On Accurate Energy Consumption Models for Wireless Ad hoc Networks

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Abstract

Energy conservation is important for ad hoc networks. However, little effort has been made to carefully study the energy cost metrics upon which the design of various energy efficient algorithms is based. More specifically, most existing energy consumption models only considered energy cost in exchanging data packets, although common wireless protocols also need control packets (e.g., ACK) for reliable data transmissions. Without considering the energy cost for exchanging control packets, these existing models tend to underestimate the actual energy consumption, and thus leading to suboptimal energy efficient designs. In this paper, we develop energy consumption models that take into account energy consumption due to data packets, control packets and retransmission. We verify by simulation that our models match the actual energy consumption much better than existing models. In addition, we show that a minimum energy routing protocol based on an accurate model of ours performs much better than those based on existing models.

Index Terms

Power control, Energy efficiency, Wireless networks, Routing, Optimization

I. INTRODUCTION

In wireless networks with battery powered nodes, energy efficiency is a very important consideration. The most common technique to achieve energy efficiency in wireless networks 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.

Since the power of a transmitted signal is attenuated at the rate of $1/d^n$, where d is the distance between a sender and a receiver and n is the path loss exponent between 2 and 6, transmitting data packets directly to a node may consume more energy than going through some intermediate nodes. Accordingly, several energy-aware multi-hop routing protocols for wireless ad hoc networks have been proposed to minimize the total power over all the nodes along the path between a source and a destination [1]–[5]. The energy consumption models used in these protocols can be generally classified into the following three categories:

(1) *Total Transmission Power model*: This model simply sums up the transmission power of the data packet at each link. With this model, a minimum energy routing protocol can use the transmission power as the link cost and select the route that minimizes the total transmission power along the path. For example, PAMAS [1] uses the Dijkstra's shortest path algorithm to search for the minimum energy path, while DSR has been modified in [2] to support minimum energy routing. In PARO [5], power-aware route optimization is performed across MAC and Network layers. Instead of sending packet directly between two nodes over a large-range hop, one or more intermediate nodes may elect to relay packets between the sending node and the receiving node to reduce the transmission power.

(2) *Total TransCeiving Power model*: As the intermediate nodes consume energy not only when forwarding packets but also when receiving packets, this model sums up both the transmission power and the receiving power for transmitting the data packet at each link. The link cost metric developed in [3] considers the transmission and receiving power, and Bellman-Ford shortest path algorithm is used to look for the minimum energy path.

(3) *Total Reliable Transmission Power model*: If a data packet is lost during transmission at one link, such

packet has to be retransmited, which will consume some extra energy. Therefore, this mode includes the energy consumption for both the new data packet and the retransmitted packet. The authors in [4] proposed a minimum total reliable transmission power routing protocol.

All the existing cost models, however, ignore additional energy consumption in exchanging control (or signaling) packets at the Data Link layer, which therefore underestimates the actual energy consumption with various wireless protocols. For example, in an 802.11 network, RTS and CTS packets are transmitted at the maximum power level. As most collisions happen during RTS transmission, RTS may need to be retransmitted several times. Energy spent for sending RTS and CTS packets hence accounts for a significant part of the total energy consumption. As a result, an energy-aware routing protocol that does not consider such energy cost tend to select a path with a larger number of intermediate nodes, thus resulting in more energy consumption, lower throughput and higher end-to-end delay. Therefore, developing more accurate energy consumption models will have important impact on the design of more efficient energy conserving schemes.

In this paper, we analyze the energy consumption to achieve reliable transmission, and propose more accurate models to estimate the energy cost due to different factors. We verify the accuracy of the proposed models by comparing the results calculated from the models and those obtained through simulation, and also demonstrate the usefulness of the accurate model in achieving more energy efficient routing in 802.11 based networks.

The rest of the paper is organized as follows. Section II describes our energy consumption models for wireless networks. Results from simulation based performance evaluation are presented and discussed in Section III. Section IV 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 *Total Transmission Power model* nor *Total TransCeiving Power model* considers reliable transmissions, they don't distinguish the energy consumption between these two modes. More specifically, 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 *Total Transmission Power model* is

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

For a *Total Transceiving Power model*, the total power along the path [3] is calculated as

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

On the other hand, the *Total Reliable Transmission Power model* in [4] calculates the total power differently for EER and HHR modes. For the EER mode, the authors assume that a data packet would be relayed by an intermediate node to the downstream even if the packet may have been corrupted and could not be recovered. Accordingly, one has

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

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 above model is not accurate if data packets can be lost during transmissions. In addition, as mentioned earlier, all three commonly used energy consumption models mentioned so far only consider the energy consumption by data packets. Without considering the energy consumption due to control packets and retransmission, the existing energy consumption models underestimate the actual energy consumption. As a result, performing minimal energy routing based on such inaccurate models will only lead to a suboptimal solution.

In this paper, we will develop energy consumption models for three common wireless MAC protocols: CSMA, MACA and 802.11. These three MAC schemes use different control strategies, and hence their impacts on the energy consumption are different. More specifically, The first two do not provide MAC layer retransmission, therefore, we study them under the EER mode. The third (802.11) supports MAC layer retransmission, and is thus studied under the HHR mode. Other MAC protocols can be analyzed in a similar way.

