A Comprehensive Minimum Energy Routing Scheme for Wireless Ad hoc Networks

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***Abstract*— Current minimum energy routing schemes in wireless networks only consider energy consumption for transmitting data packets. However most wireless devices also transmit some control packets (such as RTS and CTS in 802.11) besides data packets. Without considering the energy consumption for control packets, the existing minimum energy routing schemes tend to use more intermediate nodes, which results in more energy consumption and less throughput. In this paper, we first propose more comprehensive energy consumption models that consider the energy consumption for data packets as well as control packets. Based on these models, we propose our minimum energy routing scheme. The simulation results verify that our scheme performs better than the existing minimum energy routing schemes in terms of energy consumption as well as throughput.**

I. Introduction

A wireless ad hoc network usually consists of mobile devices with limited battery power. Thus, energy-efficient communication techniques are very important. The most common technique is the power control scheme, in which a node transmits data packets to its neighbor at the minimum required power level [7]. However, this scheme only minimizes the transmission power within a node's neighborhood. Several energy-aware multi-hop routing protocols have been proposed to minimize the total power over all the nodes along the path between a source and its destination [1]–[5].

In wireless networks, the power of a transmitted signal is attenuated at the rate of $1/d^n$, where d is the distance between the sender and receiver and n is the path loss exponent between 2 and 6. Accordingly, transmitting data packets directly to a node may consume more energy than going through some intermediate nodes. Based on this observation, most of the proposed energy-efficient routing protocols have tried to find a path that has many short-range hops in order to consume the least amount of total energy. These protocols can be generally classified into the following three categories:

(1) *Minimum Total Transmission Power (MTTP) protocols*: These protocols set the link cost to the transmission power and use a shortest path algorithm to search for the minimum energy path. PAMAS [1] used the Dijkstra's shortest path algorithm to search for the path. The authors in [2] modified DSR into a MTTP protocol. PARO [5] performed power-aware routing optimization across the MAC and Network layers. In this scheme, one or more intermediate nodes elect to forward packets on behalf of the source-destination pairs to reduce the transmission power.

(2) *Minimum Total TransCeiving Power (MTTCP) protocols*: As the intermediate nodes consume energy not only when forwarding packets but also when receiving packets, the protocol in [3] assigned the transmission power as well as receiving power to be the link cost metric, and used the Bellman-Ford shortest path algorithm to find the minimum energy path.

(3) *Minimum Total Reliable Transmission Power (MTRTP) protocols*: The authors in [4] claimed that a link cost should be a function of both the energy required for a single transmission attempt across the link and the link error rate, which determines the number of retransmission attempts needed for a successful transmission, and accordingly, proposed a minimum total reliable transmission power protocol. This protocol aims to minimize the energy consumption in transmitting data packets from a source to a destination reliably.

However, none of these protocols considered the additional energy consumption in sending control (or signaling) packets at the Data Link layer. Therefore, the proposed energy consumption models could not capture the actual energy consumption in most wireless networks. For example, in an 802.11 network, the energy consumption by the RTS, CTS and ACK packets accounts for a significant part of the total energy consumption. Without considering such energy consumption, these protocols may tend to use a larger number of intermediate nodes, thus resulting in more energy consumption, a lower throughput and/or a higher end-to-end packet error rate.

To address the deficiency of the existing approaches, in this paper, we first analyze the energy consumption for three popular wireless ad hoc networks. After developing these more accurate energy consumption models, we propose new link costs for use by our minimum energy routing scheme. Our evaluation shows that the proposed minimum energy routing scheme performs better in terms of the total energy consumption as well as throughput than existing schemes.

The rest of the paper is organized as follows. Section II contains our energy consumption models for wireless networks. In Section III, our proposed minimum energy routing scheme is described and its implementation issues are discussed. Simulation-based performance evaluation is conducted in Section IV. Section V concludes the paper.

II. Energy Consumption Models

In wireless ad hoc networks, there are two typical reliable transmission modes [4]: *End-to-End Retransmission (EER)* and *Hop-by-Hop Retransmission (HHR)*. In the EER mode, intermediate nodes along a path do not provide any link-layer retransmission. The source node will retransmit the packet if it doesn't receive the acknowledgement packet (ACK) from the destination within some predefined period. In the HHR mode, the source node and all the intermediate nodes provide link-layer retransmissions.

Since neither the MTTP nor the MTTCP protocols considers reliable transmissions, they don't distinguish the energy consumption between these two modes. For example, consider the scenario where there are $M-1$ intermediate nodes between a source and a destination. Let the nodes along the path from the source to the destination be numbered from 0 to M in that order. Denote the packet error rate from node i to node j by $p_{i,j}$, the transmission power from node i to node j by $P_{i,j}$, and the receiving power by P_r. In addition, for a variable x, denote $1-x$ by x^*, and the mean value of x by $\overline{x}$. Then the total power in transmitting data packets to the destination calculated by a MTTP protocol is

$$P = \sum_{i=0}^{M-1} P_{i,i+1}.$$

For a MTTCP protocol, the total power along the path [3] will be calculated as

$$P = \sum_{i=0}^{M-1} (P_{i,i+1} + P_r).$$

On the other hand, the MTRTP protocol calculates the total power differently for EER and HHR. For the EER mode, the total power over the path [4] is

$$P = \frac{\sum_{i=0}^{M-1} P_{i,i+1}}{\prod_{i=0}^{M-1} p^*_{i,i+1}}.$$

For the HHR mode, the total power over the path [4] is

$$P = \sum_{i=0}^{M-1} \frac{P_{i,i+1}}{p^*_{i,i+1}}.$$

Note that, the energy consumption models used by the MTTP, MTTCP and MTRTP protocols only consider the energy consumption by data packets. However, in most wireless ad hoc networks, control packets, which also consume energy, need to be sent before and/or after the data packets are sent. Therefore, the existing energy consumption models underestimate the real energy consumption, and as a result, applying an optimization technique based on such inaccurate energy consumption models will lead to a suboptimal solution only.

