Design Considerations for an On-Demand Minimum Energy Routing Protocol for a Wireless Ad Hoc Network

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Abstract—**A minimum energy routing protocol reduces the energy consumption of the nodes in a wireless ad hoc network by routing packets on routes that consume the minimum amount of energy to get the packets to their destination. This paper identifies the necessary features of an *on-demand* minimum energy routing protocol and suggests mechanisms for their implementation. We highlight the importance of efficient caching techniques to store the minimum energy route information and propose the use of an 'energy aware' link cache for storing this information. We also compare the performance of an *on-demand* minimum energy routing protocol in terms of energy savings with an existing *on-demand* ad hoc routing protocol via simulation.**

I. INTRODUCTION

Quite a few studies have been carried out which aim at reducing the energy consumption of a wireless ad hoc network. Past research has focused on energy savings schemes at the hardware and the operating system level. However, significant energy savings can be obtained at the routing level by designing minimum energy routing protocols that take into consideration the energy costs of a route when choosing the appropriate route.

Ad hoc routing protocols can be classified as table-driven routing protocols and on-demand routing protocols. In our previous work [2] we showed that the on-demand routing protocols are more energy efficient than the table-driven protocols because of the large routing overhead incurred in the latter. Hence an on-demand approach is a good basis for designing minimum energy routing protocols.

Prior studies have been done that aim at designing minimum energy routing protocols. Subbarao [19] suggests a minimum power routing scheme that has been designed using the table-driven approach. Singh et al. [18] introduce power aware cost metrics for routes and design routing schemes that minimize these metrics. They also suggest MAC layer modifications which power down the nodes when inactive to obtain energy savings. The scheme suggested by Ramanathan et al. [15] brings about power savings by using transmit power adjustment to control the topology of a multi-hop wireless network. Rodoplu et al. [16] develop a distributed position based network protocol that uses location information to compute the minimum power relay route to the destination which minimizes the energy consumed for routing the packets. Chang et al. [4] propose algorithms to select routes and corresponding power levels in a static wireless ad hoc network such that the system lifetime (in terms of battery life) is maximized. Brown et al. [3] study the fairness of different power aware routing objectives. In this paper we enumerate the features that are required by a protocol to qualify as a minimum energy routing protocol. These features serve as a guideline for a minimum energy routing protocol design. We suggest mechanisms that can be used to derive a 'minimum energy routing' version of existing ad hoc routing protocols. Finally, we test a minimum energy routing version of the Dynamic Source Routing protocol (DSR) on the network simulator (ns) framework and compare its performance with the existing version of DSR.

II. ENERGY MODEL USED FOR THIS STUDY

In this section we present the energy model used for our analysis. This model helps us justify the required features of a minimum energy routing protocol.

The energy expended in sending a data-packet of size D bytes over a given link can be modeled as

$$E(D) = K_1 D + K_2 \tag{1}$$

Feeney et al. [6] propose a similar model in their study to describe the *per packet* energy consumption. In our model,

$$K_1 = (P_t^{packet} + P^{back}) \times 8/BR \tag{2}$$

$$K_2 = ((P_t^{MAC} D^{MAC} + P_t^{packet} D^{header}) \times 8/BR) + E^{back} \tag{3}$$

where P^{back} and E^{back} are the background power and energy used up in sending the data-packet, P_t^{MAC} is the power at which the MAC packets are transmitted, D^{MAC} is the size of the MAC packets in bytes, D^{header} is the size of the trailer and the header of the data-packet, P_t^{packet} is the power at which the data-packet is transmitted and BR is the transmission bit rate. In order to simplify our analysis, we assume P^{back} and E^{back} to be zero in our study.

III. REQUIRED FEATURES OF A MINIMUM ENERGY ROUTING PROTOCOL

This section enumerates the required features of a minimum energy routing protocol.

A. *Minimum energy routing protocols should calculate the cost of a link in terms of energy and employ transmit power control of data-packets over the link.*

Minimum energy routing protocols should take into consideration the energy cost of a route while choosing the appropriate route. The energy cost of a link in a route is the sum of the minimum energy required for transmission of a data-packet over that link and the additional signalling and packet processing cost.

