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A Multi-Objective Target-Oriented Cooperative MAC Protocol for Wireless Ad-hoc Networks With Energy Harvesting

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ABSTRACT In this paper, we present a cross layer cooperative medium access control (CMAC) protocol with energy harvesting (EH) capability. The small energy capacity and size of wireless nodes pose a great challenge to the longevity of wireless networks due to the cost of ensuring a reliable communication link between transmitting nodes characterized by path-loss, shadowing and fading effects. Besides, the inability of existing CMAC protocols to exhibit multi-objective target orientation limits their adaptation to the dynamic network requirements. To address this problem, we propose a protocol that harnesses the radio frequency (RF) EH in the physical layer to enhance the throughput, end to end delay, energy efficiency and network lifetime of energy constraint wireless networks. This ensures that beneficial cooperation is achieved in fairness and multi-objective target-oriented protocol. We then investigate the performance of deploying a selective time-switching relaying (TSR) and power-splitting relaying (PSR) schemes in the MAC layer stack for a decode-and-forward (DF) reactive relaying distributed network. In addition, the quality of service requirement, outage probability, and network lifetime optimization techniques, respectively were utilized for optimal power allocation. Also, we propose a distributed and adaptive relay selection algorithm to select the best helper node that improves the network performance and balance the network energy consumption. The results of simulation show that a multi-objective target orientation can be achieved by the proposed EH-CMAC protocol and outperforms EAP-CMAC protocol with respect to throughput, end to end delay, network lifetime and energy efficiency.

INDEX TERMS EH-CMAC, QoS, energy efficiency, network lifetime, energy harvesting, optimization.

I. INTRODUCTION

The wireless networks research community has over the past few years witnessed a considerable breakthrough in improving the network performance, through the emergence of advanced network architecture such as 5G networks for internet-of-things (IoT) applications. Cooperative relaying method is one of the emerging future technologies that has been proven to improve transmission diversity [1], [2]. The Cooperative relaying system has enjoyed a tremendous attention in the last two decades ranging from the state-of-the-art traditional cooperative relaying systems to sophisticated designs, mostly in the physical (PHY) layer theoretic to combat shadowing, and different fading effects [1]–[5]. This has helped to prove that diversity and multiplexing gain can be created in adverse channel conditions through a virtual antenna array of single-antenna mobile terminals/nodes at a considerable implementation cost [2], but with high computational design complexities [6].

One of the significant difficulties of cooperative communication networks is the size and constrained battery limit of wireless terminals [7]–[9]. Besides, the dynamic change in wireless channels results in high energy consumption which can shorten the life-span of wireless networks. The depletion of the limited energy stored in the node's battery requires adequate recharging or constant replacement to elongate the network lifetime [10]. However, this is no longer feasible in modern network architectures. Additionally, as pointed out

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in [11], utilizing helper node's energy to assist in retransmitting, results in lack of fairness (unauthorized usage) to the participating assisting node in the network. This refers as ''energy theft'' which is a common norm in cooperative transmissions [12].

Recently, energy harvesting (EH) enabled cooperative networks (green communication) techniques have evolved that provide promising methods to prolong the network lifetime and improve energy efficiency [6], [13]. In the PHY layer, numerous studies have shown the feasibilities of adapting the beneficial effect of harvesting the rich wireless radio frequency (RF) environment. These result in the network performance improvement and the cost reduction of frequent replacements of battery-powered terminal deployed in different network applications [11], [14]–[16]. Generally, EH techniques can be classified into two categories. First, the time switching relaying (TSR) scheme in which the relay switches between information processing (IP) and EH. Second, the power-splitting relaying (PSR), where a fraction of the received signal is used for EH while the other fraction is utilized for IP [13]. Also, it is worth mentioning that many of these studies are limited to PHY layer throughput. However, energy efficiency performance maximization of the network still remains a problem to be solved in the higher layer stack for proper standardization.

The medium access control (MAC) layer stack, which coordinates and shares the channel access and constraints network resources has witnessed an extension of the state-of-the-art Legacy 802.11 MAC protocol for cooperation enabled networks that ensure the adequate transfer of cooperative gains to higher layer stacks. Little attention has been seen in the ability of cooperative relaying nodes to exploit the abundantly available wireless RF energy for beneficial cooperation to take place in the MAC layer.