To address the above problem, we will develop more accurate energy consumption models for three common wireless MAC protocols: CSMA, MACA and 802.11. The first two belong to the EER mode (where end-to-end retransmission is provided by the Transport layer using e.g.,TCP) and may involve ACK packets as control packets. The third (802.11) belongs to the HHR mode, and may also contain ACK packets as control packets. Other MAC protocols can be analyzed in a similar way.

A. Energy Consumption Models for the EER mode

1) Carrier Sense Multiple Access (CSMA): In CSMA, a node transmits a data packet if the channel is sensed idle; otherwise, it will defer the transmission. If the source node doesn't receive the ACK for the transmitted data packet from its destination node for some predefined period, it will retransmit the data packet. The ACK can be transmitted separately or piggybacked. In the following, it is assumed that ACK transmission or retransmission also consumes energy. The state diagram for transmitting data packets from the source (node 0) to its destination (node M) reliably with CSMA is in Fig.1. The average total power consumed by the nodes along the path can be obtained, based on the state diagram, as:

$$\overline{P_{S,D}} = \frac{P_{0,1} * p_{0,1} + \sum_{j=1}^{M-2} \left(\sum_{i=0}^{j} P_{i,i+1}\right)\left(\prod_{i=0}^{j-1} p^*_{i,i+1}\right) p_{j,j+1}}{\prod_{i=0}^{M-1} p^*_{i,i+1}} + \frac{\left(\sum_{i=0}^{M-1} P_{i,i+1}\right)\left(\prod_{i=0}^{M-2} p^*_{i,i+1}\right)}{\prod_{i=0}^{M-1} p^*_{i,i+1}}. \quad (1)$$

If we also consider the energy consumption for receiving packets as in [3], we can modify Eq (1) into:

$$\overline{P_{S,D}} = \frac{P_{0,1} * p_{0,1} + \sum_{j=1}^{M-2} \left(\sum_{i=0}^{j} (P_{i,i+1} + P_r)\right)\left(\prod_{i=0}^{j-1} p^*_{i,i+1}\right) p_{j,j+1}}{\prod_{i=0}^{M-1} p^*_{i,i+1}} + \frac{\left(\sum_{i=0}^{M-1} (P_{i,i+1} + P_r)\right)\left(\prod_{i=0}^{M-2} p^*_{i,i+1}\right)}{\prod_{i=0}^{M-1} p^*_{i,i+1}}. \quad (2)$$

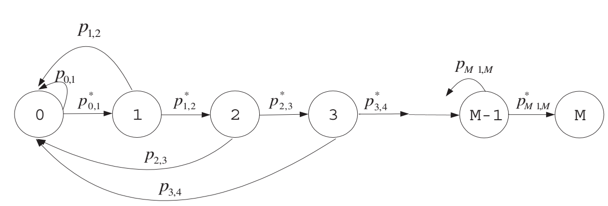

Fig. 1. State diagram for CSMA.

However, such one-way energy consumption is still not enough since the source knows the packet arriving at its destination correctly only if it receives the ACK back. But the ACK can also be lost so the destination node needs to retransmit the ACK. Usually, the destination retransmits the ACK only after it receives the retransmitted data packet from the source correctly as in the case of stop-and-wait ARQ protocol. That is, the number of ACK retransmissions equals the number of retransmitted data packets arriving at the destination correctly. In such a case, the average total power in sending a packet from the source to its destination successfully is:

$$\overline{P} = \overline{P_{S,D}} * \overline{N_{D,S}}(ACK) + \overline{P_{D,S}}(ACK), \tag{3}$$

where $\overline{N_{D,S}}(ACK)$ is the average number of ACK retransmissions given by:

$$\overline{N_{S,D}} = \frac{1}{\prod_{i=0}^{M-1} p^*_{i,i+1}};$$

and $\overline{P_{D,S}}(ACK)$ is the average total power for transmitting an ACK from the destination node to the source node correctly, which can be computed as in Eq (2).

2) Multiple Access with Collision Avoidance (MACA): MACA attempts to reduce collisions in CSMA by introducing two control messages: Request To Send (RTS) and Clear To Send (CTS). A node transmits a RTS to its receiver before transmitting a data packet. Nodes in its neighborhood will defer their transmission until they receive the CTS (or timeout). If the receiver receives the RTS, it will reply with a CTS. Nodes in the receiver's neighborhood will yield to allow the data packets to be transmitted. Once the node receives the CTS, it will transmit the data packets. If it doesn't receive the CTS, the whole process will be repeated. Let the packet error rate from node i to node j for RTS and CTS be $p_{r,i,j}$ and $p_{c,i,j}$ respectively. The state diagram for node i to transmit a data packet to one of its neighboring nodes, node j, is shown in Fig 2, where state S0 is the initial state, S1 is the state in which node j receives the RTS packet, S2 is the state in which node i receives the CTS packet, S3 is the state in which node j receives the data packet and S4 is the state in which the data packet from node i is lost. We assume that the nodes

