A Multi-Rate MAC Protocol for Mobile Ad Hoc Networks and its Cooperative Extension

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ABSTRACT

Strategies for achieving high communication throughput and efficient energy saving are research hot spots in the area of mobile ad hoc networks (MANETs). Most previous works focus only on one of the optimization goals. This paper primarily contributes a Multi-Rate Medium Access Control (MAC) protocol (MR-MAC) operating in the 802.11g environment. This protocol economizes on energy for low traffic scenarios and maintains high throughput under heavy traffic conditions. MR-MAC utilizes rate adaption and estimation of channel occupation time, thus enabling it to choose a transmission rate which satisfies the requirement of each flow. In doing so, it efficiently lowers the power consumption caused by an unnecessary high transmission rate. Another significant contribution of this paper is the Cooperative Multi-Rate MAC protocol (CMR-MAC) which balances power consumption while ensuring energy efficiency. The main idea of CMR-MAC is the active acceleration of the high energy nodes' transmission rate within the area surrounding a low-energy node. This reduces channel occupation time which, in turn, helps the low energy nodes save energy. Simulation results show that MR-MAC outperforms Receiver-Based Auto-Rate (RBAR) by 40% in terms of energy efficiency, yet maintains a comparable throughput with the latter. Meanwhile, CMR-MAC is about 20% to 30% superior to MR-MAC in network lifetime and total number of delivered packets, respectively.

1. INTRODUCTION

Energy efficiency and network throughput are the two most important metrics in mobile ad hoc networks (MANETs). There is an inherent tradeoff between these metrics. On one hand, to conserve energy, low transmit power is applied. This can hardly support the high transmission rate required by the high throughput. On the other hand, high transmission rate is needed to achieve high throughput. However, the corresponding transmit power increases disproportionately with rate as specified in [1].

Energy optimization within a certain limit of throughput has already been proven as an NP-hard problem [2]. Therefore, of finding an optimal solution, most previous works attempted to seek a sub-optimal alternative. They did this by selecting an appropriate combination of power and rate. Unfortunately, none of the existing multi-rate MAC protocols aimed at energy efficiency effectively dealt with the issues discussed in this study. First, the mechanisms of transmission rate selection are not accurate enough to reflect the channel's real utilization. Second, the lack of consideration of energy balancing probably leads to severe packet loss and even network partition. This is caused by certain low energy nodes dying out at an early stage.

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Based on the analysis of the energy consumption model in IEEE 802.11 DCF, this paper mainly proposes a novel energy-efficient multi-rate MAC protocol called MR-MAC. It seeks to achieve energy conservation without great loss of throughput. Compared with existing multi-rate MAC protocols, MR-MAC has the two following advantages. First, it provides a more precise transmission rate selection by virtue of the combination of channel utilization estimate and rate adaption mechanism. Second, the optimization goal can be dynamically adjusted between energy efficiency and throughput. In the process, it saves energy at low traffic while maintaining a high throughput at heavy traffic.

Moreover, a cooperative multi-rate MAC protocol called CMR-MAC is developed as an extension of MR-MAC. CMR-MAC addresses the energy balancing problem through an energy helping module. In this protocol, nodes with more energy raise transmission rates so as to assist nodes with less energy to lower theirs for energy-saving purposes.

The rest of the paper is organized as follows: Section 2 describes related works. For a more comprehensive approach, the system model under 802.11g DCF is presented in Section 3. Meanwhile, Section 4 details the MR-MAC and CMR-MAC protocols. Section 5 evaluates and compares the performances of MR-MAC, CMR-MAC, and two other multi-rate MAC protocols. Finally, Section 6 presents the conclusion.

2. RELATED WORK

In state-of-the-art research, some multi-rate protocols have been proposed to improve network performance in MANETs. These protocols typically probe channel conditions and select suitable rates for each link to increase network throughput. They can also control transmission power to decrease energy consumption.

The IEEE 802.11g physical layer provides a multi-rate capability to accommodate various wireless channel conditions. A rate-adaptive MAC protocol named Receiver-Based Auto-Rate (RBAR) [3] uses RTS/CTS to probe channel condition and to select rates at a receiver-end based on the signal-to-noise ratio (SNR) and a series of reception thresholds. Instead of using static

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thresholds, approaches to adjust reception thresholds dynamically according to transmission status are proposed in [4][5]. Other multi-rate MAC protocols include opportunity-based protocols [6][7][8], as well as relay-based protocols [9][10][11], among others. However, these works mainly focus on throughput optimization and tend to overlook the energy efficiency issue.

Other studies have delved into the application of Transmission Power Control (TPC) in energy-saving mechanisms [12][13][14][15]. However, most of them are based on a single transmission rate, so they are not suitable for a multiple rate environment.

More recently, energy efficient MAC protocols joining rate adaption and TPC were proposed. These works can be broadly classified into three categories, namely, single-node optimization, local cooperation, and global optimization. In a single-node optimization protocol, the information is simply provided by the node itself. In Energy-efficient Multi-Rate (EMR) [1], a typical single-node optimization protocol, calculated transmission rate is mainly determined by the traffic requirement of the upper layer application. Also, the rate varies slightly with the queue length at network layer. EMR efficiently achieves energy conservation at low traffic. However, due to a lack of consideration for other nodes, it may not select an appropriate rate when parallel communication exists within a neighborhood. More single-node optimization schemes can be found in [16][17]. A major problem in these kinds of protocols is their inability to estimate the utilization of a wireless channel crucial to rate selection. This is because the information source becomes very limited.

