An Energy-Aware Multipath Routing Protocol for Mobile Ad Hoc Networks

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***Abstract*— In this paper, a cross-layer optimized energy-aware multipath routing protocol (EMRP) for mobile ad hoc networks (MANET) is proposed. By sharing the information among the physical layer, the MAC sub-layer and the network layer, EMRP efficiently utilizes the network resources such as the node energy and the link bandwidth. Simulation results show that the protocol prolongs the network lifetime, increases the volume of packets delivered, lowers the energy dissipation per bit of data delivery and shortens the end-to-end delay.**

I. Introduction

One of the basic characteristics of a mobile ad hoc network (MANET) is the multi-hop connection, in which mobile nodes cooperate to relay traffic to the distant destination node that would otherwise be out of direct communication range. Therefore, nodes in MANET serve not only as hosts, but also as routers. The multi-hop connection can also increase network capacity and decrease the energy consumption for transmission. However, due to the frequently changing network topology and limited resources of energy and wireless bandwidth, routing in MANET is an extremely challenging task.

Basically, the routing protocol which chooses the best route between the source and destination nodes to fulfill the multi-hop transmission is called single path routing. In cases of highly dynamic network topology and strictly limited resources, however, single path routing is not the best solution. Multipath routing protocols are then introduced, which provides redundant and alternative routes to assure successful data packet transmission and, at the same time, reduce the key relay nodes' power consumption, alleviating the network partitioning problem caused by the energy exhaustion of these nodes.

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Another key issue in MANET protocol design is cross-layer optimization. Based on the OSI 7-layer model, traditional network protocol design explicitly defines and strictly restricts the information exchanged between layers. However, this prevents efficient protocol design in MANET. For example, under the layering restriction, MANET routing protocols are unable to retrieve energy and location information from the underlying data link layer and physical layer and, thus, unable to calculate good routes based on such information. We will use the term "cross layer design" and "cross layer optimization" interchangeably hereafter to refer to protocol design and optimization based on the inter-layer exchange of information beyond the OSI-layer structure definition.

Based on the rationale of multipath routing and cross-layer design, we introduce the Energy-aware Multipath Routing Protocol (EMRP) for MANET. EMRP is a multipath routing protocol which uses information from the physical layer and the MAC layer in choosing routes, focusing on the energy efficiency and the overall network performance. Simulation results show that EMRP outperforms the traditional single path routing protocol in providing longer network lifetime and lower energy consumption per bit of information delivered. In addition, as in other multipath routing protocols, it reduces the end-to-end delay and improves the volume of packets delivered.

The rest of this paper is organized as follows. Section 2 reviews the related research on multipath routing protocols. In Section 3, we discuss the basic ideas of the EMRP and present the details of its implementation. The simulation considerations and results are discussed in Section 4, and Section 5 concludes the paper.

II. Related Work

Multipath routing protocols transmit data packets in multiple paths simultaneously. Compared to single path transmission, concurrent transmission on multiple paths performs better in end-to-end delay, network throughput and path robustness with no doubt in most cases. Due to these advantages, multipath routing has been extensively studied in ad hoc networks [1-13].

The multipath routing protocol seeks disjoint routes between source and destination nodes. Modeling the network as an undirected graph $G = (V, E)$, where V is set of $|V|$ nodes and E is set of $|E|$ undirected links connecting nodes in V, for any two nodes S and D, a multipath routing protocol looks for N sets of nodes $< V_1^i, ..., V_n^i, >$, which satisfy:

1) $V_1^i = S$, $V_n^i = D$; $\forall i$, $1 \leq i \leq N$
2) $(V_j^i, V_{j+1}^i) \in E$; $\forall i, j$, $1 \leq i \leq N$, $1 \leq j \leq n-1$
3) $V_j^i \neq V_l^k$; $\forall i, j, k, l$; $1 \leq i, k \leq N$, $1 \leq j, l \leq n$, $i \neq k$, $j \neq l$

Note that sometimes it may not be possible for paths to be completely disjoint, and 3) is relaxed. Multipath routing was first introduced in wired-line networks for the purpose of load balance and error tolerance. In [2], Pearlman et al. applied Alternate Path Routing (APR), commonly used in wired-line network, into MANET and discussed the performance degradation caused by the coupling of transmission paths [3](Here coupling means different paths sharing one node). After that, research on multipath routing is mainly focused on the case of disjoint paths. In [4], Split Multipath Routing (SMR) only uses two shortest and decoupled paths to transmit packets simultaneously. Wu[5] developed a new way to acquire disjoint paths through re-directed Route Reply Packets. Tsirigos[6,7] found a new application of multipath which divides one data packet into a few smaller pieces and transmits them simultaneously in different paths and include some redundant pieces to ensure the receiver can re-build the original packet even when some pieces are lost on their way.

