and this delay replying technique was first used in DSR [12].

Same as AODV, if a node detects a link break during route maintenance phase, it sends a Route Error (RERR) packet to the source node. Upon receiving the RERR, the source node initiates a new round of route discovery.

C. Improvement: MMRP-I

However, MMRP can not guarantee optimal path selection since intermediate nodes only process the first received RREQ message (i.e., it drops all later received RREQ message). For example, in a network shown by Figure 1, from the source S to the destination D, path $S \rightarrow M1 \rightarrow M2 \rightarrow D$ is the minimum energy path. If we use the MMRP and set $(\alpha_1, \alpha_2, \alpha_3) = (0, 0, 1)$, ideally the routing method will pick up the minimum energy path. However, it is possible that the RREQ message from node $M0$ (not the RREQ from node $M1$) first arrives at node $M2$. Then the MMRP will select the non-optimal route: $S \rightarrow M0 \rightarrow M2 \rightarrow D$, since in MMRP the intermediate node only forwards the first arrived RREQ message. In order to address this problem, we propose to enhance the above method by allowing intermediate nodes to process later received RREQ messages as long as it has a better cost value. Hereafter, we call the enhanced method MMRP-I. So for the example in Figure 1, when the RREQ from node $M1$ arrives at $M2$, since it has a better path than the RREQ from $M0$, $M2$ will forward it so that the optimal path can be selected by the destination.

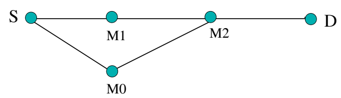


Fig. 1. MMRP may select non-optimal path.

Notice that since MMRP-I allows the intermediate nodes to rebroadcast multiple RREQ messages for a RREQ message from the same source, the overhead of the routing method increases. This is the price for getting possibly better routes. There is a trade-off between overhead and performance. One way to balance this trade-off is to define a threshold t and allow only a RREQ with a cost value which is at least t better than the previous RREQ from the same source to be processed.

D. Adaptive Cost for Heterogenous Networks: MMRP-A

With MMRP-A, we further extend the flexibility of the path cost calcuation by adaptively determining the metric weights. In equation (1), we assume that the values for load, energy cost, and other similar metrics that could be added, are determined by the mobile devices themselves. This enables mobiles to set and advertise their costs. The metric weights $(\alpha_1, \alpha_2, \alpha_3)$ are determined on a system-wide basis. However, for heterogeneous networks, metric weight selection may vary by device class. Device classes could, for example, be differentiated based on the battery type, the amount of memory, or the air interfaces present in a particular type of mobile device. Alternatively, one may choose to vary the metric weights based on real-time measurements of system performance.

MMRP-A uses adaptive cost functions for heterogenous networks. As a simple example, in our simulation for heterogenous networks (presented later), we define two classes of nodes: one is common mobile nodes with limited battery capacity, and the other is static nodes with fixed energy supply. MMRP-A will adaptively change the weight value based on the node class during the route discovery phase.

IV. Performance Evaluation

We analyze MMRP, MMRP-I and MMRP-A using NS-2 [13]. In our simulations, IEEE 802.11 distributed coordination function (DCF) MAC protocol and two-ray ground propagation model are used. We first simulate a simple network set up to illustrate how MMRP-I better balances network traffic, as compared to sole use of energy, load or hop count (AODV), and as compared to MMRP. We then perform extensive simulations for larger wireless networks with random topologies to evaluate our protocols.

A. Multiple Routing Metrics

Before presenting our simulation, we first describe how we use the multiple routing metrics. In the simulations, we use three simple routing metrics: hop count, traffic load, and energy cost. Here, the selection of these three routing metrics is just for demonstration of our multiple metrics method. To achieve better performance, more metrics could be considered.