Some typical local cooperative MAC protocols [2][18] collect more information than its neighbors. In Cooperative Rate Adaption(CRA) [2], each node collects its neighbors' information to calculate a rate distribution for all links that minimize energy consumption in a local area. Afterwards, it negotiates the results with its neighbors. However, CRA only focuses on minimizing overall energy consumption and it lacks an energy balancing mechanism. Global optimization MAC protocols, such as [19][20], usually require complete information of the network. For this reason, deploying such in practical systems is difficult.

In this study, the MR-MAC protocol collects information from within, as well as from its neighborhood. In this manner, it is able to perform a much more precise estimate of channel occupation than single-node optimization protocols. Moreover, by introducing cooperative mechanism into MR-MAC, the CMR-MAC scheme provides an effective solution to address the energy balancing issue, an aspect not present in previous works.

3. SYSTEM MODEL

Before presenting details of the protocols, a system model is first set up. This model, along with several factors, is based on the assumptions that each node (1) has an identical radio configuration and (2) experiences the same propagation environment. The said factors include the transceiver power consumption, the energy consumption computation and the relation among rate, the power and the maximum transmission range.

3.1 Transceiver Power Consumption

A wireless node can be in one of the following modes: transmit, receive, idle, and doze. When a node is in doze mode, it consumes very little energy which is negligible. Hence, this investigation on power consumption focuses on the other three modes.

a) Transmit Power

The RF power amplifier works in transmit mode, with P_{in} as its input power. It generates two powers, denoted by P_{dr} and P_{tr}, where the latter is the desired transceiver output power driven by the former. Moreover, both P_{dr} and P_{tr} are a function of P_{in} :

$$P_{dr} = f_d(P_{in}) \text{ and } P_{tr} = f_t(P_{in})$$

According to [21], both f_d and f_t are strictly increasing function of P_{in}, and the difference P_h= P_{dr} – P_{tr} is the power converted into heat due to the non-ideal characteristic of a power amplifier, which can be assumed as a constant. For the sake of convenience, P_{tr} is used instead of P_{dr} when calculating the energy consumption of data transmission.

b) Receive Power

In receive mode, the receiving front end operates with power denoted by P_r. This depends on the particular transceiver design and slightly varies with modulation techniques. The value P_r is assumed as a constant in this paper.

c) Idle power

In idle mode, the node is required to monitor the channel and consumes a similar amount of power as when it is in the receive mode [12]. Therefore, P_r is likewise used to denote idle power.

3.2 Energy Consumption Model

Assuming that transmission rate R_{data} and power P_{t_data} are already selected, the average energy consumed was analyzed during the 802.11g DCF four-way handshake as shown in Fig. 1[4].

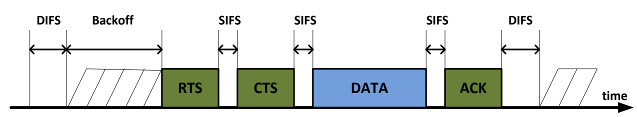

Figure 1: Four-way handshake in 802.11 DCF

Before transmitting a data frame, the node monitors channel with power P_r for a DIFS time (50us), as well as a random back off period. The back off period is a multiple of SlotTime, which is 20us as specified in the 802.11b-compatible 802.11g standard. The number of slots is drawn from a uniform distribution over the interval [0, CW], where CW is the size of the contention window, ranging from CW_{min} to CW_{max} . The expected value of CW is used as an estimate. The total time a node has to wait before transmitting is expressed as:

$$T_{pre} = T_{difs} + T_{slot} \cdot EX(CW) = 50\mu s + 20\mu s \cdot \left(\frac{CW}{2}\right) \quad (1)$$

RTS, CTS, and ACK, are transmitted at maximum power P_{max} and at the lowest rate of R_{basic} equals to 6Mbps. A PLCP preamble and a PLCP header, as specified in 802.11g ERP-OFDM standard, are added to the MAC protocol data unit. This is expected to create a PLCP protocol data unit at the physical layer, taking 16us and 4us when transmitted, respectively. The total time used for sending PLCP as T_{plcp} is revealed to be 20us. Thus, the

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time to transmit an RTS frame and a data frame are evident in (2) (3), respectively:

$$T_{rts} = T_{plcp} + \frac{L_{rts}}{R_{basic}} \quad (2) \qquad T_{data} = T_{plcp} + \frac{L_{data}}{R_{data}} \quad (3)$$

The transmission time of CTS and ACK can be calculated in the same manner.

a) Long data frame

Four-way handshake is required when the size of transmitted frame is larger than a specified threshold. During this process, the transmit and the receive energy are expressed as in (4)(5), respectively:

$$E_{s\_long} = P_r \cdot T_{pre} + P_{max} \cdot T_{rts} + P_{t\_data} \cdot T_{data} + P_r \cdot (T_{cts} + T_{ack} + 3T_{sifs}) \quad (4)$$

$$E_{r\_long} = P_{max} \cdot (T_{cts} + T_{ack}) + P_r \cdot (T_{rts} + T_{data} + 3T_{sifs}) \quad (5)$$

b) Short data frame

A frame with a shorter length than the threshold is communicated by DATA-ACK two-way handshake. Given this, the transmit and receive energy are expressed by (6)(7):

$$E_{s\_short} = P_r \cdot T_{pre} + P_{t\_data} \cdot T_{data} + P_r \cdot T_{sifs} + P_r \cdot T_{ack} \quad (6)$$

$$E_{r\_short} = P_r \cdot T_{data} + P_r \cdot T_{sifs} + P_{max} \cdot T_{ack} \quad (7)$$

c) Broadcast frame

Broadcast frame is transmitted with the lowest 6Mbps. Energy consumption of transmitting and receiving is illustrated by (8)(9):

$$E_{s\_broad} = P_r \cdot T_{pre} + P_{max} \cdot \left(T_{plcp} + \frac{L_{data}}{R_{basic}} \right) \quad (8)$$

$$E_{r\_broad} = P_r \cdot \left(T_{plcp} + \frac{L_{data}}{R_{basic}} \right) \quad (9)$$

Based on the analysis above, the total energy consumption of the network over a certain period of time is obtained as:

$$E_{total} = \sum_{node} \left(\sum_{frame\_send} E_{send} + \sum_{frame\_recv} E_{recv} + E_{nop} \right) \quad (10)$$

According to each frame type, E_{send} and E_{recv} refer to one of the three cases above, while $E_{nop} = P_r * T_{nop}$ is the energy consumed when the node monitors the channel, and T_{nop} can be measured at the MAC layer.