A. Energy Consumption Models for the EER mode

In the following analysis, we assume that both data and control packets are transmitted over lossy links, and hence may not reach the next intermediate receiving node. In other words, a transmitted packet may be lost entirely or severely corrupted and could not be recovered. In this case, the source (not the immediate upstream node) will retransmit the packet upon a time-out. This assumption is more realistic than that used in [4], where it was assumed the corrupted packets will still be relayed by the intermediate nodes in order to simplify the analysis. A completely different energy consumption model is thus required under the more realistic assumption. Below, we will analyze the two MAC protocols for the EER mode, namely CSMA and MACA, separately.

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 (time-out) period, it will retransmit the data packet. The ACK can be transmitted separately or piggybacked. In either way, such an ACK transmission (or retransmission) also consumes energy. In the following, we will first focus on the energy consumption due to data packet transmissions, and then incorporate the energy consumption due to ACK transmissions. For simplicity, we assume that ACKs are neither piggybacked in data packets nor sent using an accumulated ACK packet. Due to low reliability of wireless transmissions, piggybacking an ACK in a data packet or sending an accumulated ACK containing multiple ACKs (as in TCP) may introduce excessive delays and trigger unnecessary time-outs and retransmissions.

The state diagram for transmitting data packets from the source (node 0) to its destination (node M) reliably with CSMA is shown in Fig.1. When a packet is sent successfully between nodes i and $i+1$, the state will change correspondingly from i to $i+1$. If a transmission fails at an intermediate node i, the packet will be retransmitted by the source, and the state will return from i to 0. As before, $P_{i,j}$ denotes the power needed to transmit a data packet from node i to node j, and the parameters $p_{i,j}$ and $p^*_{i,j} = 1 - p_{i,j}$ represent the probability that a packet transmission from node i to j will fail and succeed, respectively.

With this diagram, we can calculate the average total power needed to send a data packet along the path from source to destination, denoted by $\overline{P_{S,D}}$, as follows. Let $p(N)$ be the probability that the most recently transmitted packet by the source successfully arrives at each node along the path, up to node N, where $0 \leq N \leq M$. We have:

$$p(N = i) = \begin{cases} p_{0,1} & : \quad i = 0 \\ \prod_{j=0}^{i-1} p^*_{j,j+1} p_{i,i+1} & : \quad 0 < i < M \\ \prod_{j=0}^{M-1} p^*_{j,j+1} & : \quad i = M. \end{cases}$$

Also, let $E\{P_{S,D}|N\}$ be the expected total power if the most recently transmitted packet by the source arrives at each node up to node N only. Observe that if $N < M$, the source node will retransmit the packet later so the additional amount of expected power consumption is $\overline{P_{S,D}}$ by definition. Accordingly, we have:

$$E\{P_{S,D}|N = i\} = \begin{cases} \overline{P_{S,D}} + \sum_{j=0}^{i} P_{j,j+1} & : \quad i < M \\ \sum_{j=0}^{M-1} P_{j,j+1} & : \quad i = M. \end{cases}$$

Since the expected total power is a weighted sum of $E\{P_{S,D}|N=i\}$, we have

$$\overline{P_{S,D}} = \sum_{i=0}^{M} E\{P_{S,D}|N=i\} \cdot p(N=i)).$$

Solving for $\overline{P_{S,D}}$, we have

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

Intuitively, the above formula can also be derived (or explained) as follows. The average number of transmissions needed by node 0 to successfully send a data packet to the destination is $T_0 = \frac{1}{\prod_{j=0}^{M-1} p^*_{j,j+1}}$, so the average total energy consumed by node 0 is $P_{0,1}T_0$. Out of these T_0 transmissions by node 0, the average number of times the packet will arrive successfully at node 1, and then be relayed by node 1 is only $T_1 = \frac{1}{\prod_{j=1}^{M-1} p^*_{j,j+1}}$. Therefore, the average total energy consumed by node 1 is $P_{1,2}T_1$. In general, the average total energy consumed by node $0 \leq i < M$ is thus $\frac{P_{i,i+1}}{\prod_{j=i}^{M-1} p^*_{j,j+1}}$.

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

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

To take into consideration the effect of control packets (e.g., an ACK packet) on the power consumption, it is reasonable to assume that (i) the destination will send an ACK only when it receives the data packet, (ii) the source knows that a data packet arrives at its destination only when it receives the ACK back, and (iii) an ACK packet may be lost, and when this happens, the destination will not retransmit the ACK until it receives the packet from the source again, and meanwhile, the source will retransmit the data packet after a time-out period.

Let the average number of times the receiver has to retransmit the ACK be $\overline{N_{D,S}}(ACK)$, and the average power consumed before the ACK can reach the source be $\overline{P_{D,S}}(ACK)$. Since wireless links may be asymmetric, and in addition, an ACK packet may be smaller than a data packet, it is possible that the probability that an ACK packet can be successfully transmitted from node $i+1$ to node i, denoted by $p^*_{i,i+1}(ACK)$, will be different from $p^*_{i+1,i}$. In any case, we have

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

In addition, let $P_{i+1,i}(ACK)$ and $P_r(ACK)$ be the power needed to transmit and receive an ACK from node $i+1$ to node i. The average power consumed before the ACK can reach the source successfully can be calculated in a way similar to Eq. II-A.1. More specifically, we have

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

Finally, based on the assumptions (i) through (iii) made above, the number of times a data packet has to reach the destination correctly before the corresponding ACK can reach the source successfully is also $\overline{N_{D,S}}(ACK)$. This implies that the average total power needed by a data packet is equal to $\overline{P_{S,D}} * \overline{N_{D,S}}(ACK)$. Therefore, the average total power in sending a data packet and receive an ACK in the EER mode is:

$$\overline{P} = \overline{P_{S,D}} * \overline{N_{D,S}}(ACK) + \overline{P_{D,S}}(ACK). \tag{2}$$

