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DESIGN OF AN ENERGY-AWARE ENHANCED COOPERATIVE MAC PROTOCOL IN MOBILE AD HOC NETWORKS

Jaeshin Jang[1] and Balasubramaniam Natarajan[2]

Key words: cooperative communication, e[2]BT-COMAC protocol, energy efficient, helper-node selection, received SNR.

ABSTRACT

In this paper, we present a new energy-efficient cooperative MAC protocol, called the e[2]BT-COMAC protocol for mobile ad hoc networks, and evaluate its performance. In the proposed MAC protocol, which is an enhanced version of our previous eBT-COMAC protocol, a cross-layer energy-aware strategy for cooperative communication is employed using mobile nodes. Considering a random waypoint mobility model for all mobile nodes, we compare the system throughput and network lifetime of the e[2]BT-COMAC protocol with previously proposed cooperative MAC protocols. Using a new metric that is a weighted combination of normalized system throughput and lifetime, we determine optimal values of system parameters, e.g., the number of mini-slots used during helper-node selection. Numerical simulation results reveal that the e[2]BT-COMAC protocol offers system throughput similar to that of the eBT-COMAC protocol but provides the best network lifetime performance among four different schemes. The calculation of optimal mini-slot values for a varying number of helper nodes can guide the design and operation of the proposed e[2]BT-COMAC protocol into a conducive way.

I. INTRODUCTION

For a long time, the goal of wireless and mobile communications has been to provide quality of service (QoS) similar to that of wired communications. Two typical QoS goals that are critical to the operation of mobile wireless communication systems are enhanced packet transmission rate and elongated device battery lifetime. With wireless technologies such as multiple-input multiple-output (MIMO), orthogonal frequency division multiplexing (OFDM), and carrier aggregation (CA) for 100 MHz bandwidth, mobile devices with 4G long-term evolution advanced (LTE-A) can have peak data transmission rates up to 3 Gbps (3GPP, 2009). However, when mobile nodes are located around a cell boundary, meeting the QoS requirements can be challenging, and other transmission/reception techniques may be required to deal with severe wireless channel impairments. Cooperative communication has been introduced as a distributed MIMO technology for wireless networks that utilizes the broadcast characteristic and spatial diversity of the wireless medium (Nosratinia et al., 2004). Cooperative communication strategies can be used to increase the effective packet transmission rate in mobile ad hoc networks, such as the example shown in Fig. 1. In this example, the helper node, which is located between a sender and a receiver node, can help increase system throughput. The cooperative communication idea is adopted in the 4G LTE-A system as coordinated multi-point (CoMP) to increase the transmission rate of mobile nodes that are located at the fringe region of more than one cell (3GPP, 2009).

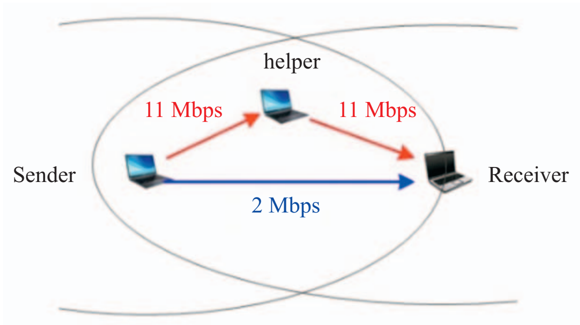

Fig. 1. Example of cooperative communications.

With the increasing number of battery-operated mobile devices, power management and/or energy efficiency has become a critical issue in wireless communication. In a Toshiba 410 CDT mobile computer, for example, about 36% of the power is consumed by display, 21% by the CPU, 18% by wireless interface, and 18% by hard drive (Jones et al., 2001). Previous efforts to improve energy efficiency in mobile ad hoc networks have focused largely on reducing the power consumption of a

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wireless local area network (WLAN) interface (Chandrakasan and Brodersen, 1995; Tsao and Huang, 2011; IETF, 2016). On the other hand, an energy-efficient medium access control (MAC) protocol can reduce the period that a WLAN interface stays awake (Tsao and Huang, 2011), and thus, aside from energy-efficient hardware design, adopting energy-efficient technologies at the data link and upper layers can further reduce energy consumption.

In this paper, a new energy-efficient cooperative MAC protocol with busy tone signal (the e^2BT-COMAC protocol) is proposed, and its performance is evaluated. The main contributions of our study are (1) a new energy-efficient reactive helper-node-selection scheme for increasing network lifetime, (2) the use of a new composite performance metric taking into account two metrics with different characteristics, and (3) derivation of the optimized number of mini-slots over various system environments. This paper consists of six sections. A survey on related work in energy-efficient cooperative MAC protocols for mobile ad hoc networks is presented in Section II, and the new energy-efficient cooperative MAC protocol is described in Section III. The performance evaluation and numerical results are presented in Sections IV and V, respectively, and Section VI concludes the paper.

