Energy-Efficient Cross-Layer Double Cooperative MAC for Wireless Sensor Networks

Xiongli Rui[1,2], Xuehong Cao[2], Jie Yang[2], and Rui Chen[2]
[1]Department of Communication and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing, 210003, China
[2]Department of Communication Engineering, Nanjing Institute of Technology, Nanjing, 211167, China
Email: {ruixiongli, yangjie, chenrui}@njit. edu.cn; caoxh@njupt.edu.cn

Abstract —In this paper, an Energy-Efficient Cross-Layer Double Cooperative Media Access Control (ECDC-MAC) protocol is proposed with respect to battery-limited Wireless Sensor Networks (WSNs). In this MAC, to extend the network lifetime, Cooperative Communication (CC) is applied in data transmission between the source node and the destination node. In contrast to the previous works, the relay node in our approach can transmit its own data during the CC. The overhead of the control packets, Channel State Information (CSI) and the total transmit power minimization are considered to reduce energy consumption. Simulation results show that the network energy is saved and the network lifetime is extended.

Index Terms—Energy-Efficient, lifetime, MAC, cooperative communication, cross-layer, WSN

I. Introduction

Wireless Sensor Networks (WSNs) have developed for more than 20 years and have been applied in nearly every area, such as environmental monitoring, industrial process controlling, battlefield surveillance and consumer applications [1]. Sensor nodes in WSNs have to guarantee their energy for a long time because of the difficulty to recharge or replace a discharged battery. Effective energy management is an important issue for WSNs, which has led to many studies on Media Access Control (MAC) protocols.

Duty cycle is the most popular technique used to save energy consumption in WSNs [2]. In duty cycle, sensor nodes switch between sleeping and awake states. MAC protocols based on the duty cycle for WSNs can be classified into two categories: synchronous protocols and asynchronous protocols [2]-[5]. In synchronous MAC protocols, all sensor nodes wake up to exchange packets synchronously and turn into sleep duration synchronously [3], [4]. In asynchronous MAC protocols [2], [5], sensor nodes wake up at different time. Both synchronous and asynchronous MAC protocols regulate energy consumption by tunable duty cycling. However, in a busy WSN, frequent switching between awake and sleeping states costs additional time and energy resource.

On the other hand, Cooperative Communication (CC) [6] is an efficient method in throughput improvement [7], coverage enhancement [8] and energy saving [9]-[12]. Cooperative MAC (CMAC) is a widely researched issue of CC, where data packets are cooperatively transmitted at MAC layer. Nodes in CMACs transmit data packets by adopting the neighbor nodes as relay nodes, which can help them to forward the data packets. In [14], the end-to-end packet delay was optimized and a relay selection strategy considering the delay and residual energy was proposed to improve the network lifetime. In [15], a CMAC combining both duty cycle and CC techniques was proposed. But, transmit power optimization wasn't considered in [14] and [15]. On the other hand, it was demonstrated that deploying a proper relay with transmit power optimization can efficiently reduce the energy consumption [16], [17]. In [18], the device lifetime increased 12 times by deploying a power optimized cooperative relay. In [19], the total transmit power under the constraint of the receiver Bit Error Rate (BER) was minimized and a relay with the maximal residual energy was selected to balance the node energy and overcome the energy hole [20]. However, the overhead of control packets between two data packets wasn't considered. In a multi-hop network environment, the node near the AP or sink consumes more energy due to forwarding the peripheral nodes' data [10]. So, the energy consumed by the control packets cannot be neglected. In [15], the relay sends its own data packet after forwarding the source's data packet without exchange Request to Send /Clear to Send (RTS/CTS) packets to improve energy efficiency. But power optimization wasn't considered. In [21], the relay employed superposition coding (SPC) to jointly encode both the source's data and its own data before forwarding it to the destination. RTS/CTS exchange wasn't needed while transmitting the relay's own data. But, in the relay selection procedure, the Relay Request to Send (RRTS) packets in [21] as well as the Interference Indicator (II) packets in [22] cost non-ignorable energy and time duration in high density network.

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Corresponding author email: caoxh@njupt.edu.cn

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To sum up, although there already exist many CMAC protocols, few CMAC protocols consider not only the minimization of total transmit power, but also the overheads of control packets in the relay selection procedure and between two independent data packets. Motivated by this observation, this paper focuses on energy saving and provides an Energy-Efficient Cross-Layer Double Cooperative MAC (ECDC-MAC) protocol. Procedure of the control packets exchange is simplified in the new MAC, because we find that CC is not always an energy saving method when the overhead of control packets is considered or the source node is very close to destination node. In contrast to the previous works, the relay node in our approach can transmit its own data to the destination node without any RTS/CTS exchange after forwarding the source node's data. Furthermore, similar to the source node's data, the relay node's data can be transmitted by cooperative or non-cooperative method. The difference is that the relay node doesn't need any relay selection procedure while transmitting its own data packet in CC method. Once the relay node chooses the cooperative method, the source node will forward the relay node's data. Thus, the relay node and source node cooperatively transmit two independent data packets in one handshake. For the sake of convenience, we call this method double CC.