In this paper, the E_{total} is used in the definition of energy efficiency J. The said value is defined as the total amount of successfully delivered data over total amount of energy consumption:

$$J = \frac{\sum_{succ\_delivered} L_{data}}{E_{total}}$$

3.3 Transmit Power, Rate, and Maximum Communication Range

The relation of power, rate, and distance is specified as [12]:

$$\frac{P_{tr} \cdot (G_t \cdot G_r \cdot h_t^2 \cdot h_r^2)}{d^{\alpha} \cdot \lambda} = P_{recv}$$

where P_{tr} is the transmit power, P_{recv} is the reception power sensed at receiver-end, G_t and G_r are antenna gains of transmitter and receiver, respectively, and h_t and h_r are the heights of the antenna. λ is the carrier-sense wave length, d is the distance between transmitter and receiver, and α is path loss exponent between 2 and 4.

To successfully demodulate a received frame, P_{recv} must be larger than the reception sensitivity. This determines the maximum transmission distance and the transmission rate r. Discounting the interference of background noise, the transmission power $P_{tr}(r)$, eception power $P_{recv}(r)$, and reception sensitivity $P_{sensitivity}(r)$ under transmission rate r must satisfy this equation:

$$\frac{P_{tr}(r)}{d^{\alpha}} \cdot c = P_{recv}(r) \geq P_{sensitivity}(r) \qquad (11)$$

Where $c = \frac{G_t G_r h_t^2 h_r^2}{\lambda}$ is a constant. The first and second columns in Table I present the reception sensitivity of different transmission rates from the Freescale LP1072 802.11a/b/g wireless net card [22].

Table I: Relation among rate, reception sensitivity, and the maximum communication range

Rate(Mbps)	Sensitivity(dBm)	Max Range(m)
6	–91.0	250.0
9	–89.7	227.2
12	–87.3	197.8
18	–85.8	181.5
24	–81.4	140.9
36	–78.3	117.9
48	–74.8	96.3
54	–73.0	86.9

The maximum system range is assumed to be 250m, the default value in ns-2.31. The range may differ among real systems. However, it has little impact on the conclusions. The other parameters are given by [12], where $G_t = G_r = 1$, and $h_t = h_r = 1.5$. The net card works at 2.4GHz band, thus λ is 0.125. The value α is 4, considering that possible obstacles exist between transmitter and receiver.

The maximum transmit power P_{max} is defined as the power used under the lowest rate 6Mbps to reach 250m. Putting d=250m, $P_{sensitivity}(6Mbps) = -91dBm$, together with parameters specified above, into (11), P_{max} is found to be 584mW. The maximum transmission range under each possible rate r is given by:

$$d_{max}(r) = \left(\frac{P_{max} \cdot c}{P_{sensitivity}(r)} \right)^{1/\alpha} \quad (12)$$

It is a direct substitution and deduction of (11). The results are shown in the third column of Table I. Along with the first column, it helps the node identify the maximum available transmission rate. This is discussed in detail in Section 4.

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4. MR-MAC AND CMR-MAC

This section describes the proposed multi-rate MAC protocols, which are based on the system model defined in Section 3. The MR-MAC consists of three parts, namely, channel utilization estimation, transmission rate selection, and transmit power calculation. CMR-MAC adds an energy helping module to MR-MAC, in which the node periodically exchanges energy situations with its neighbors. It also adjusts its transmission rate correspondingly to accomplish the energy consumption balance in a local area.

4.1 Channel Utilization Estimation

In MR-MAC, a node makes a channel utilization estimation periodically, with the calculation period set to 1s. At the end each of period, the fraction of channel occupation within the pasting period is calculated and will be used as an estimate for the next period. In the period of [t-1,t), the overall channel occupation time $\boldsymbol{T_{use}(t)}$, from the view of the node consists of three parts:

$$T_{use}(t) = T_{send}(t) + T_{recv}(t) + T_{back}(t) \qquad (13)$$

where $\boldsymbol{T_{send}}$ is the transmitting time of the node itself, $\boldsymbol{T_{recv}}$ is the receiving time, and $\boldsymbol{T_{back}}$ is the time for back off.

a) $\boldsymbol{T_{send}}$

A node probably dispatches more than one flow per period. These flows are transmitted alternately, with each having a different transmission rate. To calculate the total channel occupation time of flows, the node keeps track of traffic information of each flow in a table, called the Self_Table. An entry in the table has the form of:

<flow id, next hop, DR, [redacted], [redacted], valid time>

where *DR* and *L* represent source injecting rates of application and data payload length, respectively. *R* is the transmission rate selected by the MR-MAC, with a default value of 6Mbps when the entry is originally created. In addition, *R*, like the other fields in the entry, is updated every time the node transmits a data frame and MR-MAC makes a transmission rate selection. Note that the broadcast frame does not have a flow id. Thus, only the number of broadcasted frames *n* and total payload length L_{send_broad} are recorded. At each period's end, the total transmitting occupation is the sum of time for all the flows in the Self_Table and for broadcasting. In a four-way handshake process, it has:

$$\begin{aligned} T_{send} &= T_{send\_data} + T_{send\_broadcast} \\ &= \sum_{i \in Self\_Table} \left(DR_i \cdot \left(T_{pre} + T_{mac} + \left(T_{plcp} + \frac{L_i}{R_i} \right) \right) \right) \\ &+ \left(n \cdot \left(T_{pre} + T_{plcp} \right) + \frac{L_{send\_broad}}{R_{basic}} \right) \qquad (14) \end{aligned}$$

where T_{pre} is the total back off time before RTS is sent, as specified in Eq. (1), and T_{mac} is the time for exchanging RTS-CTS-ACK, which is given as:

$$T_{mac} = T_{rts} + T_{cts} + T_{ack} + 3T_{sifs}$$

b) $\boldsymbol{T_{recv}}$

Similar to the calculation of T_{send} , T_{recv} is expressed as:

$$T_{recv} = T_{recv\_data} + T_{recv\_broad}$$

$$= \sum \left(T_{plcp} + T_{mac} + \frac{L_i}{R_i} \right) + \left(n \cdot T_{plcp} + \frac{L_{recv\_broad}}{R_{basic}} \right) \quad (15)$$

c) $\boldsymbol{T_{back}}$

The total back off time T_{back} is comprised of two parts. One comes from listening to neighborhood communication within its transmission range, which can be successfully decoded by the node. The duration field decoded from the MAC header of data frame specifies how long the node must back off during a currently overheard communication. From overhearing an RTS until the end of the four-way handshake, the required back off time is given by:

$$T_{back\_data} = T_{rts} + Duration(RTS) = T_{mac} + \left(T_{plcp} + \frac{L_{data}}{R_{data}} \right) (16)$$

The other part is a back off time generated by receiving error frames that cannot be correctly decoded. Once this situation occurs, a back off time T_{back_error} =70*us* is required.

Note that back off periods may be overlapped because the node may probably overhear other neighborhood communication in its last back off time period. Hence, the overlapped part should not be calculated more than once. Therefore, ***now*** is defined as the current system time, while ***nav*** is the time when the node finishes its current back off. Once the node overhears a communication with a required back off period *T*, then T^* denotes the actual back off period increment, which is given by:

$$T^* = \begin{cases} T, & nav \le now \\ MAX(now + T - nav, 0), & nav > now \end{cases}$$

If ***nav*** is smaller than ***now***, provided that the node is not backed off at the moment, and it starts to do so immediately, then the increment of time will be exactly *T*. However, if it is larger, and the current back off has not yet completed, the increment should be calculated from the point when the current back off ended. This is recorded by ***nav***, thus establishing the formula above. Consequently, the total back off time T_{back} in one calculation period can be expressed as:

$$T_{back} = \sum T^*_{back\_data} + \sum T^*_{back\_error} \qquad (17)$$

Based on the analysis above, the total channel occupation time T_{use} during the period [t-1,t) is the sum of (14), (15), and (17), taking the form of Eq. (13). After lubrication, it has:

$$T_{use}(t) = (1-\gamma) \cdot T_{use}(t-2) + \gamma \cdot T_{use}(t-1)$$

where γ is the lubricating factor with the experience value 0.2

4.2 Transmission Rate Selection

Before the node passes on a flow with source injecting rate *A* pkt/s and payload length *L*, it uses maximum power and lowest transmission rate to exchange RTS-CTS. It likewise estimates the distance *d* between itself and the receiver according to the receive power reported at physical layer via Formula (11) in Section 3.3. It determines the maximum possible transmission rate $R_{max}(d)$ under current *d* which is evident in Table I. Finally, it calculates the minimum transmission rate R_{min} required by the current flow by:

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$$A \cdot \left(T_{pre} + \left(T_{plcp} + \frac{L}{R} \right) + T_{mac} \right) \le 1 - T_{use}$$

which implies:

$$R \ge \frac{L}{\frac{1}{A}(1 - T_{use}) - T_{pre} - T_{plcp} - T_{mac}} = R_{min}$$

If R_{min} is larger than $R_{max}(d)$, it means that even the maximum possible rate of the current link does not meet the demand of the flow, thus MR-MAC directly selects $R_{max}(d)$ as its transmission rate. Otherwise, MR-MAC selects the minimum rate level R_s in the range of [R_{min} , $R_{max}(d)$], among eight rate levels provided in 802.11g.

In addition, R_s is slightly adjusted by MR-MAC with the queue's length at the network layer to obtain the final selected rate R_s^* . Thus, $\varphi_k(R_s)$ is defined as the function that promotes R_s to a k level higher rate than the current R_s. For example, a formula in Table I would be: $\varphi_1(9Mbps) = 12Mbps$, $\varphi_2(36Mbps) = 54Mbps$. The transmission rate used at the last time when the flow is forwarded is denoted as R_{prev} , Q for queue length and the strategy of rate adjustment is:

$$R_s^* = \begin{cases} Rs, & Q < \theta_1 \\ MAX\left(R_{prev}, \varphi_1(R_s)\right), & \theta_1 \le Q < \theta_2 \\ MAX\left(R_{prev}, \varphi_2(R_s)\right), & \theta_2 \le Q < \theta_3 \\ R_{max}(d), & \theta_3 \le Q \end{cases}$$

When Q is smaller than θ_1 and there is no need to adjust R_s . If it is larger than θ_1 , MR-MAC then selects the higher rate between R_{prev} and R_s after being promoted by 1 to 2 levels. On the other hand, if the Q is over θ_3 , $R_{max}(d)$ is expected to alleviate the heavy load of the node. To simplify, $\theta_1 = 10, \theta_2 = 20, \theta_3 = 30$, are used as experience values.