2) Multiple Access with Collision Avoidance (MACA): Instead of using carrier sensing, MACA attempts to reduce collisions by introducing two control messages: namely, Request To Send (RTS) and Clear To Send (CTS). A node transmits a RTS to its receiver before transmitting a data packet. Other 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 for RTS from node i to node j and CTS from node j to node i be $p_{r,i,j}$ and $p_{c,j,i}$ respectively. The state diagram for node i to transmit a data packet to its neighboring node j is shown in Fig. 2. Compared to the case with CSMA, it is helpful to think of node j as node $i+1$ in the previous discussion, and in addition, the union of three states S0, S1 and S2 in Fig. 2 as state i in Fig. 1, state S3 as state $i+1$ in Fig. 1, and state S4 as state 0 in Fig. 1.

More specifically, here in Fig. 2, S0 is the initial state. After node i transmits the RTS packet, the state will change to S1 with probability $p^*_{r,i,j}$ or remain the same with probability $p_{r,i,j}$, depending on whether the RTS packet is received by node j correctly or not. If node j receives the RTS packet, it will send out the CTS packet. With probability $p^*_{c,j,i}$, CTS will be received by node i, and the state will change from S1 to S2; With probability $p_{c,j,i}$, the state will return to S0. Once node i receives the CTS packet, it will transmit the data packet. With probability $p^*_{i,j}$, the data packet will be received by node j, and the state will change from S2 to S3; With probability $p_{i,j}$, the state will go to S4 where the source will have to retransmit the data packet later.

Normally, while the threshold energy level for receiving a packet correctly is the same for control and data packets, control packets such as RTS and CTS are normally sent at a higher power level than the data packets for more reliable transmission and for correctly clearing the neighborhood around the sender and receiver to avoid hidden terminals. This, coupled with the fact that RTS and CTS packets may be much smaller than the data packets, requires us to consider the normalized power consumption by the RTS and CTS packets. More specifically, let the transmission and receiving power of a data packet of length N data bits from node i to its neighbor node j be $P_{i,j}$ and P_r as before. Denote the power level used for RTS and CTS by P_m ($> P_{i,j}$). In addition, denote the MACA header size for each data packet by N_{maca}, the RTS and CTS packet sizes by N_{rts} and N_{cts} respectively, and the physical layer overhead for each packet by N_{phy}. The average total power in transmitting and receiving a packet from node i to node j (only once and without any guarantee of success) can be expressed based on the state diagram in Fig. 2 in a way similar to Eq. II-A.1 as follows:

$$\overline{P_T(i,j)} = (P_{i,j} + P_r) + \frac{N_r}{N_m}\frac{P_m+P_r}{p^*_{c,j,i}p^*_{r,i,j}} + \frac{N_c}{N_m}\frac{P_m+P_r}{p^*_{c,j,i}} \tag{3}$$

where $N_r = N_{rts} + N_{phy}$, $N_c = N_{cts} + N_{phy}$, and $N_m = N + N_{maca} + N_{phy}$.

Considering the scenario with $M-1$ intermediate nodes between the source (node 0) and the destination (node M) as in the case of CSMA, the average total power in transmitting a data packet from node 0 to node M correctly is:

$$\overline{P_{S,D}} = \sum_{i=0}^{M-1} \left(\frac{\overline{P_T(i,i+1)}}{\prod_{j=i}^{M-1} p^*_{j,j+1}} \right). \tag{4}$$

Similar to Eq. 2 for the case of CSMA, if we also consider the energy consumption for sending and receiving an end-to-end ACK packet, the average total power will be:

$$\overline{P} = \overline{P_{S,D}} * \overline{N_{D,S}}(ACK) + \overline{P_{D,S}}(ACK). \tag{5}$$

where $\overline{N_{D,S}}(ACK)$ and $\overline{P_{D,S}}(ACK)$ can be calculated similarly as in the case for CSMA.

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) 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 $p_{a,i,j}$. As before, the power needed to transmit and receive an ACK from node j to node i will be denoted by $P_{j,i}\frac{N_a}{N_8}$ and $P_r\frac{N_a}{N_8}$ respectively. The state diagram for transmitting a data packet from node i to one of its neighboring nodes, node j, is depicted 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 sending a packet from node i to node j successfully is given by

$$\overline{P_T(i,j)} = \frac{P_{i,j}}{p^*_{i,j}p^*_{a,j,i}} + \frac{P_{j,i}}{p^*_{a,j,i}}\frac{N_a}{N_8}. \tag{6}$$

Similiarly, the average total receiving power consumed 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

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

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

$$\overline{P_{total}} = \sum_{i=0}^{M-1}\left(\overline{P_T(i,i+1)} + \overline{P_R(i,i+1)}\right). \tag{7}$$

2) 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.

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

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

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

$$\overline{P_R(i,j)} = P_r\frac{\frac{N_r}{N_8} + (\frac{N_c}{N8} + p^*_{i,j} + \frac{N_a}{N_8}p^*_{i,j}p^*_{a,j,i})p^*_{c,j,i}}{p^*_{c,j,i}p^*_{i,j}p^*_{a,j,i}}. \tag{9}$$

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

$$\overline{P_{total}} = \sum_{i=0}^{M-1}\left(\overline{P_T(i,i+1)} + \overline{P_R(i,i+1)}\right). \tag{10}$$

[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.

