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A Network Lifetime Extension-Aware Cooperative MAC Protocol for MANETs With Optimized Power Control

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ABSTRACT In this paper, a cooperative medium access control (CMAC) protocol, termed network lifetime extension-aware CMAC (LEA-CMAC) for mobile ad-hoc networks (MANETs) is proposed. The main feature of the LEA-CMAC protocol is to enhance the network performance through the cooperative transmission to achieve a multi-objective target orientation. The unpredictable nature of wireless communication links results in the degradation of network performance in terms of throughput, end-to-end delay, energy efficiency, and network lifetime of MANETs. Through cooperative transmission, the network performance of MANETs can be improved, provided a beneficial cooperation is satisfied and design parameters are carefully selected at the MAC layer. To achieve a multi-objective target-oriented CMAC protocol, we formulated an optimization problem to extend the network lifetime of MANETs. The optimization solution led to the investigation of symmetric and asymmetric transmit power policies. We then proposed a distributed relay selection process to select the best retransmitting node among the qualified relays, with consideration on a transmit power, a sufficient residual energy after cooperation, and a high cooperative gain. The simulation results show that the LEA-CMAC protocol can achieve a multi-objective target orientation by exploiting an asymmetric transmit power policy to improve the network performance.

INDEX TERMS CMAC, LEA-CMAC, MANET, network lifetime, power control, optimization.

I. INTRODUCTION

Cooperative communication has evolved as one of the mitigating techniques in combating the ever-changing nature of wireless networks. By exploring the broadcast nature and independent fading characteristics of wireless channel, mobile terminals in the vicinity of an ongoing transmission can assist in retransmitting/forwarding their successfully decoded packets to its intended destination via a dual-hop transmission i.e. reactive relaying.

This arrangement has proven to drastically reduce the high cost of deploying infrastructural based networks such as multiple input multiple output (MIMO) systems through the exploitation of virtual antennas to achieve spatial diversity, improve throughput, delay and extend the coverage area of wireless networks [1], [2]. On the other hand, harnessing the virtual antenna array of mobile terminal comes with the high cost of energy consumption and shortens the network lifetime of energy-constrained mobile terminals [3], [4] due to size and lifetime-limited battery capacity which results in instability and unreliability of communication networks.

To improve the network performance of wireless network through the exploitation of spatial diversity gain in the medium access control (MAC) layer stack of cooperative communication, an efficiently designed cooperative medium access control (CMAC) protocol becomes essential and challenging to achieve in practice. A vast list of literature on CMAC protocol designs have emerged over the last decade to address the fundamental issues hindering the standardization of cooperative communication [5]–[7]. The authors in [8]–[11] have classified CMAC protocols based on different network characteristics and performance. In this paper, we classify CMAC protocols based on objective (performance) target orientation same as in [9] i.e. ability to achieve certain objective(s).

Earlier works on CMAC protocols in [12] and [13] proposed the incorporation of an additional node to enhance the network throughput and latency of cooperative network

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through the modification of the Legacy 802.11 MAC. These protocols focus on single-objective target orientation. Based on the successes achieved in these works, the MAC layer protocol design witnessed tremendous attention. Previous protocols that were proposed to achieve single-objective orientation are presented in [12]–[20]. In [12], [13], and [16]–[20], different relay selection backoff process have been proposed to improve the throughput performance, while those in [5], [14], [15], and [21] have focused on energy efficiency enhancement.

Also, different design approach has emerged in designing an energy-efficient CMAC protocol to improve the network performance for different wireless applications [3], [14], [15], [21]–[26]. In [3], [14], and [21]–[26], the extension of the network lifetime through adaptive power control, energy-aware and cross-layer optimization designs were considered to trade-off the gains between throughput and energy consumption.

Some of the existing CMAC protocols with focus on single-objective target orientation are presented. In [12], a throughput-oriented protocol was presented called the CoopMAC that improves the throughput bottleneck experienced by a low data-rate node through the assistance of a high data-rate intermediate node. However, other factors that could erode the potential benefits of cooperation were absolutely neglected. A cross-layer distributed energy-adaptive location-based CMAC protocol (DEL-CMAC) was proposed in [14], mainly for prolonging the network lifetime of mobile ad-hoc networks (MANETs). The protocol was designed based on some important network characteristics such as geographical location, power control, and residual energy. The authors assume a symmetric topology with helper nodes strategically located to experience equal data-rate, distance and transmit power. Though the protocol prolongs the network lifetime of MANETs, the network throughput suffers serious degradation because the protocol focuses on energy and location of the helper nodes rather than their channel state condition.

Also, a power control backoff based CMAC protocol named EECO-MAC for MANETs was proposed in [15] with a similar approach in [14]. The protocol selects an assisting relay before the completion of ready-to-send/clear-to-send (RTS/CTS) handshake and also utilized the power level capability of the IEEE 802.11b PHY to reduce the energy consumption. The drawback of this protocol is that the helper selection process precedes the completion of RTS/CTS handshake. This results in out-of-date information for cooperative transmission process to take place, as the information may no longer be adequate to improve the network performance.

Besides, CMAC protocols with ability to achieve dual-objective targets are as presented. Zhou *et al.* [25] proposed a link utility based CMAC (LC-MAC) protocol for multi-hop networks. The protocol employed the joint adjustment of transmitting power and data-rate through the instantaneous channel measurement to improve the throughput and energy efficiency of the network. However, other network parameters for practical implementation of CMAC protocols were ignored. In Zhang *et al.* [3] an energy-efficient cross-layer optimization algorithm was developed for wireless sensor networks using symmetric network characteristics to balance the energy consumption in the network. The optimal relays to retransmit the packet is based only on nodes with higher residual energy which may not provide improvement in terms of network lifetime.

Recently, Shamna and Lillykutty [24] proposed a distributed cooperative MAC (DCMAC) protocol that achieved multi-objective target orientation in terms of improvement in throughput, energy efficiency and network lifetime. The authors assumed a fixed transmit power at the source and relaying nodes and utilized the multi-rate capability of the Legacy 802.11 MAC in selecting the best helper nodes. However, transmitting at a fixed power level is not always efficient due to increase in interference area which results in degradation of the spatial frequency reuse and prevent other nodes from transmission.

Based on this classification i.e. objective (performance) target orientation, it is obvious that majority of the existing CMAC protocols are unfit for the future generation wireless networks due to their inability to achieve multi-objective, thus, remains a major drawback. Secondly, most existing CMAC protocols mentioned have assumed that for a helper terminal to cooperate optimally, it must be located midway between the source and destination terminals [14], [15] or possesses similar link characteristics [3] thereby having the same transmit power and distances (i.e. symmetric policy). This may not provide the best helper node in practice because helper nodes may experience similar data-rate transmission due to the IEEE 802.11b PHY multi-rate capability, but with different link characteristics such as distance, transmit power and energy consumption cost. Hence, the need for asymmetric policy so that different transmit power at the source and selected relay can be utilized.