4.3 Transmit Power Calculation

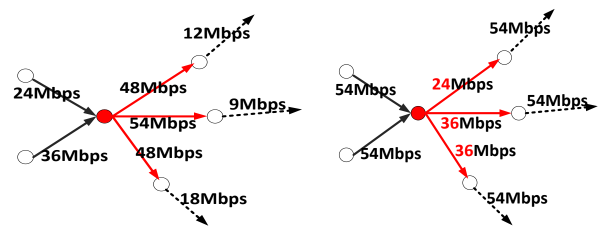
The transmit power under selected transmission rate R_s^* , denoted by $P_t^*(R_s^*)$, can be calculated as:

$$P_t^*(R_s^*) = P_{sensitivity}(R_s^*) \cdot d^{\alpha} / c$$

where $P_{sensitivity}(R_s^*)$ is the reception sensitivity under R_s^* obtained from Table I in Section 3.3, d is the estimated distance between the transmitter and receiver provided via Formula (11), and c is the propagation constant specified in Section 3.3. Eventually, the kernel work of MR-MAC is done since the expected transmission rate R_s^* and corresponding power $P_t^*(R_s^*)$ are already selected.

4.4 Energy Helping Module of CMR-MAC

A node with a very low energy or heavy traffic usually dies out earlier than others. This invariably results in packet loss or network partition. As an illustration, the red node shown in Fig. 2(a) has a heavier traffic load compared with neighboring nodes. It will use a higher transmission rate by MR-MAC, which will ultimately consume more energy. Meanwhile, neighbors using a lower rate will take more fractions of channel access time, thereby aggravating its energy problem.



(a) before cooperation (b) after cooperation

Figure 2: Cooperation process of CMR-MAC

CMR-MAC addresses this problem via the cooperation among neighbors. In CMR-MAC, neighbors with high energy initiatively promote their transmission rates for the purpose of reducing their channel occupation. Consequently, low energy nodes will be able to select a lower transmission rate to achieve energy conservation. The effect of cooperation among nodes is shown in Fig. 2(b). The whole process includes two steps: energy state judgment and energy cooperation.

a) Energy state judgment

The CMR-MAC divides nodes into two classes according to energy level: *Helped* node and *Helping* node. A *helped* node needs the help of others since its energy is lower than the average energy level of its neighbors. Contrastingly, a *helping* node helps low energy nodes through a relatively high energy level. CMR-MAC adds a 4-byte field, called Energy Left, indicating the current energy left by the transmitter to the data frame's header. This allows other nodes to get the transmitter's energy information by monitoring the data frame it sends. Moreover, a 1-byte flag called Help Request is added to indicate whether or not the transmitter needs help from other nodes. Each node maintains a table, called NTable, to record all the energy information of its neighbors. At the end of each calculation period, a node selects which class to belong to based on the collected energy information of the previous periods.

The judgment made by a node is evidently influenced by extra-high energy nodes in the area. For example, in a network containing both car-based and hand-based wireless devices, the former's energy can be considered infinite compared with the latter's. Thus, hand-based devices near a car-based one will probably misappropriate themselves as low energy nodes. This problem is dealt with the method called Average Twice.

The *helped* node can be defined as a node having energy lower than the result obtained by the Average Twice method. The method is described as follows: First, the node calculates the average energy of all the nodes in its NTable, denoting the result by E_{ave1} . Here, neighbors with energy below E_{ave1} will be averaged for a second time and the result is denoted by E_{ave2} . Now, if the node energy is less than E_{ave2} , it is regarded as a *helped* node. It then requests its' neighbors help by setting the help flag in the data frames it sends. Similarly, the *helping* node is defined as a node whose energy is greater than or equal to E_{ave2} . Figure 3 shows the pseudo-coded algorithm of Average Twice.

