A Cooperative Lifetime Extension MAC Protocol in Duty Cycle Enabled Wireless Sensor Networks

Hongzhi Jiao†, Mary Ann Ingram‡, Frank Y. Li†
†Dept. of Information and Communication Technology, University of Agder (UiA), N-4898 Grimstad, Norway
‡School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332-0250, USA
E-mail:†{hongzhi.jiao, frank.li}@uia.no, ‡mai@gatech.edu

***Abstract*—To reduce energy consumption in wireless sensor networks, the concept of duty cycle is used in many MAC protocols. Although these protocols provide efficient energy-conservation solutions, they cannot resolve the energy hole problem in a multi-hop network, where a few nodes near the sink must relay the packets from the rest of the network, and consequently exhaust their batteries earlier. The previously proposed REACT forwarding protocol triggers the cooperation of several nodes to extend transmission range and hop over the highly burdened node, thereby allowing it to save its energy and extend the lifetime of the network. However, the previous work lacked a MAC protocol with a duty cycle. In this paper, we propose a novel cooperative duty cycle MAC (CDC-MAC) protocol, by employing a wake-up rendezvous selection scheme for multiple sensor nodes to exchange messages and a cooperator recruiting mechanism that favors nodes with more residual energy than the highly burdened node. Simulation results demonstrate that CDC-MAC can prolong the entire network longevity efficiently in comparison with another duty cycle MAC protocol, OC-MAC.**

***Index Terms*—Wireless sensor networks, Medium access control, Duty cycle, Cooperative transmission, Lifetime extension**

I. INTRODUCTION

In multi-hop wireless sensor networks (WSNs), energy consumption is one of the most critical concerns, since recharging or replacing the exhausted batteries of sensor nodes is usually costly. Therefore, a primary design principle is not only to reduce the energy consumption of sensor nodes but also to avoid the exhaustion of a single node in order to prolong the entire network lifetime. Here, network lifetime is defined as the time when the first sensor has depleted its energy.

Duty cycle medium access control (MAC) has been proposed as an effective mechanism to extend the lifetime of WSNs, in which sensor nodes turn their radio on and off periodically to save energy. Duty cycle MAC protocols mainly fall into two categories: synchronous and asynchronous protocols. Synchronous approaches such as S-MAC [1] and DW-MAC [2], typically make sensor nodes wake up at the same time for data exchange. However, these types of protocols require precise synchronization, which causes more control overhead. On the other hand, in asynchronous duty cycle MAC protocols, such as RI-MAC [3], each node falls asleep and wakes up following its own schedule independently. Although such protocols reduce energy consumption, they may introduce significant latency in packet delivery, since a node with a packet to transmit must keep awake until its targeted receiver becomes active. Generally speaking, which protocol is more appropriate mainly depends on the network and application requirements.

However, these approaches in the current literature are still not sufficient to deal with the energy hole problem in multi-hop WSNs, in which the nodes around the sink are more heavily burdened than the others because they must relay packets to and from the rest of the network. These heavily burdened nodes consume energy at a high rate and deplete early since the data collected from the sensors is usually gathered at the sink. To cope with this problem, cooperative transmission (CT) with the benefit of range extension has been proposed to avoid the energy hole [4]. CT provides the spatial diversity benefits of an array transmitter, enabling a significant signal-to-noise ratio (SNR) advantage in a multi-path fading environment [5]. The Residual Energy Activated Cooperative Transmission (REACT) forwarding protocol in [4] triggers a CT when a node on a primary route to the sink determines through control packet exchange that it has higher residual energy than the next-hop node on the route. The node then recruits cooperators to transmit copies of the packet through independently fading channels, to extend the range and therefore hop over and protect the heavily burdened node. While [4] demonstrated that this approach shows significant promise, it assumed a highly idealized MAC protocol and it did not consider duty cycling. The objective of this paper is therefore to propose a realistic synchronous duty cycling MAC to support the CT operation in REACT. To our knowledge, there is no previous work about duty cycling in networks that also do CT.