II. RELATED WORK

The power save mode (PSM), as described in the IEEE 802.11 specification (IEEE, 2012), works as follows: An access point (AP) broadcasts a beacon frame at every beacon interval. If a WLAN station (STA) does not have a packet to send or receive, it notifies the AP with a listening interval and then makes a transition into sleep mode (or doze state). The STA wakes up to listen to beacon frames at each listening interval. If the AP receives a packet for the sleeping STA, the AP stores the packet in its buffer and then indicates the arrival of packets by embedding traffic-indicator-map (TIM) information in the beacon frames. When the STA wakes up and receives a TIM beacon frame for itself, it sends *PS-Poll* frames to the AP to get the buffered packets. If the STA does not retrieve the packet for one listening interval, the AP may discard the buffered packets (Tsao and Huang, 2011). However, this PSM mode has several inefficiencies; it incurs a significant packet delay and lower system throughput, especially under heavy traffic or several interactive applications (Baiamonte and Chiasserini, 2006).

Several studies have focused on increasing system throughput or decreasing packet delay in PSM mode. A bidirectional sleep distributed coordination function (BDSL-DCF) scheme was proposed, and its performance results were described in Palacios et al. (2014). After exchanging request-to-send (RTS) and clear-to-send (CTS) frames in the BDSL-DCF scheme, STA and AP transmit DATA frames to each other. This scheme is especially efficient when the size of the DATA frame is large. However, Palacios et al. (2014) did not consider back-off and contention procedures in their analysis, and thus it is too simplistic. In Tsao and Huang (2011), a survey of energy-efficiency improvement efforts in the MAC layer and cross-layer regions was presented. According to the study, the MAC layer can contribute to energy efficiency by reducing contentions, avoiding packet loss, and speeding up frame transmission. In cross-layer approaches, the prediction of packet arrivals from upper layers can contribute to increasing energy efficiency, and the considerations required to predict packet arrivals from different upper layers are enumerated. In Baiamonte and Chiasserini (2006), an energy-efficient distributed access (EDA) scheme was proposed to conserve energy during channel contentions. The contention scheme in EDA is somewhat different from the IEEE 802.11 WLAN DCF scheme, as the EDA scheme does not overhear the wireless channel. During channel contention in the EDA scheme, every STA switches to a low-power state without listening to the channel. The low-power state is different from the doze state in the PSM mode because the transition time from the low-power state to the active state is negligible in comparison to the transition time from the doze state. When an STA's back-off counter expires, the STA wakes up from the low-power state and listens to the channel to determine whether the wireless channel is busy or idle. If the channel is idle, the STA transmits its RTS frame. Otherwise, the STA generates a new back-off value and switches into the low-power state again. In Muhamad et al. (2016), a comprehensive review of energy-saving approaches for WLAN was presented. According to the study, the key techniques for saving energy in the physical (PHY) layer are MIMO and OFDM schemes, and the three key technologies for an energy-efficient MAC protocol are link adaptation, contention window adaptation, and packet size adaptation. In Jones et al. (2001), the authors presented a comprehensive survey of energy-efficient design technologies within the wireless network protocol stack, physical, data link, network, transport, OS/ middleware, and application layers.

Many studies have aimed to enhance the system performance of IEEE 802.11 WLAN by redesigning the system parameters. For example, in Parker et al. (2015), back-off parameters were optimized to increase throughput while considering heterogeneous traffic sources and a non-saturated traffic model. As shown in previous studies (Tsao and Huang, 2011; Muhamad et al., 2016), reducing frame transmission time is one way to increase energy efficiency in the MAC layer. Cooperative communication techniques have gained attention in mobile ad hoc networks because they represent a means of overcoming the effect of channel fading and thus of reducing frame transmission time (Nosratinia et al., 2004; IETF, 2016). When the sender and receiver nodes are located beyond a certain distance from each other, any mobile node called a helper node, which is placed at an intermediate position, can help increase system throughput. Therefore, finding the best helper node in cooperative communication directly contributes to increasing system throughput. There are two different types of helper-node-selection schemes: proactive and reactive schemes. Proactive schemes require all mobile nodes to maintain their relay tables where transmission rates with their neighboring nodes are stored and then to share the relay tables with their neighboring nodes by broadcasting some messages (Zhu and Cao, 2006; Liu et al., 2007). Whenever a sender node has a packet to transmit, it can find its helper node easily by searching its relay table. In most earlier studies of cooperative MAC protocols, proactive schemes were considered, as such schemes appear simple and can determine a helper node quickly. However, proactive schemes actually consume more energy and resources than reactive schemes, and the overheads caused by managing relay tables and sharing these tables with neighboring nodes are not considered in performance evaluations. Another limitation of proactive schemes is that there is no guarantee that the chosen helper node is optimal at data transmitting time. By contrast, in reactive schemes, the sender node begins the search for a helper node after the exchange of control frames (Nosratinia et al., 2004; Guo and Carrasco, 2009; Shan et al., 2011; Zhou et al., 2011). A reactive helper-node-selection scheme with three-step helper-node competition was adopted in two studies (Shan et al., 2011; Zhou et al., 2011). The three-step helper-node-selection scheme consists of group indication (GI), member indication (MI), and K mini-slot contention. In Shan et al. (2011), the optimal cooperation region and system parameters were derived using analysis and simulation. A novel link-utility-based cooperative MAC (LC-MAC) protocol was proposed in Zhou et al. (2011). In the LC-MAC protocol, the authors used a new metric called link utility, defined as the difference between a utility function and a cost function. The helper node with the greatest link-utility value is chosen as the best helper node. In this case, the utility function depends on the frame transmission time, and the cost metric is a linear function of the energy required for transmission. A naive linear combination of the utility and cost functions can be problematic because these two metrics have distinct characteristics. The delay and energy-aware cooperative MAC (DEC-MAC) protocol was proposed in Ahmed et al. (2013). These authors defined a new metric called average weight W_n, which is a linear combination of two different metrics similar to the LC-MAC protocol. In contrast to the LC-MAC protocol, Ahmed et al. (2013) employed normalized values of remaining energy E_{res} and packet transmission delay D, that is, $W_n = \omega_1 E_{res}/E_{ini} + \omega_2 (D_{\max} - D)/D_{\max}$, where ω_1 and ω_2 are weighting factors with $\omega_1 + \omega_2 = 1$. Therefore, two normalized metrics have the same scale factor between the minimum 0 and the maximum 1. However, this approach still has one problem. In Ahmed et al. (2013), the authors used two weighting factors, $\omega_1 = 0.3$ and $\omega_2 = 0.7$, for performance evaluation. Here, even a candidate helper node with almost zero remaining energy can have an average weight value of 0.7 when its wireless channel condition is the best. Therefore, this candidate helper node should participate in the helper-node-selection scheme even though it has almost zero remaining energy. In the DEC-MAC protocol, the relay-selection procedure is a mandatory step, and thus, even when there is no candidate relay node between the sender and receiver nodes, the two nodes must wait until the relay-selection procedure ends. This causes a deterioration in system performance, as shown in Fig. 7. In Jang and Natarajan (2018), we proposed an enhanced cooperative MAC protocol with busy tone (eBT-COMAC) and evaluated its performance via both a mathematical analysis and simulation. In this paper, we propose the e^{2}BT-COMAC protocol, which is an energy-efficient version of the eBT-COMAC protocol. For energy efficiency, the remaining energy requirement is added for candidate helper nodes to participate in the helper-node-selection contention. In addition, any candidate helper node that is not in the competition moves into sleep mode in order to save energy consumption.