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```
E_ave1 = Average(Node[i].Energy for all Node[i] in NTable)
if (Self.Energy < E_ave1) {
E_ave2 =Average(Node[i].Energy where Node[i].Energy < E_ave1)
    if (Self.Energy < E_ave2) {  setStatus(Helped_Node)  }
}
```

Figure 3: Pseudo-coded algorithm of Average Twice

b) Energy cooperation

For each Self_Table entry, CMR-MAC adds an energy cooperation state field, which can be in one of the following four possible states:

Initial state: Basically, this is the state when a system starts. Nodes can either enter a Help waiting state to become a *helped* node if its energy is below E_{ave2} or a Helping state to be converted into the opposite if it overhears a request for help and its energy is above E_{ave2}.

Help waiting state: Provided that the help request has been sent and the help flag in the data frame is kept valid for this state, a *helped* node can lower its rate with the help of neighbors according to the calculation in Section 4.2. When this happens, it goes to a Help acquired state using the lower rate instead of a previous higher rate. Otherwise, if the transmission rate doesn't decrease within two periods, meaning that the *helped* node may not get effective help at the moment, it goes into Help invalid.

Help acquired state: In this state, the *helped* node has already successfully lowered its transmission rate through the help of neighbors. Hence, a node no longer sets the help flag. However, if the selected rate in subsequent communication increases, the node has to go back to the Help waiting state because the energy consumption rate will go up eventually.

Help invalid state: This occurs when the transmission rate of the helped node does not lower after a help request had been sent for two periods. The purpose of introducing this state is to reduce the unnecessary energy consumption of neighboring nodes. Indeed, keeping a *helping* node in high rates while the help is not valid is a sheer waste of its energy. In this state, a *helped* node purges the request by clearing up the help flag. Thus, *helping* nodes can use their original lower transmission rates to save energy. Moreover, the *helped* node can only go back to a Help waiting state and ask for help again after 10 periods.

Helping state: The *helping* node adds the *helped* node into its Help_Table when it overhears a help request. As long as the Help_Table is not empty, the *helping* node keeps the transmission rate of all links at the maximum available rate. When the *helping* node does not overhear the *helped* node for a certain period of time, it deletes the corresponding entry. At the end of any period if the energy it has left is below E_{ave2}, the *helping* node stops assisting. It removes all entries in the Help_Table and goes back to the Initial state.

In addition, when the *helped* node's energy left is above E_{ave2}, regardless of being in the help acquired or help invalid state, it goes into the Initial state. Figure 4 presents the diagram of energy state transition.

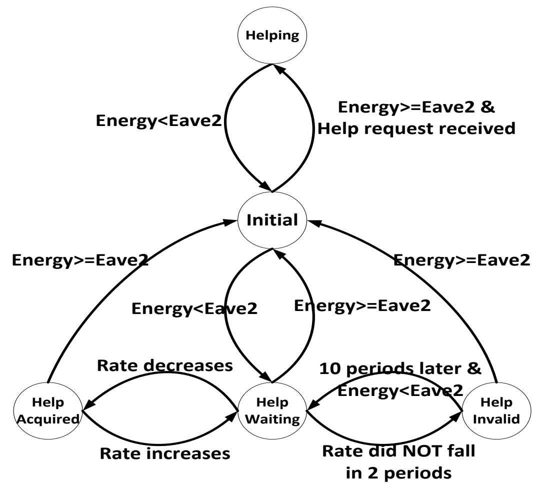

Figure 4: Diagram of energy state transition

5. PERFORMANCE EVALUATION

The effectiveness of MR-MAC and CMR-MAC via the ns-2 simulator is evaluated in this section, after enhancing the original 802.11 DCF module to support the 802.11g physical layer, the rate adaption, as well as the energy consumption model. At the network layer, the multiple-route ad hoc on-demand distance vector (MR-AODV)[23], an AODV-based multi-rate protocol using media transmission time (MTM), was chosen over the hop count as the metric for route selection and as the routing protocol. It prioritizes a route with higher bandwidth rather than a few hops to provide more choices for rate selection in MR-MAC. The four testing schemes: MR-MAC, CMR-MAC, RBAR[3], EMR[1], were then evaluated. Simulations with various static and dynamic network topologies were conducted below.

5.1 Static Crossing Topology

In the crossing topology shown in Fig. 5, two concurrent flows intercrossing at Node 2 start from nodes 0 to 4 and nodes 5 to 8, respectively. The simulated data payload length is 1000 octets and 2000 packets in total. Both flows have the same source injecting rate ranging from 55 to 200pkt/s.

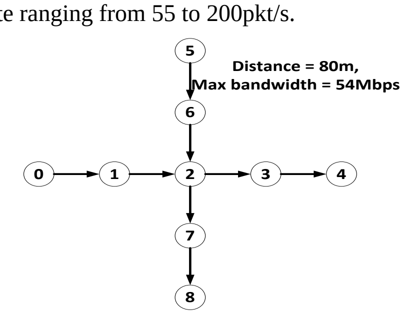

Figure 5: Crossing topology

Scenario a) Node 2 with sufficient energy

In this scenario, all nodes have the same initial energy at 5J. Granting that none of the nodes died out during the whole simulation, Fig. 6 shows the results in terms of energy efficiency and throughput. Except for RBAR, the energy efficiency of all protocols in Fig. 6(a) goes down as the traffic load goes up. This is because a higher traffic load requires a higher transmission rate. This greatly increases energy consumption which results in low energy efficiency. For this case, three observations were made:

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First, MR-MAC's energy efficiency was consistently highest, with an average of 40% promotion compared with RBAR, and 20% higher than that of CMR-MAC. MR-MAC has comparable performance with EMR in terms of energy efficiency in a low traffic load. However, it significantly outperforms EMR when the traffic load is high. Still, CMR-MAC does not overcome MR-MAC in terms of energy efficiency. This is because Nodes 1, 3, 6, and 7 serve as helping nodes in CMR-MAC, which consume more energy in total. In addition, EMR tends to use a low transmission rate even if it is under high traffic load because it cannot precisely estimate the channel utilization. In turn, this will lead to severe packet loss which will degrade energy efficiency and throughput.