Numerous solutions such as in [17]–[20] have been proffered to ensure such PHY layer benefits of cooperation are replicated in the higher layer stacks to improve the network performance. Additionally, the work in [21] introduced cooperative MAC (CMAC) protocols with energy harvesting capability in wireless body area networks (WBANs) for modern healthcare systems, and in [22] the authors presented a reservation time division multiple access (TDMA) based CMAC protocol which can be applied in cognitive networks. Besides, to effectively harness the RF energy in the MAC layer for a cooperative network, practical implementation (i.e. standardization and deployment) of the protocol is essential to be considered as presented in [23]–[25].

There have been various existing CMAC protocols that focus on energy efficiency and optimization of network lifetime target-objectives through power control and energy balancing. For example, in [26] the authors proposed an energy efficient CMAC protocol that can jointly enhance the energy consumption and throughput of multi-hop networks. In [27], the work introduced an energy efficient network coding-based MAC protocol for cooperative wireless network where the energy efficiency was increased at a required quality-of-service (QoS). Only the impact of QoS requirement on energy efficiency, throughput and delay were investigated in the MAC layer. Another interesting work in mobile ad-hoc networks (MANETs) is presented in [17]. The protocol exploited the power control, geographical location, and leftover energy of distributed nodes in the network to prolong the network lifetime. This work assumed that network topology was symmetric with regard to the transmit power, distance and relays' data-rate. In spite of the fact that the MANETs network lifetime is extended, the network performance throughput experienced severe performance debasement because the protocol was also focusing on the energy and relays' location rather than the channel state conditions only.

The authors in [28] presented an efficient distributed multi-hop relay that supports MAC protocol to optimize the network lifetime and energy efficiency of wireless sensor networks (WSNs). The work introduced a selection of an appropriate relay node based on the queue size, the remaining energy of the relay terminal, and the link quality with other terminals.

Furthermore, the work presented in [19] proposed a CMAC protocol with power control backoff for MANETs application which utilizes the same assumption used in [17]. The protocol presents a modification to the usual exchange of control packet handshake to choose the optimal helper node prior to the completion of RTS/CTS. In [18] a distributed CMAC protocol for multi-hop networks was presented that enhanced the throughput, delay, and packet delivery ratio. While in [20], presented a CMAC protocol with energy-aware for wireless ad-hoc networks. The protocol showed a significant improvement in network lifetime and energy efficiency over CoopMAC. The work in [29], proposed a CMAC protocol with the ability to have network lifetime extension. Optimization, in this work was accomplished based on multi-objective targets. The work in [30], introduced a joint optimization of topology control and network coding to maximize the lifetime of WSNs. In that protocol, the transmission energy consumption and reception were jointly considered.

In spite of various research works done to elongating the lifetime of energy-constrained wireless networks, only a few works have adopted the RF-EH relaying technique. The proposed EH protocols in [31]–[33] analyzed the network performance based on throughput. In [31], broadcast nature of wireless networks and the RF signal were exploited for indoor wireless local area networks (WLAN) to ease the problem of inconsistent power supply to wireless devices. In this protocol, idle nodes glean energy from the ongoing packet transmission's RF signal to enhance the network throughput. The work in [32], introduced a harvest then transmit based extended distributed coordination function (DCF) MAC protocol that efficiently organized the transmission of data packets for wireless powered sensor networks (WPSNs). The authors in [33] presented a simple carrier sense medium access/collision avoidance (CSMA/CA) protocol for indoor WLAN application that integrated data and energy transfer but neglecting the throughput performance. All of these aforementioned protocols with RF-EH are applied in point-to-point communications.

Most of the existing CMAC protocols assumed the perfect EH process in order to ensure the maximization of the network throughput. Therefore, they can be categorized as a single objective-oriented protocol. In view of this, we propose a new adaptive decode-and-forward (DF) EH enabled CMAC protocol, named as EH-CMAC protocol that can attain a multi-objective target orientation. Additionally, the EH-CMAC protocol exhibits a different transmission methods. This helps to ensure that the protocol can enhance the network's energy efficiency, lifetime and throughput based on the instantaneous network information and requirements. Below list the contributions of this paper:

- We propose a new EH-CMAC protocol that able to attain a multi-objective target orientation in a DF EH enabled reactive relaying wireless ad-hoc networks by transmitting in different methods based on the instantaneous network requirements.
- We adopted the TSR and PSR EH schemes in a selective manner in the proposed EH-CMAC protocol based on network information requirements to improve the performance of the network. This is achieved by having different transmission methods to analyze the outage probability QoS requirement [19] and by formulating a network lifetime optimization problem. In addition, the optimal values of EH ratio namely: TSR and PSR were obtained from the instantaneous channel condition during the ready-to-send/clear-to-send (RTS/CTS) handshake in order to ensure a successful data packet transmission.
- An efficient power allocation and relay selection algorithm is proposed for the EH-CMAC protocol to choose the best relay node with consideration on harvested energy, nodes' location, and the current leftover energy information before cooperation.

