Energy Efficient MAC Protocol with Power and Rate Control in Multi-rate ad hoc networks

Masaki Bandai, Satoshi Maeda, and Takashi Watanabe
Dept. of Computer Science, Shizuoka University
Hamamatsu, 432–8011 Japan
E-mail: bandai@inf.shizuoka.ac.jp

Abstract—In this paper, a novel medium access control (MAC) protocol with transmission power and transmission rate control in multi-rate ad hoc networks is proposed to realize high energy efficient data transmission. In the proposed protocol, each node prepares a table that includes energy efficiency in all combinations of transmission power and rate. By exchanging of control frames and looking up the transmission power and rate table, direct and relay transmission sequences are used arbitrarily. When relay transmission by intermediate node between sender and receiver is more effective in terms of power consumption, relay sequence is adopted instead of direct transmission. We show that the proposed protocol can realize high energy efficient data transmission via computer simulations.

I. INTRODUCTION

Recently, the rapid progress in wireless technologies enables ad hoc networks to be realized. One of the important issues of ad hoc networks is to alleviate energy consumption for miniaturization of nodes. There are extensive researches to develop energy efficient medium access control (MAC) and routing protocols in ad hoc networks.

As the effective approach to realize energy efficient data transmission, transmission power control and transmission rate control are presented [1]-[8]. MAC protocols with transmission power control [1]-[3] are derived from IEEE 802.11 DCF. Data are transmitted with required minimum transmission power to improve energy efficiency of data transmission. The required minimum received power is calculated according to measurement of received power of control frames. MAC protocols with transmission rate control [4]-[6] are used in ad hoc networks with multi-rate physical layer such as IEEE 802.11b [7]. In these protocols, data are transmitted in a high data transmission rate to shorten data transmission time. Therefore, the energy consumption efficiency of data transmission can improve. The minimum-energy transmission strategy (MiSer) introduces both transmission power and rate control [8]. In MiSer, each node has a table that includes energy efficiency of all combinations of transmission power and transmission rate. When a node transmits a data, the node looks up the table and selects a suitable combination of transmission power and rate. However, as well as the above protocols, improvement of energy efficiency becomes small with minimum hop routing. In addition, exact estimation of number of neighbor nodes and RTS collision probability are necessary to prepare the transmission power and rate table. However, it is difficult to estimate the information. In multi-rate aware topology control algorithm (MATC) [9] and efficient multi-rate relaying (EMR) [10], data relay by a neighbor node is introduced to improve energy efficiency with minimum hop routing. It is shown that these protocols can achieve good throughput. However, since these protocols control only data rate, they cannot be used with multi-rate devices. It is necessary to realize energy efficient MAC protocol with data relay with transmission power and rate control.

In this paper, a novel MAC protocol with transmission power and rate control is proposed to realize high energy efficient data transmission. In the proposed protocol, each node prepares a table that includes energy efficiency of all combinations of transmission power and rate. The table is only based on the specification of the network card without exact estimation of network topology and traffic. By exchanging control frames and looking up the transmission power and rate table, direct and relay transmission sequence are used arbitrarily. We show that the proposed protocol can realize high energy efficient data transmission via simulations.

II. PROPOSED PROTOCOL

The proposed protocol alleviates energy consumption by means of data relay with both transmission power control and transmission rate control. The proposed protocol has the following two features.

1) Transmission power and rate table:
Each node has a table in which energy efficiency of all combinations of transmission power and rate is calculated in advance. Data sender selects most energy efficient combination of transmission power and transmission rate according to the table.

2) Two communication sequences:
Two communication sequences that are direct and relay sequences are used arbitrarily. Data receiver selects a communication sequence with better energy efficiency.

A. Transmission power and transmission rate table

The transmission power and rate table includes the energy efficiency of all combinations of transmission power and transmission rate. In MiSer, it is necessary to acquire precisely the number of neighbor nodes, RTS collision probability and bit error rate. On the contrast, the transmission power and rate table of the proposed protocol is prepared by only the specification of network card. Therefore, it is unnecessary to
TABLE I  
TRANSMISSION POWER AND RATE TABLE.