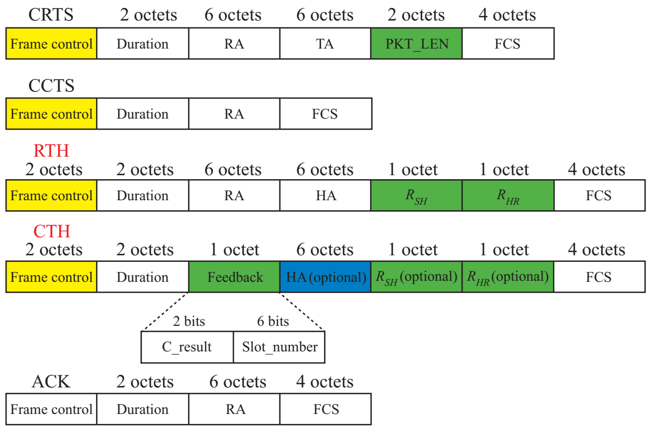

Fig. 2. Frame formats for newly defined control frames.

III. THE E^{2}BT-COMAC PROTOCOL

As noted in Section II, the e^{2}BT-COMAC protocol is an enhanced version of our previous cooperative MAC protocol, the eBT-COMAC (Jang and Natarajan, 2018), as this new protocol includes an energy-aware operation. This scheme requires a cross-layer design because the MAC layer should have information on the node's remaining energy, which is a PHY parameter. The e^{2}BT-COMAC protocol is based on the channel access mechanism of IEEE 802.11 WLAN operating in ad hoc mode. The frame format for the e^{2}BT-COMAC protocol is shown in Fig. 2.

The cooperative request-to-send (CRTS) frame has a new field, PKT_LEN, representing the length of the data frame. This field will be used by candidate helper nodes to calculate the two effective transmission rates expressed by Eq. (1). The cooperative clear-to-send (CCTS) frame has the same frame format as the clear-to-send (CTS) frame. Two new control frames are proposed, request-to-help (RTH) and clear-to-help (CTH). The CTH frame has two formats, long CTH and short CTH. When any sender node has packets to transmit, it begins channel contention by transmitting the CRTS frame. If the CRTS frame transmission is successful, the receiver node sends the CCTS frame as a positive answer. After exchanging the CRTS and CCTS frames, the optimal-helper-node-selection procedure begins, which the sender node is in charge of managing. If an optimal helper node is selected, the sender node sends its data frame to the optimal helper node and the helper node forwards the data frame to the receiver node. When the data frame

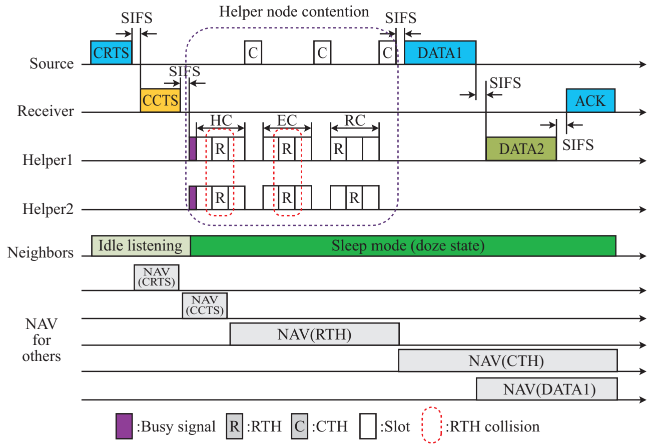

Fig. 3. Example of a frame-exchange diagram.