Second, MR-MAC and CMR-MAC perform better in terms of energy efficiency under low and middle traffic loads than with a high load. Both achieve high energy performances by using a lower transmission rate in place of an unnecessary higher rate. However, when the traffic load is high, MR-MAC and CMR-MAC will have to use a high rate as in RBAR to satisfy the requirement of throughput. Hence, the promotion of energy efficiency decreases to a certain extent.

Third, MR-MAC and CMR-MAC can achieve comparable throughput with RBAR under various network traffic loads. An in depth simulation was conducted to illustrate the validity of the rate selection in MR-MAC and CMR-MAC. In the simulation, the queue length at the network layer of node 2 was examined under the source injecting rate of 150pkt/s. The result is shown in Fig. 6(c).

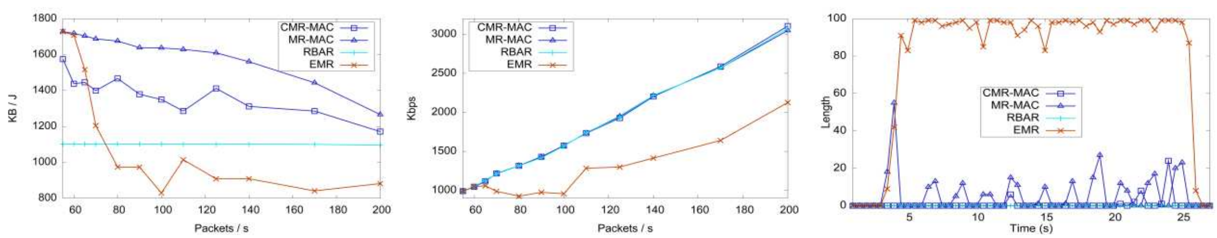
The queue length shown in Fig. 6(c) is kept effectively below 20 by MR-MAC, and is outperformed by CMR-MAC by keeping it close to zero most of the time. This occurs since *helping* Node 2 allows more time to access the channel under the help of its neighbors in CMR-MAC. The EMR then uses an improper transmission rate due to the lack of channel availability estimation. Therefore, the queue grows quickly and overflows under a high traffic load.

Scenario b) Node 2 with limited energy

In this scenario, Node 2's initial energy is set to a very low level (0.5J), while other configurations remain unchanged. Figure 7 shows the results in terms of total packets delivered and energy efficiency before Node 2 died out.

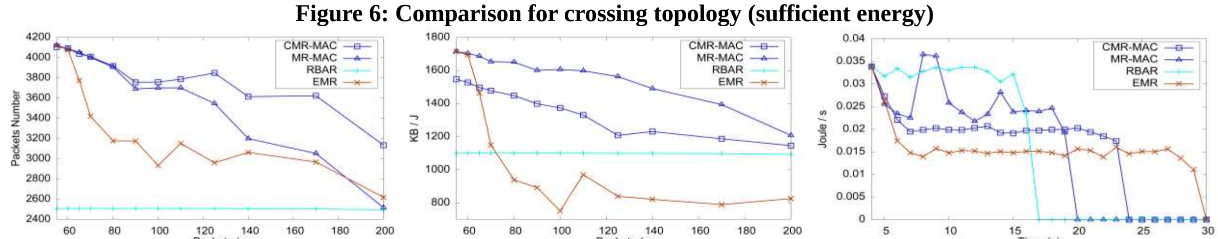
It can be observed from Fig.7(a) that under a low traffic load, both MR-MAC and CMR-MAC deliver about 60% more packets than RBAR does. This is owing to the fact that they conserve more energy and effectively prolong the lifetime of Node 2. Another observation is that CMR-MAC greatly outperforms the other three protocols under high traffic load because Node 2 uses a high rate in such conditions. When Node 2 receives help, the amount of saved energy becomes significant by adjusting its rate from a very high level to a lower one. The result of energy efficiency in Fig. 7(b) is similar to that of crossing topology.

Figure 7(c) shows the energy consumption rate of Node 2 under a source injecting rate of 150pkt/s, where the X and Y-axes denote the time and the rate of energy consumption, respectively. On the X-axis, the intersection point of each curve represents the lifetime of Node 2 for each protocol. Most of time, the energy consumption rate of RBAR is highest among the four protocols, which consequently died out first at around 17s. In contrast, Node 2's lifetime in MR-MAC is slightly longer. However, on MR-MAC's curve, there is an energy consumption peak during the 8-9s period. This is because the highest 54Mbps in this period is used to decrease the queue length according to the rate adjustment strategy in Section 4.2. In addition, CMR-MAC reduces energy consumption rate by 50% compared with RBAR via its cooperation mechanism. The observation that Node 2 in EMR has the longest lifetime is surprising at first sight, but this result is only obtained from using overly low transmission rates, it does not actually signify high performance as illustrated in Fig. 7(b).



(a)Energy Efficiency (b) Throughput (c) Queue length of Node 2

Figure 6: Comparison for crossing topology (sufficient energy)



(a)Total Packets (b) Energy Efficiency (c) Energy consumption rate of Node 2

Figure 7: Comparison for crossing topology (limited energy)

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5.2 Static Grid Topology

Simulations were conducted in a more complicated scenario by extending the crossing topology to a 5*5 grid topology as shown in Fig. 8. The maximum bandwidth of each link is 54Mbps. In this case, 10 flows each with a packet size of 1000 octets and the same source injecting rate varying from either 15 to 30pkt/s run parallel. The initial energy of each node is 0.5J and the simulation did not stop until the first node in the network died out. Results are shown in Fig. 9.

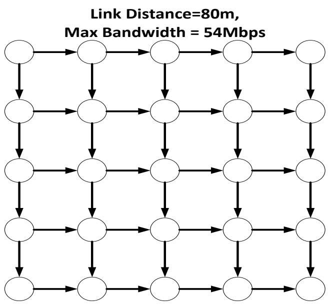


Figure 8: Grid topology

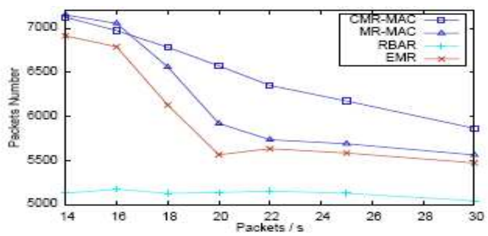


Figure 9: Packets delivered in grid topology

To gain a better understanding of how CMR-MAC performs in energy balancing, the energy consumption rate of all 25 nodes was examined under a source injecting rate of 20pkt/s. The result is shown in a 3D diagram in Fig. 10, where the X-Y plane indicates the position of nodes and the Z-axis is the energy consumption rate.

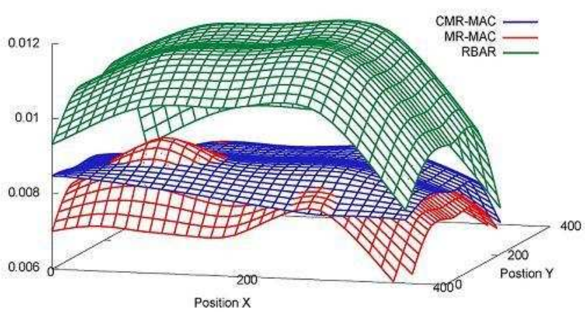


Figure 10: Energy consumption rate in Grid topology (20pkt/s)

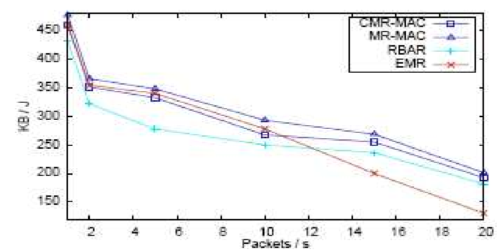