In this paper, we propose a network lifetime extension-aware cooperative medium access control (LEA-CMAC) protocol that is oriented to achieve a multi-objective target. The contributions of this paper are as follows:

- We propose multi-objective oriented CMAC protocol that integrates an efficient relay selection process, to improve network lifetime, energy efficiency and throughput in decode and forward (DF) reactive relaying.
- We formulate an optimization problem with an objective of extending the network lifetime of MANETs, while constraining the power control, post cooperation residual energy and link quality dependent cooperative gain.
- We exploit an asymmetric transmit power i.e. the transmit power allocation at both the source and helper nodes to be adaptive.
- Lastly, we propose an efficient best relay selection procedure that ensures sufficient residual energy after cooperation while also balance the energy consumption in the network.

In this paper, unless stated otherwise, relay/helper, nodes/terminals, and retransmission/forwarding are used interchangeably.

The remainder of this paper is organized as follows. In Section II, the details of network model for the protocol are provided. Section III describes the proposed protocol which includes protocol description, relay selection algorithm, network lifetime and energy model, and optimization based distributed power allocation. Simulation results and performance comparison are presented in Section IV. Conclusions are drawn in Section V.

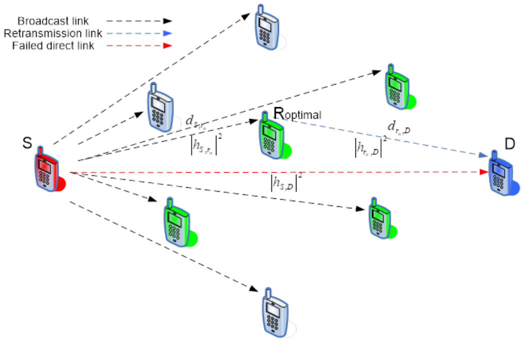


FIGURE 1. Network model.

II. NETWORK MODEL

The proposed LEA-CMAC protocol is a DF reactive relaying based cooperative transmission. All terminals in the network are equipped with an omnidirectional antenna and possess the same radio parameters. Consider a wireless ad-hoc network depicted in Fig. 1 that comprises of N randomly distributed relay nodes $r_n, n \in \{1, ...N\}$, located in the vicinity of the source and destination nodes. All nodes in the network share the same wireless channel medium and exchange control packets (RTS/CTS/ACK) transmitted at a fixed rate of 1 Mbps and data packets (DATA) transmitted at a higher rate greater than the direct transmission rate between the source and destination nodes.

The nodes are uniformly distributed with source nodes always having data packet to transmit to the destination node. The N relay nodes can assist in forwarding the correctly decoded transmitted data packet to the destination node at a reduced transmission cost and therefore, improves the overall network performance.

Each node estimates the channel gain between itself and the source and destination nodes in terms of signal-to-noise ratio (SNR) of their received control packets which is a function of distance, path-loss and fading to correctly decode the data packet. The fading channel between two nodes is assumed to be an independent-identically-distributed (i.i.d) block Rayleigh fading during the transmission of a data packet. Each node in the network is half duplexed with a constraint maximum transmission power. In this paper, we utilize the IEEE 802.11b PHY layer [27] that can support multi-rate capability with their transmitting range as shown in Table 1.

TABLE 1. Properties of IEEE 802.11b multi-rate capability.

Data rate (Mbps)	Transmission range (m)
11	60
5.5	120
2	180
1	250

All nodes are characterized by the same initial energy, and the current energy (battery level) of each node is randomly generated before the transmission process to depict the real-time characteristics of node battery level in an ad-hoc network. In the cooperative transmission mode, the source node transmits its data packet to the destination node via a selected best relay node in a dual hop manner. This is to improve the network performance as compared to the traditional direct transmission which is assumed to always be in deep fade due to severe degradation in the SNR between the source and destination nodes. Maximum ratio combiner (MRC) is utilized at the destination node to decode the received data packet at the PHY layer stack when more than one independent link is combined.

III. PROPOSED LEA-CMAC PROTOCOL

This section describes the proposed LEA-CMAC protocol, relay selection algorithm, network lifetime and energy model, and the optimized transmit power allocation.

A. PROTOCOL DESCRIPTION

Details description of the LEA-CMAC protocol for MANETs using a dual-hop DF reactive relaying is described below. The basic operation of LEA-CMAC is based on the Legacy 802.11 MAC.

To extend the Legacy 802.11 MAC for cooperative transmission, the RTS and CTS control frames were modified to contain extra fields, and an additional control frame called helper-ready-to-forward (HRF) is introduced. In the RTS frame, a distance information field is created to acquire the location of the destination node. The CTS frame has an additional two extra fields for location information and choice of the transmission mode (0 for direct transmission and 1 for cooperative transmission). The HRF frame is used to select the best helper node in a distributed manner. This control frame is transmitted/broadcast by the winning best relay node after a successful relay selection period. This is to inform the source, destination and other nodes in the network of its intention to assist in forwarding the successfully decoded data packet. In this paper, the best relay node is defined as the helper node that can achieve higher throughput, reduce the total transmit power and extend the lifetime of the network. The frame exchange of LEA-CMAC is as shown in Fig. 2.

All control frames are transmitted at a basic rate of 1 Mbps to reserve the channel medium for successful transmission to take place between communicating nodes by setting their network allocation vector (NAV). T_{RTS}, T_{CTS}, T_{HRF} and T_{ACK}

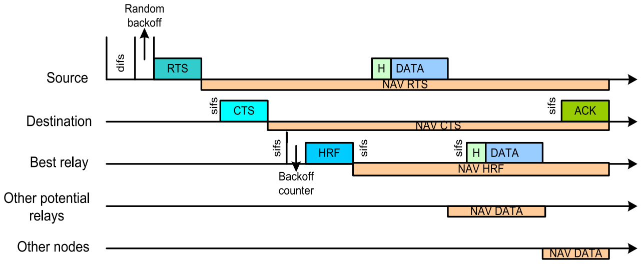


FIGURE 2. **Packet transmission for LEA-CMAC protocol.**

are the transmission time of the control frames RTS, CTS, HRF and ACK frames respectively. The operation at each node for cooperation is discussed as follows:

Operation at the source node

a. When a source node has a data packet of L bytes to transmit, it senses the channel medium for an idle state. If the channel medium is in an idle state for distributed coordination function (DCF) inter-frame spacing (*difs*), the source node goes into random backoff by setting its backoff timer between [0, $CW_{\min}$], where $CW_{\min}$ is the minimum contention window size. When the backoff timer expires, the source node transmits RTS to an intended destination node to reserve the channel. The estimated distance (location information) between the source and destination node is contained in the RTS frame. The time duration for RTS transmission is

$$D_{RTS} = T_{CTS} + \frac{8\,(L + L_H)}{R_{S,D}} + T_{ACK} + 3sifs,$$

where L_H is the header packet in bytes, $R_{i,j}$ is the transmission rate between the link i and j, and *sifs* is the short inter-frame spacing.

b. If the source node does not receive CTS within $T_{RTS} + T_{CTS} + sifs + 2\delta$, where δ is the propagation delay, a new retransmission process is initiated. Otherwise, if the transmission mode field of CTS is set to 0, cooperative relaying is not initiated and LEA-CMAC reduces to the Legacy 802.11 MAC. If the transmission mode field in the CTS is set to 1, the source node waits for another $T_{\max\_BO} + sifs + T_{HRF} + \delta$, where $T_{\max\_BO}$ is the maximum backoff for the relay nodes. In case, HRF is not received, which implies no helper node is available, the source node transmits its data packet directly to the destination and the ACK timeout is set to $\frac{8(L+L_H)}{R_{S,D}} + T_{ACK} + sifs + 2\delta$.

c. If both CTS and HRF is received, the source will initiate cooperative transmission by transmitting its data packet to the best-selected helper node based on the estimated optimal transmitting power piggybacked in the HRF, which implies that the cooperative transmission can support a two data-rate transmission based on optimal transmit power at the source and relay nodes which will be shown in Section D. The ACK timeout is then set to $\frac{8(L+L_H)}{R_{S,r_n}} + \frac{8(L+L_H)}{R_{r_n,D}} + T_{ACK} + 2sifs + 3\delta$.

d. If an ACK is not received within ACK timeout, the source would go into random backoff process to contend for the channel medium just as applicable in the Legacy 802.11 MAC. Otherwise, the transmission process is successful and the next transmission process starts at the source node.