Notice that the pair terms in this paper are always used interchangeably, such as the relay/helper, nodes/terminals, and retransmission/forwarding. The organization for the rest of this paper is as follows. Section II presents the network model. In Section III, the proposed protocol that includes a description of the protocol, relay selection algorithm, wireless energy harvesting, power allocation, and EH factor optimization is presented. Section IV dispenses simulation results and performance comparison, while Section V concludes the paper.

II. NETWORK MODEL

In this paper, the DF reactive relaying transmission system is utilized in the put forward EH-CMAC protocol. As illustrated in Figure 1, a wireless ad-hoc network involves the source, destination and relay terminals $r_i : i \in \{1, \ldots, N\}$ that are distributed in random fashion. They are placed in the middle of the source and destination terminals. In a reactive relaying transmission system, data packets are transmitted by the source terminal to the destination terminal with dual-hop transmission only via the best relay terminal. Each of the terminals in the network is equipped with an omnidirectional single-antenna that operates in half-duplex mode, and operating in the same wireless channel. In addition, the energy of the source terminal is unconstrained and uses maximum transmission power P_S to transmit its data packets [11], [12]. While the relaying nodes are equipped with selective TSR and PSR RF-EH mechanism to garner energy from the transmitted source signal. The exchange of control packets (RTS/CTS/ACK) and data packet using EH transmission methods are transmitted at 1 Mbps constant bit rate while for traditional cooperation is done at a higher rate than the Legacy 802.11 MAC. Each of the relaying terminals in the network can assist in forwarding the successfully decoded transmission from the source to the destination terminal. It is assumed that the channel between the source and destination terminals to be extremely unfavorable because of path-loss, shadowing, and fading effects. If the simultaneous wireless energy harvesting and data packet decoding conditions are satisfied, then only cooperation relaying is initiated to guarantee a successful retransmission process.

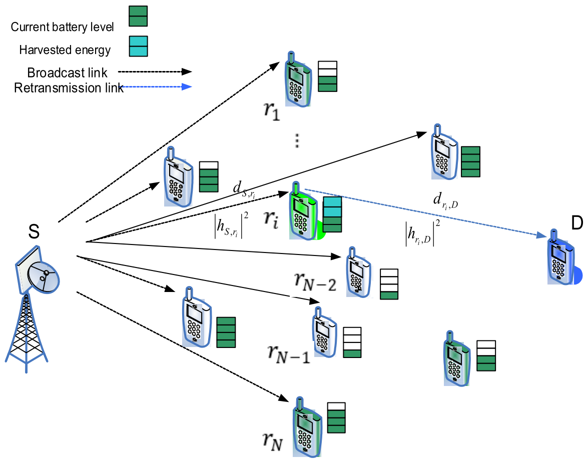

FIGURE 1. Network model [12], [29].

The source-relay and relay-destination links are experiencing independent Rayleigh block fading. While data packets are transmitted, the links are assumed to be invariant [20], [26]. Therefore, their independent dual-hop channel gains can be measured in respect of outage probability, the received control frames' QoS requirement at the PHY layer.

Specifically, the initial energy of all relaying terminals are similar, and the information of current leftover energy (battery level) for each terminal is also needed to avoid energy spill-over (wastage). This happens when the harvested energy cannot be contained by the relay's battery buffer and/or the use of relay's own energy in an unjustified manner (energy theft) which is peculiar to cooperative relaying scheme [12].

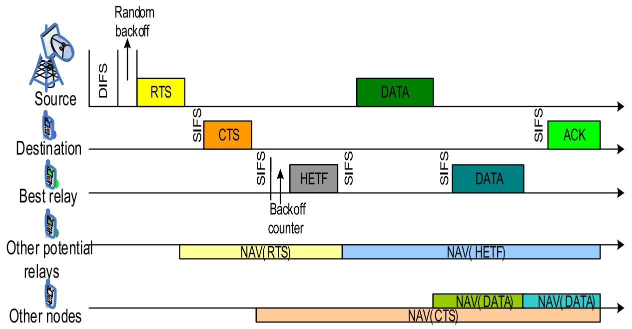

FIGURE 2. Packet transmission for EH-CMAC protocol [12], [29].