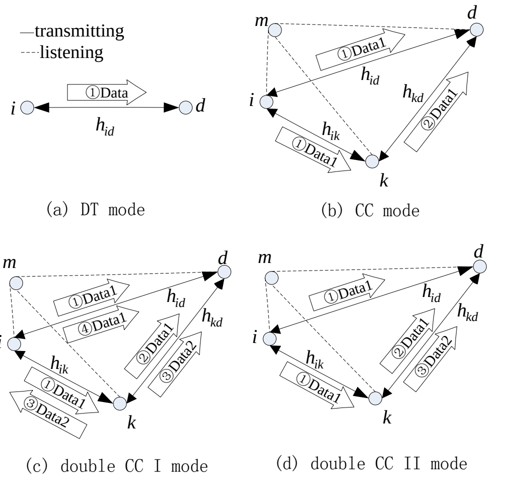

Fig. 1. Four transmission modes

In this paper, the transmission between the source node and the destination node is designed as four modes, which are Direct Transmission (DT), CC, double CC I and double CC II (see Fig. 1). The source node in DT transmits data directly to destination node, while it deploys a relay node in CC mode. The relay node in double CC I and II transmits its own data after forwarding the source's data. In double CC I, the relay node transmits its own data in CC method and the source node acts as a relay node during the transmission. In double CC II, the relay node's data is transmitted directly to the destination node. Power optimization is adopted in all four modes. At the perspective of energy saving, the transmission mode, which requires the least energy consumption, will be selected. Meanwhile, the energy consumptions considering the overheads of control packets and transmission time durations are analyzed. In this paper, a relay selection strategy based on the residual energy and the minimal total energy consumption is provided. The overhead of control packets is reduced by using opportunistic relay selection and double CC. Based on the 802.11 Distributed Coordination Function (DCF), a cooperative MAC protocol, named ECDC-MAC is designed for WSNs.

The other parts of this paper are organized as follows. Section II describes the system model and power analysis of four transmission modes. Section III presents the detail of the proposed ECDC-MAC protocol. The power control, relay selection strategy, protocol operation and analysis are discussed in this section. Simulations are shown in Section IV. Finally, Section V concludes the paper.

II. System Model

Consider a WSN with large number of uniformly distributed sensor nodes in a circle area. Each node can calculate its residual energy. In order to reduce energy consumption, some neighbor nodes can provide CC for the source node and destination node. We address these neighbor nodes as candidate relay nodes. Fig. 1 (b) shows the CC between node i and node d . Node k and m are both candidate relay nodes covered in the transmission range, but only node k participates in the CC as a relay node.

In Fig. 1, h_{ik} , h_{kd} and h_{id} are channel gains of $i-k$, $k-d$ and $i-d$ which are assumed as circularly symmetric complex Gaussian random variable with zero mean and variance σ_{ik}^2, σ_{kd}^2 and σ_{id}^2, respectively. The variance can be expressed as $\sigma^2 = \eta L^{-\alpha}$, where η is a constant determined by the propagation environment. L denotes the distance between the source node and the destination node. α is the path loss factor. BPSK modulation and Decode-and-Forward (DF) protocol are applied.

Fig. 1 (a) shows the DT mode. In this mode, the source node i transmits data packets to the destination node d directly. Under BER constraint, the minimum transmit power of direct transmission between i and d can be calculated as $P_d^i = N_0 L_{id}^{\alpha} / (4\varepsilon\eta)$ [23], where ε stands for the maximum allowable value of BER. N_0 is the variance of noise.

Fig. 1 (b) shows the CC mode, where transmission between source node i and destination node d is divided into two phases: 1) i transmits a data packet using power P_s^i , k and d receive the data packet. 2) Relay k decodes the received packet and forwards it to d using power P_r^k . d combines these two data packets by maximum ratio combing (MRC). The total transmit power is $P_s^i + P_r^k$.

In double CC I mode (see Fig. 1 (c)), source node i and relay k transmit data packets with mutual help. First, i

transmits a data packet to d and k forwards it. The total transmit power is $P_s^i + P_r^k$.Then, k transmits its own data packet to d using power P_s^k and i forwards it using power P_r^i. Then, we can get the average power for one data packet as $(P_s^i + P_r^k + P_s^k + P_r^i)/2$.

In double CC II mode (see Fig. 1 (d)), i cooperatively transmits its data packet and k forwards it, the total transmit power is $P_s^i + P_r^k$. Then, k directly transmits its own data packet to d using power P_d^k. Then, $(P_s^i + P_r^k + P_d^k)/2$ is the average power for one data packet.

III. Proposed ECDC-MAC Protocol

A. Basic Idea

In this section, a new cooperative MAC protocol based on 802.11 is proposed. The main idea of this new MAC is to reduce the total energy consumption of the network. ECDC-MAC considers three key points when transmitting a data packet: when to adopt cooperative transmission, whom to cooperate with and how to operate the cooperative procedure.