For a given threshold power P_r, the minimum transmit power P_t required for successful reception, assuming no fading, can be given as

$$P_t(d) = P_r d^n / K \tag{4}$$

where d is the distance between the two nodes, n is the path loss exponent and K is a constant. Typically n takes the value of 4. In case of maximum power minimum hop routing used in typical ad hoc routing protocols like the current version of DSR, this transmit power is fixed to 280mW (as per wireless LAN 802.11 specifications).

To gain maximum energy savings, the minimum energy routing protocol should transmit the data-packet at power P_t instead of the fixed transmit power. This can be achieved by employing dynamic transmit power control on the link.

Using (2) and (3), K_1 and K_2 in (1) are

$$K_1 = K_1' P_t$$
$$K_2 = K_1' P_t D^{header} + K_2' \tag{5}$$

Typical values for K_1' and K_2' in a two frame exchange 802.11 MAC environment with ACKs sent at full power and a 2Mbps bit rate are $4\mu s/byte$ and $42\mu J$ respectively.

The minimum energy routing protocol should compute the link energy cost using (1) and should choose the route such that the energy cost of the route E_{route} given by

$$E_{route} = \sum_{links\ in\ route} E(D) \tag{6}$$

is the minimum over all available routes.

B. *Minimum energy routing protocols should discover the minimum energy routes.*

Consider a case where there are 4 nodes a, b, c, d in a straight line. The minimum energy route from Node a to Node d assuming that the value of K_2 in (1) is negligible is the multi-hop route a-b-c-d. [16] shows that the minimum energy routes in a network translate to multi-hop routes and the minimum energy routing protocol should be able to discover these minimum energy routes. The route discovery mechanisms of existing on-demand protocols are similar in the way the route discovery is initiated. For finding a route from Node a to Node d, the mechanisms initiate a Route Request packet broadcast from Node a. Assuming that this packet is heard by Nodes b and c, both nodes rebroadcast the packet. The packets broadcasted by Nodes b and c are heard by all nodes. However since Node c has already broadcasted the same request earlier, it ignores the request packet from Node b and Node d replies back to the requests it hears from Nodes b and c . Hence the on-demand routes discovered by Node a are a-b-d and a-c-d: The minimum energy route a-b-c-d is not discovered. Hence the existing versions of on-demand ad hoc routing protocols cannot qualify as minimum energy routing protocols.

C. *Minimum energy routing protocols should track the energy cost in the minimum energy routes.*

In the current version of on-demand ad hoc routing protocols, route maintenance is carried out by the route error packets only when the links are broken. No route maintenance is done to indicate the change in the quality of a link. No mechanism updates the information about the changing power requirements that occur on that route due to node mobility. Even after the minimum energy routes are discovered, the changes in the energy costs of the links have to be tracked so that the energy expended is as close to the minimum value as possible. In case the energy cost of a certain link rises due to the nodes moving apart, the route may no longer be the minimum energy route. Therefore, these changes in the energy cost need to be conveyed to the source node, so that it can choose other lower energy routes as needed. Hence a minimum energy routing protocol must have a mechanism for tracking the energy cost changes in the routes. Mobility also causes the creation of new lower energy routes. For example, with 3 nodes a, b, and c and the minimum energy route from Node a to Node c at one instance of time is a-c. Now because of node mobility, Node b moves to a position between Node a and Node c making the new optimal minimum energy route from Node a to Node c as a-b-c. Therefore, to maintain minimum energy routing, additional route maintenance which goes beyond achieving basic connectivity is required.

D. *Minimum energy routing protocols should scale with the number of nodes in the network.*

The overhead incurred by the minimum energy protocols in the process of minimum energy route discovery and maintenance should scale well with the number of nodes in the network. Minimum energy routes essentially translate to multi-hop routes and as the number of nodes in the network increase, the number of hops in the minimum energy route increase and so does the overhead in discovering and maintaining these routes. This overhead should be $O(N)$ to ensure scaling of the protocol.

IV. MECHANISMS TO IMPLEMENT THESE FEATURES

Existing versions of on-demand ad hoc routing protocols do not possess most of the required features of a minimum energy routing protocol as demonstrated in the previous section. This section suggests mechanisms for the easy implementation of these features in the routing logic.