Operation at the relay node

a. If the RTS is received, the destination node will reply by transmitting CTS to the source node and any neighboring nodes that receive both RTS and CTS with the transmission mode field set to 1 are potential helper nodes. The CTS frame contains the estimated distance and the transmit power of the direct link. If the transmission mode field of the CTS is set to 0, this implies that direct transmission has been decided and all neighboring nodes set their NAV to the specified duration contained in the duration field of the transmitted CTS frame.

b. If the transmission mode field of the CTS is set to 1, each of the potential helper node computes its backoff utility value (based on its optimal transmit power, energy level and cooperative gain) and then goes into contention to select the best helper node among themselves. If the source and destination node do not receive HRF within $T_{\max\_BO} + T_{CTS} + sifs + T_{HRF} + 2\delta$, it assumes direct transmission due to non-availability of potential helper node that can support energy saving.

c. Otherwise, if the transmission mode field of the CTS is set to 1, the contending relay nodes that have received the HRF frame transmitted by the best-selected helper node set their NAV and defer for the successful transmission period after which the channel medium will become idle. The best helper node intuitively is characterized by a backoff timer which expires first and therefore, other contending potential relays abort their respective backoff processes. The duration field in the HRF is

$$D_{HRF} = \frac{8\,(L + L_H)}{R_{S,r_n}} + \frac{8\,(L + L_H)}{R_{r_n,D}} + T_{ACK} + 3sifs.$$

d. After, transmitting its HRF, the best helper node waits for a duration of $T_{HRF} + \frac{8(L+L_H)}{R_{S,r_n}} + sifs + 2\delta$ to receive the data packet from the source. If within this duration, the data packet is not received, the best helper node relinquishes its participation to assist and goes into idle state. Otherwise, it changes its duration field to $D_{DATA\_r_n,D} = T_{ACK} + sifs$, and then forwards the data packet to the destination.

Operation at the destination node

a. If the RTS is received at the destination node, CTS frame is transmitted to the source node after *sifs*. If the CTS transmission mode field is 0, direct transmission takes place and the duration field reads $\frac{8(L+L_H)}{R_{S,D}} + T_{ACK} + 2sifs$, and wait to send ACK after a duration

$T_{CTS} + \frac{8(L+L_H)}{R_{S,D}} + 2sifs + 2\delta$, if it has successfully received the data packet from the source node. If neither data packet nor HRF is received, the destination node goes into an idle state.

b. Otherwise, if CTS transmission mode field is set to 1, cooperative transmission is required and the duration for CTS transmission will be

$$D_{CTS} = T_{\max\_BO} + T_{HRF} + \frac{8\,(L + L_H)}{R_{S,r_n}} + \frac{8\,(L + L_H)}{R_{r_n,D}} \ldots + T_{ACK} + 4sifs + 4\delta$$

before ACK is transmitted to the source node after it has successfully received data packet from the best helper node. If ACK is not transmitted, it goes into an idle state.

The flowchart of source, relay and destination nodes is depicted in Fig. 3

B. RELAY SELECTION

The relay selection procedure of the proposed LEA-CMAC protocol is based on extending the network lifetime and maintaining a high network throughput with reduced transmit power. Since the relaying nodes are randomly distributed in the vicinity of the source and destination nodes and can assist in forwarding the overheard data packets, the throughput of the network can be enhanced provided that the data-rate in the two-hops is greater than that of the direct transmission as seen in CoopMAC [12].

The backoff utility function developed in this paper is similar to [14], [15], [24], and [26]. The optimal helper node is selected among potential helpers based on the optimal transmit power obtained from the optimization problem formulated to be presented through equations in Section D. By solving this problem, using the asymmetric policy, an adaptive transmit power is obtained at the source and helper node, respectively (i.e. equal power is not allocated at both nodes). Also, the residual energy of the nodes is considered to ensure that the selected helper possesses sufficient energy in its buffer after participating in cooperation. By so doing, the network lifetime is extended and other performance objectives are likewise enhanced.

The backoff utility function for the optimal helper r_n^* is then expressed as

$$BU_{r_n^*} = \beta \quad \min\left(\left(\frac{P_t^C}{P_t^D}\right) \times \left(\frac{E_o}{E_{r_n} - E_{r_n}^C}\right) \times \left(\frac{R_{S,r_n,D}}{R_{S,D}}\right)\right) \tag{1}$$

where P_t^D is the direct link transmit power, P_t^C is the optimal cooperative transmit power which is defined as $P_t^C = P_t^{*S} + P_t^{*r_n}$, P_t^{*S} and $P_t^{*r_n}$ is the optimized transmit power at the source and individual relaying nodes respectively to be obtained later from Section D. E_o is the initial energy which is the same for all nodes, $E_{r_n}^C$ is the estimated energy