Once a source node has a data packet to transmit, it performs the RTS/CTS handshake. During this process, neighbors who have heard both RTS and CTS packets estimate the Channel State Informations (CSIs) by the strength of the RTS and CTS packets. Thus, the total energy consumptions of the four transmission modes can be calculated. After comparison, the relay node decides whether to participate in the transmission or not. If more than one neighbor can reduce the energy consumption, a relay selection strategy with energy balancing and minimizing criterion will be adopted to select the best relay. When a relay node is selected, it sends a helper ready to send (HTS) packet or a HTS2 packet declaring to participate in data transmission. HTS and HTS2 correspond to CC mode and double CC I/II mode, respectively. All control packets are transmitted using the fixed power.

B. Total Transmit Power Minimization

To reduce the energy consumption, we minimize the total transmit power under the constraint of receiver BER in DF protocol. According to the average BER performance of CC [11], the constrained minimization problems of the total transmit power in double CC I can be expressed as:

$$\min_{P_s^j, P_s^j, P_s^j, P_s^j} P_s^i + P_r^i + P_s^k + P_r^k$$
$$\text{s.t.} \begin{cases} \dfrac{16N_0^2 P_r^k \sigma_{kd}^2 + 9N_0^2 P_s^i \sigma_{ik}^2}{256 (P_s^i)^2 P_r^k \sigma_{id}^2 \sigma_{ik}^2 \sigma_{kd}^2} \geq BER \\ \dfrac{16N_0^2 P_r^i \sigma_{id}^2 + 9N_0^2 P_s^k \sigma_{ik}^2}{256 (P_s^k)^2 P_r^i \sigma_{kd}^2 \sigma_{ik}^2 \sigma_{id}^2} \geq BER \\ P_s^i, P_r^i, P_s^k, P_r^k \geq 0 \end{cases} \tag{1}$$

Since $P_s^i, P_r^i, P_s^k, P_r^k \geq 0$ and the channels are time varying, (1) can be divided into (2) and (3).

$$\min_{P_s^i, P_r^k} P_s^i + P_r^k, \quad \text{s.t.} \begin{cases} \dfrac{16N_0^2 P_r^k \sigma_{kd}^2 + 9N_0^2 P_s^i \sigma_{ik}^2}{256 (P_s^i)^2 P_r^k \sigma_{id}^2 \sigma_{ik}^2 \sigma_{kd}^2} \geq BER \\ P_s^i, P_r^k \geq 0 \end{cases} \tag{2}$$

$$\min_{P_s^k, P_r^i} P_s^k + P_r^i \quad \text{s.t.} \begin{cases} \dfrac{16N_0^2 P_r^i \sigma_{id}^2 + 9N_0^2 P_s^k \sigma_{ik}^2}{256 (P_s^k)^2 P_r^i \sigma_{kd}^2 \sigma_{ik}^2 \sigma_{id}^2} \geq BER \\ P_s^k, P_r^i \geq 0 \end{cases} \tag{3}$$

By substituting the BER threshold ε into (2), expressing P_r^k in term of P_s^i and setting the derivative to be zero, the value of P_s^i and P_r^k can be expressed as:

$$\begin{cases} P_s^i = \dfrac{N_0^2 (2\sigma_{kd}^2 + 3\sigma_{ik}^2 + \sigma_{ik}\sqrt{24\sigma_{kd}^2 + 9\sigma_{ik}^2})}{64\varepsilon \sigma_{id}^2 \sigma_{ik}^4} \\ P_r^k = \dfrac{3N_0^2}{2\varepsilon \sigma_{id}^2} \cdot \dfrac{(2\sigma_{kd}^2 + 3\sigma_{ik}^2 + \sigma_{ik}\sqrt{24\sigma_{kd}^2 + 9\sigma_{ik}^2})}{3\sigma_{ik}^2 + \sigma_{ik}\sqrt{24\sigma_{kd}^2 + 9\sigma_{ik}^2} - 2\sigma_{kd}^2} \end{cases} \tag{4}$$

Similarly, the values of P_s^k and P_r^i can be expressed as:

$$\begin{cases} P_s^k = \dfrac{N_0^2 (2\sigma_{id}^2 + 3\sigma_{ik}^2 + \sigma_{ik}\sqrt{24\sigma_{id}^2 + 9\sigma_{ik}^2})}{64\varepsilon \sigma_{kd}^2 \sigma_{ik}^4} \\ P_r^i = \dfrac{3N_0^2}{2\varepsilon \sigma_{kd}^2} \cdot \dfrac{(2\sigma_{id}^2 + 3\sigma_{ik}^2 + \sigma_{ik}\sqrt{24\sigma_{id}^2 + 9\sigma_{ik}^2})}{3\sigma_{ik}^2 + \sigma_{ik}\sqrt{24\sigma_{id}^2 + 9\sigma_{ik}^2} - 2\sigma_{id}^2} \end{cases} \tag{5}$$

Based on (4) and $P_d^k = N_0 L_{id}^{\alpha} / (4\varepsilon\eta)$, the minimum total transmit power of double CC II can be calculated. The minimum total transmit power of CC mode can also be calculated using (4).