<table>
<thead>
<tr>
<th>i</th>
<th>j</th>
<th>Power $P_i$ dBm</th>
<th>Rate $R_i$ Mbps</th>
<th>Req. Rx Pow. Gap $\Delta(P_i, R_i)$ dBm</th>
<th>Pow. Cons. Ratio $\rho(P_i, R_j)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>14.77</td>
<td>1</td>
<td>0.00</td>
<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>13.01</td>
<td>2</td>
<td>1.78</td>
<td>0.844</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>14.77</td>
<td>2</td>
<td>3.00</td>
<td>0.508</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>13.01</td>
<td>2</td>
<td>4.76</td>
<td>0.429</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>14.77</td>
<td>5.5</td>
<td>5.00</td>
<td>0.195</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>13.01</td>
<td>5.5</td>
<td>6.76</td>
<td>0.164</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>6.99</td>
<td>1</td>
<td>7.76</td>
<td>0.611</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>14.77</td>
<td>11</td>
<td>9.00</td>
<td>0.105</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>13.01</td>
<td>11</td>
<td>10.76</td>
<td>0.089</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0</td>
<td>11</td>
<td>23.77</td>
<td>0.058</td>
</tr>
</tbody>
</table>

estimate any parameters about network topology, traffic pattern and radio propagation.

We assume $n$ levels of transmission power available which are $P_0, P_1, ..., P_{n-1}$ ($P_0 > P_1 > ... > P_{n-1}$) dBm. Especially, the maximum transmission power $P_0$ is defined as base transmission power. We also assume $m$ levels of data rate available which are $R_0, R_1, ..., R_{m-1}$ ($R_0 < R_1 < ... < R_{m-1}$) Mbps. Especially, the lowest data rate $R_0$ is defined as base transmission rate. We define the energy efficiency ratio $\rho(P_i, R_j)$ as follows:

$$\rho(P_i, R_j) = \frac{E(P_i, R_j)}{E(P_0, R_0)},$$

(1)

where $E(P_i, R_j)$ is the energy consumption when transmission power $P_i$ and rate $R_j$ are adopted. In addition, we also define required power gap to receive a data $\Delta(P_i, R_j)$ dBm as follows:

$$\Delta(P_i, R_j) = \pi(P_i, R_j) - \pi(P_0, R_0),$$

(2)

where $\pi(P_i, R_j)$ dBm is required power to receive a data $\rho(P_i, R_j)$ and $\Delta(P_i, R_j)$ is calculated by the specification of network card.

The transmission power and rate table for Cisco Aironet 350 is shown in Table I. The card has four levels of transmission power which are $P_0 = 14.77$ dBm, $P_1 = 13.01$ dBm, $P_2 = 6.99$ dBm and $P_3 = 0$ dBm. It also has four levels of transmission rate which are $R_0 = 1$, $R_1 = 2$, $R_2 = 5.5$ and $R_3 = 11$ Mbps. There are 16 combinations of transmission power and rate in the table. For example, when $P_0 = 14.77$ dBm and $R_3 = 11$ Mbps are selected, the energy consumption is 0.105 times as that of base transmission power and rate. Moreover, the required power at a receiver is 9.00 dBm larger than that of base transmission power and rate.

When a node receives a control frame such as RTS, the node measures the received power. We assume that the received power of the RTS is $p$ dBm. In this case, the required power gap is calculated as $p - \pi(P_0, R_0)$, therefore, one of the combinations satisfying $\Delta(P_i, R_j) < p - \pi(P_0, R_0)$ is selected from the table I. For example, when $p - \pi(P_0, R_0) = 8$ dBm is measured, among all combinations satisfying $\Delta(P_i, R_j) < 8$, a combination with the minimum energy consumption ratio $\rho(P_i, R_j)$ is selected. For example, in the above case, $\rho(13.01, 5.5) = 0.164$ is the minimum energy consumption ratio, therefore, the combination with $P_1$ and $R_2$ is selected.