Traffic load: In the simulation, we use the interval time between receiving two data packets to estimate the traffic load of a node. To do that, each node maintains a weighted interval value $intvl$ which is scaled and unbounded in a range of $[0, 1]$, where 1 means no traffic load and 0 means high load. Upon receiving a data packet, $intvl$ is updated by $intvl = (1 - \beta) \times intvl_{old} + \beta \times intvl_{new}$. Here $intvl_{old}/intvl_{new}$ are the old/new interval values and β is an adjustable parameter (in our simulation, $\beta = 0.2$).

Energy cost: In our simulation, we only consider the transmission power (i.e., the power consumed by a one-hop link uv is proportional to $c||uv||^4$, where $||uv||$ is the distance between node u and v and c is a constant)as the power cost metric. Notice that remaining power capacity can be used as a power cost metric, but here we only use the simple transmission power to demonstrate the efficiency of our combination metrics for energy aspect. In NS-2, the power consumed by the maximum transmission range $250m$ is 0.66 watt per second, so the transmission power consumed by a link uv is $0.66 \times ||uv||^4/(250)^4$. Therefore, the range of power consumed each hop is from 0 to 0.66.

Then the multiple metrics path cost is computed by $cost = cost' + \alpha_1 \times 1 + \alpha_2 \times (1 - intvl) + \alpha_3 \times energy\_cost$. We set $(\alpha_1, \alpha_2, \alpha_3) = (1, 1, 1/0.66)$ for simulation. This normalizes the three metrics from $(0, 1)$ and gives almost equal weights to the three metrics.

B. Simple Network Illustration

In this subsection, we set up a simple network with 15 static nodes to demonstrate our new routing method. The topology of the network is given by Figure 2. There are 5 CBR (continuous bit-rate) traffic source nodes in the left circle S, and 5 destination nodes in the right circle D. The 5 source-destination pairs are: $0 \sim 5$, $1 \sim 6$, $2 \sim 7$, $3 \sim 8$, and $4 \sim 9$. It is easy to see that Path 1 is the shortest path with only 2 hops and Path 2 is the minimum energy path.

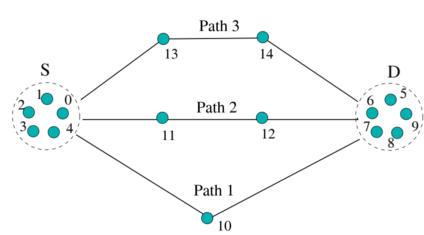


Fig. 2. A simple network for illustration of route selection.

We test five routing protocols: energy efficient routing, load aware routing, shortest path routing, MMRP and MMRP-I using 40 simulation runs. We study the route selections by these five routing methods. For each node, we record the total number of connections using that node. The result is shown in Figure 3. Clearly, the shortest-hop path routing mainly chooses Path 1 (node 10). The energy efficient routing mainly chooses Path 2 (node 11 and 12). The load aware routing first chooses Path 1. As the traffic load increases, it selects Path 2. With further increase in traffic it chooses Path 3. The MMRP routing similarly selects paths based on load balancing, but also attempts to use shorter hop paths. For MMRP-I routing, the traffic is nearly evenly distributed on the three paths. This simple simulation illustrates that, MMRP-I outperforms the other 4 routing methods in term of load balancing.

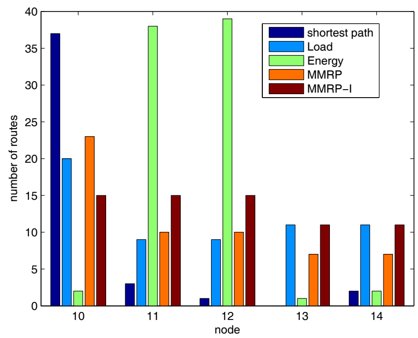


Fig. 3. Route selection results from different routing methods.

C. Simulation on Random Network Topologies

We then test the performance of our routing methods for random network topologies. We use the following four metrics to evaluate the routing performance:

- *Packet delivery ratio:* ratio of the data packets received at destinations to that sent out from sources.
- *End-to-end delay:* average time between data packets sent out from sources and received at destinations.
- *Normalized routing overhead:* ratio of control packets transmitted to data packets received at destination.
- *Energy:* average per-node energy capacity at the end of the simulation.