C. Reley Selection

In our scheme, the candidate relay node which has more residual energy and results in less energy consumption is more outstanding. Due to the different locations, different relay node results in different total energy consumption. To select the most optimal relay node, we define a weighted metric consisting of the energy consumption and the residual energy, which is expressed as:

$$W_k = a\frac{E_{init} - E_{res}^k}{E_{init}} + (1-a)\frac{E_{coop}^k}{E_d} \tag{6}$$

where a is a smoothing factor with value range (0,1). E_{init} is the initial energy of a node. In our scheme, each sensor node in the network has the same initial energy. E_{res}^k stands for the residual energy of node k. E_{coop}^k is the total energy consumption when node k participates in the transmission as a relay node. E_d denotes the energy consumption when the data packet is transmitted in DT mode. It should be noted that all the energy consumptions need to consider the overhead of the control packets. The first term on the right hand of (6) considers the residual energy of the candidate relay node k and the second term considers the total energy consumption. If E_{coop}^{k} is larger than E_d, node k gives up competition. Then, the value of W_k will be at the maximum of 1, i.e., $W_k \le 1$. And the candidate relay which has the lowest value of W_k is the best relay node.

D. Protocol Operation

Fig. 2 shows the packets exchange of four transmission modes in the proposed ECDC-MAC. ECTS and EACK are extended CTS and ACK, respectively. HTS and HTS2 are added control packets transmitted by the relay node. The packet formats of ECTS, EACK, HTS and HTS2 are introduced in Section IV-E.

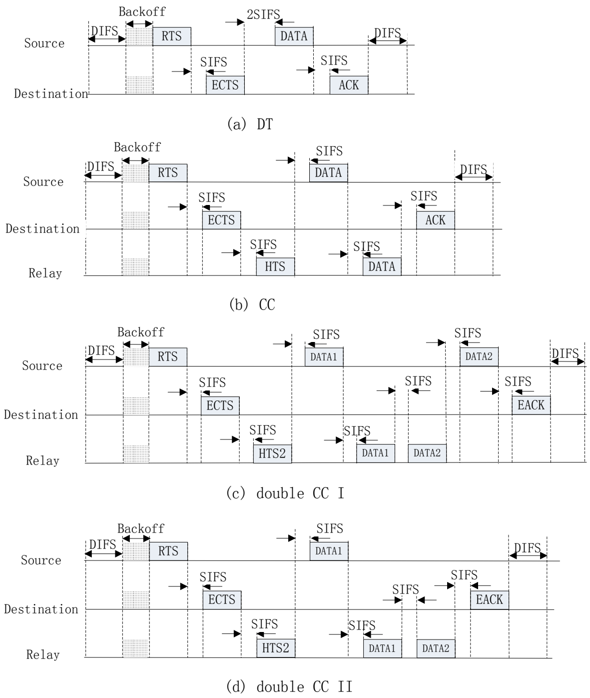

Fig. 2. ECDC-MAC timing

Nodes in the network operate according to the following process.

1) Source node

Once a source node i tries to transmit a data packet, it senses the channel. If the channel keeps idling for DIFS duration, i transmits the RTS packet to the destination node d. Then, it waits for the ECTS packet.

The data packet will be transmitted after the reception of ECTS and the transmit power depends on the reception of HTS or HTS2 after the ECTS. (i) If no HTS or HTS2 packet is received during 2SIFS duration after receiving an ECTS packet, the transmission goes in DT mode (see Fig. 2 (a)). i extracts P_d^i from the ECTS packet and transmits its data packet using power P_d^i. (ii) If a HTS packet is received, CC mode is operated (see Fig. 2 (b)). i extracts P_s^i from the HTS packet and transmits its data packet using power P_s^i. (iii) If i receives a HTS2 packet, P_s^i is extracted from the HTS2 packet and the data packet is transmitted using power P_s^i. Then, it checks the P_r^i field in the HTS2 packet. If $P_r^i \neq 0$, which means the transmission goes in double CC I mode as shown in Fig. 2 (c), i waits and forwards k's data packet. Instead, If a HTS2 packet with $P_r^i = 0$ is received, the transmission goes in double CC II mode and i doesn't need to forward the data packet after transmitting its data packet (see Fig. 2 (d)).

When finishing the data transmission, i waits an ACK packet for condition (i) and (ii), or an EACK packet for condition (iii) and (iv). If an EACK packet with the address of i in the Receiver Address (RA) field is received, it means the data packet of i is correctly received. i will handle the next data packet in its queue. Otherwise, it restarts the handshake.