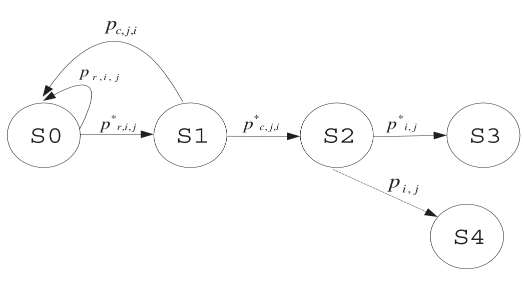

Fig. 2. State diagram for transmitting a packet from node i to node j in MACA.

transmit data packets at the minimum necessary power level, but transmit RTS and CTS at the maximum power level P_m. Denote the MACA header size for data packets by N_{maca}, the RTS and CTS packet sizes by N_{rts} and N_{cts} respectively, the physical layer overhead size by N_{phy} and the data packet size by N, then the average total power in sending a packet from node i to node j can be expressed, based on the state diagram in Fig. 2, as:

$$\overline{P_T(i,j)} = P_{i,j} + P_m \frac{N_r + N_c p^*_{r,i,j}}{N_m p^*_{c,j,i} p^*_{r,i,j}}, \tag{4}$$

where $N_r = N_{rts} + N_{phy}$, $N_c = N_{cts} + N_{phy}$, $N_m = N + N_{maca} + N_{phy}$. Considering the scenario with $M-1$ intermediate nodes between the source (node 0) and the destination (node M), the average total power in transmitting data packets from node 0 to node M reliably is:

$$\overline{P_{S,D}} = \frac{\overline{P_T(0,1)} * p_{0,1} + \sum_{j=1}^{M-2}\left(\sum_{i=0}^{j}\overline{P_T(i,i+1)}\right)\left(\prod_{i=0}^{j-1} p^*_{i,i+1}\right) p_{j,j+1}}{\prod_{i=0}^{M-1} p^*_{i,i+1}} + \frac{\left(\sum_{i=0}^{M-1}\overline{P_T(i,i+1)}\right)\left(\prod_{i=0}^{M-2} p^*_{i,i+1}\right)}{\prod_{i=0}^{M-1} p^*_{i,i+1}}. \tag{5}$$

Similar to the case for CSMA, if we also consider the energy consumption for receiving the packet, we can modify Eq (4) to be:

$$\overline{P_T(i,j)} = (P_{i,j} + P_r) + (P_m + P_r)\frac{N_r + N_c p^*_{r,i,j}}{N_m p^*_{c,j,i} p^*_{r,i,j}}. \tag{6}$$

In addition, the average number of source retransmission until the packet can reach the destination reliably is

$$\overline{N_{S,D}} = \frac{1}{\prod_{i=0}^{M-1} p^*_{i,i+1}}.$$

Hence, as in the case for the end-to-end retransmission in CSMA, the average total power in sending a packet and getting an ACK back successfully will be:

$$\overline{P} = \overline{P_{S,D}} * \overline{N_{D,S}}(ACK) + \overline{P_{D,S}}(ACK). \tag{7}$$

B. Energy Consumption Models for the HHR mode

802.11 is a typical HHR scheme. There are two ways of transmitting data frames over a channel: the *Two Frame Exchange scheme* and the *Four Frame Exchange scheme*. In the following, we will analyze the energy consumption for both schemes.

To simplify the expressions in the analysis, we denote the 802.11 header size and ACK packet size by N_{802} and N_{ack} respectively. And we also define the following symbols:

$$N_8 = N + N_{802} + N_{phy}, N_r = N_{rts} + N_{phy}$$
$$N_c = N_{cts} + N_{phy}, \text{and} N_a = N_{ack} + N_{phy}.$$

In 802.11, the number of retransmissions is limited (e.g., the short retry limit is 7 and the long retry limit is 4) [6]. However, to simplify our analysis, we assume unlimited retransmissions which should not affect the accuracy too much as most of the packet retransmissions will not be over the limits.

1) the Two Frame Exchange scheme: In the Two Frame Exchange scheme, a node transmits a data packet if the channel is idle for a period that exceeds the Distributed Inter Frame Space (DIFS). If the channel is busy, it will defer the transmission and keep monitoring the channel until it is idle for a period of DIFS. And then,it starts backoff with a random backoff time. The backoff timer will be paused if the channel is busy and continued once the channel is idle again for the DIFS period. Once the backoff timer reaches zero, the node will transmit the data packet immediately. The receiver replies with an ACK to the sender after receiving the data packet successfully. If the transmitter doesn't receive the ACK within a predefined time period, the whole process will be repeated. Let the ACK packet error rate from node i to node j be $p_{a,i,j}$. The state diagram for transmitting a data packet from node i to one of its neighboring nodes, node j, is in Fig. 3, where S0 is the initial state, S1 is the state in which node j receives the data packet, S2 is the state in which node i receives the ACK packet. Then, the average total transmission power in transmitting a packet from node i to node j successfully is given by

$$\overline{P_T(i,j)} = \frac{P_{i,j} + P_{j,i}\frac{N_a}{N_8}p^*_{i,j}}{p^*_{i,j}p^*_{a,j,i}}. \tag{8}$$

Similiarly, the average total receiving power in receiving a packet from node i at node j successfully is obtained as

$$\overline{P_R(i,j)} = P_r\left(\frac{1}{p^*_{a,j,i}} + \frac{N_a}{N_8}\right).$$

Therefore, the average total power in sending a packet from node i to node j successfully is

$$\overline{P(i,j)} = \overline{P_T(i,j)} + \overline{P_R(i,j)}.$$

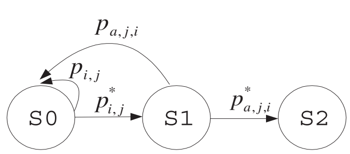

Fig. 3. State diagram for the Two Frame Exchange scheme.