B. Two communications sequences

In order to alleviate energy consumption with minimum hop routing, the proposed protocol uses two communications sequences arbitrarily according to the transmission power and rate table. When the destination node receives RTS, the node measures the received power of the RTS. When the received power is smaller than the pre-defined sequence selection threshold $Th$ dBm, the node selects relay sequence. Otherwise, the node selects direct sequence. Fig. 1 gives pseudo-code of the proposed protocol in senders nodes. When the received power of RTS is large, the distance between sender and receiver is near. In this case, direct communications is sufficiently effective in terms of energy consumption. On the contrast, when the received power of RTS is small, the distance between the sender and the receiver is far. In this case, direct communications has a room for improvement in terms of energy consumption because large transmission power and low transmission rate are necessary. Therefore, relay communication is effective to alleviate energy consumption. In relay sequence, request-to-relay (RTR) and clear-to-relay (CTR) frames are introduced in addition to RTS/CTS/DATA/ACK. Direct sequence is the same as IEEE 802.11 DCF.

In Figs. 2 and 3, we show a sample operation when relay sequence is selected. Let’s consider a case where Node S sends data to Node D.

1) S senses carrier in the contention window. If no carrier is detected, S transmits RTS as shown in Fig. 2a.
2) When the received power is smaller than $Th$, D selects relay sequence, and broadcasts RTR to one-hop neighbors. When the received power is larger than $Th$, D selects direct sequence, and transmits CTS to S. Fig. 2b shows the case where relay sequence is selected.
In the proposed protocol, a node that receives RTS and does not receive RTR such as Node X in Fig. 2 cannot set appropriate network allocation vector (NAV) duration because the node cannot realize whether direct or relay sequence begins. In addition, a node which receive RTS and does not receive CTR such as Node Z in Fig. 2 also cannot set appropriate NAV duration because the node does not know transmission rate of CTR such as Node Z in Fig. 2 also cannot set appropriate NAV duration because the node cannot realize whether direct or relay sequence begins.

3) A and B which have received both RTS and RTR measure backoff time to transmit CTR at an intermediate node is determined to specify a relay node as the following priority backoff mechanism. We use the energy consumption ratio \( \rho(P_i, R_j) \) of transmission power and rate table to set backoff time to a node.

We assume the case where S has a data to D. In addition, there is a relay candidate node X as shown in Fig. 4. D calculates energy consumption ratio of the link between S and D \( \rho_{SD} \) based on the received power of the RTS from S. RTR transmitted by D includes the received power of the RTS from S. X calculates energy consumption ratio of the link between X and D \( \rho_{DX} \) based on the received power of the RTR from D. X also calculates energy consumption ratio of the link between S and D \( \rho_{SD} \) based on the received power of the RTR from D.

TABLE II

<table>
<thead>
<tr>
<th>Priority Level</th>
<th>Sum of Power Cons.</th>
<th>Backoff Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[0, 0.222]</td>
<td>[0, 10]</td>
</tr>
<tr>
<td>2</td>
<td>[0.222, 0.444]</td>
<td>[11, 20]</td>
</tr>
<tr>
<td>3</td>
<td>[0.444, 0.667]</td>
<td>[21, 30]</td>
</tr>
</tbody>
</table>

\[
D_{\text{nav}} = T_{max} + T_{CTR} + 2T_{DATA,R_0} + T_{ACK,R_0} + 3T_{SIFS}
\]

(3)

where \( T_{max} \) is maximum backoff time (See next subsection), \( T_{CTR} \) is transmission time of CTR, \( T_{DATA,R_0} \) is transmission time of DATA at base rate, \( T_{ACK,R_0} \) is transmission time of ACK at base rate, \( T_{SIFS} \) is short IFS (SIFS). The above equation means the duration of relay transmissions with two base rate links in order to prevent interference. These NAV durations are very conservative. Setting more appropriate NAV duration is our future work.