2) Destination node

After receiving the RTS packet from the source node i, the destination node d measures the CSI of $i-d$, calculates the minimum direct transmit power P_d^i and attaches it to the P_d^i field in the ECTS packet. Then, it transmits the ECTS packet and waits for the HTS or HTS2 packet. (i) If a HTS packet is received, d prepares to receive two same data packets from i and k, respectively. MRC is used to combine these two data packets. An ACK packet is transmitted after correct reception. (ii) If a HTS2 is received, d checks the P_r^i field. $P_r^i = 0$ means that there are three data packets to be received, while $P_r^i \neq 0$ means four data packets. An EACK packet is transmitted if all the data packets are correctly processed. The RA field in the EACK is set as the address of i, and $Flag = 1$ indicates the correct reception of k's data packet. If not all data packets are correctly received, the RA field is set as the address of the node whose data packet is correctly received. At the same time, $Flag = 0$ indicates the incorrect reception of the other node's data packet. (iii) If both HTS and HTS2 are not received, d prepares to receive the unique data packet from i and transmit an ACK after correct reception.

3) Candidate relay node

Each candidate relay node k which has heard both RTS and ECTS packets estimates the CSIs of channel $i-k$ and $k-d$, calculates σ_{ik}^2 and σ_{kd}^2 by the strengths of the RTS and ECTS packets. σ_{id}^2 can be calculated according to P_d^i in the ECTS. Then, under the constraint of BER, P_s^i, P_r^k, P_s^k and P_r^i can be calculated using (4) and (5). Naturally, total energy consumptions of all four communication modes can be calculated (see Section IV-

F) and compared. The comparison is carried out according to whether k itself has a data packet to be transmitted. Let's denote E_d , E_c , E_{dcI} and E_{dcII} as the total energy consumption of DT, CC, double CC I and double CC II considering the overhead of control packets. (i) If k itself just has no data packets to be transmitted in its queue, it calculates out E_d and E_c . When $E_c \geq E_d$, k gives up competing and keeps silence. Otherwise, it sets $E_{coop}^k = E_c$ and calculates the weighted metric W_k , and then starts the countdown timer to participate in the relay selection competition. P_s^i is attached to the HTS packet. (ii) If the candidate relay node k itself just has a data packet to be transmitted, it calculates E_{dcI} and E_{dcII} . W_k is calculated using $E_{coop}^k = \min\left(E_{dcI}, E_{dcII}\right)$. After attaching P_s^i and P_r^i to the HTS2 packet, k set the timer and participates in the relay selection competition. P_r^i is set as 0, when $E_{dcI} > E_{dcII}$. At the end of the competition, a HTS or HTS2 will be transmitted by the winner, which is the selected optimal relay.

4) Relay node

Once the HTS or HTS2 is transmitted successfully, relay node k waits for the data packet from source node i . Data packets are transmitted according to the transmission modes. (i) In CC mode, if k decodes the data packet correctly, it forwards the data packet to the destination node d using power P_r^k . (ii) In double CC I mode, after forwarding the data packet for i , k transmits its own data packet to d with power P_s^k . (iii) In double CC II, k transmits its own data packet using power P_d^k instead of P_s^k . In (ii) and (iii), k forwards i 's data packet using P_r^k . After transmitting its own data packet, k waits for the EACK packet to confirm the reception of its own data packet.

Octets	2	2	6	2	4
	Frame Control	Duration	RA	P_d^i	FCS

(a) packet format of ECTS

Octets	2	2	6	2	4
	Frame Control	Duration	RA	P_s^i	FCS

(b) packet format of HTS

Octets	2	2	6	2	2	4
	Frame Control	Duration	RA	P_s^i	P_r^i	FCS

(c) packet format of HTS2

Octets	2	2	6	1	4
	Frame Control	Duration	RA	Flag	FCS

(d) packet format of EACK

Fig. 3. Packet format

E. Frame Format

To select the relay node and exchange the estimated CSI messages, we add two new control frames and extend the format of CTS and ACK. The packet formats are shown in Fig. 3. A 2 bytes field is added for P_d^i in ECTS. HTS and HTS2 are two additional control packets to select the relay node for CC and double CC I/II, respectivelly. In double CC I/II, the ACK packet format is extended as Fig. 3 (d). RA is the address of the node whose data packet is received correctly. If both the packets of i and k are correctly received, i has the priority on RA. Flag indicates the reception of the other data packet with 1 for success and 0 for failure.

F. Average Time and Energy Consumption Analysis

According to Fig. 2, we can get the average time duration and the energy consumption for one data packet. In DT, the average time duration T_D for one data packet considering the control packets can be calculated as:

$$\begin{aligned} T_D &= T_{DIFS} + 4T_{SIFS} + (CW_{\min}/2) \times T_{slot} \\ &+ T_{RTS} + T_{ECTS} + T_{ACK} + T_{DATA} \end{aligned} \tag{6}$$

where T_{DIFS} is the time of DCF inter-frame space (DIFS), T_{SIFS} is the time of short inter-frame space (SIFS), $CW_{\min}$ is the minimum for the contention window, T_{slot} is the basic unit of time slot. T_{RTS}, T_{ECTS}, T_{ACK} and T_{DATA} are the transmission time of the RTS, ECTS, ACK and DATA packets, respectively. The energy consumption for one data packet in DT, denoted as E_D, can be calculated as:

$$E_D = E_{RTS} + E_{ECTS} + E_{ACK} + P_d^i \times T_{DATA} \tag{7}$$

where E_{RTS} , E_{ECTS} and E_{ACK} stand for the energy consumption of the RTS, ECTS and ACK packet respectively.