Cooperative transmission works only when there are multiple active neighboring senders. Successful transmission of the necessary control messages and copies of the data is extremely challenging when the duty cycles are asynchronous. OC-MAC [6] is an asynchronous duty cycle MAC considering a different kind of cooperation between active senders. However, this cooperation scheme focuses merely on how nodes can help each other to relay packets rather than addressing cooperative diversity. In this paper, we propose a multiple wake-up provisioning cooperative duty cycle MAC protocol (CDC-MAC), which aims to balance the energy consumption of distributed nodes from the entire network point of view by exploiting cooperative diversity gain. CDC-MAC employs a receiver-initiated approach to establish wake-up rendezvous between sender, receiver and cooperator(s). More specifically, when the residual energy difference is detected, neighboring nodes are allowed to exchange data and do cooperative transmission directly towards a two-hop-away receiver. In this way, the energy-bottleneck node could avoid depleting its battery early, resulting in prolonged network lifetime, since energy consumption is evenly balanced across the network. The performance of CDC-MAC is evaluated by simulations.

The remaining part of this paper is organized as follows. The network model and protocol design consideration are presented in Sec. II. In Sec. III, we present CDC-MAC design in details. Then the system performance is evaluated and compared with other duty cycle MAC protocols in Sec. IV. Finally the paper is concluded in Sec. V.

II. Network Model and Protocol Design Consideration

In a typical WSN, multiple data flows converge towards a single point or sink, constructing a tree topology. Correspondingly, routing protocols in WSNs normally form a collection tree. For instance, the default routing protocol in TinyOS 2.x is the collection tree protocol, in which one or more nodes in the network declare themselves as the sink node(s) and all other nodes in the network recursively form a routing tree [7]. As shown in Fig. 1, a number of sending nodes, like C, D, E etc, will transmit packets to Node A via Node B. Since Node B needs to help other sensors to forward packets, it would consume more energy. When the consumed energy at Node B exceeds certain threshold, an energy hole is formed. No matter how much residual energy is left in the rest of the network, it becomes disconnected due to this energy hole.

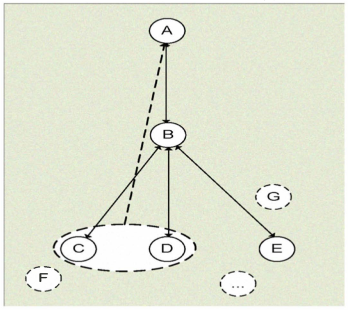

Fig. 1. Network model for CT to overcome energy hole.

To keep the network alive, one solution is to perform transmission with longer distance which could jump over the heavily burdened node and reach the two-hop away node directly. Transmission range extension can be achieved through cooperative transmission by forming a virtual multiple-input-single-output (MISO) transmission [5], [8], which was demonstrated experimentally in [9]. However, to perform CT in a duty cycle WSN, it is necessary to ensure that the corresponding nodes are active at the same time interval for data transmission. In this case, synchronous duty cycle protocol is a better option since nodes can be synchronized to wake up at the same time period.

III. CDC-MAC Design

In this section, we describe the basic principle of CDC-MAC. We also discuss the main goals and challenges of integrating cooperative transmission into a duty cycle MAC protocol.

A. Rendezvous Selection for Data Transmission

Similar to DW-MAC [2], CDC-MAC is a synchronized duty cycle MAC protocol, which assumes that the network synchronization is implemented by a separate mechanism during the Sync period. The basic idea of CDC-MAC is to schedule the involved sensors, including the sender, the receiver and the cooperator(s), to wake up at the same period when there are packets to transmit. It employs a receiver-initiated procedure with multiple wake-ups in a cycle to establish rendezvous for exchanging data among them.

CDC-MAC utilizes a Sync packet initiated by the receiving node, e.g., Node B in Fig. 1, to schedule and synchronize the other nodes in its vicinity. More specifically, CDC-MAC works in two phases as described below.

Phase I) *Network initialization and rendezvous*: before initialization, each node has its own wake-up pattern. To initiate synchronization with other nodes, Receiver B wakes up at its scheduled time sending a Sync message to potential senders as a beacon, as shown in the upper part of Fig. 2. Other senders, e.g., C or D in the same figure, follow their original wake-up patterns during a cycle. Once waked up, a node scans the network and remains active until a Sync message is received. When Sync is captured, it sends an ACK to B, acknowledging the reception of the Sync message. When this procedure is completed, a sender is locked to a specific wake-up interval for its data transmission in Phase II. For example, $w_{B,1}$ is locked as the transmission rendezvous for Node C to communicate with B. Note that a sender may keep awake for almost one wake-up interval of B (e.g., $\frac{1}{4}$ of T_{cycle} for Node D in Fig. 2) in order to receive Sync, but when the transmitting and receiving nodes are synchronized, the active window size of the transmitter will be decreased significantly. For next cycle, each node follows the new wake-up and sleep schedules. For example, Node B establishes the transmitting rendezvous at A's wake-up period $w_{A,1}$ with Receiver A, and at its own wake-ups $w_{B,0}$ and $w_{B,1}$ with Nodes C and D respectively, as shown in Fig. 3(a).