III. Performance Studies

In this section, we evaluate the proposed energy consumption models via simulation in GloMoSim. First, we simulate packet transmissions along a given path, and compare the energy consumption obtained from simulation with that estimated by different energy consumption models. We show that our models are much more accurate than the existing ones. Second, we apply different HHR energy consumption models to minimum energy routing in 802.11 ad hoc networks and compare the energy consumption using different models. We show that the protocol based on our model is more energy efficient than those based on existing models.

To simplify the expression, we denote the minimum energy routing protocol with *Total Transmission Power model*, *Total TransCeiving Power model*, and *Total Reliable Transmission Power model* by *MTTP*, *MTTCP* and *MTRTP* respectively.

A. Accuracy of Energy Consumption Models

In this subsection, we evaluate the accuracy of our models as well as that of MTTP and MTRP using GlomoSim. In our simulation, the transmission power level is set to 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 and consider only one path from the source (numbered as node 0) to a destination node that is 2 to 6 hops away along the path (numbered as nodes 2 to 6, respectively).

For simplicity, we will only compare the accuracy of the energy consumption models used in MTTP and MTRTP with that of our models in terms of the transmission power (as the former two do not consider receiving power). Note that, in terms of predicting the transmission power, the MTTCP is as inaccurate as MTTP. If receiving power were also considered, our model would be even more accurate than MTTP and MTRTP. It would also be more accurate than MTTCP because the latter does not consider control packets and retransmissions.

1) Estimation for the EER mode: 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 have almost the same energy consumption estimate due to the low packet error rate (especially in the case of MACA), underestimate the energy consumption significantly and the underestimation increases with the number of intermediate nodes. In addition, the underestimation is much larger in MACA than in CSMA. The reason is that the MTTP and MTRTP models in MACA ignore not only the energy consumption by ACK and the number of ACK retransmissions, but also the energy consumption for RTS and CTS in the MAC layer.

2) Estimation for the HHR mode: 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 very well in both schemes. Again, both MTTP and MTRTP underestimate the energy consumption and they get worse as the number of intermediate nodes increases. In addition, the underestimation is much more serious in the *Four Frame Exchange scheme* than in the *Two Frame Exchange scheme*.

B. Application to Minimum Energy Routing in 802.11 Ad hoc networks

In this subsection, we modify the AODV routing protocol to support minimum energy routing with link costs calculated from different energy consumption models. Since the authors in [4] already showed that

MTRTP is better than MTTP, we will only compare the routing protocol based on our model to MTRTP. We will also study the *Power Control Scheme*, which uses AODV as the routing protocol to find a shortest path and adjusts the transmission power according to the distance between the sender and the receiver.

Given that wireless transmissions are error prone due to many factors such as fading, interference, mobility and collision, the HHR mode prevails in the wireless ad hoc networks [4]. Accordingly, we will only study the performance of the energy consumption models for the HHR mode. The two performance metrics we investigated are: 1) *Energy consumption per packet*, which is defined as the total energy consumption divided by the total number of packets transmitted successfully; (2) *Percentage of packets received*, 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 reflects the throughput if the end-to-end delay is almost the same for each packet. The higher the percentage of the packets received, the higher the throughput.

In our simulation, the network area 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 0.05 mW. By default, there are 50 nodes which are uniformly distributed and the pairs of source and destination nodes are randomly selected. The connection requests arrive according to a Poisson process and the connection duration is exponentially distributed. The application protocol is CBR with 5 packets/second. Also by default, the data packet size is 512 bytes and the transmission rate is 2Mbps.

In the following, we will study the effect of network density, load and packet size on the performance of the minimum energy routing protocols based on different energy consumption models. We simulate the protocols using the *Two Frame Exchange scheme* and the *Four Frame Exchange scheme* respectively, and monitor the amount of energy consumed, the number of packets received correctly and the total number of packets sent.

1) Variable network density: In this set of simulations, the connection arrival rate is set to 50 per hour and the average connection duration is 3 minutes. The packet size is fixed to the default value (512 bytes).

However, the number of nodes in the network domain is varied from 40 to 70. Each routing scheme was simulated for one hour. The simulation results are depicted in Figs. 9 through 12.

As can be seen from these figures, our model results in the best performance in terms of energy consumption per packet, followed by MTRTP and the Power Control scheme. Our model also allows a higher percentage of packets to be transmistted 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 packets loss is due to 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 received*, followed by those based on MTRTP and the power control protocol.

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 based protocol has the lowest percentage of packets received because it uses the largest number of intermediate nodes and hence has the highest number of radio transmissions. The power control based protocol has the highest percentage of packets received, 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 higher transmission power.

2) Variable connection arrival rate: In this set of simulations, the connection arrival rate varies (so does the network load) with the average connection duration set to 6 minutes. All other parameters are set to its default value. We simulated each routing scheme for five hours. The simulation results are depicted in Figs. 13 through 16.

From Figs 13 and 15, it is clear that our protocol performs better in terms of *energy consumption per packet* using either the *Two Frame Exchange* or *Four Frame Exchange* schemes under various load conditions. In addition, with regard to the *percentage of packets received*, our protocol performs the best in *Two Frame Exchange Scheme,* followed by MTRTP and the Power Control protocol; while the Power Control based protocol performs the best in the *Four Frame Exchange Scheme*, followed by our protocol and MTRTP based protocol.