The green, blue, and red surfaces are the energy consumption rate distribution of RBAR, CMR-MAC, and MR-MAC before the first node died out in the network, respectively. All of them were measured in the unit of J/s. In this situation, there were three observations made. First, all three surfaces are convex surfaces, indicating that the nodes in the middle of the grid consume more energy than the nodes at the edges. It has been noted that these middle-placed nodes contend with more neighbors for channel. Second, the energy consumption rate of each node in MR-MAC and CMR-MAC is significantly reduced compared with that of RBAR, which once more illustrates the effectiveness of the protocols. The third and most important observation is that although the majority of the CMR-MAC's surface is above that of the MR-MAC's, it can effectively eliminate energy consumption peaks on the MR-MAC surface. This will keep the energy of busy nodes from being overused. Therefore, the surface of CMR-MAC in the figure appears much smoother than the others.

5.3 Random Topology

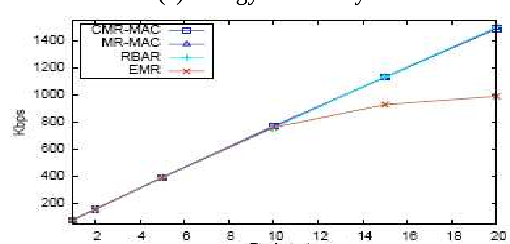
To validate the comprehensive effect of the protocols, the random topology scenario was also considered. Hence, 100 nodes are randomly positioned within a 1000*1000 flat area with the speed uniformly distributed in [1, 5] m/s and a pause time of 30s. Simultaneously, 10 flows are set up with the same source injecting rate varying from 1 to 20pkt/s. Each flow with a number of 800 packets and a size of 1000 octets are produced. Each point in the figure is averaged from over 20 simulation runs.

a) Identical and sufficient initial energy

In this scenario, all nodes have identical and sufficient initial energy set at 5J. The results of energy efficiency and throughput are depicted in Fig. 11. Similar to static topology, the energy efficiency of MR-MAC is always highest in Fig. 11(a). When traffic load is low (source injecting rate is less than 10pkt/s), MR-MAC, CMR-MAC, and EMR achieve comparable performances better than RBAR. In contrast, if the source injecting rate is larger than 10pkt/s, EMR drops many packets due to its low selected rate. Hence, its energy efficiency falls below RBAR. The discrepancy of energy efficiency between the two proposals and RBAR becomes smaller, yet better. Besides, the throughput of the protocols shown in Fig. 11(b) catches up with RBAR and outperforms EMR significantly.



(a) Energy Efficiency



(b) Throughput

Figure 11: Comparison for random topology (Identical and sufficient initial energy)

b) Different and limited initial energy

In a real environment, there is energy diversity among wireless devices. In order to simulate the real environment settings, 20% of the nodes are set at a low energy level, uniformly

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distributed in [0.3, 0.5]. The other 60% of the nodes are set at a common energy level, uniformly distributed in [0.5, 1], while the left nodes are set at a high energy level of 5J. Lifetime, which is defined as the time before the first node in the network died out under different source injecting rates, is investigated in Table II.

Table II: Lifetime under different source injecting rates

Source injecting rate(pkt/s)	Lifetime(s)			
	CMR-MAC	MR-MAC	RBAR	EMR
1	383	317	284	386
2	269	255	237	260
5	69	66	53	70
10	40	36	29	40
20	20	19	15	19

Table II indicates that CMR-MAC outperforms MR-MAC and RBAR owing to its energy balance strategy. Moreover, the lifetime of CMR-MAC is superior to that of RBAR by at least 30% in most cases. Note that although EMR has almost the same performance as CMR-MAC in this metric, it cannot satisfy the throughput requirement when the traffic load is high. Thus, it does not exhibit a high performance overall.

According to the simulations above, it is evident that MR-MAC effectively improves energy efficiency, especially under low and middle traffic load levels. It also maintains high throughput when the load is heavy, due to its accurate channel estimation. On the other hand, CMR-MAC's advantage lies within its energy consumption balancing and prolonging node's lifetime, which is more notable under a high load. Thus, CMR-MAC is suitable for nodes with low energy on critical paths.

6. CONCLUSION

In this paper, a novel energy efficient multi-rate MAC protocol or MR-MAC is mainly proposed. In MR-MAC, the accurate estimation of communication time of the node itself and occupation fraction of its neighbors is the basis of transmission rate selection. The combination of throughput requirement and channel availability determines a transmission rate for each flow. This achieves higher energy efficiency than traditional protocols while maintaining a comparable throughput.

Considering that all existing multi-rate energy efficient MAC protocols lack an energy balancing mechanism, it is extended to get a cooperative CMR-MAC. The key idea behind CMR-MAC is cooperation among nodes, thus enabling the re-adjustment of occupation time among them in accordance to their energy distribution. Nodes with high energy actively increase their transmission rate, reduce their occupation time, and make more available channel time for nodes with low energy. In this case, nodes which got helped can use a lower transmission rate, thus prolonging their lifetime. In particular, CMR-MAC is much more significant when the low energy node is a busy one or is in some critical paths.

Future work shall include an in-depth analysis of parameters used in the protocols. For example, the impact of different queue length thresholds in rate adjustment and the extensions of the schemes in a multi-channel environment may be investigated.

7. ACKNOWLEDGEMENT

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