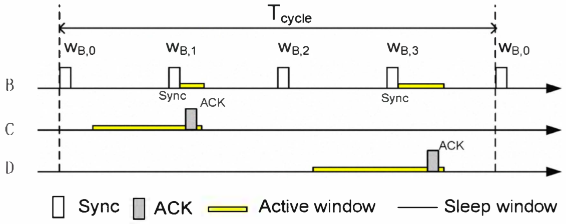

Fig. 2. Phase I: Network initialization.

Phase II) *Data transmission*: For data transmission, two requirements are considered: 1) to ensure that the corresponding nodes in the CT group store their selected rendezvous and wake up at the same rendezvous in the duty cycle; and 2) to minimize energy consumption and transmission delay. When a regular or non-CT transmission is performed, as shown in Fig. 3(b), Nodes C and D will adhere their transmissions to B during the same wake-up period which was originally assigned to C (how this is performed will be explained in the next subsection) as the first hop transmission. B will then forward these packets to A at A's immediate wake-up period $w_{A,1}$ as the second hop transmission. Otherwise, the second hop transmission has to be performed in the next cycle, incurring long delay. When cooperation transmission is needed, B, C and D will utilize B's wake-up period $w_{B,0}$ for cooperation handshake represented by the triangles under $w_{B,0}$ (more details in the next subsection). Then C and D will perform CT directly towards A over one hop represented by the rectangles under $w_{A,1}$ in Fig. 3(c). In the same manner, nodes on different hops adaptively build up an almost synchronized data forwarding structure.

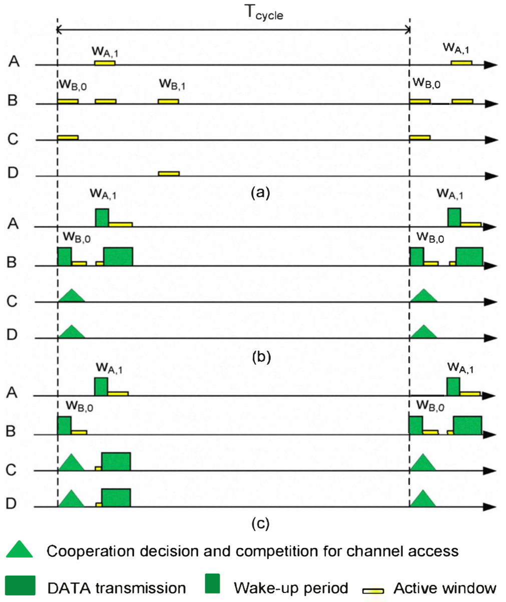

Fig. 3. (a) Synchronized multiple nodes in a duty cycle. (b) Non-cooperative transmission in a duty cycle with two hops, C/D→B at $W_{B,0}$, and B→A at $W_{A,1}$ respectively. (c) CT in a duty cycle with one hop, C/D→A at $W_{A,1}$.

B. Energy-Balance-Oriented Scheduling

In a single-channel WSN, packet collision may happen when multiple nodes try to access the shared medium at the same time. In this study, based on different considerations on node selection, we develop two variations of CDC-MAC, as CDC-MAC-I and CDC-MAC-II respectively. While nodes with pending DATA to send will apply *random backoff* scheme for channel access in CDC-MAC-I, CDC-MAC-II utilizes a distributed *timer-based* node selection scheme to select the CT initiator and cooperator(s) considering both individual node residual energy and load balancing among nodes.

Examples corresponding to the *Data transmission* phase in CDC-MAC including both regular two-hop transmission and direct cooperative transmission are illustrated in Fig. 4 and Fig. 5 respectively. These two figures provide zoomed-in details about the procedures that happen within the large rectangle or the triangle shown in Fig. 3 (b) and 3 (c) respectively. In the beginning of each triangle period, Node B sends a ready to receive (RTR) message to the sending nodes to initiate DATA communication, if the medium is sensed as idle. In addition to requesting for data transmission, the RTR message contains also its residual energy and distance information. Upon receiving RTR, the sending node, e.g., C, obtains the distance information between Node B and Node A, and between Node B and itself. It also derives the residual energy of the receiver. Comparing with its own residual energy, the sending node decides whether to do CT or not [4].