The rules under which data packets are assigned to multiple paths are not always the same. Commonly, round-robin is used. But to achieve better system performance, more complicated route selection criteria may be implemented. To satisfy the QoS demand, MP-DSR [8] used end-to-end reliability to evaluate the value of routes. In [11-13], Multipath Source Routing (MSR), which selects the routes according to their round trip time (RTT), was proposed and analytical results were presented verifying that the optimum RTT was achieved under this route-selection criterion.

None of the multipath routing schemes in [1-13] considers how to achieve energy efficiency while still improving the system performance such as end-to-end delay, robustness, and throughput. EMRP uses information from the physical layer and the MAC layer to evaluate energy efficiency and available bandwidth of the currently selected routes. It achieves the goals of lowering the energy dissipation per bit of data delivery and distributing the energy consumption of network evenly in both the spatial and temporal domains.

III. Details of EMRP

EMRP is a multipath source routing protocol derived from Dynamic Source Routing (DSR)[14]. It inherits the basic framework of DSR but makes some important changes in the phases of Route Reply, Route Selection, and Route Maintenance according to energy and queuing information obtained from the underlying layers. EMRP is designed to run over an enhanced version of the IEEE 802.11 MAC protocol[15], providing efficient information for route selection and a power control scheme.

A. Route Reply Phase

On commencing a new data transmission, the source node checks its route cache first to see whether there are available routes to the destination node. If routes are available, the protocol goes into the route selection phase, which will be presented in next sub-section. Otherwise, the source node goes into the route request phase to discover available routes.

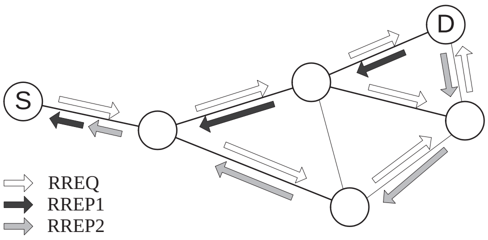

Fig. 1. Route Reply Phase of EMRP

The source node broadcasts a Route Request (RREQ) packet, which contains the source and destination IDs, to all other nodes in the network. When a destination node receives an RREQ, it sends a Route Reply (RREP) packet to the source node to establish a route following the reverse path on which the RREQ arrives, as shown in Fig.1. Different from DSR, in EMRP, while an RREP packet is being sent back to the source node, each node on the traverse route will stamp its current status in the RREP packet, which is finally collected by the routing agent at the source node. This status information is shown in Table I, in which i is the index for the mobile nodes.

Information Field	Contents
$d_{i,i+1}$	Distance between this node and the next-hop node, provided by the physical layer (see [15] for details).
$N^i_{retrans}$	Number of retransmission attempts corresponding to the last successful transmission, provided by the MAC layer.
N^i_{queue}	Current length of queue, provided by the network layer.
E^i_{remain}	Current remaining energy of this node, provided by the physical layer.

TABLE I
Information Fields of RREP Packets

B. Route Selection Phase

In EMRP, the source node waits a certain period of time to collect RREP messages from the destination nodes along various paths, which is exactly what DSR does. But, different from DSR, EMRP chooses the working set of routes from all available routes according to the following rules.

First of all, EMRP calculates the weight of each available route according to the following equation:

$$W = \sum_{i=1}^{n} (\alpha \times W^i_{energy} + \beta \times W^i_{queue}) \qquad (1)$$

where W is the weight of the route and W^i_{energy}, W^i_{queue} are the weights of node i considering the energy and queue length respectively. α and β are the weighting factors which normalize $W^i_{energy}$and W^i_{queue} . A route is selected based on ascending values of *W*.