All simulation results are given in terms of these four metrics, for networks with high mobility to low mobility.

1) Evaluation of MMRP & MMRP-I: We compare MMRP, MMRP-I, AODV, and energy efficient routing protocols.

Simulation Setting: We simulate a network with 50 mobile nodes randomly distributed in a $1500m \times 300m$ rectangular region, with 600 seconds each simulation run. We used the random waypoint model, with node speed between $(0-20)mps$. We generated various mobility degrees with different pause time values, varying from high mobility (low pause time) to very low mobility (high pause time and even static). CBR sources were used, and the communication pairs were randomly chosen over the network. There were 30 and 40 connections in the first and second set of simulations, respectively. In addition, the waiting time of the destination to reply to the RREQ message is set as $50ms$.

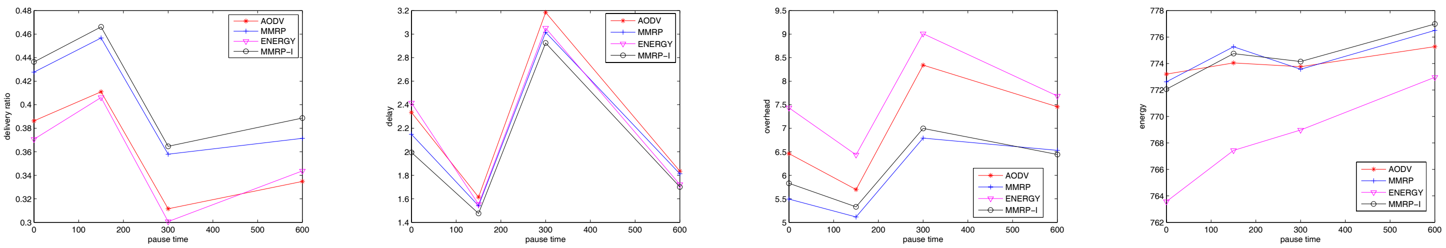
Performance: Figure 4 shows the simulation result for the first set of simulations, comparing performance of different routing protocols. The x-axis shows results for simulation scenarios with decreasing mobility (as pause time increases). The y-axis shows system packet delivery ratio, average end-to-end delay, normalized routing overhead, respectively. From Figure 4(a), we can see that, MMRP-I has the highest delivery ratio among the four protocols. Although MMRP can perform almost the same as MMRP-I for the low mobility scenario, MMRP-I can achieve up to 5% higher delivery ratio than MMRP. This is because MMRP-I can distribute traffic more evenly among the network, as we can see from Figure 3 for the simple network. Energy efficient routing prefers routes with more hops to conserve energy, thus, it has the lowest packet delivery ratio. For the same reason, energy efficient routing has the highest average end-to-end delay as shown in Figure 4(b). Even though AODV selects routes with the minimum delay, it still has a higher delay compared to MMRP or MMRP-I. This is because AODV can not evenly distribute the traffic, which degrades its performance. It is clear that MMRP-I has the smallest delay.

In Figure 4(c), MMRP-I has a higher average overhead, as compared to MMRP, when node mobility is high, causing the need for added route discovery due to broken links. However, since a static network has less route discovery due to link breakage, MMRP-I has less overhead than MMRP when pause time is 600 second. Notice that the energy efficient routing has the highest overhead. This may be due to its preference of longer paths. However, MMRP-I considers not only the energy, but also the hop count, so that it does not always take the best energy path with a large hop count. Thus, it has lower overhead than the energy efficient routing.

As shown in Figure 4(d), for average remaining energy capacity, energy efficient routing has the worst performance. This is because energy efficient routing protocol prefers routes with more hops, which are less reliable and more likely to get disconnected due to node mobility. Therefore, the difference of the remaining energy capacity between energy efficient routing protocol and MMRP is higher when pause time is 0 (high mobility) as compared to that when pause time is 600 (no mobility). We can also see that MMRP-I cannot achieve higher remaining energy capacity with high mobility, as compared to MMRP. This is due to overhead. Thus, MMRP-I can achieve better delivery ratio and delay, but with the cost of more overhead and energy consumption. In order to better balance these two aspects, we also study MMRP-I with a trade-off between the overhead and the performance by variating threshold t and only letting the RREQ with a cost value which is at least t better than the previous RREQ from the same source to be processed. Due to the space limit, we skip presenting the result. But it clearly illustrates that the average routing overhead drops as the value of t increases.