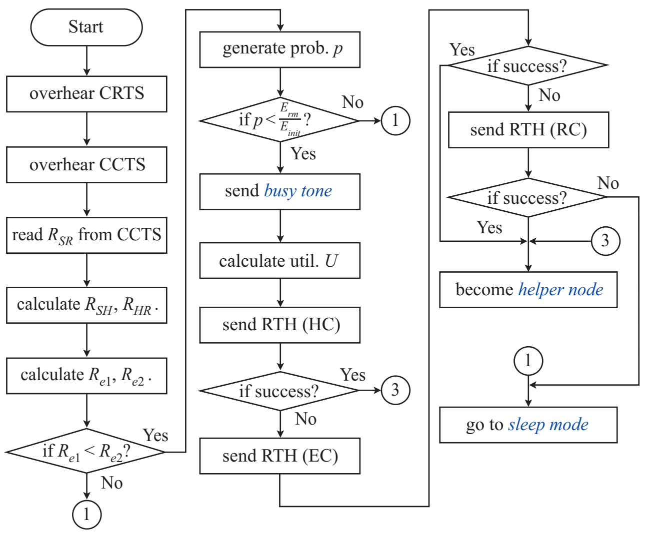

Fig. 4. Flow chart depicting the process at a candidate helper node.

is successfully received by the receiver node, the receiver node sends the acknowledgment (ACK) frame to the sender node directly. If the selection of an optimal helper node fails, then direct transmission between the sender and receiver nodes begins. Candidate helper nodes that do not participate in this contention move into sleep mode until the end of the reception of the ACK frame. Fig. 3 presents the frame-exchange chart for this procedure.

Next, we discuss the selection of an optimal helper node. The details of the helper-node-selection procedure are depicted in Fig. 4. There are two requirements for the eligibility of any candidate helper node to participate in the helper-node-selection procedure: the effective transmission rate requirement and the remaining energy requirement. Candidate helper nodes can read the direct transmission rate between the sender and receiver node R_{SR} from the PHY header of the CCTS frame; they can then derive two transmission rates—the transmission rate between the sender and itself (R_{SH}) and the transmission rate between itself and the receiver node (R_{HR})—based on the received signal-to-noise ratio (SNR) value. Since IEEE 802.11 WLAN share the same frequency band for the forward and reverse links, it is possible for candidate helper nodes to calculate R_{SH} and R_{HR} utilizing the channel reciprocity (Guey and Larsson, 2004). The helper-node-selection procedure consists of three contention steps: harsh contention (HC), exact contention (EC), and random contention (RC). HC is mandatory, but EC and RC are optional. HC (EC) consists of $N_{HC(EC)}$ mini-slots, and RC consists of N_{RC} slots.

The size of each mini-slot is as large as the slot size σ in IEEE 802.11, and the slot size is shown in Table 2. The size of each RC slot is as large as the RTH frame transmission time when the RTH frame is sent at the basic rate. The goal of the HC and EC mini-slots is to choose one candidate helper node with the best channel condition as soon as possible. On the other hand, the goal of the RC slot is to choose exactly one node from among candidate helper nodes that are involved in RTH frame collisions at the EC mini-slot contention. Based on the three transmission rates, R_{SR}, R_{SH}, and R_{HR}, all candidate helper nodes calculate two effective transmission rates, the one-hop (or direct) transmission rate R_{e1} and the two-hop transmission rate R_{e2}, as shown in Eq. (1). An effective transmission rate represents the ratio of data packet size in bits to the time period required for the ACK frame to be received successfully. Only candidate helper nodes whose two-hop effective transmission rate is greater than their one-hop transmission rate satisfy the first requirement for participating in the helper-node-selection procedure.

$$
\begin{aligned}
R_{e1,2} &= \frac{L_d}{T_O + T_D}, 1: S\text{-}R,\ 2: S\text{-}H\text{-}R \\
T_D &= \begin{cases} \dfrac{L_d}{R_{SR}} & S\text{-}R \\ \dfrac{L_d}{R_{SH}} + \dfrac{L_d}{R_{HR}} & S\text{-}H\text{-}R \end{cases} \\
T_O &= \begin{cases} T_{ACK} + SIFS & S\text{-}R \\ (N_{HC} + N_{EC})\sigma + N_{RC}T_{RTH} + 3T_{CTH} + 3SIFS & S\text{-}H\text{-}R \end{cases}
\end{aligned}
\qquad (1)
$$

In Eq. (1), L_d is DATA length in bits; $SIFS$ is a MAC parameter representing short interframe space; and T_{ACK}, T_{RTH}, T_{CTH} are the transmission times of control frames ACK, RTH, and CTH, respectively.

All candidate nodes that satisfy the first requirement generate a random probability value p; they then compare p with E_{rm}/E_{init}, where E_{rm} and E_{init} are their remaining and initial energies, respectively. Only those candidate helper nodes whose generated probability p is less than their energy ratio E_{rm}/E_{init} meet the second requirement to participate in the three-step helper-node-contention procedure. Any candidate helper node that fails to meet the two requirements can move into sleep mode to save its remaining energy. All candidate nodes that meet the two requirements successfully calculate their utility values, defined as $U \equiv \log SNR_{rcvd}$.