The average total power consumed along the path from the source (node 0) to the destination (node M) is

$$\overline{P_{total}} = \sum_{i=0}^{M-1}\left(\overline{P_T(i,i+1)} + \overline{P_R(i,i+1)}\right) \tag{9}$$

2) the Four Frame Exchange scheme: In the Four Frame Exchange scheme, nodes exchange two more frames before transmitting data packets: RTS and CTS. More specifically, the sender transmits a RTS packet after the channel is available for a period longer than DIFS or the backoff timer reaches zero. The receiver responds with a CTS packet after receiving a RTS packet[1]. If the CTS is not received within a predetermined time interval, the sender retransmits the RTS packet. After receiving the CTS, the sender will send out the data packet and the receiver will reply with an ACK packet after receiving the data packet successfully. If the transmitter doesn't receive the ACK packet within a predefined time period, the whole process will be repeated. The state diagram for transmitting a data packet from node i to one of its neighboring nodes, node j, is shown in Fig 4, where $S0$ is the initial state, $S1$ is the state in which node j receives the RTS packet, $S2$ is the state in which node i receives the CTS packet, $S3$ is the state in which node j receives the data packet, and $S4$ is the state in which node i receives the ACK packet.

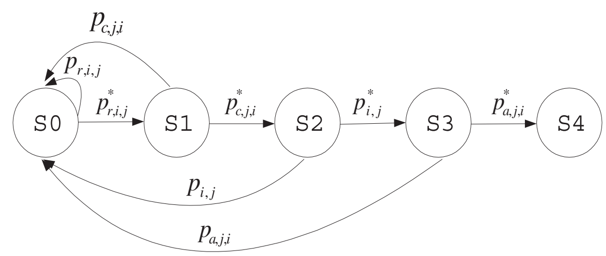

Fig. 4. State diagram for the Four Frame Exchange scheme.

Therefore, the average total transmission power in successfully transmitting a packet from node i to node j is

$$\overline{P_T(i,j)} = \frac{P_m(\frac{N_r}{N_8} + \frac{N_c}{N_8}p^*_{r,i,j})}{p^*_{r,i,j}p^*_{c,j,i}p^*_{i,j}p^*_{a,j,i}} + \frac{P_{i,j} + P_{j,i}\frac{N_a}{N_8}p^*_{i,j}}{p^*_{i,j}p^*_{a,j,i}}. \tag{10}$$

And the average total receiving power in successfully receiving a packet from node i at node j is

$$\overline{P_R(i,j)} = P_r\frac{\frac{N_r}{N_8} + (\frac{N_c}{N8} + p^*_{i,j} + \frac{N_a}{N_8}p^*_{i,j}p^*_{a,j,i})p^*_{c,j,i}}{p^*_{c,j,i}p^*_{i,j}p^*_{a,j,i}}. \tag{11}$$

The average total power consumed along the path from the source (node 0) to the destination (node M) is thus

$$\overline{P_{total}} = \sum_{i=0}^{M-1}\left(\overline{P_T(i,i+1)} + \overline{P_R(i,i+1)}\right). \tag{12}$$

III. Minimum Energy Routing Scheme

A key element in any minimum energy routing scheme is the link cost assignment. The accuracy of link costs determines the performance of these schemes in terms of energy consumption as well as throughput. Therefore, we need to determine link costs that can represent real energy consumption in wireless networks as accurately as possible. Once we get the link costs, we can then modify the traditional shortest path routing

[1]If a node receives a RTS but can't reply with a CTS because the channel is busy, we treat it as a RTS packet error in our analysis even though the RTS packet is received correctly. We call this as the busy channel problem.

protocols (e.g. Bellman-Ford, DSR, and AODV) to support minimum energy routing.

Currently, there exist three types of link costs: (1) *Transmission Power Level* ($P_{i,j}$) in the MTTP protocols; (2) *TransCeiving Power Level* ($P_{i,j} + P_r$) in the MTTCP protocols; (3) *Reliable Transmission Power Level* ($\frac{P_{i,j}}{(1-p_{i,j})^L}$, where $L = 1, 2, 3, ...$) in the MTRTP Protocols. However, these link costs could not accurately represent the energy consumption since they do not take the extra energy consumption in MAC and Physical layers into account. Therefore, we need to derive new link costs for our minimum energy routing scheme.

In Section II, we have introduced more accurate energy consumption models for wireless networks. In this section, we will derive new link costs for our minimum energy routing scheme based on these models.

A. Link costs for the EER mode

Based on the energy consumption models for two MAC protocols (CSMA and MACA) in the eer mode developed earlier, the minimum energy routing scheme would find a path that minimizes Eq (3) for CSMA or Eq (7) for MACA. Given these two equations, the average total power over the path can not be expressed as a linear sum of individual power levels. Therefore we need to simplify these two equations. By using the same assumption as that in [4] that transmission errors on a link do not stop downstream nodes from relaying the packet, we can approximate Eq (3) in CSMA by:

$$\overline{P} = \frac{\sum_{i=0}^{M-1}(P_{i,i+1} + P_r)}{\prod_{i=0}^{M-1} p^*_{i,i+1} p^*_{i+1,i}}, \tag{13}$$

and Eq (7) in MACA by

$$\overline{P} = \frac{\sum_{i=0}^{M-1}\left(P_{i,i+1}+P_r+(P_m+P_r)\frac{N_r+N_c p^*_{r,i,i+1}}{N_m p^*_{r,i,i+1} p^*_{c,i+1,i}}\right)}{\prod_{i=0}^{M-1} p^*_{i,i+1} p^*_{i+1,i}}. \tag{14}$$

Note that, the numerators in these two equations can be expressed as a linear sum of power levels and the logarithm of the denominators can be expressed as a linear sum of the logarithm of packet error rates. Therefore, we can let each node advertise two different metrics: one is $P_{i,j}+P_r$ for CSMA and $P_{i,j} + P_r + (P_m + P_r)\frac{N_r+N_c p^*_{r,i,j}}{N_m p^*_{r,i,j} p^*_{c,j,i}}$ for MACA; the other is $log(p^*_{i,j} p^*_{j,i})$. With these two metrics and their cumulative values, every node can calculate $\overline{P}$ and select the minimum energy path.