It is worth noting that the increase in the arrival rates and in turn the network load will lead to a higher probability of collision among the RTS and CTS packets in the *Four Frame Exchange Scheme* and among the data packets in the *Two Frame Exchange Scheme*. In addition, increasing the load will increase the interference, which leads to higher bit error rates. Therefore, the energy consumption per packet will increase with the network load, while the percentage received will decrease as illustrated in Figs. 13 through 16. Comparing the trends in the *Two Frame Exchange scheme* and *Four Frame Exchange Scheme*, we can see that the effect of the network load is more prominent in the *Four Frame Exchange Scheme*. This is because the *Four Frame Exchange Scheme* uses two more control packets (RTS and CTS), both of which are transmitted at the maximum power level. For the *Four Frame Exchange* scheme, it is also apparent that the increase in the *energy consumption* or the decrease in the *percentage received* is more dramatic with MTRTP based protocol than with our protocol. That is because as the network load and packet error rate change, our protocol can adapt to a more energy efficient route by considering the energy consumption of the RTS and CTS packets.

3) Variable Packet Size: In this set of simulations, the average connection duration is set to 6 minutes and the average arrrival rate is 40 connnections/hour, with every other parameter set to its default value.

However, the size of data packet varies, so does the network load. Each routing scheme is simulated for five hours. The simulation results are depicted in Figs. 17 through 20.

From Figs. 17 and 20, it is apparent that our protocol performs better than the other two schemes in terms of energy consumption per packet for both the *Two Frame Exchange Scheme* and the *Four Frame Exchange Scheme* under various load conditions. In addition, our protocol performs the best in terms of *percentage of packets received* in the *Two Frame Exchange* scheme, followed by MTRTP based protocol and *power control* based protocol; On the other hand, in the *Four Frame Exchange* scheme, the *power control* scheme has the highest percentage of packets received, followed by our protocol and MTRTP based protocol. As expected, the results also show that increasing the data packet size will increase the energy consumption per packet and reduce the percentage of packets transmitted for the same reasons mentioned earlier for the case of increasing the arrival rate.

IV. Concluding Remarks

In this paper, we have examined the energy cost metrics widely used in the existing energy efficient routing protocols, and developed more accurate energy consumption models for common MAC protocols CSMA, MACA, and 802.11. Unlike existing models that ignored energy consumption due to various control messages and thus underestimated the actual energy cost, our models take into account such energy consumption. The accuracy of our models have been verified through simulations. More specifically, our energy consumption models developed for both the EER and HHR modes have been shown to be much closer to the actual energy consumed than the existing models. Our results have also shown that our energy consumption model for the HHR mode can be used to determine paths with a minimum energy cost and thus achieving better energy conservation performance than other models. On the other hand, although our models for the EER mode are useful in predicting the actual energy consumption along a given path more accurately than existing models, the energy consumption per link, as predicted by the models, is not additive and thus cannot be directly used by shortest-path algorithms. Thus, a future research topic is how to approximate our energy consumption models developed for the EER mode so as to make them applicable to minimum energy routing while still maintaining better accuracy than the existing models.

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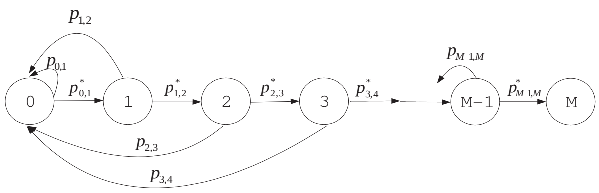

Fig. 1. State diagram for CSMA.

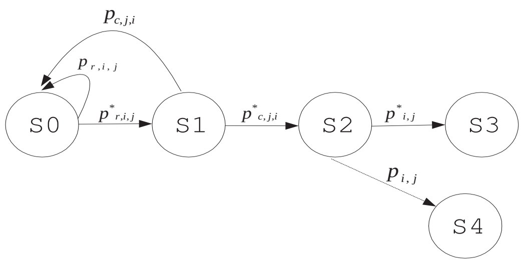

Fig. 2. State diagram for transmitting a packet from node i to node j in MACA.

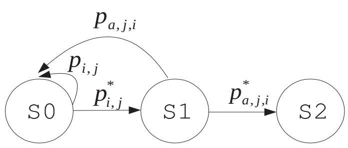

Fig. 3. State diagram for the Two Frame Exchange scheme.

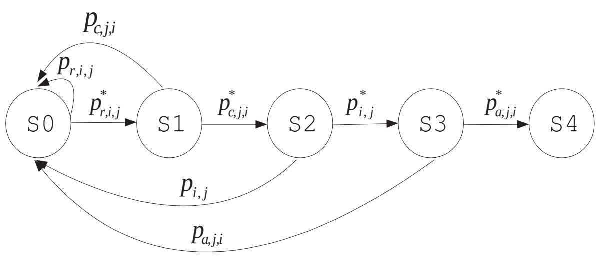

Fig. 4. State diagram for the Four Frame Exchange scheme.