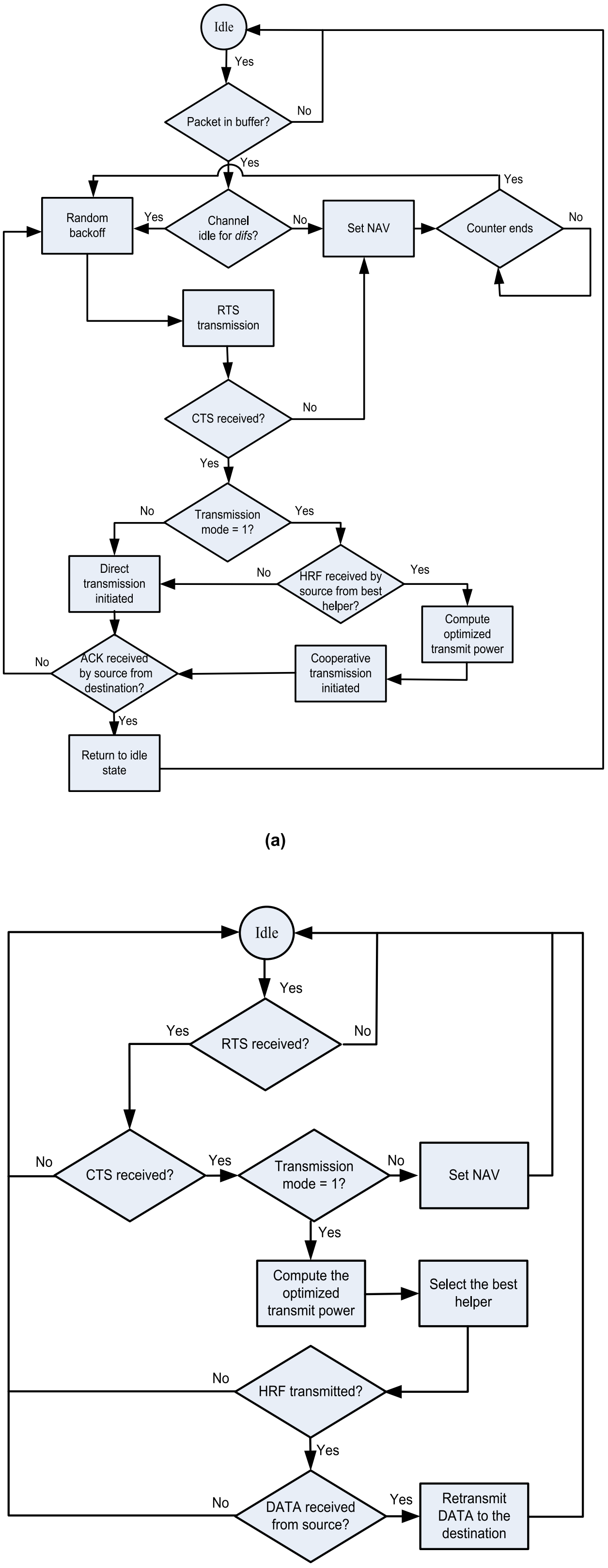
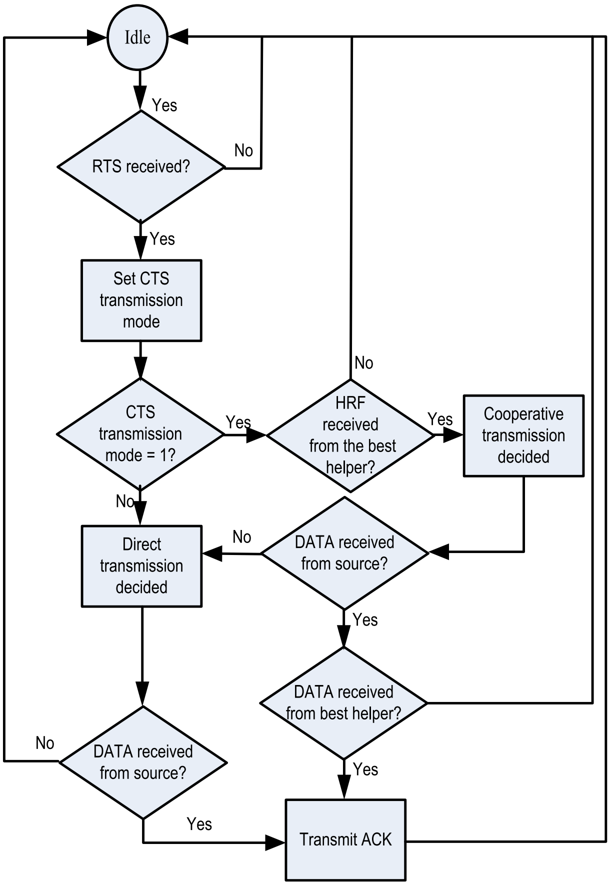


FIGURE 3. Flowchart of the operation at (a) the source node, (b) the relay node, and (c) the destination node.



(c)

FIGURE 3. ***(Conytinued.)*** **Flowchart of the operation at (a) the source node, (b) the relay node, and (c) the destination node.**

to be consumed by the individual potential relay nodes when cooperating, which would be shown in Section C, E_{r_n} is the current energy of individual nodes in the network, β is set to ensure timely selection of the relay, while $R_{S,D}$ and $R_{S,r_n,D}$ are the data-rate of the direct and cooperative transmission modes respectively. Intuitively, the best helper node with the minimum backoff utility function has its backoff time expires first. Then this winning best helper responds with the transmission of HRF while other nodes that overhear its packet transmission quit the backoff process.

C. PROPOSED NETWORK LIFETIME AND ENERGY MODEL FOR LEA-CMAC PROTOCOL

This protocol is designed for a distributed ad-hoc network where there exist no centrally controlled coordination in sharing or allocating network resources. The network lifetime of a node has been defined by many researchers as the average time for a node in the network to totally exhaust it power and quit the network [4], [14], [23]. Since each node is powered by an energy source (battery), its lifetime is a function of its initial energy and energy consumption per unit time. Therefore, to maximize the lifetime of a network, emphasis is laid on the node's battery to ensure that a node does not totally run out of power [28].

In [23], the energy consumed in transmitting the data packet was considered in extending the network lifetime with multiple relaying. The model considered does not reflect the total energy required in CMAC protocol design. If considered, the protocol will suffer additional overhead cost and thereby reduces the network lifetime. Wang and Li [14], took into consideration the energy consumed in transmitting, receiving and processing of the control and data packets. The selected relaying node was defined as the node characterized by the maximum residual energy with minimum transmitting power. Though the protocol performed better in prolonging the lifetime of MANETs through transmitting power allocation, however, it suffers serious throughput degradation. Hence, requires energy and throughput tradeoff.

In this paper, we use the network lifetime as defined in [14], [23], and [28]. We further reduce the transmission energy by optimizing the transmitted power

$$e = \min\left\{E_s - P_t^s T, E_{r_1} - P_t^{r_1} T, \ldots, E_{r_n} - P_t^{r_N} T\right\} \tag{2}$$

where e is the minimum residual energy of the nodes in the network that would remain after possibly participating in cooperation, E_s is the current residual energy of the source, P_t^S is the estimated transmitted power at the source, $\left\{P_t^{r_1}, P_t^{r_2}, \ldots, P_t^{r_N}\right\}$ is the estimated transmitted power subset of the number of participating relay nodes, in order to reduce the energy consumption, T is the estimated total transmission time. The estimated energy consumed E_S^D for direct transmission is expressed as

$$E_S^D = (P_{t\max} + P_{rx} + P_c)\, T_{CON} + \left(P_t^s + P_{rx} + P_c\right) T_{DATA\_S,D} \tag{3}$$

and that consumed when relay node cooperates $E_{r_n}^C$ is given as

$$\begin{aligned} E_{r_n}^C = {} & (P_{t\max} + P_{rx} + P_c)\,(T_{CON} + T_{HRF}) \ldots \\ & + \left(P_t^s + P_{rx} + P_c\right) T_{DATA\_S,r_n} \cdots \\ & + \left(P_t^{r_n} + P_{rx} + P_c\right) T_{DATA\_r_n,D} \end{aligned} \tag{4}$$

where $P_{t\max}, P_{rx}$ and P_c are the maximum transmitting power for control frames at 1 Mbps, the receiving power, and the processing power respectively.

$T_{CON} = T_{RTS} + T_{CTS} + T_{ACK}$ and $T_{i,j} = \frac{8(L+L_H)}{R_{i,j}}$, The energy consumption of the direct transmission is also compared with that of cooperative relaying transmission before a relay node can be a potential helper node.