CC needs more time to transmit one data packet. We estimate the average time duration spend on the relay selection as 0.5 T_{SIFS}. Then, the average time duration for one data packet, denoted as T_c, can be expressed as:

$$\begin{aligned} T_c &= T_{DIFS} + 5.5T_{SIFS} + (CW_{\min}/2) \times T_{slot} \\ &+ T_{RTS} + T_{ECTS} + T_{ACK} + T_{HTS} + 2 \times T_{DATA} \end{aligned} \tag{8}$$

where T_{HTS} denotes the transmission time of the HTS packet. Let E_c denote the average energy consumed for one data packet in CC mode. Then, it can be expressed as:

$$E_c = E_{RTS} + E_{ECTS} + E_{ACK} + E_{HTS} + (P_s^i + P_r^k) \times T_{DATA} \tag{9}$$

Based on (6) ~ (9), the average transmission time of one data packet in double CC I and II can be expressed as (10) and (11), respectively.

$$\begin{aligned} T_{dcI} &= (T_{DIFS} + 7.5T_{SIFS} + (CW_{\min}/2) \times T_{slot} \\ &+ T_{RTS} + T_{ECTS} + T_{EACK} + T_{HTS2} + 4 \times T_{DATA}) / 2 \end{aligned} \tag{10}$$

$$\begin{aligned} T_{dcII} &= (T_{DIFS} + 6.5T_{SIFS} + (CW_{\min}/2) \times T_{slot} \\ &+ T_{RTS} + T_{ECTS} + T_{EACK} + T_{HTS2} + 3 \times T_{DATA}) / 2 \end{aligned} \tag{11}$$

Similarly, the average energy consumption of one data packet in double cooperative transmission I and II can be calculated as (12) and (13).

$$E_{dcI} = (E_{RTS} + E_{ECTS} + E_{EACK} + E_{HTS2} + (P_s^i + P_r^k + P_s^k + P_r^i) \times T_{DATA}) / 2 \quad (12)$$

$$E_{dcII} = (E_{RTS} + E_{ECTS} + E_{EACK} + E_{HTS2} + (P_s^i + P_r^k + P_d^k) \times T_{DATA}) / 2 \quad (13)$$

According to the average energy consumption of one data packet, the energy consumption of one single bit can be calculated. With that, the total number of bits that a signal node can transmit under the constraint of E_{init} can be calculated. Let E_{avr}, T_{avr} denote the average energy and time consumption of one data packet, respectively. The lifetime of a sensor node can be estimated as:

$$Lifetime = \frac{E_{init} \times T_{avr}}{E_{data}} \quad (14)$$

IV. Simulation Results

In this section, we provide some numerical simulations to evaluate the performance of the proposed ECDC-MAC protocol by our developed packet-level simulation tool in Matlab. We consider that each sensor node has a single omni-directional antenna and the channels are assumed as Rayleigh flat fading during one packet transmission period. The carrier frequency is set 2.4 GHz and the max BER value is 10^{-3}. Path loss factor α is 2. N_0 is -40 dBm and η is 1. All data packets are transmitted at the rate 10 Kbps. The data packet size is 8192 bits. Control packets are transmitted using the max power 0.2 W, while data packets are transmitted using the minimized transmit power. We set T_{slot}, T_{DIFS} and T_{SIFS} as 20 us, 50 us and 10 us, respectively. $CW_{\min}$ and $CW_{\max}$ are set as 31 and 1023. The RTS and ACK packets are both 14 bytes. First, we compare the four transmission modes in ECDC-MAC protocol in performances of the energy consumption per bit and the lifetime of a sensor node. Then, we compare the network lifetime and average wasted energy of ECDC-MAC with DEC-MAC [14] and WcoopMAC [17] in the same network environment. DEC-MAC and WcoopMAC are both aimed to prolong the lifetime of the network. We locate the destination node in the center of a circular area while sensor nodes randomly distributed in this circular range. The smoothing factor a is 0.2. The transmission range according the max power is set to 89 meters.

Fig. 4 compares the average energy consumptions under different distance between the source node i and the relay node k. In this comparison, the distance between i and d is 88 meters and k locates in the straight line $i-d$. It can be seen that when the distance between i and k increases, the average energy consumption of one data packet in double CC II decreases. This is because k needs less energy to transmit its own data packet directly. It can also be seen that double CC I costs the least average energy consumption for one data packet than other modes. That owes to the fact that double CC I needs fewer control packets while transmitting data packets.