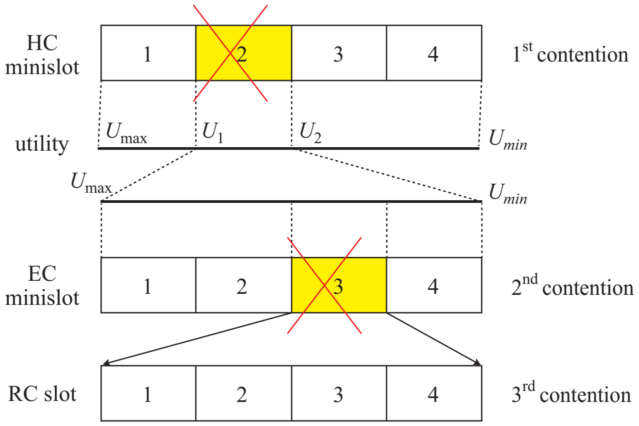

Fig. 5. Mapping example between mini-slots and utility threshold.

The helper-node-selection competition is conducted by transmitting an RTH frame in the appropriate mini-slot. The candidate helper node with the greater utility value is assigned an earlier HC and EC mini-slot. In the HC and EC mini-slot contention, if any candidate helper node finds that another node has sent an RTH frame earlier than itself, it quits the competition immediately. Two utility values, $U_{\max}$ and $U_{\min}$, are implementation dependent, and the utility window between $U_{\max}$ and $U_{\min}$ is uniformly divided into $N_{HC(EC)}$ sections. The mapping rule between utility threshold values and $N_{HC(EC)}$ is illustrated by Fig. 5 and expressed by Eq. (2) when $N_{HC} = N_{EC} = N_{RC} = 4$.

$$U_i = U_{\max} - i \cdot U_{inc},\ i = 1, \ldots, N_{HC(EC)} - 1 \quad (2)$$

where

$$U_{inc} = \frac{U_{\max} - U_{\min}}{N_{HC(EC)}}.$$

In Fig. 5, because there is a collision in mini-slot 2 at the HC mini-slot contention, all the candidate helper nodes involved in the collision resume their contention at the EC mini-slots. In this case, two utility thresholds, U_1 and U_2, become $U_{\max}$ and $U_{\min}$ in the EC mini-slot contention, respectively. Because there is a collision again in mini-slot 3 at the EC mini-slot contention, the candidate nodes involved in the collision move onto the RC slot contention. The RC slot contention uses the different contention mechanisms from the HC and EC mini-slot contentions, and it is a probability-based competition. Those candidate helper nodes generate a random number between 1 and N_{RC} and then transmit their RTH frame in the assigned slot. If there are multiple successful slots in the RC slot contention, the candidate helper node that transmitted its RTH frame in the earlier slot has the final permission as the helper node. If any RTH frame transmission in the HC or EC mini-slot contention is successful, then the helper-node-selection procedure ends and the sender node then transmits the DATA frame to the chosen helper node immediately after the *SIFS* time period. The sender node has the responsibility of deciding the winner of three competition steps. The sender node provides the feedback for helper-node contentions by sending the CTH frame, the format of which is shown in Fig. 2. When the competition is successful, the sender node sends the long CTH frame, which contains the feedback, helper address (HA), and fields of the two transmission rates, R_{SH} and R_{HR}. When the competition fails, the sender node sends the short CTH frame, which contains the feedback field only. The feedback field has two subfields: **"*C_result*"** and **"*Slot_number*"**. "11" in **"*C_result*"** means successful competition, and "00" means failure in the competition. **"*Slot_number*"** has the information regarding successful slot number in the RC contention.

Table 1. Transmission rates and distance.

data rate (Mbps)	11	5.5	2	1
distance (m)	≤ 48.2	≤ 67.1	≤ 74.7	≤ 100

IV. PERFORMANCE EVALUATION

The setup for evaluating the performance of the proposed e^{2}BT-COMAC protocol is described in this section. All mobile nodes are assumed to be uniformly distributed within the 200 m × 200 m communication area, and they move independently within the communication area based on a random waypoint mobility model. The log-distance path loss model is used to model the WLAN wireless channel, and its relationship between path loss and transmission distance is shown by Eq. (3) (Rappaport, 2002).

$$L_p(d)(dB) = L_s(d_0)(dB) + 10n\log_{10}(d/d_0), \quad (3)$$

where d_0 is the reference distance and n is the path loss exponent (in this paper, we use $n = 3$). For the performance evaluation, we use the relationship shown in Table 1 between transmission rates and the distance between a sender and a receiver node.

The mobile nodes are classified into three types: sender, receiver, and helper nodes. It is assumed that communication connections between senders and receivers are fixed throughout the simulation period. In order to derive maximal system throughput, we use a saturated traffic model in which all sender nodes have data traffic in their buffers all the time. All helper nodes are assumed to participate actively in helper-node-selection process until their remaining energy E_{rm} becomes less than $E_{\min}$. It is assumed that all control frames are transmitted at the basic rate and that data frames are transmitted at a rate determined according to Table 1.