Comparing (3) and (4), we have $E_S^D - E_{r_n}^C \neq 0$, which must be a non-zero value to achieve energy gain. This implies that the energy consumed by any cooperating node must be less than that of direct transmission due to the distance between the source and destination nodes which is assumed to always experience severe fading.

D. OPTIMIZATION BASED DISTRIBUTED POWER ALLOCATION

The allocated transmit power for the direct transmission and DF reactive relaying are obtained from Shannon capacity theorem as seen in [29] and [30], respectively. In CMAC protocols, the channel gain between two communicating nodes $\left|h_{i,j}\right|^2$ is modeled as a Rayleigh fading distribution and dependent on the distance between i and j (i.e $d_{i,j}^{-\alpha}$) and α is the path-loss exponent. This channel gain is known to all nodes that have overheard the transmission of both the RTS and CTS packet during the RTS/CTS handshake.

The allocated transmit power at the relay node is then estimated and piggybacked through the HRF frame of the best helper node to the source. Also, most existing protocols have assumed the same power for both the source and the relay node. Transmitting at these power results in degradation of spatial frequency reuse (due to increase in interference area) and network lifetime. In order to obtain the optimal power that will maximize the network lifetime, the total power constraint must satisfy $P_t^S + P_t^{r_n} \leq P_{tot}$, which is a linear optimization problem [31] and [32].

Consider an ad-hoc network with relay nodes $r_n, n \in \{1, \ldots N\}$, our aim is to maximize the network lifetime and still maintain a higher network throughput in the MAC layer while reducing the total energy consumption in transmitting a data packet. The optimal power allocation can maximize the achievable rates [33] and ensure fairness among the relay nodes by ensuring that the total transmitting power using cooperation is less than direct transmitting power and subsequently improve the network performance. To reduce the total transmission power when cooperating, local information is required by each node in the network due to limited access [34]. Since the transmission rate is dependent on the transmit power, more than one assisting relay nodes may possess the same achievable rate but at different transmitting power. Hence, resulting in an asymmetric transmit power policy while also reducing the total energy consumption as compared to employing equal power at both nodes in [14] and [24].

We formulate an optimization problem to maximize the network lifetime as

$$\begin{aligned} &\max_{P_t^S, P_t^{r_n} \geq 0, n \in N} imize \quad e \\ (c1) \quad & s.t\; P_t^S + P_t^{r_n} \leq P_{tot}, \quad \forall n \in N \\ (c2) \quad & R \leq C, \quad \forall n \in N \\ (c3) \quad & E_S - P_t^S T_{S,r_n} \geq E_{\min}, \quad \forall n \in N \\ (c4) \quad & E_{r_n} - P_t^r T_{r_n,D} \geq E_{\min}, \quad \forall n \in N \\ (c5) \quad & 0 \leq P_t^S \leq P_{t\max}, \quad \forall n \in N \\ (c6) \quad & 0 \leq P_t^{r_n} \leq P_{t\max}, \quad \forall n \in N \end{aligned} \tag{5}$$

The objective function in (5) is obtained from (2) and constraint to total transmit power in (c1), the achievable Shannon capacity for a DF two-hop cooperative transmission is given in (c2) and is as expressed in [30], where R is the minimum transmission rate, the residual energy after current transmission (c3) and (c4) at the source and relay nodes, respectively, and maximum transmitting power in (c5) and (c6).

The solution to this optimization problem is obtained by finding the optimal solution of the transmitting power at both the source and relay nodes. To obtain the optimal solution, we apply the Lagrangian function to (5) and is expressed as

$$\begin{aligned} L & \left\{P_t^S, P_t^{r_n}, \lambda, \mu, z, u, \sigma, \rho\right\} \\ &= e - \lambda\left(P_t^S + P_t^{r_n} - P_{tot}\right) \ldots \\ &\quad -\mu\,(R - C) - z\left(E_{\min} - E_S + P_t^S T_{S,r_n}\right) \ldots \\ &\quad -u\left(E_{\min} - E_{r_n} + P_t^{r_n} T_{r_n,D}\right) - \sigma\left(P_t^S - P_{t\max}\right) \ldots \\ &\quad -\rho\left(P_t^{r_n} - P_{t\max}\right) \end{aligned} \tag{6}$$

where $\lambda, \mu, z, u, \sigma, \rho$ are the Lagrangian multiplier function for the total transmit power constraint, achievable cooperative rate, source and relay residual energy after participating in cooperation, the source transmits power and relay nodes transmit power constraints, respectively. Two cases are investigated in this Section: i) when the source and the selected relay transmitting power are the same (symmetric policy) and ii) when their respective transmit powers are not the same (asymmetric policy).

Case 1 (Symmetric Policy): For simplicity of expression, let assume equal transmit power at the source and relay nodes such that $P_t^S = P_t^{r_n}$ and that their transmission rates and distances are the same $d_{S,r_n} = d_{r_n,D}$, with channel gains between source-relay and relay-destination approximately equal i.e. $\left|h_{S,r_n}\right|^2 \approx \left|h_{r_n,D}\right|^2$. This is a special case similar to the assumption in [3], [14], [15], and [30]. Without loss of generality, we assume that these conditions: $\left|h_{S,r_n}\right|^2 \geq \left|h_{S,D}\right|^2$ and $\left|h_{r_n,D}\right|^2 \geq \left|h_{S,D}\right|^2$ must always be satisfied. The optimal solution is obtained by taking the first derivative of (6) w.r.t $P_t^{r_n}$. For simplicity, let $T_{S,r_n} = T_{r_n,D} = T$. The optimal solution of (5) can be obtained according to the Karush Kuhn-Tucker (KKT) conditions [35], which holds for the constraint $P_t^S, P_t^{r_n} \geq 0$

$$\begin{aligned} \frac{\partial L\{\cdot\}}{\partial P_t^{r_n}} &= T - 2\lambda - \mu \frac{2\left|h_{r_n,D}\right|^2 d_{r_n,D}^{-\alpha}}{N_o} \\ &\quad \times \left(\ln 2\left(1 + \frac{2P_t^{r_n}\left|h_{r_n,D}\right|^2 d_{r_n,D}^{-\alpha}}{N_o}\right)\right)^{-1} \ldots \\ &\quad -zT - uT - \sigma = 0, \end{aligned} \tag{7}$$

Therefore, the optimal allocated power at the source and relay node is obtained after mathematical manipulation which gives

$$P_t^{*r_n} = P_t^{*S} = \left(\Gamma - \frac{N_o}{2\left|h_{r_n,D}\right|^2 d_{r_n,D}^{-\alpha}}\right)^{+}, \tag{8}$$

where $\Gamma = \frac{\mu}{2\ln 2(2\lambda + T(1+z+u))}$.

If $\Gamma \leq \frac{N_o}{2|h_{r_n,D}|^2 d_{r_n,D}^{-\alpha}}$ the total power constraint condition is not satisfied, therefore Γ is chosen to satisfy the total power constraint and yields the relay optimal transmit power for $(\cdot)^+ = \min\left(P_t^{*S}, P_{t\max}\right)$.