Fig. 5 shows the energy consumptions under different distance between the source node i and the destination node d. In this experiment, the relay node k is located at the middle of the straight line $i-d$. In this figure, we can see that when the distance between i and d increases, all the average energy consumptions for one bit increase. That is because long distance needs more transmit power to meet the same BER constraint. Energy consumption of DT increases much greater than the other three cooperative modes. But when i is very close to d, DT cost less energy consumption than CC because of the extra control packet. Due to the same reason, double CC I consumes a little more energy than double CC II when i is very close to d. So, it is necessary to choose a proper transmission mode according to the energy minimizing criterion.

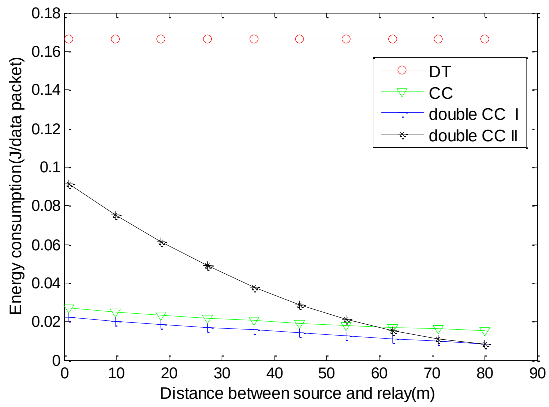

Fig. 4. Average energy consumptions under different distance of $i-k$

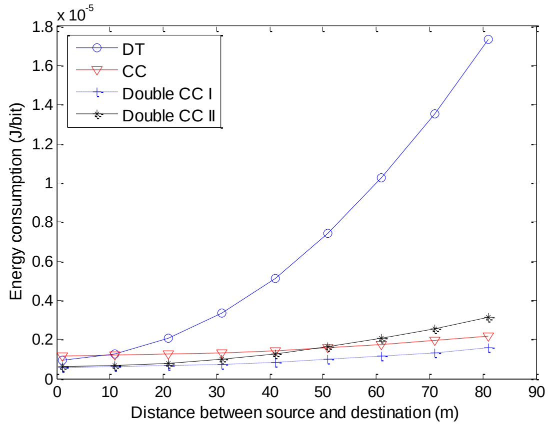

Fig. 5. Average energy consumptions under different distance of $i-d$

Energy consumptions versus different packet sizes are compared in Fig. 6. In this experiment, we assume the distance of $i-d$ is 80 meters and the relay node locates at the middle of the straight line $i-d$. It can be observed that, for all four transmission modes, the energy consumptions of one single bit reduce when the data packet size increases. This is due to the reason that the efficient number of bits is increased when larger size data packet is deployed, while the number of control packets keeps invariable.

Fig. 7 shows the node lifetime versus different distance between the source node *i* and the destination node *d*. We locates relay node at three-quarters of the line $i-d$, close to *d*. As can been seen in the figure, double CC I has the longest lifetime among the four modes, which benefits from the fewer control packets between two different data packets. It can also been seen that when *i* is close enough to *d*, the lifetime of CC is lower than DT. This is due to the fact that energy saved from the cooperative transmission can't compensate for the extra energy overhead of control packets. On the other hand, when the distance of $i-d$ increases, the DT costs more energy to meet the BER constraint and the energy saved from the decrease of the control packet cannot compensate for the incremental energy. This causes the lower lifetime of double CC II compared with CC.

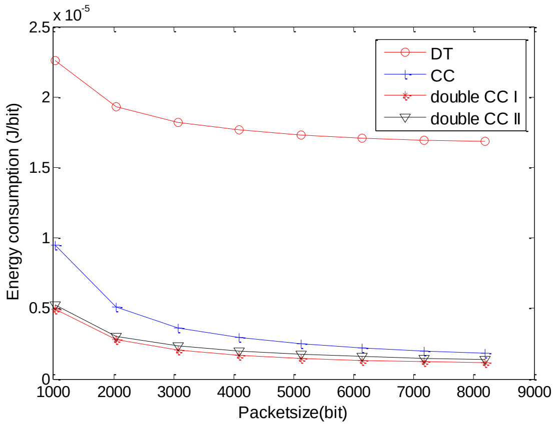

Fig. 6. Energy consumptions under different data packet sizes

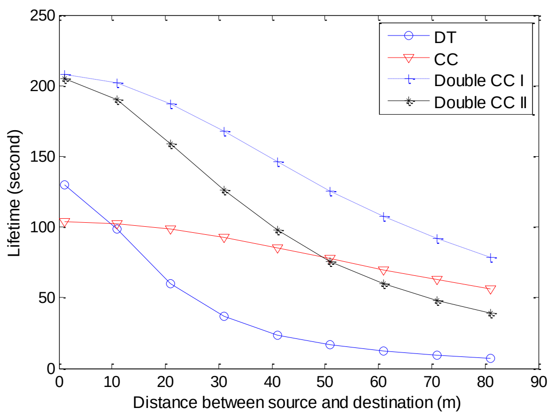

Fig. 7. Node lifetime under different distance of $i-d$

Fig. 8 compares the network lifetime of different MAC protocols in the same network parameters. The smooth factor of DEC-MAC is 0.3. For simplicity, we define the network lifetime as the total data packets number of the destination node received when the network cannot receive any data packet from any source node. It is clear from the figure that DEC-MAC has the lowest lifetime, because it transmits data packets using the fixed power. WcoopMAC has the longer lifetime because it minimized the total transmit power. Compared with WcoopMAC and DEC-MAC, ECDC-MAC has the longest lifetime. We owe this to the power minimization, control packets decrease and the flexibility to switch between four transmission modes.