From Eqs (13) and (14), we can see that the variation in the data packet error rates for each link ($p_{i,i+1}$ or $p_{i+1,i}$) has a significant effect on the total energy consumption as $\overline{P}$ is proportional to $\frac{1}{p^*_{i,i+1}}$, which can be approximated as $(1 + p_{i,i+1})$ by using the Taylor expansion. For example, if the data packet error rate on one link changes from 0.01 to 0.1, the total energy consumption will be increased for about 10 percent. If data packet error rates on more than one link change, the total energy consumption will be affected more dramatically.

For CSMA, this could be a big problem as the data packet error rates are very senstive to environment change (such as noise, interference, and number of competing nodes) so that they may change very fast. To keep track of data packet error rates in CSMA will require a lot of routing overhead, which may consume more energy than the savings from minimum energy path. Therefore, CSMA is not suitable for minimum energy routing if the enviroment is not static enough. On the other hand, in MACA, the sender exchanges RTS and CTS with the receiver before sending a data packet, the data packet error rates will not vary too much to cause a major concern.

B. Link costs for the HHR mode

It is easier to derive the link costs for the HHR mode since the average total power over the path is a linear sum of power levels in each link. More specifically, for 802.11, we can use $\overline{P_T(i,j)}+\overline{P_R(i,j)}$ as the link cost. For the *Two Frame Exchange* scheme, the link cost is

$$C_2(i,j) = P_{i,j}\frac{1+\frac{N_a}{N_8}p^*_{i,j}}{p^*_{i,j}p^*_{a,j,i}} + P_r\left(\frac{1}{p^*_{a,j,i}} + \frac{N_a}{N_8}\right). \tag{15}$$

For the *Four Frame Exchange* scheme, the link cost is

$$\begin{aligned} C_4(i,j) = {} & \frac{P_m(\frac{N_r}{N_8} + \frac{N_c}{N_8}p^*_{r,i,j})}{p^*_{r,i,j}p^*_{c,j,i}p^*_{i,j}p^*_{a,j,i}} + \frac{P_{i,j}(1 + \frac{N_a}{N_8}p^*_{i,j})}{p^*_{i,j}p^*_{a,j,i}} \\ & + P_r\frac{\frac{N_r}{N_8} + \frac{N_c}{N8}p^*_{c,j,i} + p^*_{c,j,i}p^*_{i,j} + \frac{N_a}{N_8}p^*_{c,j,i}p^*_{i,j}p^*_{a,j,i}}{p^*_{c,j,i}p^*_{i,j}p^*_{a,j,i}}. \end{aligned} \tag{16}$$

From Eqs. (15) and (16), we can see that the variation in the packet error rates may have some high effects on the energy consumption for transmitting the data packet from one node to another. However, this is not as significant as in EER since the energy consumption in one link is far smaller than the total energy consumed along the path from the source to the destination, especially when the number of links is large enough.

IV. Simulation Results

In this section, we evaluate the proposed energy consumption models and compared several minimum energy routing schemes via simulations.

A. Energy Consumption Models

In this set of simulations, We obtain the energy consumed for transmitting data packets from the source (node 0) to the destination (node 2, 3, 4, 5, or 6) using GlomoSim. The transmission power level is 1mW for data packets, and 5mW for RTS and CTS packets. To exclude the impact of finding a route on the energy consumption, we use static routing. In addition, we assume that there is no power saving mode for the nodes, and accordingly, a receiving node will spend the same amount of energy in monitoring the channel even if it doesn't receive a packet. In this way, we need to focus only on the transmission power in simulations and compare that with the transmission power predicted by various models. For this reason, we will only compare the accuracy of the energy consumption models used in MTTP and MTRTP with our models. Note that, in terms of predicting the transmission power, the model used in MTTCP is as inaccurate as the model used in MTTP. In terms of predicting the total energy consumption, the model used in MTTCP is more accurate than that in MTTP (and MTRTP), but still not as accurate as our model as the energy needed for receiving control packets is ignored in the model used in MTTCP (as well as MTTP and MTRTP).

1) Energy Consumption Models for EER: In this mode, we use FTP (File Transfer Protocol) to transmit 360,000 data packets with 512 bytes per packet. To reduce the impact on the energy consumption due to FTP control packets, we set the size of FTP control packets to one byte. The packet error rates for CSMA and MACA are set to 0.015 and 0.001 respectively. The simulation results and the energy consumption estimated by each model are shown in Figs. 5 and 6. It is clear that our models match the simulation results very well in both CSMA and MACA. On the other hand, both MTTP and MTRTP models, which resulted in almost the same energy consumption estimate due to the low packet error rate (especially in the case of MACA), are seen to underestimate the energy consumption significantly and the underestimation increases with the number of intermediate nodes. In addition, the underestimation is much more in MACA than in CSMA. The reason is that the MTTP and MTRTP models in MACA not only do not consider the energy consumption by ACK and the number of ACK retransmissions on the Transport layer, but also ignore the energy consumption for RTS and CTS in the MAC layer.