W^i_{energy} is calculated as follows:

$$W^i_{energy} = (\frac{P^i_{tx}}{E^i_{remain}} + \frac{P^{i+1}_{rx}}{E^{i+1}_{remain}}) \times (1 + N^i_{retrans}) \quad (2)$$

where P^i_{tx} and P^{i+1}_{rx} are the transmitting energy cost from node i to the next-hop node $i+1$ and the receiving energy cost of the next-hop node $i+1$, respectively. P^i_{tx} may be calculated by $d_{i,i+1}$, the distance between node i and the next-hop node $i+1$ using propagation models, i.e. the Free Space Model or the Two-ray Ground Reflection Model. P^{i+1}_{rx} is chosen to be a constant according to the property of the physical layer. E^i_{remain} is the remaining energy of node i and $N^i_{retrans}$ is the number of retransmission attempts corresponding to the last successful transmission on node i, which equals to zero at the beginning.

W^i_{energy} is a function of the distance, remaining energy, and degree of contention in the wireless channel of node i and the next-hop node $i+1$. More remaining energy, shorter distance, and fewer number of retransmissions indicate less W^i_{energy}.

W^i_{queue} is given below:

$$W^i_{queue} = \log(1 + N^i_{queue}) \quad (3)$$

where N^i_{queue} is the queue length at node i.

W^i_{queue} depends on the queue length along the current route. If there are more packets in the queues along the route, the transmission will inevitably suffer a longer delay. W^i_{queue} increases rapidly with N^i_{queue}.

For each returned RREP packet, the source node calculates corresponding route's W with the values of $d_{i,i+1}$, $N^i_{retrans}$, N^i_{queue}, and $E^i_{remain}(1 \leq i \leq n)$ brought back in the packet. EMRP then sorts available routes in an ascending order of W and takes the top N sets of routes as the primary paths to transmit the data simultaneously and take the next N sets of routes as backup paths. In the current version of EMRP, N is designated as 3 in reference to [16]. Packets are then distributed according to inverse weighted assignment, i.e. a route with smaller weight will win more packets. This is because a smaller weight usually indicates that along the path, there is more remaining energy, less energy consumption due to transmitting and receiving, less crowded channel in the vicinity around the path, and thus more bandwidth available. Simultaneously transmitting packets along these routes achieves better energy efficiency, lower end-to-end delay, and higher volume of packets delivered. The energy dissipation per bit of data is reduced, and the energy consumption of the network is evenly distributed spatially and temporally.

C. Route Maintenance Phase

Since the information on location, remaining energy, and available bandwidth of nodes fluctuates in MANET, it is important to keep such information up-to-date.

There are two mechanisms implemented in EMRP to update this information. The first one piggybacks the nodes' information on the Ack packets of TCP flow transmitted along the reverse path. Or, if a data flow exists on the reverse path, the information may also be piggybacked on this data flow. This mechanism introduces hardly any control overhead and is feasible for most current applications which are based on TCP or have bi-directional information exchanges. But this mechanism is unable to update the backup routes because there are no data traffics on these routes.

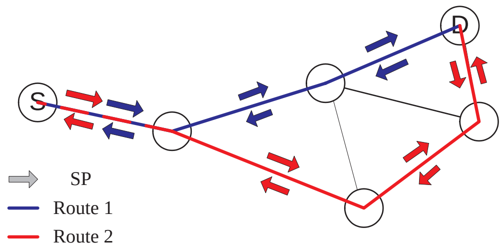

Fig. 2. Route Maintenance Phase

Therefore, we introduce the second mechanism, in which a source node periodically sends out Sniffer Packets (SP), containing the route record information, along all the primary routes and backup routes. Upon receiving an SP, the destination node sends it back to the source following the reverse path on which it arrives. The SPs carry the information about the nodes along the route as they traverse the network. According to the information gathered by the SPs, the source node updates the routes' weight and determines the interval of sending SPs. If the change of the route's weight does not affect the composition of the primary and backup route set selected, the interval between two SPs will be expanded exponentially until it reaches a maximum; otherwise, the interval will be shortened until it reaches a minimum value. The minimum interval bounds the control overhead while keeping route information up-to-date.

EMRP re-calculates the weight of each route and upgrades the primary and backup route sets.

IV. Evaluation of the Protocol

We use the *ns-2* (Network Simulator version2) with the MANET extension[17] to evaluate the performance of the protocol, comparing it to conventional layered protocol stack, which uses IEEE 802.11 in the MAC sub-layer and DSR in the network layer.