The performance of the e^{2}BT-COMAC protocol is evaluated using computer simulations. The simulation code is programmed with a GNU C++ compiler using the SMPL library (MacDougall, 1992). Each simulation result is based on the average of ten Monte Carlo trials with a different seed. For simplicity, it is assumed that there are no transmission errors due to a bad wireless channel. For the performance comparison, we use two performance metrics: system throughput ***TH*** and network lifetime ***LT***. System throughput is defined as the ratio of the total size in bits of successfully transmitted DATA frames to the simulation time. Network lifetime is defined as the total simulation time elapsed until the first helper node is fully devoid of its energy and thus has remaining energy less than $E_{\min}$. Therefore, computer simulation stops when the first failed helper node reaches its minimum energy.

The energy consumption model is applied only to helper nodes. In order to calculate the consumed energy, we consider four states for helper nodes: transmitting, receiving, idle, and sleep states, where each state has a different power consumption ratio, P_t, P_r, P_{idle}, and P_{sleep}, respectively as shown in Table 2. Any helper node that is transmitting or receiving a frame as a transmitter or a receiver node is considered as being in the transmitting or receiving state. Other helper nodes, which are overhearing control or data frames, are set to an idle state. The energy consumed by transmitting, receiving, or overhearing a frame with frame size L_f is given as $P_t \cdot L_f/R$, and $P_{idle} \cdot L_f/R$, respectively, where R is the frame transmission rate. When a helper node is in a sleep mode, the consumed energy corresponds to $P_{sleep} \cdot T_{sleep}$, where T_{sleep} is the sleeping-time duration.

In order to derive the optimal values of several system parameters in the e²BT-COMAC protocol, a new metric, balanced weight W, is defined as the weighted sum of normalized system throughput and normalized network lifetime.

$$W = \theta \frac{TH}{TH_{\max}} + (1-\theta)\frac{LT}{LT_{\max}}, \quad (4)$$

where θ has a value between 0 and 1. Our goal is to determine the optimal number of mini-slots for maximizing the value of the balanced weight function in Eq. (4), which is expressed by Eq. (5).

$$N_{HC}^{opt} = arg \max_{N_{HC},\theta,N_h} W. \quad (5)$$

In order to compute the optimal number of mini-slots, we conduct a computer simulation many times by changing the number of helper nodes, the weighting factor θ in Eq. (4), and the number of HC mini-slots; we then obtain numerical results that show the greatest balanced weight value.

V. NUMERICAL RESULTS

The system parameters used in the performance evaluation are shown in Table 2. For simplicity, it is assumed that N_{HC}, N_{EC}, and N_{RC} have the same value and that there are 10 sender and 10 receiver nodes in the communication area. Because we assume that the e²BT-COMAC protocol operates over the IEEE 802.11b WLAN standard, the system parameters not shown in Table 2 have regular parameter values, as defined in the IEEE 802.11b WLAN standard.

Fig. 6 shows the system throughput comparison of eBT-COMAC with and without sleep mode and the e²BT-COMAC protocol where N_{HC} = 5 with a 95% confidence interval. These three schemes provide better system throughput performance than IEEE 802.11 WLAN DCF, whose analytic performance result is derived from Jang and Natarajan (2018). Although it is difficult to judge at a glance, it can be seen that the e²BT-COMAC protocol has better system throughput performance when there are between 40 and 60 helper nodes. When the number of helper nodes is approximately less than 40, the e²BT-COMAC protocol provides somewhat lower system throughput. This is because the candidate helper nodes of the e²BT-COMAC protocol tend to be reluctant to participate in the helper-node-selection procedure as their remaining energy approaches $E_{\min}$ (according to the second requirement). However, when the number of helper nodes is greater than 60, the e²BT-COMAC protocol provides the greatest system throughput among three schemes, as there are sufficient candidate helper nodes for the e²BT-COMAC protocol but too many candidate helper nodes for the other two protocols. The numerical results of the network lifetime metric among four different mechanisms, including the DEC-MAC protocol (Ahmed et al., 2013), are provided in Fig. 7 where N_{HC} = 5 with 95% confidence interval, too. According to these results, the e²BT-COMAC protocol has the best network lifetime performance over the entire range of the number of helper nodes, and the eBT-COMAC protocol without sleep mode exhibits the worst network lifetime performance. It is shown that

Table 2. System parameters.

parameter	value	parameter	value
CRTS length	176 bits	SIFS	10 µs
CCTS length	112 bits	DIFS	50 µs
RTH length	176 bits	$CW_{\min}$	32 slots
DATA length	1024 bytes	$CW_{\max}$	1024 slots
MAC header	272 bits	PLCP hdr	192 bits
CTH size (L/S)	136/72 bits	basic rate	1 Mbps
slot size, σ	20 µs	sim. time	1500 sec
N_{HC}, N_{EC}, N_{RC}	3-18	E_{init}	100 J
$E_{\min}$	0.01 J	Pt, Pr	0.5 W
P_{idle}	0.45 W	P_{sleep}	0.05 W

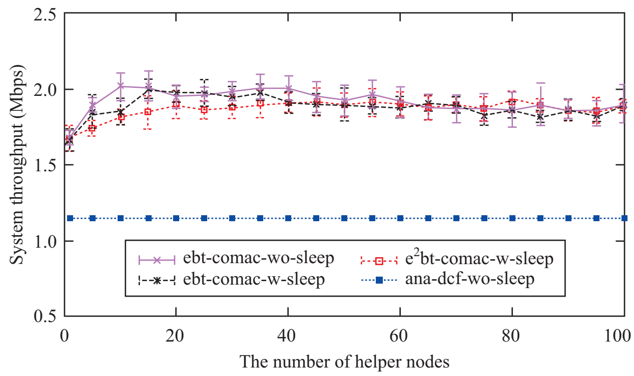

Fig. 6. Throughput comparison of three schemes.