A. *Implementing link energy cost computation and transmit power control*

This mechanism can be implemented by modifying the route request packet header to include the power at which the packet was transmitted by the source node. Let P_{TX} be this transmit power in dBW. The receiving node receives this packet at power P_{RX} in dBW. Let P_{Thresh} be the the minimum power level required for a successful reception in dBW. The minimum power required for the transmission of the packet so that it is successfully received by the receiver (P_{TXmin}) can be then calculated in dBW by the receiving node as

$$P_{TXmin} = P_{TX} + P_{Thresh} - P_{RX} + M \tag{7}$$

where M is a margin to overcome the problem of unstable links due to channnel fluctuations and node mobility. The receiver node can read the value of P_{TX} from the header of the received packet. What essentially is being done in (7) is determining the value of P_t in (5) so that the value of K_1 and K_2 in (1) can be computed. This power value P_{TXmin} is included along with the node ID in the route request packet information and the packet is re-broadcasted by the receiver node. The destination node reverses the route in the route request packet and inserts this power information for each hop in the routing header of the route reply packet to route the route reply packet to the source node using transmit power control at each hop. Each node in the reply path stores the value of this minimum transmit power required to get to the next hop P_{TXmin}. The source node gets the exact power values for each hop from the route reply from which it can calculate the total energy cost of the route by using (5) and assuming a suitable value for K_2. For routing the data-packet, in case of protocols like AODV [14], nodes of the network can simply look up the value of the minimum transmit power from their routing table and transmit the data-packet at the controlled power. For source routing on-demand protocols like DSR [10], this minimum transmit power value for each hop is included in the routing header of the data-packet by the source node and each node forwarding the packet simply looks up the next hop in the source route and the minimum power required to get there and transmits the packet at the controlled power level.

B. Implementing route discovery of minimum energy routes

This mechanism enables the node to store the route power information it hears in the route request packets. The node then snoops on route replies not directed to the node and checks if it lies on a lower energy path than advertised in the route reply using the stored route power information and the route reply power information. In case it lies on a lower energy path, the node sends a gratuitous route reply with the lower energy path to the source. In this manner the nodes can discover the minimum energy route.

C. Implementing minimum energy route maintenance and link energy cost tracking

This mechanism enables the nodes in a data-packet's source route to sense the power changes in the source route as the data-packet is forwarded to the destination. Each node senses the power at which it receives the data-packet and computes the new minimum transmit power $P_{TXminnew}$ and the new minimum transmit energy $E_{TXminnew}$ required by the previous node to successfully transmit the packet to it using (7) and (5) respectively. The current node compares this energy value to the original value E_{TXmin} calculated from P_{TXmin} (which is advertised in the source route in case of DSR and is present in the routing table in case of AODV) and if

$$|E_{TXminnew} - E_{TXmin}| > T \qquad (8)$$

where T is a threshold value in dB, the node sets a flag in the routing header of the data-packet about the changed energy cost of the link and writes this new power value in the routing header. Now once the destination gets the data-packet, it checks the flag in the routing header of the data-packet and sends a gratuitous route reply packet containing the route with the new power information to the source. The intermediate nodes and the source node update their cache/routing table with this new power information and thus keep track of the energy cost changes of the links of the route.

In case of node mobility, lower energy routes can form after the initial route discovery of a low energy route on which the data-packet flow is being sent. The route maintenance logic should discover and take advantage of these routes. This mechanism modifies the MAC ACK header to include the transmit power information of the ACK frame. A node can snoop on a data-packet not directed to itself and then on the ACK for the data-packet from the receiver. The node computes the energy cost from itself to the transmitter node (E_{toTX}) from the data-packet power information and the energy cost from itself to the receiver node (E_{toRX}) from the ACK power information. Let E_{TXmin} be the advertised energy cost to get from the transmitter to the receiver node. Now if

$$E_{toRX} + E_{toTX} < E_{TXmin} \qquad (9)$$

the node understands that it lies on a lower energy path between the transmitter and the receiver nodes. It then sends out a gratuitous route reply to the source of the data-packet informing it about the lower energy route. This mechanism enables the nodes to keep track of the optimum minimum energy route over time.