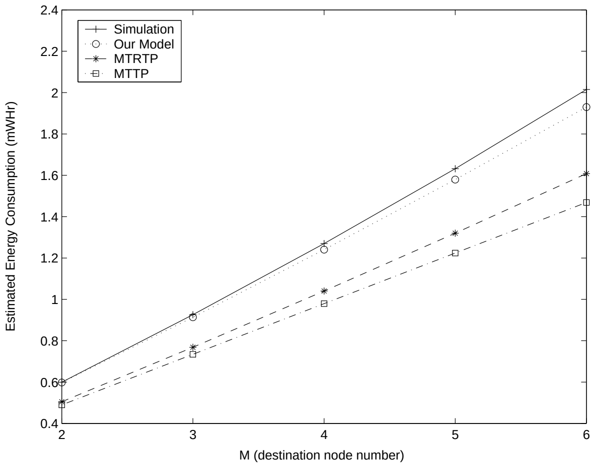

Fig. 5. Estimated energy consumption vs. simulation results with CSMA.

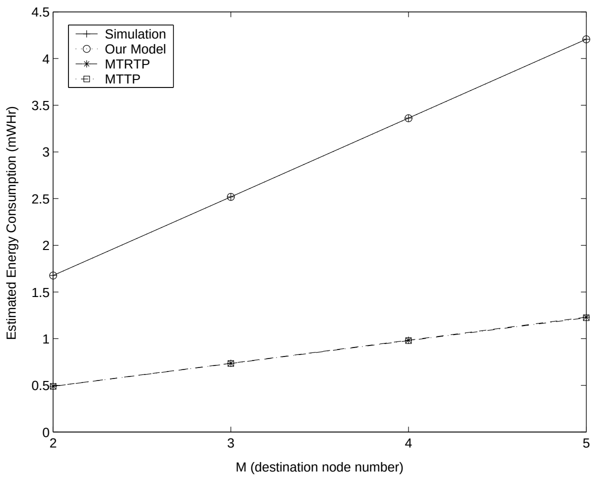

Fig. 6. Estimated energy consumption vs. simulation results with MACA.

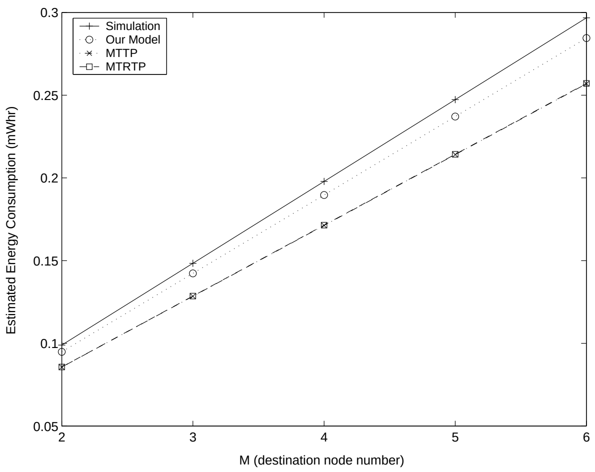

Fig. 7. Estimated energy consumption vs. simulation results with the Two Frame Exchange scheme.

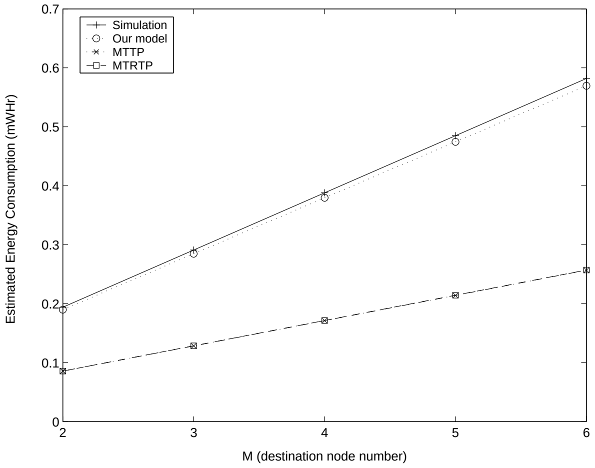

Fig. 8. Estimated energy consumption vs. simulation results with the Four Frame exchange scheme.

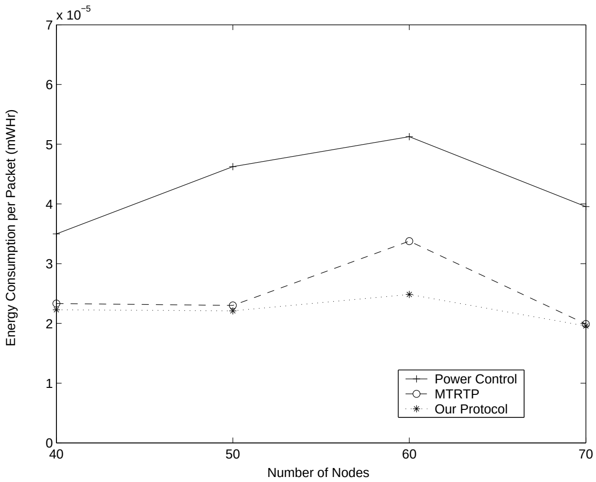

Fig. 9. Energy consumption per packet in the two frame scheme.

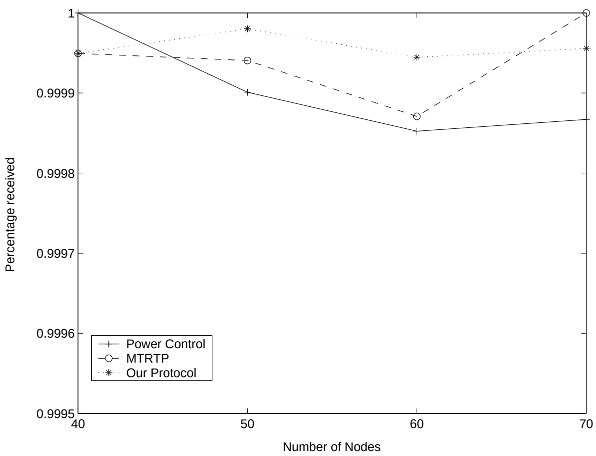

Fig. 10. Percentages of packets received in two frame scheme.