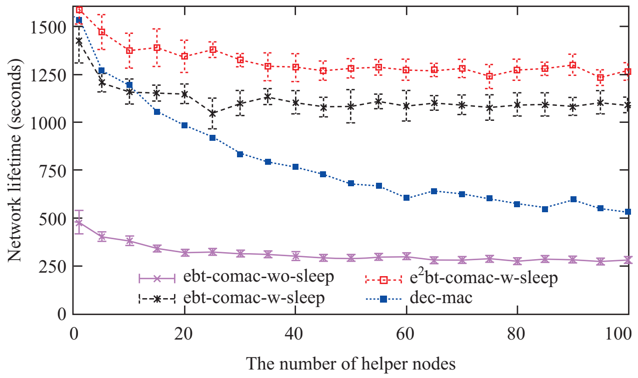

Fig. 7. Network lifetime comparison of four schemes.

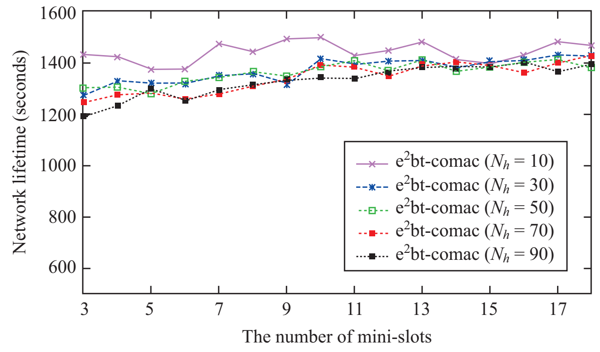

Fig. 9. Network lifetime performance of the e^{2}BT-COMAC protocol.

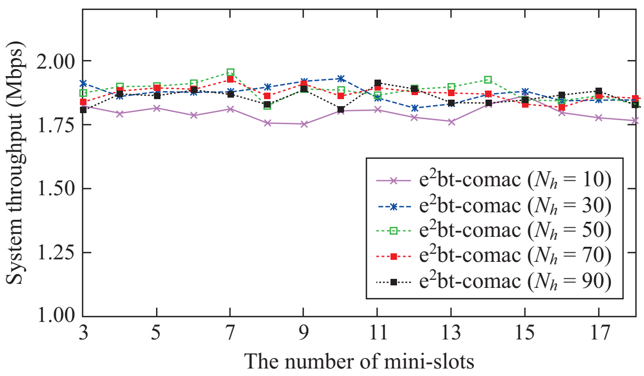

Fig. 8. Throughput performance of the e^{2}BT-COMAC protocol.

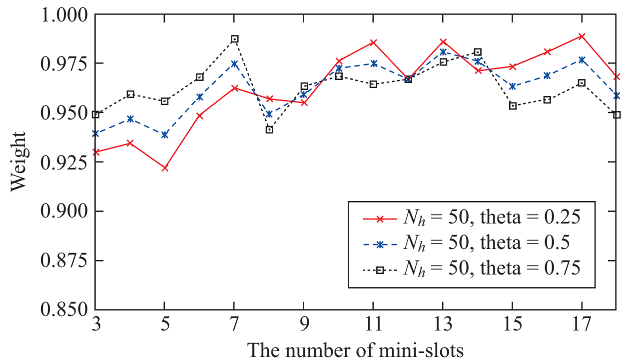

Fig. 10. Relationship between weight and the number of mini-slots.

the DEC-MAC protocol exhibits worse network lifetime performance than the e^{2}BT-COMAC protocol. The DEC-MAC protocol has good network lifetime performance only for a smaller number of helper nodes. The computer simulation shows that the splitting algorithm used by the DEC-MAC protocol to identify the optimal relay node requires extra time. In addition, in DEC-MAC, the relay-node-selection process always begins after exchanging RTS and RTH, even when there are no feasible relay nodes in the network. When the number of helper nodes is the smallest—i.e., when there is only one helper node in the network—the network lifetime is the greatest. This is the case because there is no longer any RTH frame collision in the helper-node-selection competition.

Fig. 8 shows the system throughput performance of the e^{2}BT-COMAC protocol as a function of the number of mini-slots over various numbers of helper nodes in the networks. As the figure shows, the e^{2}BT-COMAC protocol has better system throughput when the number of mini-slots is approximately between 7 and 14. As a matter of fact, it is not easy to find the optimal number of mini-slots from the viewpoint of system throughput only. According to our conjecture, this is due to the fact that the HC mini-slot contention is mandatory while the EC mini-slot and RC slot contentions are optional. On the other hand, it is easy to find the optimal number of mini-slots when the network lifetime performance is considered.