Priority backoff

In the proposed protocol, an appropriate relay node should be selected by distributed manner to minimize energy consumption. Backoff time to transmit CTR at an intermediate node is determined to specify a relay node as the following priority backoff mechanism. We use the energy consumption ratio \( \rho(P_i, R_j) \) of transmission power and rate table to set backoff time to a node.

\[
D_{\text{nav}} = T_{max} + T_{CTR} + 2T_{DATA,R_0} + T_{ACK,R_0} + 3T_{SIFS}
\]

(3)

where \( T_{max} \) is maximum priority backoff time (See next subsection), \( T_{CTR} \) is transmission time of CTR, \( T_{DATA,R_0} \) is transmission time of DATA at base rate, \( T_{ACK,R_0} \) is transmission time of ACK at base rate, \( T_{SIFS} \) is short IFS (SIFS). The above equation means the duration of relay transmissions with two base rate links in order to prevent interference. These NAV durations are very conservative. Setting more appropriate NAV duration is our future work.

Priority backoff

In the proposed protocol, an appropriate relay node should be selected by distributed manner to minimize energy consumption. Backoff time to transmit CTR at an intermediate node is determined to specify a relay node as the following priority backoff mechanism. We use the energy consumption ratio \( \rho(P_i, R_j) \) of transmission power and rate table to set backoff time to a node.

We assume the case where S has a data to D. In addition, there is a relay candidate node X as shown in Fig. 4. D calculates energy consumption ratio of the link between S and D \( \rho_{SD} \) based on the received power of the RTS from S. RTR transmitted by D includes the received power of the RTS from S. X calculates energy consumption ratio of the link between S and D \( \rho_{SD} \) based on the received power of the RTS from S. Moreover, X also calculates energy consumption ratio of the link between X and D \( \rho_{DX} \) based on the received power of the RTR from D. X calculates own backoff time according to summation of energy consumption ratio when X relays the data \( \rho_{relay}(= \rho_{SX} + \rho_{SD}) \). Shorter backoff time is set at smaller summation of energy consumption ratio \( \rho_{relay} \).

We assume that number of priority levels is \( L \) (level 1 to \( L \)), maximum backoff time is \( T_{max} \) slottime, and the energy consumption ratio of direct communication is \( \rho_{direct} \). Nodes when summation of energy consumption ratio is \( (l-1)\frac{T_{max}}{L} \leq \rho_{relay} < l\frac{T_{max}}{L} \) is classified as the priority level \( l \). Backoff time of priority level \( l \), \( T_{boff}(l) \) is set as \( (l-1)\frac{T_{max}}{L} \leq T_{boff}(l) < l\frac{T_{max}}{L} \).

In Fig. 4, an example of priority backoff is shown. We assume that number of priority levels is defined as \( L = 3 \).
maximum backoff time is $T_{\text{max}} = 30$ slot time, and the power efficiency adopting direct communications is $\rho_{\text{direct}} = 0.667$. We also assume that backoff levels are defined as Table II. At node X, summation of power consumption ratio becomes $\rho_{\text{relay}} = 0.07 + 0.07 = 0.14$. Therefore, priority level 1 is adopted, and a random time in $[0, 10]$ is set as its backoff time. At node Y, since $\rho_{\text{relay}} = 0.105 + 0.19 = 0.295$, the range $[11, 20]$ of priority level 2 is adopted as well.

In the proposed protocol, smaller backoff time is set at node with smaller summation of energy consumption ratio. Therefore, the node on the way of more energy efficient route relays on the priority basis.

### III. PERFORMANCE EVALUATION

We develop an event driven simulator in C# language. Simulation parameters are shown in Table III. Destination node is randomly selected among all nodes in the network. The transmission power and rate table is as shown in Table I. The transmission range with $P_0$ and $R_0$ becomes is 195 m. We evaluate the following five models.

1) IEEE 802.11 DCF with $P_0$ and $R_0$, referred to as Conv.
2) Proposed protocol with transmission power and rate table, where variable transmission power $P$ and base rate $R_0$, referred to as Prop(Power)
3) Proposed protocol with transmission power and rate table, where base transmission $P_0$ and variable rate $R$, referred to as Prop(Rate)
4) Proposed protocol with transmission power and rate table, where transmission power $P$ and rate $R$, referred to as Prop(Power, Rate)
5) Proposed protocol with transmission power and rate table and relay communication, referred to as Prop(Power, Rate, Relay)

We evaluate total energy consumption, throughput and energy efficiency. Total energy consumption is defined as a summation of total energy consumption to transmit and receive all frames of all nodes. Throughput is defined as a ratio of total received data to total delay of all nodes. Energy efficiency is defined as a ratio of throughput to total energy consumption.