Case 2 (Asymmetric Policy): In this case, we assume that $P_t^S \neq P_t^{r_n}$, $d_{S,r_n} \neq d_{r_n,D}$ and $\left|h_{S,r_n}\right|^2 \neq \left|h_{r_n,D}\right|^2$ are not the same for the two-hop, but still has the same data transmission rate due to the IEEE 802.11b PHY multi-rate capability. By taking the first order derivative of (6) i.e. $\frac{\partial L\{\cdot\}}{\partial P_t^{r_n}}$, we obtain the optimal solution for the estimated transmitting power at the relay nodes after successfully received both RTS and CTS packets. After mathematical manipulation, the estimated optimal transmit power at the relay nodes is calculated to be

$$P_t^{*r_n} = \left(\psi - \frac{2^{2R} N_o}{\left|h_{r_n,D}\right|^2 d_{r_n,D}^{-\alpha}}\right)^+, \tag{9}$$

where $\psi = \frac{\mu}{2\ln 2(\lambda+\rho+T(1+u))}$. This estimated $P_t^{*r_n}$ is then piggybacked in the HRF frame, broadcast by the winning best node that has its backoff timer expires first during the contention relay selection process in (1).

Also, the best-selected relay allocated power must satisfy the power constraint condition when the first term is set to a value greater than the second term and $(\cdot)^+ = \min\left(P_t^{r_n}, P_{t\max}\right)$, otherwise the condition is not satisfied. The source node then estimates it's optimal transmits power P_t^{*S} as a function of $P_t^{*r_n}$. By taking the first order derivative of (6) w.r.t P_t^S i,e, $\frac{\partial L\{\cdot\}}{\partial P_t^s}$, we obtained

$$P_t^{*S} = \left(\zeta - \frac{P_t^{*r_n}\left|h_{r_n,D}\right|^2 d_{S,r_n}^{-\alpha}}{\left|h_{S,r_n}\right|^2 d_{r_n,D}^{-\alpha}}\right)^+, \tag{10}$$

where $\zeta = \frac{\mu}{2\ln 2(\lambda+\sigma+T(1+z))}$. The optimal allocated power at the source must also satisfy the constraint conditions with $(\cdot)^+ = \min\left(P_t^S, P_{t\max}\right)$. This makes the allocation flexible and independent of the direct transmitting power, therefore enhancing energy efficiency and spatial frequency reuse. The optimal solution of the symmetric policy in (8) and the asymmetric policy in (9) and (10) are obtained iteratively through simulation by updating the Lagrangian multipliers in (11) according to the KKT conditions from (6), with ε chosen to be a small step size. The algorithm 1 shows the optimal transmit power using asymmetric policy. All potential helpers that qualify perform this action to obtain their optimal values in (9) and (10) which is then used to compute their backoff utility function in (1) to select the best helper.

Algorithm 1 Optimized Transmit Power Using Asymmetric Policy

```
1). **Begin**
2). initialize $N, I, P_{t\max}, \alpha, T, R, N_o, E_o$ and the Lagrange
    multipliers such that $\lambda, \mu, z, u, \sigma, \rho \geq 0$.
3). for 1:length $(N)$ do
4). generate randomly $d_{S,r_n}$ and $d_{r_n,D}$ such that relay node
    $r_n$ is located in the cooperative region between source-
    destination, such that $d_{S,r_n} \neq d_{r_n,D}$ and $E_{r_n}$
5). find $E_{\min} = \min\left\{E_S, E_{r_1}, E_{r_2}, \ldots, E_{r_N}\right\}$
6). for 1:length $(I)$ do
7). generate randomly $h_{S,D}$, $h_{S,r_n}$ and $h_{r_n,D}$
8). if $\left|h_{S,r_n}\right|^2 \geq \left|h_{S,D}\right|^2$, $\left|h_{r_n,D}\right|^2 \geq \left|h_{S,D}\right|^2$ and
    $d_{S,r_n} \neq d_{r_n,D}$ then
9). compute (9) and (10), then update using their
    appropriate Lagrange multipliers in (11)
10). else
11). no potential helpers that satisfy 9),
12). end if
13). end for
14). obtain the optimal value of $P_t^{*r_n}$ and $P_t^{*S}$.
15). end for
16). End
```

$$\begin{aligned}
\lambda(i+1) &= \left[\lambda(i) + \varepsilon\left(P_t^{*S} + P_t^{*r_n} - P_{tot}\right)\right]^+ \\
\mu(i+1) &= \left[\mu(i) + \varepsilon\left(\left(2^{2R}-1\right) - \gamma_{S,r_n}^* - \gamma_{r_n,D}^*\right)\right]^+ \\
z(i+1) &= \left[z(i) + \varepsilon\left(E_{\min} - E_S + P_t^{*S} T\right)\right]^+ \\
u(i+1) &= \left[u(i) + \varepsilon\left(E_{\min} - E_{r_n} + P_t^{*r_n} T\right)\right]^+ \\
\sigma(i+1) &= \left[\sigma(i) + \varepsilon\left(P_t^{*S} - P_{t\max}\right)\right]^+ \\
\rho(i+1) &= \left[\sigma(i) + \varepsilon\left(P_t^{*r_n} - P_{t\max}\right)\right]^+.
\end{aligned} \tag{11}$$

IV. SIMULATION

In this section, we evaluate the performance of the proposed LEA-CMAC protocol with some existing protocols. The proposed LEA-CMAC, Legacy 802.11 MAC, CoopMAC [12], DEL-CMAC [14] and DCMAC [24] were implemented and simulated in MATLAB v8.5, R2015a software environment. The simulation was carried out under the assumption that the source node always has data packet in its buffer to transmit. We then compare the performance of the protocols in term of saturated throughput, E2E delay, energy consumption, packet delivered, network lifetime and energy efficiency.

In the simulation, the relay nodes are uniformly distributed in the network topology with a square area of 300 m × 300 m. The source and destination nodes are symmetrically located at the center line with distance 200 m apart with the maximum transmitted power of 300 mW for all nodes. We considered also a two-way ground reflected model for the wireless channel and the IEEE 802.11b parameter was adopted for our simulation. The simulation parameters employed in this paper is as shown in Table 2.

The simulation was carried out with node generated randomly with different seed values, and the average taken for 10000 runs. The metric evaluated are as follow:

1) Saturated throughput: is the number of successfully received data bits at the destination node in a unit time.

TABLE 2. Simulation parameters.

Parameter	value	Parameter	value
RTS/CTS	44/34 bytes	CW_{min}/CW_{max}	31/1023
HRF/ACK	38/38 bytes	*Retry limit*	6
MAC header	34 bytes	β	0.1ms
PHY header	24 bytes	E_o	1 J
difs/sifs	50/10 µs	P_{tmax}	300 mW
σ	20 µs	P_{rx}	1 mW
Basic rate	1 Mbps	P_c	10 mW
α	3	Noise power	-90 dBm

2) E2E delay: is the time spent between when a packet is ready to be transmitted until it is successfully received at its intended destination.
3) Packet delivered: is the average number of packets successfully delivered during the lifetime of a network.
4) Network lifetime: is the time it takes one of the node in the network to totally run out of energy supply.
5) Energy efficiency: is the energy consumed to successfully transmit one data packet to its intended destination.