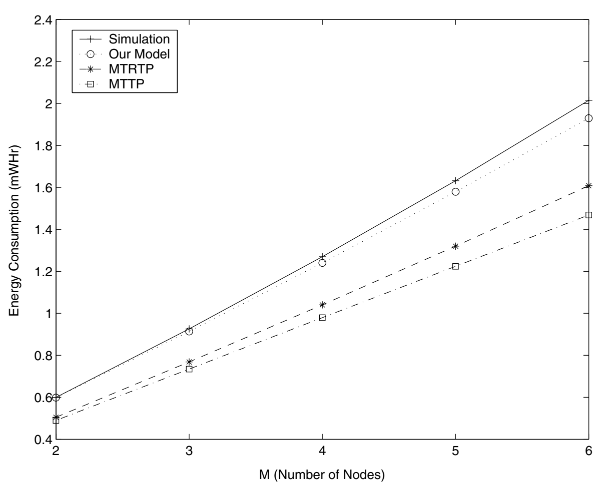

Fig. 5. Energy consumption for simulation and analysis with CSMA.

2) Energy Consumption Models for HHR: In this mode, we use CBR (Constant Bit Rate) to transmit 65,536 data packets. The packet error rate is set to 0.001 for both the Two Frame Exchange scheme and the Four Frame Exchange scheme. The simulation results and the energy consumption estimated by each model are shown in Figs. 7 and 8. Our models match the simulation results quite well in both schemes. Again, MTTP and MTRTP models underestimate the energy consumption

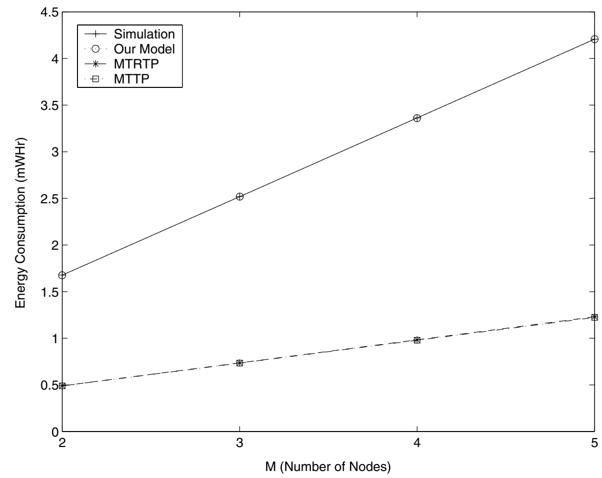

Fig. 6. Energy consumption for simulation and analysis with MACA.

and the underestimation is more serious as the number of intermediate nodes increases. In addition, the underestimation is much larger in the Four Frame Exchange scheme than in the Two Frame Exchange scheme.

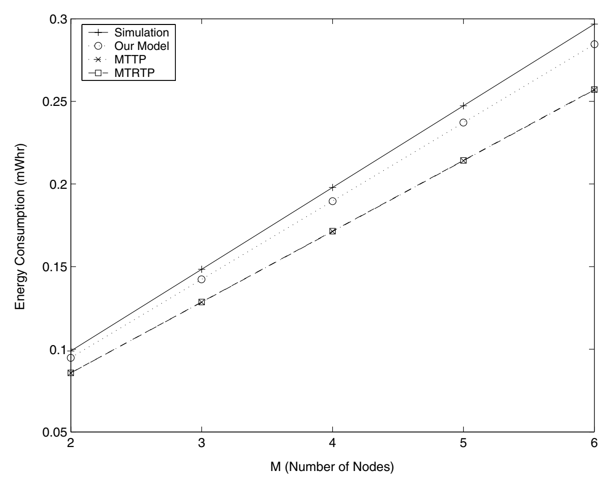

Fig. 7. Energy consumption for simulation and analysis with Two Frame Exchange scheme.

B. Minimum Energy Routing Schemes

In this set of simulations, we modified AODV to support minimum energy routing schemes in GlomoSim. We changed the battery model in GlomoSim by setting the battery efficiency to 1, and in addition removed the energy consumption for receiving packets or monitoring the channel. The area simulated is 1200m$\times$1200m, the received power threshold is set to -80 dBm, the available transmission power levels are 1, 5, 10, 15, 20, 25, 30 and 35mW, and the processing power level is 0.05mW. The nodes are uniformly distributed and the pairs of source and destination nodes are randomly selected. The connection requests arrive according to a Poisson process

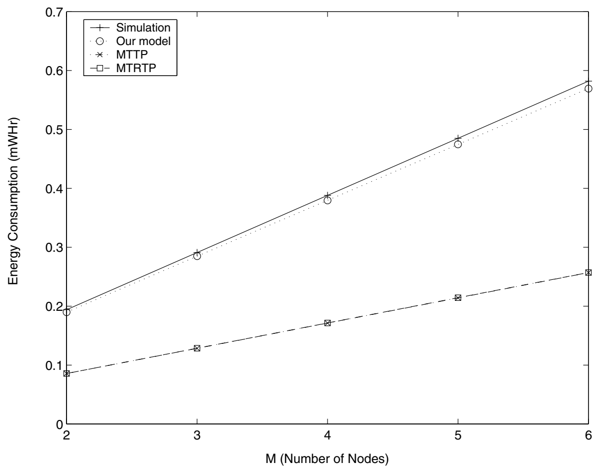

Fig. 8. Energy consumption for simulation and analysis with Four Frame exchange scheme.