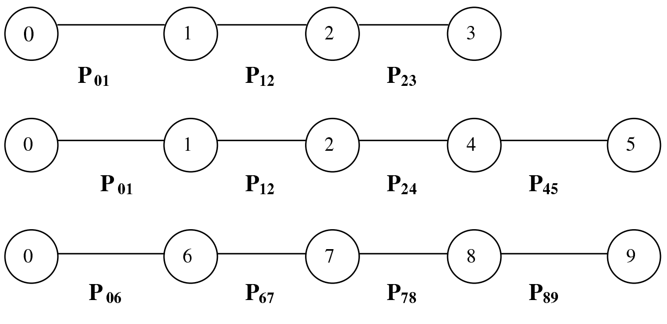
D. Ensuring scaling of the minimum energy routing protocol

To ensure scaling, the protocol must converge to the minimum energy route keeping the overhead as $O(N)$. This can only be done if the routing and power information obtained in the route replies is stored and processed in an intelligent manner so that every route reply leads to a clearer topology view of the network at each node. This calls for storing the routing and the power information in a unified graph data structure of the node's current view of the network topology. [8] uses a similar structure, the so-called *link cache* for storing the information obtained from the route replies. We suggest the use of a similar data structure, the *energy aware link cache*, where the cost of each link is set as the energy cost. The energy aware link cache saves the information about the energy cost of each link (K_1 and K_2 from (1)) from the route reply in an array and the well-known Dijkstra's shortest path algorithm is used to find the current minimum energy cost path through the graph to the destination node. Thus each route reply contributes in building up a perfect topology view of the network and it takes $O(1)$ replies from each node to obtain the perfect energy cost graph. The minimum energy routing protocol can thus converge to the minimum energy route with the routing overhead bounded as $O(N)$.

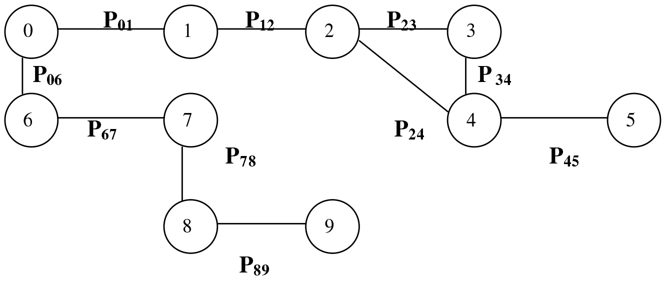
V. A 'MINIMUM ENERGY ROUTING' VERSION OF DSR

We implemented the mechanisms discussed in the previous section in the DSR protocol logic in the network simulator (ns) to obtain a *minimum energy routing* version of the DSR protocol. We used the network simulator (ns) version 2.1b6 [5] for our simulations. We used the DSR version with the promiscuous tap disabled. The energy model we used was the one bundled with the ns-2.1b6 package with the receiving cost of a packet set as zero in order to simplify our analysis. We employed the two frame exchange scheme for the MAC layer data transmission by setting the dot11RTSThreshold parameter to a value greater than the simulated data-packet size. We introduced a few other changes in the DSR code other than the mechanisms discussed above to obtain the minimum energy routing protocol version. They were:

- Cache replies off: Maltz et al. [11] discuss the effect of on-demand behavior in ad hoc routing protocols and state in their results that in a typical simulation scenario, the majority of the route reply packets are based on cached data and only 59% of those replies carry valid routes. Hence for minimum energy routing where freshness of routes is even more important, we disabled route replies from the cache.
- MAC layer ACK power control: In order to reduce the signaling cost per hop, we employed transmit power control of the MAC ACK packets on the link.



(a) Path Cache with power information



(b) Energy Aware Link Cache

Fig. 1. Different types of caches. P_{ij} is the minimum transmit power required to get from Node i to Node j

For a clear analysis of the energy expended by the nodes during the simulation, we categorized the energy consumed into various components to understand the effect of the different routing modifications/options on these components. Hence the total energy consumed was broken up as the follows:

- Energy expended in DSR routing packets ($E_{routing}$)
- Energy expended in MAC signalling packets (E_{mac})

The data-packet energy was divided further into the following parts :

- Energy consumed by the MAC header (E_{machdr})
- Energy consumed by the routing header ($E_{routinghdr}$)
- Energy consumed by the data payload ($E_{datalen}$)

Here we introduce a concept called the God energy: let us assume that nodes are given the precise routing information so that they have a perfect picture of the network topology. Each node then can determine the path that takes up the least energy to get a packet to its destination and the data is sent without any overheads. This energy is termed as the God energy of that packet. The routing efficiency of the protocol in terms of energy can be measured with respect to the God energy, E_{god}. $E_{datalen} - E_{god}$ can be considered as the routing inefficiency. These energies were logged into the trace file by modifying the trace code to include these fields.