III. PROPOSED EH-CMAC PROTOCOL

This section describes the proposed EH-CMAC protocol with backward compatibility to the Legacy 802.11 MAC and CoopMAC [34]. In addition, the wireless EH mechanism, the relay selection algorithm and the optimal allocated transmit power of the proposed protocol are provided.

A. PROTOCOL DESCRIPTION

The EH-CMAC protocol depicted in Figure 2 is similar to that in [12], [29]. It is an extension of the Legacy 802.11 MAC to ensure a better overall MAC layer stack performance of a network. In the RTS/CTS frame of the proposed protocol, extra fields are introduced to obtain the destination location. Unlike the RTS frame, the CTS frame contains two additional fields. To select the transmission method, *flag_1* is used while for the EH capability (TSR/PSR) at the relaying nodes, *flag_2* is employed. It is worth mentioning that *flag_1* determines the necessity for cooperation to be activated. Furthermore, a new control frame named helper-eager-to-forward (HETF) is created to the proposed protocol to choose the best assistant terminal in a spread fashion.

The relaying node that wins the backoff contention process announces its presence by sending HETF frame. The field of the HETF frame contains the estimated value of the harvested power which is used by the source node in transmitting its data packet. All the other nodes that receive this broadcast will amend the setting of their NAV. Thus, this enhances the network spatial frequency reuse. Also, the proposed protocol has its control frames which are transmitted at certain power, whereas the transmission power for the data packet is dynamically allocated which is as a result of the transmission method selected. The parameters T_{ACK}, T_{DATA}, T_{HETF}, T_{CTS}, and T_{RTS} denote the transmission time of the ACK, DATA, HETF, CTS, and RTS frames respectively.

Without loss of generality, the design of EH-CMAC is assumed to adapt to the uncertain and changing essence of wireless network. Three transmission methods are supported by the proposed protocol that are; direct transmission with the Legacy 802.11 MAC, traditional cooperative transmission with the CoopMAC or EH-enabled cooperative transmission with the EH-CMAC. The selected transmission method relies on the destination node's approximated received SNR and leftover energy information of the relay node. The mechanism for each transmission is explained as the following:

- Direct transmission: The direct link transmission method is supposed to guarantee a better QoS (i.e. $(\gamma_{S,D} > \gamma_{th})$) where $\gamma_{S,D}$ and γ_{th} are the instantaneous received signal-to-noise ratio (SNR) between the source and destination link and the threshold SNR, respectively. This implies that cooperation is not required and cannot contribute a beneficial effect to the network performance. Therefore, CTS frame *flag_1* is set to 0 and the data packet is transmitted directly to the destination.
- Cooperative transmission: The EH-CMAC transmission method performs in the same way as CoopMAC due to the incapability of the relaying nodes to gather RF energy. In this case, the destination terminal's QoS requirement should assure a high cooperative gain that is $(\gamma_{r_i,D} > \gamma_{th})$ where $\gamma_{r_i,D}$ is the instantaneous SNR between the relay and the destination link. Additionally, the residual energy of the relay terminal is sufficient and cannot accommodate the battery capacity. Therefore, $flag\_1 = 1$ and $flag\_2 = 0$.
- EH-enabled cooperative transmission: EH transmission is enabled in this method with both *flag_1* and *flag_2* are set to 1. This indicates that the direct transmission link is unable to meet the desired requirement due to outage. Also, the information of each of the relays' residual energy can allow the harvested energy of the current transmission signals to be accommodated in each of their batteries. It is imperative to note that the EH-CMAC with TSR or EH-CMAC with PSR can be chosen based on immediate network requirement and the EH factor that attains optimal value first.