Fig. 5 shows the total energy consumption versus packet size. Number of nodes is ten, and packet arrival rate at each node is 1 packet/s. In Fig. 5, we find that the energy consumptions of all models are proportional to packet size. Energy consumption of Conv becomes worst because Conv always uses base transmission power and rate. It is also found that prop(Rate) is smaller energy consumption than Prop(power). This is because that for example, when transmission rate is changed from 1 to 11 Mb/s, the energy consumption alleviates to about 1/10. On the other hand, when transmission power is changed from 14.77 to 0 dBm, the energy consumption alleviates to only half. Moreover, although transmission rate is controlled in addition to the transmission power in Prop(Power, Rate), Prop(Power, Rate) consumes slightly less energy than Prop(Rate). The reason is that when minimum hop routing is adopted, long links tend to be selected and the merit of transmission power control cannot be received. Moreover, Prop(Power, Rate, Relay) is the superior performance among all models. We confirm that relay sequence is effective to alleviate energy consumption.

Fig. 6 shows throughputs versus packet size. Number of nodes and packet arrival rate are same as Fig. 5. Since data transmission rate that is always base rate is the same in both Conv and Prop(Power), throughput becomes the same. In addition, when packet size is 128 byte, throughput of Prop(Power, Rate, Relay) becomes lower than that of Prop(Power, Rate). In Prop(Power, Rate, Relay), performance degrades because...
the overhead of priority backoff and adding RTR and CTR frames. On the contrary, in a large packet size, improvement of throughput provided by relay sequence is more dominant than the effect of control overhead in Prop(Power, Rate, Relay). Moreover, we can say that Prop(Power, Rate, Relay) achieves superior throughput even with the conservative NAV setting.

Fig. 7 shows the energy efficiency versus packet size. Number of nodes and packet arrival rate are same as Fig. 5. In Fig. 7, it is found that in all models when packet size is middle, energy efficiency is almost maximum. In addition, the energy efficiency degrades when packet size is large. This is because that energy consumption is proportional to packet size, on the other hand, throughput becomes saturated when packet size is large.

Figs. 8, 9 and 10 show total energy consumption, throughput and energy efficiency versus number of nodes, respectively. Packet size is 1,500 byte, and packet arrival rate is 1 packet/s. In Fig. 8, we find that when number of nodes is large, all proposed protocols improve energy efficiency. In Fig. 9, it is found that all protocols except Prop(Power, Rate, Relay) degrade throughput when number of nodes is large. The reason is that data frame collision occurs more frequently as number of nodes increases. In Prop(Power, Rate, Relay), when number of nodes is small such as five nodes, number of candidates for relay node becomes less, therefore, throughput improvement becomes small. On the contrast, when number of nodes is large such as 15 nodes, CTRs collide more frequently, therefore, throughput also becomes small. In Fig. 10, all models can achieve best energy efficiency when number of nodes is small. Therefore, power efficiency improves more in middle or small number of nodes.

**IV. CONCLUSIONS**

In this paper, a novel MAC protocol with transmission power and rate control has been proposed to realize high energy efficient data transmission. In the proposed protocol, each node prepares a transmission power and rate table. By exchanging control frames and looking up the table, direct and relay transmission sequences are used arbitrarily. We have shown that the proposed protocol can realize high energy efficient data transmission via simulations. Especially, under large packet size or middle node density or low packet arrival rate, Prop(Power, Rate, Relay) can achieve superior energy efficient performance. In addition, we have shown that Prop(Power, Rate) is effective when packet size is small.

**ACKNOWLEDGMENT**

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientist (B), no. 19700057, 2007.

**REFERENCES**