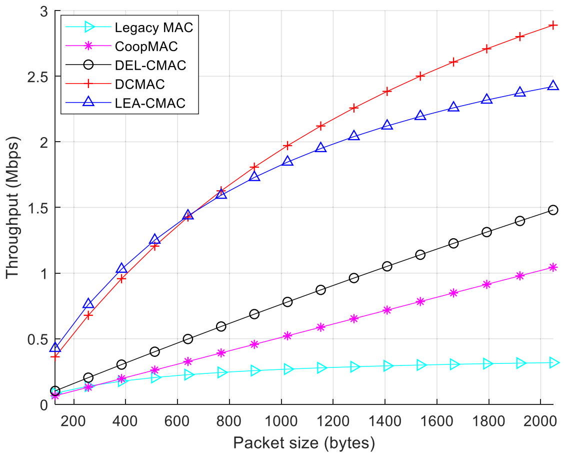


FIGURE 4. The network throughput against packet size of simulated protocols at N = 50.

The performance of the network saturated throughput of LEA-CMAC and other protocols at $N = 50$, with varying packet size is provided in Fig. 4. It can be seen that the throughput of all protocols increases with increasing packet sizes. The proposed protocol and DCMAC outperform other protocols with increasing sizes of packets and allows more bits to be transmitted at fixed overhead. LEA-CMAC has a better performance at lower packet size than other protocols because of its lower reservation time during the transmission of data packets and the cooperative region analysis similar to [16] employed in this simulation to enhance the network throughput. At a packet size of 256 bytes, LEA-CMAC recorded a throughput percentage gain of 11.49%, 115.70% and 141.41% over DCMAC, DEL-CMAC and CoopMAC respectively. With the increase in packet size, DCMAC performs better than other protocols. For instance, at 1024 bytes of packet, DCMAC recorded an average percentage gain of 6.55% over LEA-CMAC because its transmitted packet is shared between two best relays to achieve higher throughput in the network. This implies that LEA-CMAC is more efficient in throughput performance than DCMAC which employs two relays to retransmit data packet at lower packet size and subsequently results in wastage of network resources.

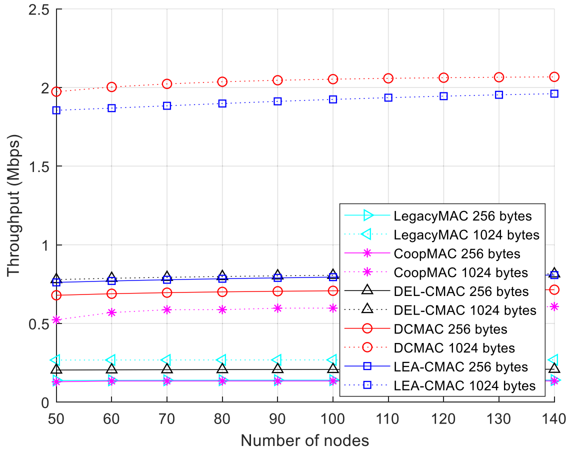


FIGURE 5. The network throughput of simulated protocols with varying number of nodes.

In Fig. 5, the comparison of the saturated throughput of the protocols with a varying number of nodes is drawn, at packet sizes of 256 bytes and 1024 bytes. It can be seen that the proposed LEA-CMAC protocol shows a better performance over all other protocol at all packet sizes. At $L = 256$ bytes of packet, LEA-CMAC outperforms DCMAC which employ two best relay at data-rate regions of (5.5,5.5) and (11,2) Mbps to share its traffic by 11.38%. However, LEA-CMAC suffers a reduction of 6.17% for $L = 1024$ bytes against DCMAC. It is important to mention that LEA-CMAC performs better than all other protocols because it takes advantage of the efficient and robust relay selection process.

In the relay selection process employed, the backoff function ensures timely selection of the optimal best helper node. Also, the best helper node among the potential helpers possesses minimum total transmit power and higher residual energy after cooperation, thereby, reduces the selection time. In addition, the data-rate transmission region of the relaying nodes (5.5, 5.5) Mbps ensures the enhancement of the overall network throughput. Because helper nodes must also possess high cooperative gain to be selected the best node and the best helper node that satisfies this criterion improves the network throughput.

The comparison based on the E2E delay with all other protocols is presented in Fig. 6. As the number of nodes increases, the E2E delay performance of all the protocols degrades.

It can be seen from the result that LEA-CMAC and DCMAC experiences a significant reduction as compared

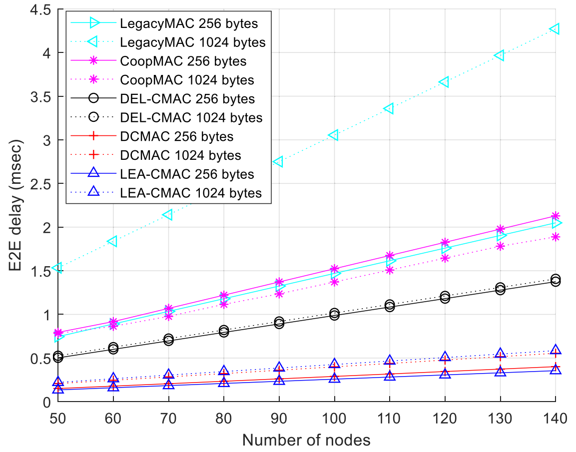


FIGURE 6. **The E2E delay of simulated protocols with varying number of nodes.**

to other protocols. The reason for this is due to lower collision occurrence in the relay selection process of the two protocols. In LEA-CMAC, the asymmetric transmit power policy employed reduces the possibility of having more relays possessing the same backoff values. Whereas in DCMAC, the scheduling and traffic sharing characteristics takes care of this effect. This consequently reduces successful transmission time for the two protocols. Considerably, the E2E delay difference of our proposed LEA-CMAC protocol shows a significant decrease of 0.03, 0.76 and 1.27 ms, over DCMAC, DEL-CMAC and CoopMAC respectively, at $N = 100$ and $L = 256$ bytes. However, with $L = 1024$ bytes at the same number of nodes, DCMAC shows a decrease of 0.023 ms over LEA-CMAC protocol.

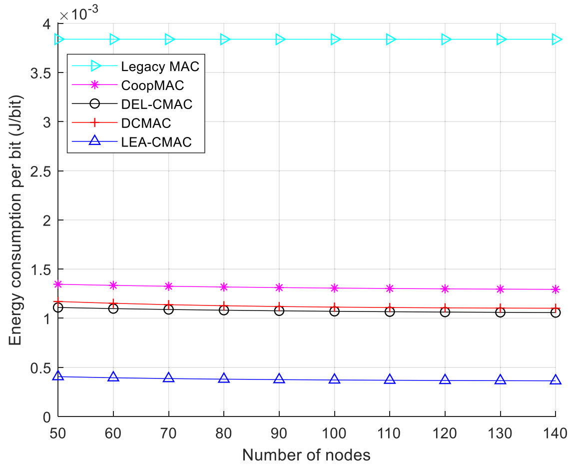


FIGURE 7. **The energy consumption of simulated protocols with varying number of nodes at L = 1024 bytes.**

Fig. 7 presents the performance comparisons based on the packet energy consumption at a packet size of 1024 bytes. We observe that the energy consumption of LEA-CMAC is the least among the CMAC protocols. This intuitively implies that long range transmission of data packet is characterized by long E2E delay and poor channel link which consequently lead to increase in energy consumption as seen in the Legacy 802.11 MAC. LEA-CMAC protocol has a considerably low energy consumption with an average energy reduction of 96.87%, 99.86% and 111.38% over DEL-CMAC, DCMAC and CoopMAC respectively. This is because the transmission time is compensated for due to more availability of energy efficient helper node to assist in retransmitting the failed packet using an optimized transmit power at both the source and helper nodes. Moreso, this also helps to lower the retransmission attempt and reduce the energy consumption in the network.