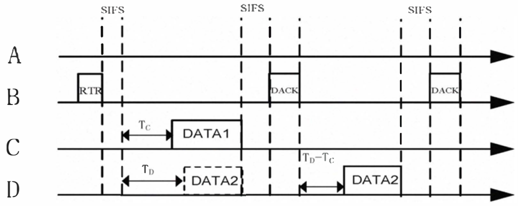

Fig. 4. Regular transmission within the same wake-up period.

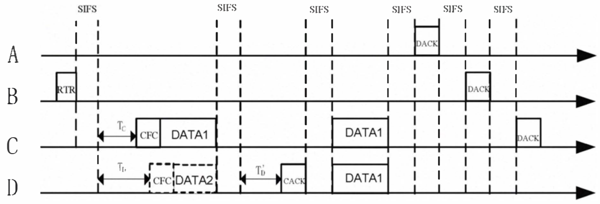

Fig. 5. CT within the same wake-up period.

CDC-MAC-I: As shown in Fig. 4, Nodes C and D are both sending nodes. Each of them waits for a SIFS period after receiving the RTR message and then contends for channel access using a random backoff scheme. The dashed line packet indicates the node, e.g., D in Fig. 4, that lost the competition. The node that captures the channel will send DATA to receiver B directly if its residual energy is lower than B's. Node B replies with DATA-ACK (DACK) when it receives DATA. In the meantime, other nodes which lose the previous contention will freeze their backoff counters. They resume counting to send DATA when the medium is sensed free again. On the other hand, *if the sending node which captures the channel has higher energy than the receiving node, it will initiate CT* by sending out a call for cooperation (CFC) message piggybacked with DATA. Assume it is Node C that first accesses the channel as illustrated in Fig. 5. CFC is sent by C to recruit other nodes to initiate cooperative transmission. Additionally, it also contains residual energy information of Node B which is derived from the RTR message received by Node C. Meanwhile, the CFC message stores the information on how many cooperators are required for CT (how this number is determined is explained in the next subsection). Upon overhearing the CFC packet, the energy-bottleneck Node B will go to sleep and other node will compare its own residual energy with the received residual energy of Node B. Consequently, the nodes with their remaining energy above Node B's become cooperator candidates and they will store the overheard DATA message. After a SIFS, the cooperator candidate acknowledges Node C with cooperative ACK (CACK). Note that collision may happen if multiple candidates try to send CACK to the common Node C at the same time. Thus, another backoff scheme is required to avoid potential collision of CACKs.

In CDC-MAC-I, we still utilize the random backoff scheme to avoid CACK collision. When Node C receives enough number of CACKs as required in the CFC packet, it will prepare for CT. Nodes that are not participating in CT should update their network allocation vectors (NAVs) to reflect that the channel is busy for the duration specified in the message. Since CACK transmission with low data rate covers larger distance than the DATA transmission, we assume each candidate could overhear the CACK transmission of other cooperative candidates. When the required number of CACKs has been sensed, the candidate that has not sent its CACK yet will terminate its transmission. CT by Node C and the selected cooperators will then be concurrently performed [10] after another SIFS interval from the time that the last required CACK has been received. Once Node A receives the DATA packet sent through CT, it will respond with DACK to Node C over two hops, from A to B and then from B to C. Since DACK for CT will be sent back to Node C via Node B in the current cycle, Node B has to wake up again before the arrival of the DACK packet. Even though this procedure consumes energy to reactivate Node B, we can still conserve energy instead of keeping Node B always awake. In order to capture DACK sent from A, Node B needs to wake up at the instant $(2 * DATA + CACK + DACK + 3 * SIFS)$ seconds after it goes to sleep, given the number of cooperators is 3. If CT fails by the default number of cooperators, retransmission of CT (reCT) will be initiated as described in the next subsection.