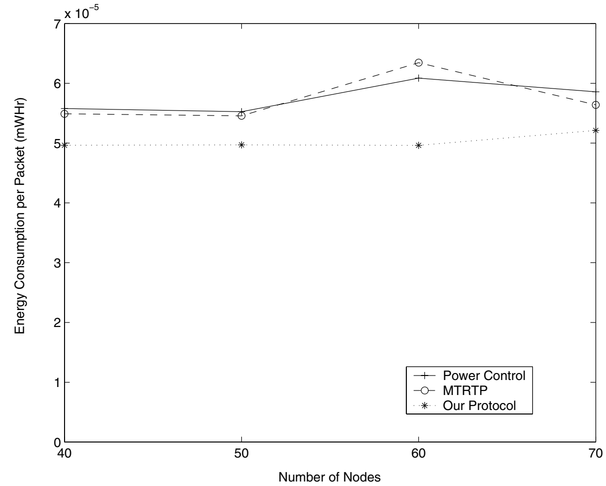

Fig. 9. Energy consumption per packet in MACA.

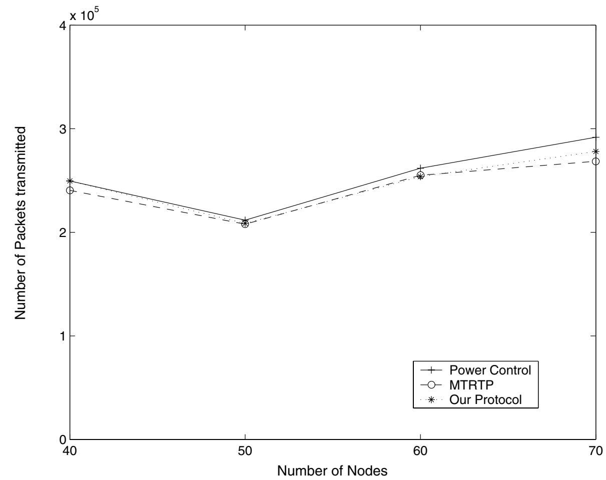

Fig. 10. Number of packets transmitted in MACA.

and the connection duration is exponentially distributed. The data packet size is 512 bytes and the data rate is 2Mbps.

Since the authors in [4] already showed that the MTRTP is better than the MTTP, we will only compare our protocol to MTRTP and *Power Control Scheme*, which uses AODV as the routing protocol and adjusts the transmission power according to the distance between the sender and the receiver. We study two performance metrics for these three protocols. For the EER mode, these two metrics are: (1) *Energy consumption per packet*, which is defined as the total energy consumption divided by the total number of packets transmitted successfully; (2) *Number of packets transmitted*, which represents the effective throughput. For the HHR mode, the two performance metrics are: (1) *Energy consumption per packet*; (2) *Percentage of packets transmitted*, which is defined as the number of packets received by the destination correctly divided by the number of packets transmitted by the source. This metric also reflects the throughput if the end-to-end delay is almost the same for each packet. The higher the percentage of the packets transmitted, the higher the throughput.

1) EER mode: In this mode, we use FTP as our application protocol. The connection arrival rate is 30 per hour and the average connection duration is 6 minutes. We simulate each protocol for 10 hours in MACA. The amount of energy consumed and number of packets transmitted are collected. The simulation results are shown in Figs. 9 and 10.

As can be seen from Fig. 9, our protocol has the least energy consumption per packet, followed by MTRTP and the Power Control scheme. However, in terms of the number of packets transmitted, The Power Control scheme performs the best, followed by our protocol and MTRTP. That is because the *number of packets transmitted* is mainly determined by end-to-end delay and packet error rate. The larger end-to-end delay and packet error rate, the less number of packets transmitted. As the Power Control uses the least number of intermediate nodes, it will have the least delay and end-to-end packet error rate. Therefore it has the most number of packets transmitted.

It is worthwhile to point out that we simulated the protocols using topologies with different density and only allowed discrete transmit power levels so that the curve for each protocol is not so smooth. However, as we are only interested in comparing the performance of three protocols with the same number of nodes, but not the performance of any given protocol with different numbers of nodes, this phenomena doesn't affect our analysis.

2) HHR mode: In this mode, we used CBR (5 packets per second) as our application protocol. The connection arrival rate is 50 per hour and the average connection duration is 3 minutes. We simulated each protocol for one hour using the *Two Frame Exchange scheme* and the *Four Frame Exchange scheme*. The amount of energy consumed, the number of packets transmitted and the number of packets received correctly are monitored. The simulation results are depicted in Fig. 11 through 14.

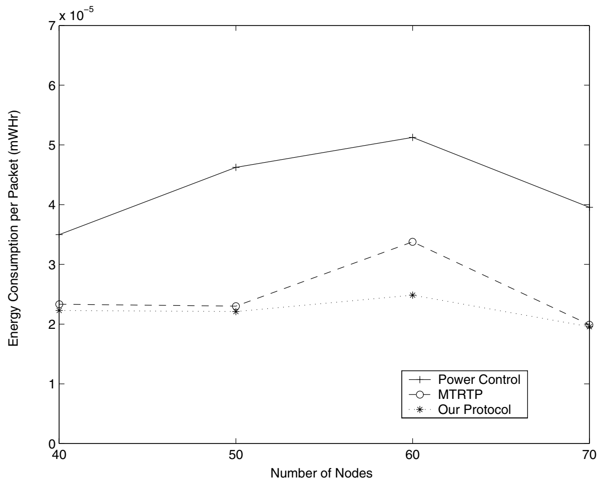

Fig. 11. Energy consumption per packet in two frame scheme.