The network lifetime performance of the e^{2}BT-COMAC protocol is shown in Fig. 9. The numerical results indicate that the network lifetime tends to increase as the number of mini-slots increases and as the number of helper nodes decreases. This is the case because network lifetime is closely related to the time taken to identify a helper node. The helper-node-selection procedure includes many RTH frame collisions, and these collisions increase energy consumption in candidate helper nodes. Therefore, as Fig. 7 shows, MAC protocols have the best network lifetime when the number of helper nodes is the smallest, i.e., one helper node in the example network.

Next, we identify the regions where the proposed e^{2}BT-COMAC protocol provides the best performance. Fig. 10 shows the numerical results of the balanced weight metric as a function of the number of mini-slots when N_h = 50 in the e^{2}BT-COMAC protocol. We can easily conjecture that the balanced weight metric will be heavily dependent on the value of θ from Eq. (4). The numerical results show that, with a different θ value, the balanced weight values have a reversed increasing order in two different cases when the number of mini-slots is small and large. The numerical results for the relationship of the number of mini-slots to θ is shown in Fig. 11. According to Eq. (4), a smaller value of θ means putting a higher weight on the network lifetime, and a greater value of θ represents a higher weight on the system throughput. Therefore, in the case of N_h = 50, 70, the number of mini-slots required to obtain the maximum balanced weight value tends to decrease when the value θ increases.

Table 3. Ratio of cooperation and contention steps.

N_h	# of complete trans. (COOP:DT)	# of successful contentions (HC:EC:RC)
20	51,015:317,516	49,111:1,770:135
50	70,791:229,508	57,043:11,263:2,485

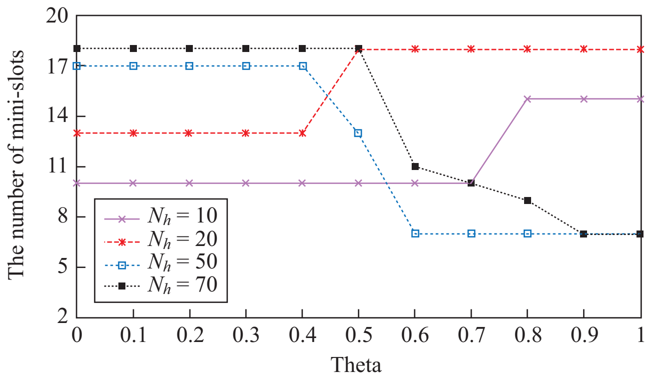

Fig. 11. Relationship between the number of mini-slots and theta.

With the smaller number of mini-slots, the probability of RTH frame collisions at the HC mini-slot contention increases. However, the probability of successful helper node selections at the second or third contention step increases, too. This movement of successful helper node selection from the HC mini-slot contention to the EC mini-slot and RC slot contention contributes to the increase of system throughput. On the other hand, when the number of helper nodes is small, i.e., N_h = 10, 20, the required number of mini-slots increases as the value of θ increases. This is because most of successful helper node selections take place in the first contention step. This case can be explained using the numerical results shown in Table 3. First, cooperative communication tends to take place more frequently when there are many candidate helper nodes. For example, cooperative communication takes place at about 23.6%(= 70,791/(70,791 + 229,508)) when N_h = 50, whereas it occurs at about 18.8%(51,015/(51.015 + 317,516)) when N_h = 20. Secondarily, increasing the number of mini-slots divides the window between $U_{\max}$ and $U_{\min}$ into more sections and thus increases the probability of choosing a helper node successfully. Especially when N_h is smaller, i.e., N_h = 10, 20, increasing the number of mini-slots contributes to selecting the best helper node at the first contention step, i.e., at HC. However, as N_h exceeds 20, the collision probability also increases, and thus the helper-node contention procedure is no longer confined to the first step but continues up to the second or the third step. As Table 3 shows, the percentages of successful helper-node selection at HC, EC, and RC are 96.3%, 3.5%, and 0.2%, respectively, when N_h = 20. When N_h = 50, however, the percentages are 80.6%, 15.9%, and 3.5%, respectively.

VI. CONCLUSION

In this paper, we present a new energy-efficient cooperative MAC protocol and evaluate its performance via computer simulations. The new helper-node-selection scheme in the e^2BT-COMAC protocol is based on received SNR at each candidate helper node. In contrast to prior efforts in this area, in order to participate in helper-node selection, any candidate helper node should meet two requirements: (1) an effective-transmission rate requirement and (2) a remaining-energy requirement. For performance comparison with other schemes, two metrics, system throughput and network lifetime, are used. To derive an optimized value of system parameters, $N_{HC(EC(RC))}$, a new comprehensive metric, balanced weight W, is used. According to the numerical results, the e^2BT-COMAC protocol has somewhat low system throughput when the number of helper nodes is under 40, but its system throughput is similar to the eBT-COMAC protocol when the number of helper nodes is over 40. On the other hand, the e^2BT-COMAC protocol provides the best network lifetime performance among four cooperative MAC protocols. Our future work will focus on an energy-efficient routing protocol for mobile ad hoc networks using the NS-3 network simulator (Network, 2016).

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