CDC-MAC-II: Although being able to avoid collision by random backoff, CDC-MAC-I does not consider the residual energy in the contention phase of sending nodes. Therefore, a timer-based sender selection scheme which relies on the residual energy of nodes is proposed as CDC-MAC-II. This scheme ensures that the most preferred node transmits first for both CT candidate selection and CACK collision avoidance. For regular transmission, it is not critical on which candidate node should access the channel first. However, *if the node with highest energy acts as the first sending node, CT will occur more frequently, consuming potentially extra energy of other nodes in the network.* This may happen if a random node is selected, e.g. as a result of the backoff scheme used in CDC-MAC-I. Considering that the node with least energy may concentrate on its own packet transmission rather than cooperation, it is preferred that this node accesses the channel first. Based on this observation, the node with least energy is considered as the most appropriate initiator for CT in CDC-MAC-II and will capture the channel first according to the following timer:

$$T_i = \lfloor \frac{V_i}{V_{max}} \Delta \rfloor, \tag{1}$$

where V_i represents the residual energy of node i, V_{max} is a constant, and $\lfloor \cdot \rfloor$ is the floor function. It is shown that nodes will transmit only at finite discrete time instants. The granularity of T_i could be configured flexibly. However, if the T_i values are too close to each other, the DATA message may also collide. On the other hand, if the T_i values are far away from each other, it will result in longer delay. Hence, we determine the granularity of T_i based on Δ, depending on an acceptable value of the collision probability [11].

Furthermore, when CT is initiated, another cooperator selection scheme needs to be performed in order to avoid potential collision of the CACK packets from cooperator candidates. To keep energy consumption balanced, selecting the node with higher energy as the cooperator could better balance the energy distribution in the network. Thus in CDC-MAC-II, the nodes with higher residual energy will be the preferred cooperators according to the following timer-based node selection scheme,

$$T_i' = \lfloor (1 - \frac{V_i'}{V_{max}'}) \Delta' \rfloor. \tag{2}$$

As a result, the node whose timer first elapses to 0, will send CACK first. Consequently, the information on residual energy in the CFC packet is not necessary when CDC-MAC-II is employed. This decreases the complexity of the protocol.

C. Cooperator Recruiting Algorithm

Cooperative transmission in our MAC protocol forms a virtual MISO transmission, which has been demonstrated to be able to extend the transmission range [9]. In MISO techniques, range extension mainly depends on the number of cooperators, N_c, which determines the diversity gain. As concluded in [8], the cooperative diversity gain is monotonically increasing with N_c. However, if N_c is too large, the total energy consumption for performing CT would be noticeably high. Therefore, it is necessary to obtain an approximation of the number of cooperators on the basis of range extension factor. The range extension factor, β, is defined as the ratio between the cooperative transmission distance, d_{ct}, and the single-input-single-output (SISO) link distance, d_{non-ct}, i.e., $\beta = d_{ct}/d_{non-ct}$. For Rayleigh fading, β is given as [8],

$$\beta = 10^{(10log_{10} N_c + G(N_c))/10\alpha}, \tag{3}$$

where N_c is the number of cooperators, $G(N_c)$ is the cooperative diversity gain by N_c number of cooperators, α is the path-loss exponent, which is typically between 2 and 4. In the proposed algorithm, given the extension factor β we could obtain the approximation of N_c. Table I provides a few examples of N_c and β at a target Bit Error Rate (BER) of 10^{-3} [4], [8].

TABLE I
DIVERSITY GAIN AND RANGE EXTENSION (BPSK. BER=10^{-3}).

N_c	2	3	4	5	10
$G(N_c)(dB)$	10	13.5	14	14.5	15.9
$\beta(\alpha = 3)$	2.71	4.07	4.65	5.2	7.3

In order to avoid a complex calculation of the optimal number of cooperators using Eq. (3), which may also give extra burden on node energy consumption, each node could store this relationship or a similar one as a lookup table. For example, if the required d_{ct} satisfies $d_{non-ct} < d_{ct} < 2.71d_{non-ct}$, we set the optimal number of cooperators, N_c^{opt}, as 2, and $N_c^{opt} = 3$ given $2.71d_{non-ct} \leq d_{ct} < 4.07d_{non-ct}$, and so on. In general, in order to further guarantee that the selected cooperators could help the sending node jump over the energy-bottleneck node, a cooperator candidate that has shorter distance to the two hop away receiver, i.e., A, in Fig. 1, is preferred in CDC-MAC. However, adding more constraints on the selection criterion could induce a new problem that there are not enough candidates for CT. This tradeoff could be determined based on node density in a network.