The flowchart of the source and helper node operations are depicted in Figure 3. Also, the detailed operations of the protocol at different nodes are provided:

Source Node Operation:

a. When a data packet of L bytes is intended to be transmitted to a destination from an originating source node, a complete transmission process is triggered. The RTS frame is broadcasted by the source node after detecting that the channel medium is idle in order to retain the channel medium. If the channel medium is detected to be idle for *DIFS*, and after the expiration of a random backoff process, all nodes that hear the RTS frame will reset their NAV to the RTS duration of $D_{RTS} = T_{RTS} + T_{HETF} + 2SIFS$.
b. If CTS is not received by the source node within $T_{RTS} + T_{CTS} + SIFS$, begins a new retransmission process. Or else, if *flag_1* reads 0, EH-CMAC operates as Legacy 802.11 MAC, and this point out to the fact that direct transmission method supports the chosen outage probability QoS requirement. In a situation when *flag_1* is 1, the source terminal defers for another $T_{\max BO} + SIFS + T_{HETF} + \delta$, where $T_{\max BO}$ is the maximum backoff for the relay terminals and

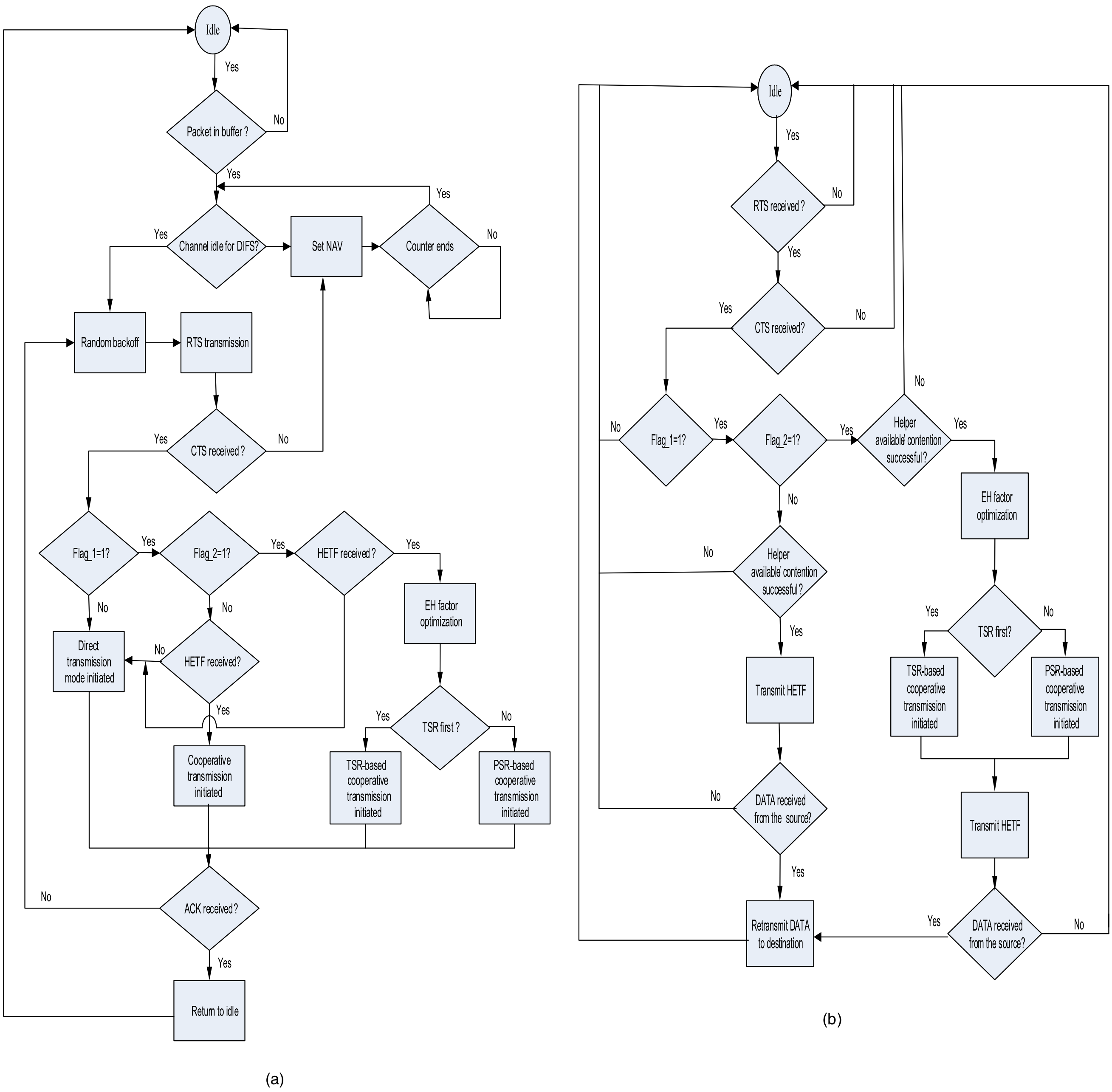

FIGURE 3. Flowchart of EH-CMAC protocol at the (a) source and (b) helper node.