DSR offers two design choices for the type of data structure used to represent the cache. In DSR, the route returned in each route reply that is received by the initiator of a route discovery represents a complete path which is a sequence of links leading from that node to the destination node. By caching each of these paths separately, a path cache can be formed. Alternatively, a link cache with an energy cost graph could be created as discussed in IV-D. Both these caching techniques are illustrated in Fig. 1. We experimented with both types of caches to observe which of these satisfy the criteria in III-D.

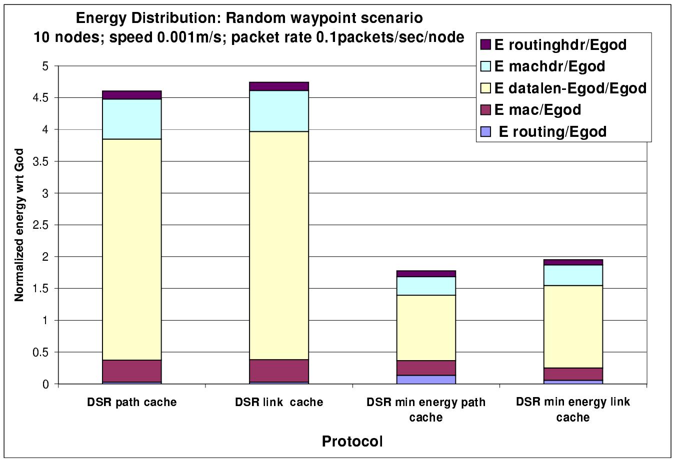


Fig. 2. 10 node Random Way-point scenario speed 0.001 m/sec

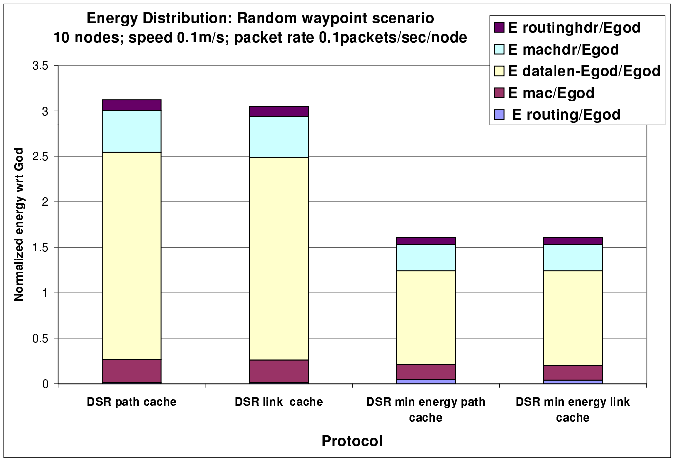


Fig. 3. 10 node Random Way-point scenario speed 0.1 m/sec

VI. TEST PROCEDURE

We compared the performance in terms of energy savings of four versions of the DSR protocol viz.

- DSR with path cache: This is the existing version of DSR that is bundled with the ns-2.1b6 simulator package. The caching mechanism used in this protocol is the path cache.
- DSR with link cache: This version of DSR is obtained by using a link cache data structure defined in [8] to store the route.
- Minimum energy routing DSR with path cache: This is the *minimum energy routing* version of the DSR using the path cache to store and process the routing and energy cost information.
- Minimum energy routing DSR with the energy aware link cache: This is the *minimum energy routing* version of the DSR using the energy aware link cache to store and process the routing and energy cost information.