Fig. 9 compares the average wasted energy when the network dies. It can be seen from the figure that ECDC-MAC has least average wasted energy compared with WcoopMAC and DEC-MAC. This is because ECDC-MAC compares the total energy consumptions of four modes and chooses the most frugal one when transmits a data packet. In this way, the average energy consumption of one data packet is lower than that of the WcoopMAC's and DEC-MAC's.

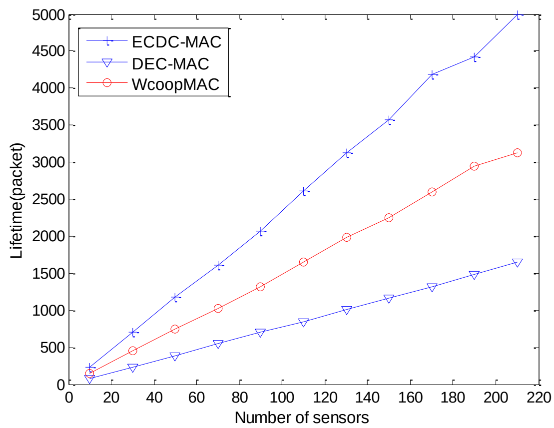

Fig. 8. Lifetime under different number of sensors

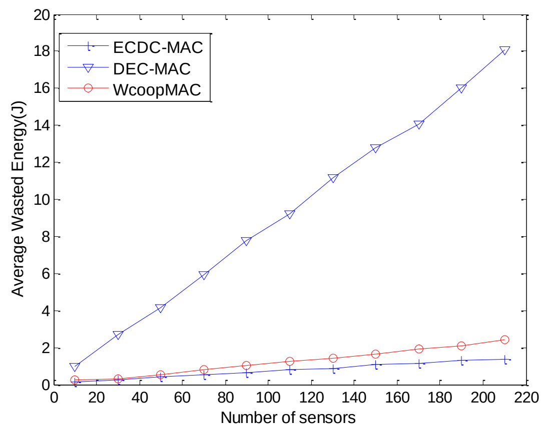

Fig. 9. Average wasted energy under different number of sensors

V. Conclusions

CMAC has been widely studied in many types of networks. It can significantly save the energy consumption. In this paper, a new protocol named ECDC-MAC is proposed based on CC, which focuses on energy saving. First, the total transmit power is minimized under the constraint of average receiver BER. Second, the relay selection strategy considering the total transmission energy consumption and node residual energy is provided. Third, the detailed operation of the proposed MAC is described. At last, the problem of network lifetime extension is solved. Compared with the existing CMACs which are implemented without consideration of the control packets overhead, our proposed new MAC can significantly decrease the average energy consumption. Numerical simulations show that the proposed new MAC can improve the energy efficiency when transmitting the data packets and prolong the network lifetime.

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Xiong-Li Rui was born in Zhejiang Province, China, in 1978. She received the B.S. degree, the M.E. degree from Hohai University, Nanjing, China, in 2000 and 2003, respectively. She is currently a Ph.D. candidate at Nanjing University of Posts and Telecommunications, Nanjing, China. Now she is a lecturer of Nanjing Institute of Technology. Her current research interests include cooperative communications, resource allocation, relaying networks and multimedia signal transmitting.

Xue-Hong Cao was born in Suzhou, China in 1964. She received the B.S. and M.S. degrees from the Nanjing University of Posts and Telecommunications in 1985 and 1988 respectively, and the Ph.D. degree in electronic engineering from Shanghai Jiaotong University in 1999. From 2004 to 2005, she worked as a visiting professor at the department of electrical engineering, Stanford University. Now she is a professor and the vice president of Nanjing Institute of Technology. Her research interests include multicarrier modulation, cooperative communication system and information theory.

Jie Yang was born in Jiangsu Province, China, in 1979. She received the B.S. and M.S. degrees from Lanzhou University of Technology in 2000 and 2003 respectively. She received her Ph.D. degree from Nanjing University of Post and Telecommunications in 2015. Now she is a vice professor of Nanjing Institute of Technology. Her current research interests include cooperative communications, relaying networks and resource allocation.

Rui Chen received the B.S degree, the M.E. degree from Southeast University, Nanjing, China, in 1991 and 1996 respectively. She received her PhD degree from Nanjing University of Post and Telecommunications in 2013. Currently she is a professor in Nanjing Institute of Technology, majoring in multimedia communication in of NGN.