δ is the propagation delay. If any of the potential helper is unable to send HETF, due to unavailability of the best helper that can meet the chosen outage probability QoS requirement, then data packet is transmitted by the source terminal directly to the destination node. Thereafter, the reception of ACK frame is awaited at the source terminal after *SIFS*.

c. If the corresponding terminals transmit both their HETF and CTS frames, the source will be set up as cooperative transmission based on the outcome of *flag_1* and *flag_2*. If *flag_1* and *flag_2* read 1 and 0, respectively then EH-CMAC will operate as CoopMAC. This indicates that the data packet transmission can guarantee a dual-hop data-rate transmission without the necessity for EH to avert the possibility of energy overflow. In this situation, the helper terminal that possesses the optimal estimated transmit power $(P_{r_i}^C)$ is chosen. The HETF frame (received by the source terminal) is piggybacked in order to estimate the transmit power required (at the source node) which is denoted as P_S^C and is dependent on the information of the helper terminal's location. The NAV setting for the

ACK timeout is then set as $T_{ACK_{timeout}} = \frac{8(L+L_H)}{R_{S,r_i}} + \frac{8(L+L_H)}{R_{r_i,D}} + T_{ACK} + 2SIFS + 3\delta$.

d. If the ACK frame of the source terminal is not received within the ACK timeout, a process of random backoff is undergone and the channel medium is contended for. Otherwise, the transmission process is said to be favourable and the next transmission process starts.

Relay Node Operation:

a. After the successful exchange of RTS/CTS frames, all the nodes that fall around thesource and destination nodes and were able to receive both RTS and CTS frames are said to be potential helper nodes. The CTS *flag_1* and *flag_2* will read 1 and 0, respectively for cooperative transmission o if *flag_1* and *flag_2* both read 1 for EH-enabled cooperative transmission will be initiated accordingly. It isessential to note here that the proposed protocol gives priority to the helper node that attains optimal value of EH factor first.

b. The location field enclosed in the RTS/CTS frames enables the relaying terminals to calculate their distance between the source-relay and relay-destination terminals, respectively. Based on the decision of transmission chosen, all neighboring nodes set their NAV in the duration field of the transmitted CTS frame to $D_{CTS} = T_{CTS} + T_{\max BO} + T_{HETF} + \frac{8(L+L_H)}{R_{S,r_i}} + \frac{8(L+L_H)}{R_{r_i,D}} + 4SIFS + 4\delta$.

c. If any of the cooperative transmission method is required; traditional cooperation or EH-enabled cooperation, all the available potential helper terminals will estimate their optimal transmission power. Afterwards the helper terminals will contend with each other to choose the best helper terminal that will deliver a better network performance which will be based on optimization technique or outage probability QoS requirement. In the situation where the unavailability of any helper terminal is witnessed, HETF frame ceases to be transmitted and direct transmission will happen within $T_{\max BO} + T_{CTS} + SIFS + T_{HETF} + 2\delta$.

d. In other ways, if either EH-enabled cooperative transmission or cooperative transmission method is initiated, all the contending helper terminals that have received the HETF frame (that is sent by the winning best helper) will update their NAV and defer for the successful transmission period after which the channel medium will be declared idle. The best assistant terminal instinctively has its backoff timer become void first. Then, all other contending helper nodes will renounce their backoff processes. The HETF's duration field is $D_{HETF} = \frac{8(L+L_H)}{R_{S,r_i}} + \frac{8(L+L_H)}{R_{r_i,D}} + T_{ACK} + 3SIFS$.

e. Then the best helper node will receive the data packet from the source node after awaiting for a duration of $T_{HETF} + \frac{8(L+L_H)}{R_{S,r_i}} + SIFS + 2\delta$ (following broadcasting HETF). If within this period, the data packet is not received, the winner of the relay selection contest will quit. Otherwise, retransmission of the data packet to the destination happens with its duration field changed to $D_{DATA} = T_{ACK} + SIFS$.

f. If no ACK frame is received within $\frac{8(L+L_H)}{R_{r_i,D}} + T_{ACK} + 2SIFS + 2\delta$ duration, the helper relay quits, otherwise, either EH-enabled cooperative transmission or cooperative transmission is successful.