Furthermore, cooperative transmission may not always succeed due to for instance the selected cooperators failed to provide the required range extension. If this happens, the sending node sets N_c as N_c+1 and initiates reCT. Note that the goal of CDC-MAC is to protect the energy-bottleneck node so that it does not die earlier than the other nodes. Thus, a bound on the number of retransmissions would decrease the incidence of exhausting all participating nodes which in turn reduces the energy consumption in comparison with the traditional point-to-point MAC protocols. Therefore, if the number of reCTs exceeds a predefined limit, regular hop-by-hop transmission will be revitalized again.

IV. PERFORMANCE EVALUATION

To show the effectiveness of the proposed protocol, the simulation results for CDC-MAC and another point-to-point MAC protocol, OC-MAC, obtained by using a custom-built MATLAB simulator are illustrated in this section. The simulation topology is similar as shown in Fig. 1. We assume that a number of sensor nodes are randomly deployed in a 500 m × 250 m area. Node B is deployed at the center of the area while a sink node is randomly deployed in the upper part of the rectangle area. Other nodes are uniformly deployed in the lower part of the rectangle area. All sensor nodes except the sink independently generate packets and send them to the sink in a multi-hop manner. The channels between nodes are modeled as i.i.d. Rayleigh fading channels. In order to measure the energy consumption of the protocol, the transmission power of the nodes is set to be the same. We measure the amount of time the radio of each node has spent in different modes: sleep, idle, transmission, and reception. The energy consumption ratios for sleep:idle:reception:transmission are set as 0:1:1.05:1.4 [12]. The retransmission limit of CT is set as 3.

A. *Lifetime Comparison of Different Protocols*

Fig. 6 depicts the lifetime comparison of these two protocols. We could observe that the lifetime of OC-MAC decreases linearly when the residual energy of node reduces. For the CDC-MAC protocols, when the residual energy is high, CDC-MAC-I demonstrates advantage with respect to lifetime. This is attributed to cooperative transmission that protects the energy constraint node. On the other hand, it is shown that CDC-MAC-II consumes energy at a higher rate when the residual energy of node is high. This is because that CT in CDC-MAC-II is usually performed when the energy-bottleneck node has lower energy, whereas hop-by-hop transmission is dominated at high residual energy range. Besides, in comparison with OC-MAC, extra synchronization in CDC-MAC needs to consume energy. However, from the network lifetime point of view (the first node depletes in the network), CDC-MAC-II has achieved maximum lifetime. The reason is as follows. When an energy hole is formed, CT in CDC-MAC-II is continually applied, which significantly extends the lifetime of the bottleneck node. In addition, selecting node with high energy as the cooperator balances the energy distribution in the network. However, protecting the energy constraint node by CT is achieved at the cost of consuming more energy on other nodes. Hence, overuse of CT may result in limited cooperator candidates later on, which in turn leading to limited lifetime extension, like CDC-MAC-I.

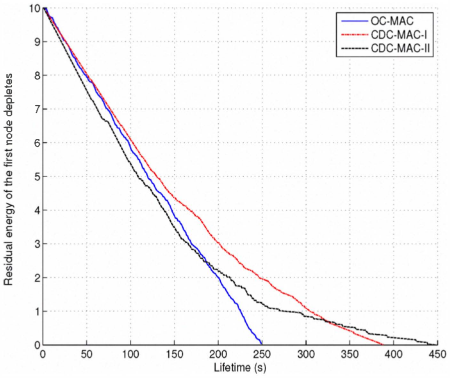

Fig. 6. Lifetime comparison of different protocols.

B. *Balanced Network Lifetime*

In order to further illustrate the merit of the proposed CDC-MAC protocols, we look at network lifetime from another angle by redefining network lifetime as the time that the last node drains its energy. In Fig. 7, we find that Node B depletes much earlier than other nodes when OC-MAC is used. It results in network exhaustion in a realistic scenario wherein the other nodes that still have lots of residual energy would be wasted. This is because in OC-MAC there is no such CT mechanism that could help save energy of the energy bottleneck node. Node B is overused in OC-MAC even though it has pretty low residual energy. This situation could be changed by means of CT in the proposed CDC-MAC protocols. Since CDC-MAC-II exhibits advantage on network lifetime over CDC-MAC-I, we focus only on CDC-MAC-II, as shown in Fig. 8. It is found that almost all nodes run out of energy at the same time. Therefore, in CDC-MAC-II, the energy of nodes could be fully and evenly utilized.