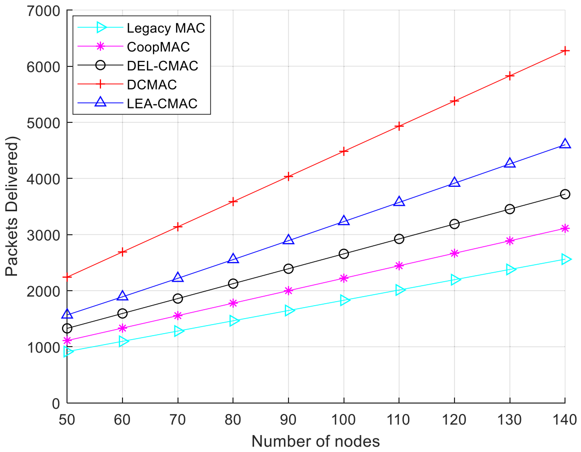


FIGURE 8. **The total packet delivered of simulated protocols with varying number of nodes at L = 1024 bytes.**

Fig. 8 illustrates the number of packets delivered during the lifetime of the network at $L = 1024$ bytes for the protocols under investigation. It is seen here that the packets delivered significantly improves in terms of the availability of more relaying nodes to participate in cooperation. The DCMAC has a higher number of packets delivered during its lifetime than the other four protocols because it balances its traffic through two selected relays. LEA-CMAC though has a lower number of packet delivered as compared to DCMAC because transmitting with asymmetric power helps to improves spatial frequency reuse while trading off the packet delivered. LEA-CMAC outperforms the DEL-MAC, CoopMAC, and the Legacy 802.11 MAC by 19.50%, 37.01% and 55.42% respectively but suffers a reduction of 32.46% as compared to DCMAC in packet delivered at $N = 100$.

The network lifetime of the protocols is drawn in Fig. 9. It is seen from this figure that the network lifetime of all protocols increases with increasing number of nodes. With the availability of more potential helper nodes in the network, LEA-CMAC significantly outperforms all other protocols by 96.88%, 99.85%, 111.40% and 164.67% for DEL-CMAC, DC-MAC, CoopMAC and Legacy 802.11 MAC respectively, when $N = 100$ and $L = 1024$ bytes.

This is because the proposed protocol takes into consideration an asymmetric transmit power policy and the final

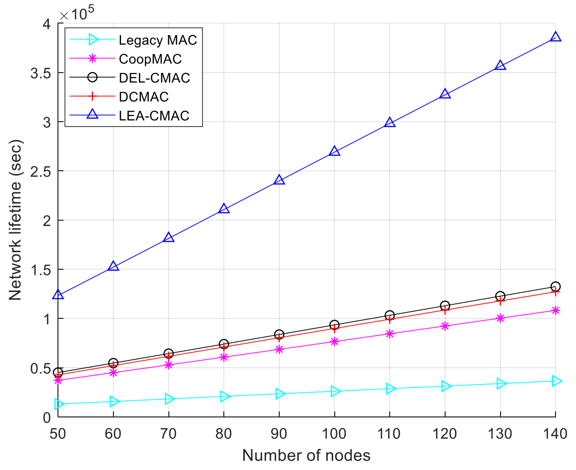


FIGURE 9. **The network lifetime of protocols with varying number of nodes L = 1024 bytes.**

residual energy of the best helper node selected after successfully assisting in forwarding the overheard packet from the source to the destination node. This is to ensure that the relay nodes do not quit or totally run out of energy supply after participating in cooperation. The optimized transmit power allocated at both the source and relay nodes is constraint to ensure that less power are allocated to achieve higher transmission rate and consequently extend the network lifetime which is evident at $N > 100$. In the case 1, equal power is allocated at both the source and the selected best relay node as seen in [14] and [24]. On the other hand, using the asymmetric transmit power policy can significantly improve the spatial frequency reuse and extend the longevity of the network.

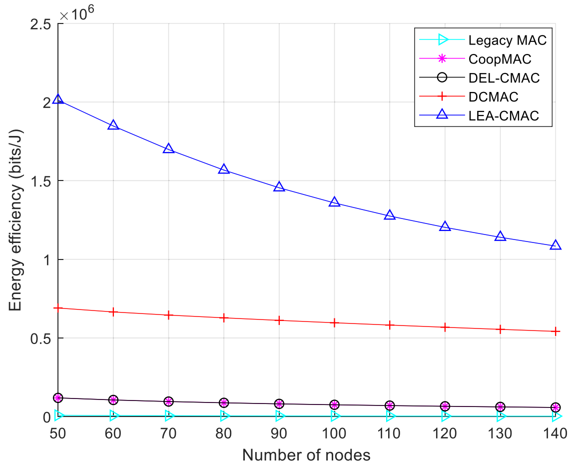


FIGURE 10. **The energy efficiency of simulated protocols with varying number of nodes L = 1024 bytes.**

Fig. 10 compares the energy efficiency of the protocols. The energy efficiency of the protocols reduces with increasing number of nodes. In the figure, it is observed that the energy efficiency achieved by LEA-CMAC outperforms the DCMAC which has better energy efficiency than all other protocols. This shows that the asymmetric transmit power policy employed in LEA-CMAC considerably enhances the energy efficiency by approximately twice that of DCMAC, hence, still play a vital role in adaptively reducing the energy consumed while maintaining a better network performance. Though power control is utilized in DEL-CMAC, the energy efficiency is slightly better than CoopMAC which is a throughput-oriented protocol. This result shows that selecting two best relays to balance the energy consumption of the network may not necessarily improve the energy efficiency of the network. Therefore, LEA-CMAC protocol has shown that adaptively adjusting the transmit power at both source and relay nodes through asymmetric policy can significantly result in energy conservation and network lifetime extension.

V. CONCLUSION

In this paper, we proposed a multi-objective target oriented network lifetime extension-aware cooperative MAC protocol termed LEA-CMAC for MANETs. To extend the network lifetime, a distributed relay selection algorithm was developed and the best helper node is selected with different transmit power allocated at the source and helper nodes respectively. Also, transmission gain and residual energy were considered in selecting the best helper node in the MAC layer. Our proposed protocol significantly improves the overall network performance in network lifetime, energy consumption, and still achieves a better network throughput as compared to other existing CMAC protocols. Through extensive simulation, our protocol shows that the best optimal relay can be selected with asymmetric transmit power control to achieve a multi-objective target oriented protocol.

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