Destination Node Operation:

a. The destination terminal transmits a CTS frame upon the reception of RTS frame from the source terminal after *SIFS*. If the CTS *flag_1* equal to 0, direct transmission happens with the duration field of $\frac{8(L+L_H)}{R_{S,D}} + T_{ACK} + 2SIFS$ and an ACK frame is awaited for a period of $T_{CTS} + \frac{8(L+L_H)}{R_{S,D}} + 2SIFS + 2\delta$. If no ACK is received, the channel medium goes into an idle state.

b. Or else, if CTS *flag_1* equal to 1, cooperative transmission is needed while *flag_2* determine whether EH is required or not for ACK frame to be received. The channel medium goes into an idle state if ACK is not received. If data packet is successful, an ACK frame is sent to the source node.

B. RELAY SELECTION

Most distributed relay selection algorithms designed for CMAC protocols, focus on specified target-objective(s) to choose the best helper node for improving certain or desired network performance(s). This has become a dominant challenge to CMAC protocol designer in achieving a multi-objective target-oriented protocol which can adjust to varying changes to network requirements [23]. In view of this challenge, we propose an adaptive distributed relay selection algorithm to enhance the network instantaneous performance. The relay selection algorithm is characterized by location, link quality, leftover energy, and energy harvesting capability information to choose the best helper node. Based on this information, the proposed EH-CMAC protocol is designed to adapt to the requirement of instantaneous network performance.

The proposed relay selection process is an extension of that in [29]. If traditional cooperation is desired, the helper nodes that satisfy this condition become the potential helper candidates. This is to ensure a better network performance at a minimal energy consumption cost. On the other hand, if any of the energy harvesting cooperation is desired, the second backoff utility function is utilized which is a modification of that presented in [12]. In this relay selection process, the data rate, energy harvesting factor and the current residual energy of individual node play a vital role. This is to ensure that helper nodes that are able to accommodate the harvested energy without exceeding their energy limits (battery capacity) are allowed to participate in the relay selection process in order to avoid energy spill-over.

The proposed protocol's backoff utility function is expressed as

$$BU_{r_i}=\tau\ \min\begin{cases}\left(\frac{P_t^C}{P_t^D}\times\frac{R_{Coop}}{R_{S,D}}\times\frac{\varepsilon_o}{\varepsilon_{r_i}-\varepsilon_{r_i}^C}\right), \\ \quad if\ flag\_2=0\\ \left(\left(\frac{P_S^X}{P_t^D}\times\frac{R_{X\_Coop}}{R_{S,D}}\times\frac{\varepsilon_{r_i}+\psi_{r_i}^X}{\varepsilon_o}\right),\beta\right), \\ \quad if\ flag\_2=1\end{cases}\tag{1}$$

where R_{X_Coop}, R_{Coop}, and $R_{S,D}$ and are the EH-enabled cooperative transmission link, cooperative, and direct data rate, respectively. P_S^X, $P_t^C = P_S^C + P_{r_i}^C$, and P_t^D are the EH-enabled cooperative, cooperative and direct transmit power respectively. ε_{r_i}, ε_o and $\psi_{r_i}^X$ are the instantaneous residual energy, initial energy and harvested energy, respectively of the helper terminals which are appropriate only for cooperative transmission to ensure the balancing of the energy at each node. $\varepsilon_{r_i}^C$ is the estimated energy to be expended by each relay node when cooperation is required and is given as [12]

$$\varepsilon_{r_i}^C = P_T T_{CON} + \left(P_S^C + P_{rx} + P_{ct}\right)\frac{8\left(L+L_H\right)}{R_{S,r_i}} \\ \ldots + \left(P_{r_i}^S + P_{rx} + P_{ct}\right)\frac{8\left(L+L_H\right)}{R_{r_i,D}} \tag{2}$$

where $P_T = P_{tmax} + P_{rx} + P_{ct}$, $T_{CON} = T_{RTS} + T_{CTS} + T_{HETF} + T_{ACK}$. P_{tmax}, P_{rx} and P_{ct} are the maximum transmit power, receive power and processing power, respectively. It is also important to state that for $flag\_2 = 0$ to be initiated, $\varepsilon_{r_i} \approx \varepsilon_o$ which implies that all nodes have sufficient energy in their buffer while $flag\_2 = 1$ is initiated for $\varepsilon_{r_i} + \psi_{r_i}^X \leq \varepsilon_o$. τ is adjusted to ensure timely relay selection process and β is a pre-set threshold to ensure that any relay that does not meet this requirement are not allowed to participate in the selection process in order to ensure a better network performance. Intuitively, the best helper node that possesses the minimum backoff utility value secures the helper selection contest and its backoff timer counts down earlier is chosen as the optimal helper node. The existence of the optimal helper is known when it declares its presence in the network, by sending HETF to all nodes. Other nodes that overhear will quit the backoff process.