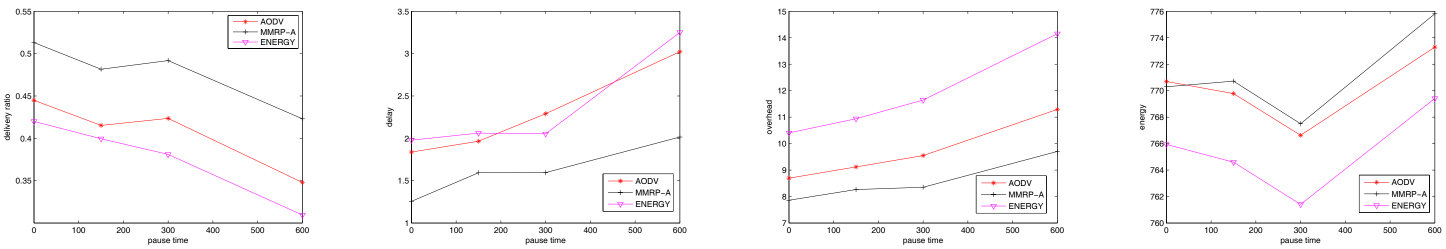
2) Evaluation of MMRP-A: In this section, we compare MMRP-A, AODV, and energy efficient routing protocols in heterogenous networks.

Simulation Setting: The simulation setting is similar as that for MMRP-I. There are only two major differences. First, the network is deployed in a $1500m \times 600m$ rectangular region;



(a) delivery ratio (b) end-to-end delay (c) routing overhead (d) remaining energy capacity

Fig. 4. Simulation results for evaluation of MMRP and MMRP-I.



(a) delivery ratio (b) end-to-end delay (c) routing overhead (d) remaining energy capacity

Fig. 5. Simulation results for evaluation of MMRP-A.

secondly, there are another 13 static nodes with unlimited battery capacity besides the 50 random mobile nodes. To consider the heterogenous devices, MMRP-A uses the same weight values for mobile nodes as defined in previous section, but sets $(\alpha_1, \alpha_2, \alpha_3) = (1, 1, 0)$ for those static nodes with unlimited battery capacity.

Performance: Figure 5 shows the simulation results for the second set of simulations. The plots show that MMRP-A achieves at least 10% higher delivery ratio, 30% lower delay, and 15% lower overhead than the other protocols. Figure 5(d) shows that MMPR-A results in higher remaining energy, except at very high mobility levels. For high mobility, the remaining energy is slightly lower for MMRP-A, as compared to AODV. However, this is a marginal added cost, given that the other metrics are significantly improved at high mobility levels. Also, MMRP-A can conserve more energy when the mobility is lower by choosing static nodes as relays during route discovery phase. It appears that MMRP-A is promising for routing protocol design for heterogenous networks.

V. Conclusion

Herein we described a set of protocols that use multiple criteria for the calculation of pathcost during multihop network route discovery. MMRP combines energy cost, hop count, and traffic load metrics into a pathcost parameter, and selects among multiple disjoint paths. MMRP-I allows intermediate nodes to forward updated route requests, enabling selection among paths that are not disjoint. MMRP-A enables the cost metric weights to be dynamically assigned based on device classification. Our simulation results indicate that the use of multiple metrics for calculating path costs results in improved performance and lower overall system resource consumption. In the simulation, we use the transmission power as the only energy cost at each node, however, the reception power can also be considered (by adding a new metric in our combined-metric). As a future work, we will focus on how to classify heterogeneous devices and how to adjust the coefficient parameters based on device types or service requirements.

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