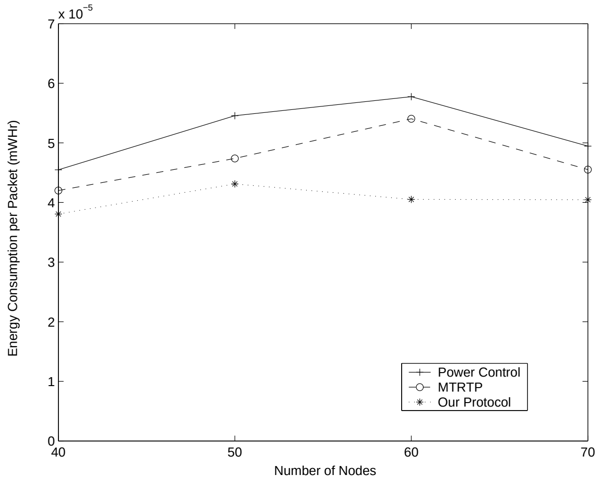

Fig. 11. Energy consumption per packet in the four frame scheme.

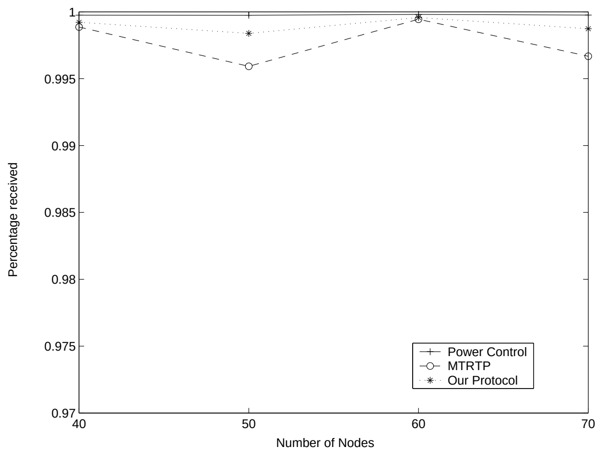

Fig. 12. Percentages of packets received in the four frame scheme.

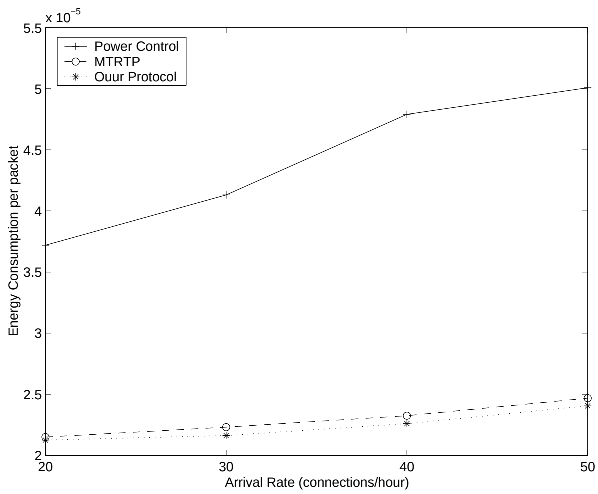

Fig. 13. Energy consumption per packet for different arrival rates in the Two Frame scheme.

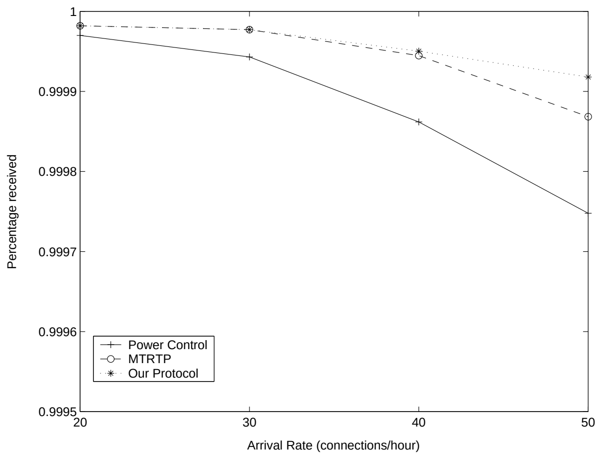

Fig. 14. Percentage of packet received for different arrival rates in the Two Frame scheme.

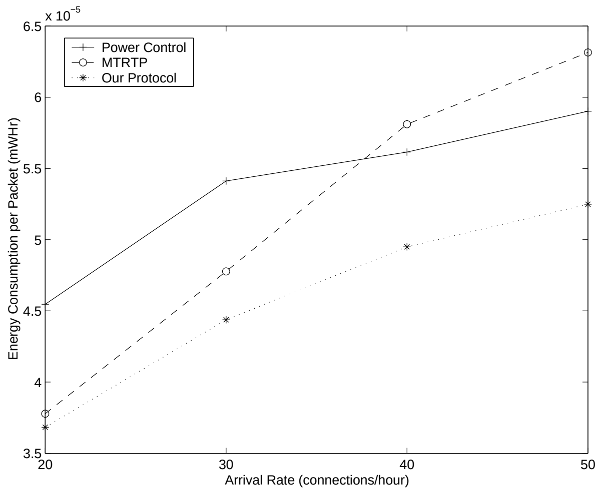

Fig. 15. Energy consumption per packet for different arrival rates in the Four Frame scheme.