A. Simulation Environment

- 50 nodes distributed randomly on a 900 meter by 900 meter square
- The maximum transmission range of each node is 250 meters
- There are at most 10 CBR (Constant Bit Rate) streams running simultaneously in the network
- Each CBR stream starts at a random time and runs till the simulation ends

- Each CBR stream is assigned to a pair of randomly selected source and destination nodes, with the condition that all these 20 nodes are different.
- The packet size of the CBR stream is 512 bytes.
- The simulation lasts 900 seconds.

The nodes in our simulations move according to the Random Way point model[14]. Each node independently starts at a random location in the simulation area and remains stationary for a period of time called the pause time. The node then uniformly generates a new location to move to and a speed to move at. Each node repeats this movement pattern over the duration of the whole simulation. We vary the number of packets per second on the CBR streams and the pause time of the nodes to study the performance of EMRP under different traffic loads and various mobility scenarios. The metrics of the energy efficiency and network performance are studied.

B. *Energy Efficiency*

We evaluate the energy efficiency with two metrics: network lifetime and energy dissipation per bit of data delivered.

Firstly, we observe the variation of network lifetime while the data rate of the CBR flow is increased and under different mobility scenarios.

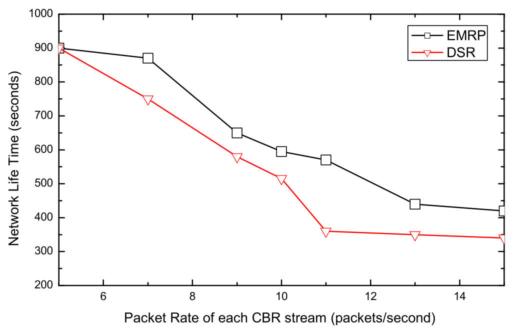

Fig. 3. The network life time (static topology)

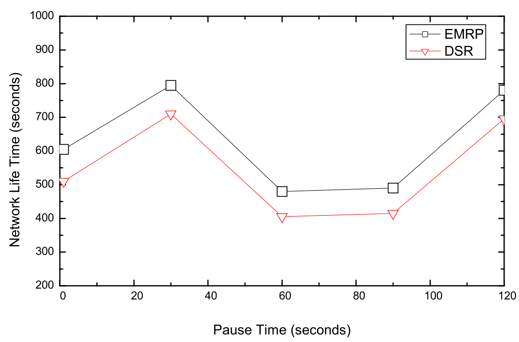

Fig. 4. The network life time (mobility scenarios)

Note that in wireless ad hoc networks, especially in those with densely distributed nodes, the death of the first node seldom leads to the total failure of the network. With the number of dead nodes increasing, the network is partitioned. Even with partitioning, end-to-end transmissions may still be feasible in each partition. Basically, we can argue that the network is alive if there exists at least one pair of adjacent nodes working, since they could transmit to each other and keep the network alive. So, the strict definition of the network lifetime is ambiguous. Taking into consideration of the statistical mean effect and the large number of repeated experiments under equivalent scenarios, we define the time when the first node in the network runs out of its energy as the network lifetime.

Fig. 3 and Fig. 4 show the simulation results on network lifetime comparing EMRP and DSR under various traffic loads and different mobility scenarios. The horizontal axis in Fig. 3 is the packet arrival rate of CBR streams in packets per second, which reflects the traffic load of the network. As expected, the network lifetime decreases when the traffic load increases. The data of Fig. 3 are obtained under a static topology. The horizontal axis in Fig. 4 represents the various intervals of pause times. From Fig. 3 and Fig. 4, we can see that networks running EMRP live longer than those running DSR.