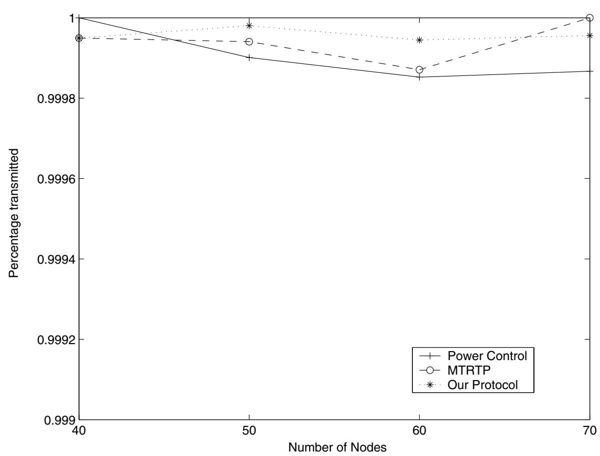

Fig. 12. Percentages of packets transmitted in two frame scheme.

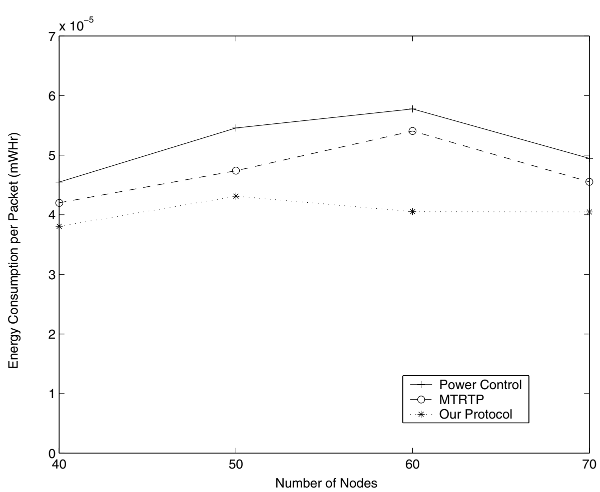

Fig. 13. Energy consumption per packet in four frame scheme.

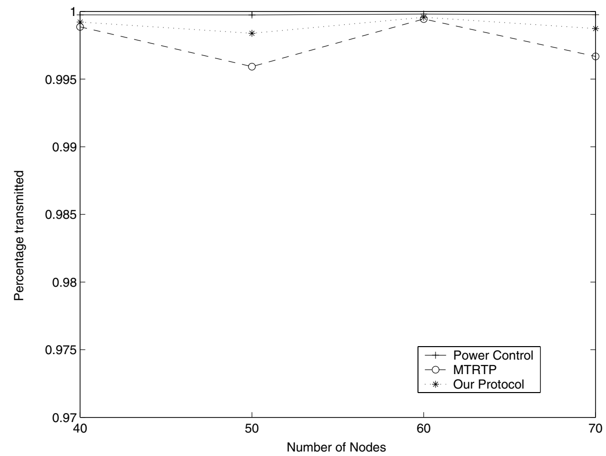

Fig. 14. Percentages of packets transmitted in four frame scheme.

As can be seen from these figures, our scheme also has the best performance in terms of energy consumption per packet, followed by MTRTP and the Power Control scheme. Our scheme can also transmit a higher percentage of packets as compared to MTRTP. However, the Power Control scheme has the lowest percentage of packets transmitted in the Two Frame Exchange scheme but the highest percentage of packets transmitted in the Four Frame Exchange scheme. This is explained as follows.

In the Two Frame Exchange scheme, most of the packets lost are caused by the *asymmetric power problem*[2]. In the Power Control scheme, the transmission power can vary between the minimum and the maximum, hence the *asymmetric problem* is very serious. MTRTP and our protocol use more short-distance links to save energy, hence the transmission power for each link does not change significantly. However, MTRTP uses more intermediate nodes than our scheme. Therefore, our protocol has the highest *percentage of packets transmitted*, followed by MTRTP and the power control scheme.

In the Four Frame Exchange scheme, as the nodes exchange RTS and CTS at the maximum power level, the *asymmetric power problem* can be ignored. However, it has the *busy channel problem* (see footnote 1). If the number of RTS retransmissions is over the limit because of the *busy channel problem*, the node has to discard the data packet. Most of the packets are lost in this way in the Four Frame Exchange scheme. Obviously, more radio transmissions would make the *busy channel problem* more serious. Therefore, MTRTP has the lowest percentage of packets transmitted because it uses the largest number of intermediate nodes that generate the highest number of radio transmissions. And the power control scheme has the highest percentage of packets transmitted, followed by our protocol.

[2]One node cannot sense other nodes' radio transmission because they use a low transmission power, however this node can cause collision if it sends packets to one of its neighboring nodes using a high transmission power.

V. Conclusion

In this paper, we have developed, for the first time, energy consumption models for common wireless ad hoc networks that take the energy consumption in sending control packets into account as well. These theoretical models have been verified to be much more accurate than existing models used by the minimum total tranmission power routing protocols, the minimum total transceiving power routing protocols, and the minimum total reliable transmission power routing protocols. Based on our models, we have also proposed a minimum energy routing scheme. Our simulation results have shown that our scheme performs better than other existing schemes in terms of both the energy consumption and the effective throughput. As many current 802.11 cards already support the functions of received power measurement and transmission power setting, it is easy to implement our scheme in real applications.

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