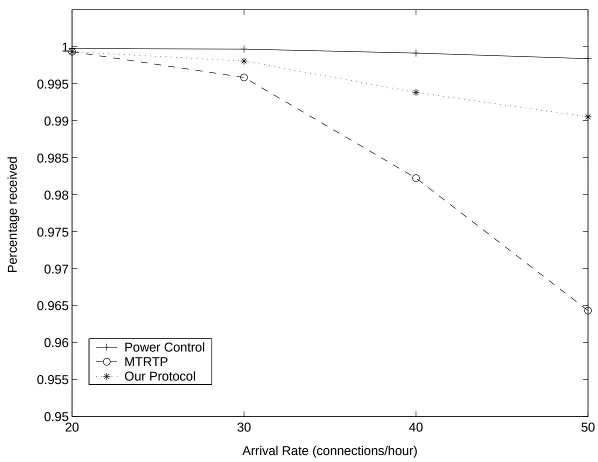

Fig. 16. Percentage of packets received for different arrival rates in the Four Frame scheme.

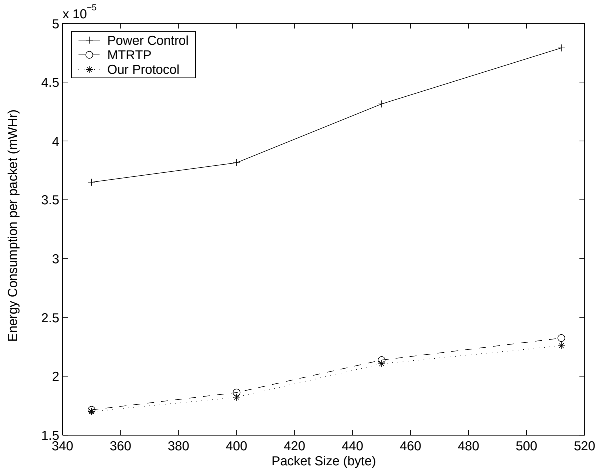

Fig. 17. Energy consumption per packet for different packet sizes in the two frame scheme.

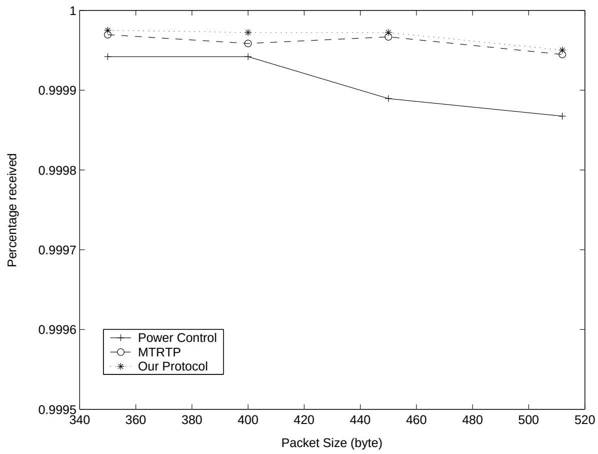

Fig. 18. Percentage of packets received for different packet sizes in the two frame scheme.

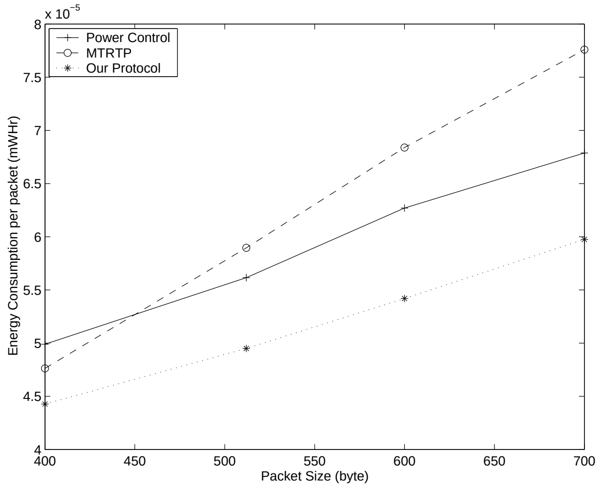

Fig. 19. Energy consumption per packet for different packet sizes in the four frame scheme.

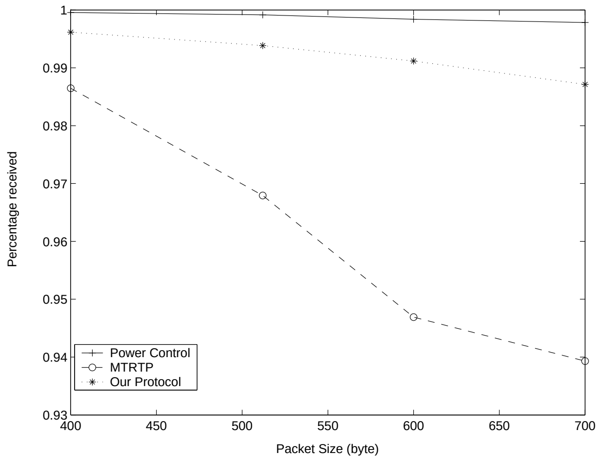

Fig. 20. Percentage of packets received for different packet sizes in the four frame scheme.