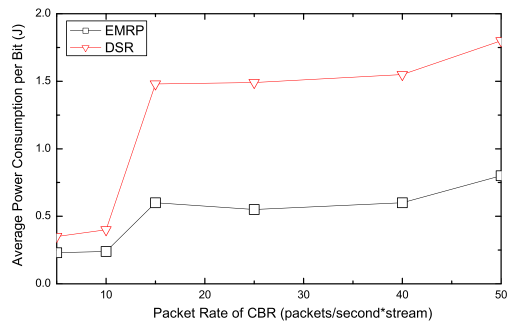

Fig. 5. The average energy consumption per data bit delivered

Fig. 5 demonstrates the average energy consumption (AEC) per bit delivery. It is obtained by dividing the sum of the energy consumption of the network by the number of successfully delivered bits. The horizontal axis represents the traffic load and the result is again obtained under static topology. We see that EMRP outperforms DSR by about 35%-150% under different traffic loads. Before the traffic load reaches 10 packets per second, the gain in AEC from EMRP over the DSR is about 35%-50%, which is mainly due to the benefit of power control in the MAC layer. Between 10 packets per second and 15 packets per second, there is a distinct increase in the AEC for the DSR network, which is because 10 packets per second is the saturation point of DSR, i.e. the maximum load which can be accommodated in a single route. The excess packets inevitably introduce more collisions to the network, wasting more energy. EMRP chooses alternative routes, avoiding the heavily burdened nodes, thus alleviating the explosion in AEC.

C. *Network Performance*

The network performance is evaluated with two metrics, namely, the volume of packets delivered and the end-to-end delay. Note that the volume of packets delivered is equivalent to the network throughput as a metric to evaluate the network's capacity of packet delivery in our simulation, because the data traffic scenarios are the same for the two networks running EMRP and DSR, respectively.

The volume of packets delivered is the total number of CBR packets received by the intended receiver during the simulation. Ideally, it should increase linearly with the traffic load. But the nodes' limited energy and excessive collisions lead to a different behaviour.

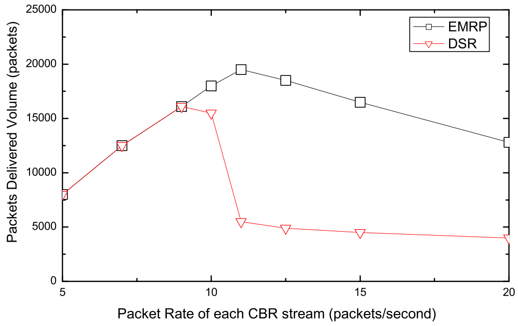

Fig. 6. The volume of packets delivered

Fig. 6 shows the network delivery amount versus the traffic load. The horizontal axis is the number of packets per second on each CBR stream. The vertical axis is the network delivery amount. The simulation data in Fig. 6 is consistent with those in Fig. 5. Before the traffic load reaches the saturation value, the network delivery amount of the two protocols are approximately the same because single path has the ability to handle all the packets. Beyond the saturation value, DSR suffers from excessive collisions and retransmissions, greatly degrading its performance, while EMRP can still enjoy the integrated capacity of multiple paths and achieves higher volume of packets delivered. Since more traffic in the network will bring more collisions and cause nodes to run out of energy more quickly, a declining trend in the volume of packets delivered can be observed in both protocols .

The end-to-end delay is another commonly used metric to evaluate the network performance.

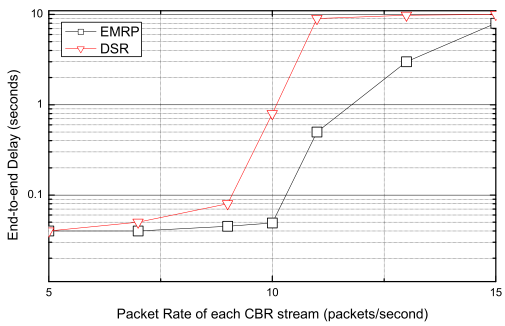

Fig. 7. The end-to-end delay

The horizontal axis of Fig. 7 is the number of packets per second on each CBR stream. The vertical axis represents the end-to-end delay in the logarithmic scale. We see that EMRP achieves lower end-to-end delay than DSR when the traffic load exceeds the saturation value. In some cases, EMRP is ten times better than DSR.

V. Conclusion

In this paper, an energy-aware multipath routing protocol for mobile ad hoc networks is proposed. As a cross-layer design, EMRP utilizes the information from the physical and the MAC layers to select better routes. Simulation results indicate that EMRP prolong network lifetime and achieves lower energy dissipation per bit of data delivery, higher volume of packets delivered and lower end-to-end delay. In the future, we plan to investigate the nodes' behavior under different mobility scenarios and further improve the performance of EMRP by tuning the parameters of the protocol.

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