C. *Cooperative Retransmission Probability*

Since reCT consumes more energy, which may compromise the benefit of CT, we investigate the reCT probability of CDC-MAC. If CT is successful, for each successful CT the sum of probabilities of CT and reCT would be equal to 1. That is,

$$\sum_{i=0}^{n} P(Success/(Nc+i)nodes) = 1, \tag{4}$$

where $P(Success)$ denotes the probability of the event that the transmission succeeds, $P(Success/(N_c{+}i))$ is the conditional

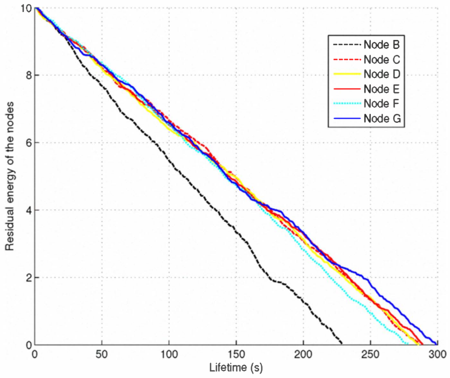

Fig. 7. Lifetime of each node in OC-MAC.

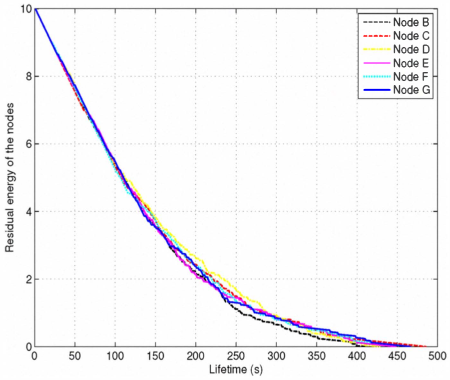

Fig. 8. Lifetime of each node in CDC-MAC-II.

probability of successful transmission given retransmission by $(N_c + i)$ nodes, and n is the number of retransmissions. In Fig. 9, reCT-i ($i \in [1, 2, 3]$) indicates retransmission times of CT. We could observe that CDC-MAC-II has higher successful cooperative transmission probability than CDC-MAC-I does, while CDC-MAC-I has higher reCT-3 than CDC-MAC-II. The main reason behind reCT is that the selected cooperator cannot provide enough diversity gain to transmit packet directly to the two-hop away receiver. For CDC-MAC-I, the situation is even worse. Random selection of sending node will result in a situation that this sending node may have higher energy than other sibling nodes. During CT initiated by this sending node, even though only the candidate that has higher residual energy than the energy-bottleneck node could be selected as the cooperator, it is still possible that there exist some nodes with lower residual energy than the energy-bottleneck node, leading to a limited number of qualified candidates. In CDC-MAC-II, as long as the neighbor nodes could hear the CFC packet, it is possible to be selected as the cooperator.

V. CONCLUSIONS

In this paper, a cooperative duty cycle MAC protocol CDC-MAC has been proposed to extend the network lifetime of WSNs. By exploiting the physical layer property that an increased transmission range can be achieved thanks to diversity gain, CDC-MAC schedules when necessary cooperative transmissions to protect the energy-constrainted node. In this protocol, both distance information and residual energy information are taken into consideration to select the CT initiator and its potential cooperator(s). The simulation results demonstrate that the energy consumption levels of sensor nodes are evenly distributed in the network by using CDC-MAC, resulting in more balanced node transmission and energy resource utilization. As a consequence, CDC-MAC could provide significant network lifetime extension in comparison with traditional point-to-point duty cycle MAC protocols.

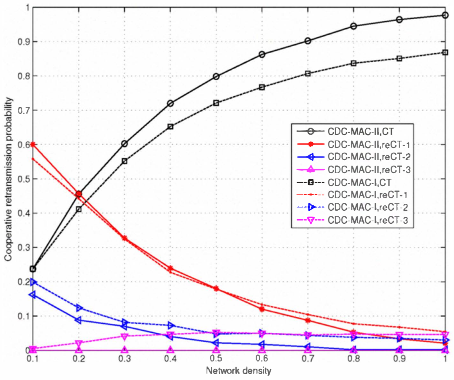

Fig. 9. Cooperative retransmission probability of CDC-MAC protocols.

ACKNOWLEDGMENT

The authors gratefully acknowledge partial support for this research from the National Science Foundation, grant number CNS-1017984, and the EU FP7 Program under the FP7-PEOPLE-IRSES S2EuNet project, grant number 247083.

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