We used random way-point movement scenarios to study the effect of mobility and scaling in terms of data traffic on the minimum energy routing protocols. The average node speeds considered were 0.001, 0.1 and 1 m/s. The number of nodes considered were 10, 15, 20 and 25 with topology sizes as 600x300, 1000x300, 1200x300 and 1500x300 m^2 respectively. The traffic sources considered were CBR sources with a packet rate of 0.1

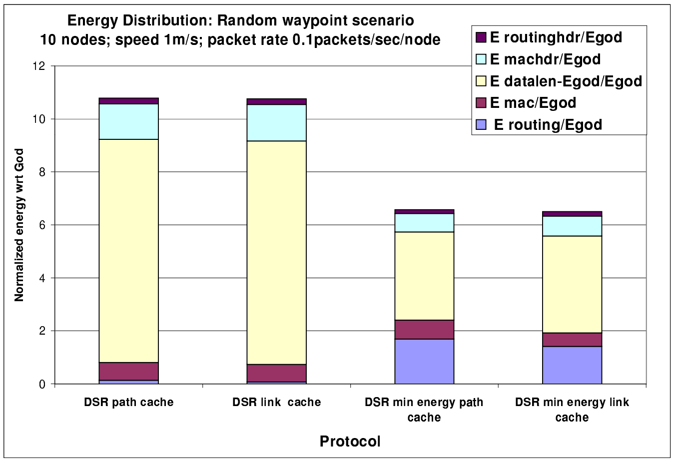


Fig. 4. 10 nodes Random Way-point scenario speed 1 m/sec

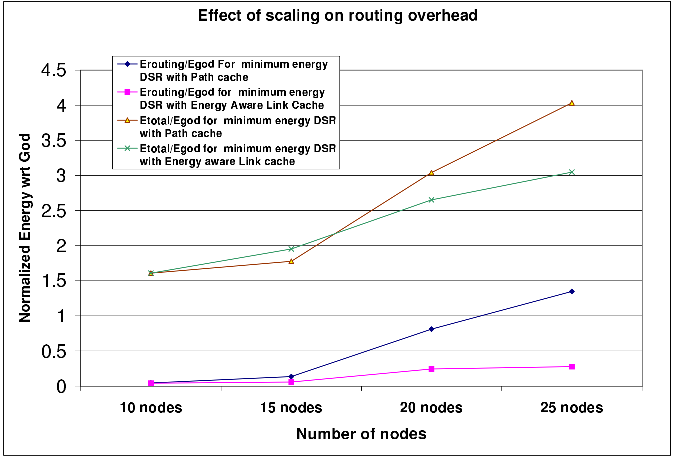


Fig. 5. Effect of scaling on energy cost

packets/sec/node and size of 512 bytes. In all of these scenarios, each node is a source and a sink for a traffic flow. The flows started at $t = 0$ and continued till the end of the simulation.

The results for each scenario can be observed for the various protocols in Fig. 2 – 5.

The results for different mobility rates indicate that the minimum energy routing protocol performs best in static and slow mobility scenarios where its energy consumption is within a factor of 3 of the god energy. As the mobility of the scenario rises, the minimum energy routing protocol's energy consuption rises above the factor of 3, but it still performs better than the existing protocol version in terms of energy savings.

The results for different number of nodes in the network gives a indication regarding scaling issues of the protocol versions. From the results it is clear that the Minimum energy routing DSR with path cache will not scale as the routing overhead is a non-linear function of the number of nodes N. The routing overhead of the Minimum energy routing DSR with the energy aware link cache is a linear function of the number of nodes as seen in the results and thus this indicates that this protocol will scale with the number of nodes in the network.

It can also be observed that the reduction in the energy consumption by using the minimum energy routing protocol is primarily due to the reduction in the routing inefficiency of the protocol and the use of transmit power control which is brought about by implementing the requirements of the minimum energy routing protocols.

VII. CONCLUSIONS

Our experimental results justify the necessity of the required features of a minimum energy routing protocol. These features are very generic in nature and can be used as a guideline for designing new minimum energy routing protocols. We have shown that these features can be easily implemented on an existing version of the protocol to derive a 'minimum energy routing' version of the protocol. The minimum energy routing protocol energy consumption is around a factor of 4 times more than the god energy as compared to a factor of 10-30 times in case of the existing protocol. It is also clear from the results that a minimum energy routing protocol should employ a unified graph data structure to store the routing and power information so that it can converge to the minimum energy route faster making the routing overhead as $O(N)$. Future work plans include implementing these features on an ad hoc routing test-bed consisting of laptops and wireless Ethernet cards.

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