C. WIRELESS ENERGY HARVESTING MECHANISM

The design of EH-CMAC is for a DF reactive relaying protocol that depends on the PHY layer stack. The assisting terminals have the ability to harvest energy for retransmission purposes from the source terminal. In this paper, we investigate the effect of utilizing the TSR and PSR relaying schemes in energy-constrained relaying terminals for the MAC layer protocol. The frame structure for the simultaneous EH and IP (at the relaying terminals) for the TSR and PSR are illustrated in Figure 4(a) and Figure 4(b), respectively, and the PHY layer EH selective TSR-PSR transmission mechanism of the proposed EH-CMAC protocol is depicted in Figure 5.

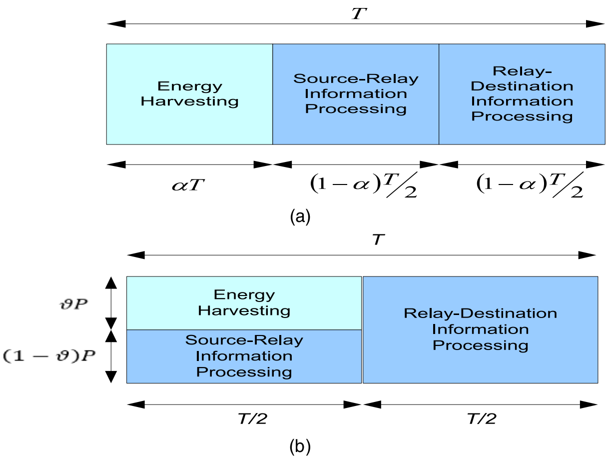

FIGURE 4. **(a) Frame structure of TSR energy harvesting and information processing mechanism at the relay, (b) Frame structure of PSR energy harvesting and information processing mechanism at the relay.**

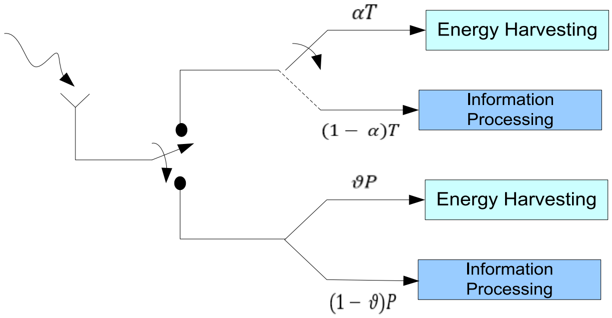

FIGURE 5. **PHY layer EH selective TSR-PSR transmission mechanism of the proposed EH-CMAC protocol.**

1) TIME-SWITCHING RELAYING BASED EH-CMAC

In this approach in Figure 4(a), there are two portions of the time slots i.e. portion αT is meant for energy harvesting while portion $(1-\alpha)\,T$ is meant for decoding and retransmission. The EH fraction (α) value of the source terminal signal ranges between 0 and 1 (i.e $\alpha \in (0, 1)$). The energy harvested (at the relay) is expressed as [11], [35], [36]

$$\psi_{r_i}^{TSR} = \eta P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v} \alpha T \tag{3}$$

where $\eta \in (0, 1)$ is the coefficient of energy efficiency conversion that depends on the harvesting circuitry, h_{S,r_i} is the gain of independently distributed Rayleigh fading channel between source S and relay r_i, d_{S,r_i} is the distance between S and r_i nodes, and v is the path-loss exponent. The retransmission power required (at the relaying node) is formulated as

$$P_{r_i}^{TSR} = \frac{\psi_{r_i}^{TSR}}{(1-\alpha)\,{}^{T}\!/_{2}} = \frac{2\alpha\eta P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}}{(1-\alpha)} \tag{4}$$

Accordingly, instantaneous received SNR (at the relay and destination nodes) for TSR after successful harvesting and data packet decoding at the relaying node are given as

$$\gamma_{S,r_i}^{TSR} = \frac{P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}}{N_o} \tag{5}$$

$$\gamma_{r_i,D}^{TSR} = \frac{2\alpha\eta P_S \left|h_{S,r_i}\right|^2 \left|h_{r_i,D}\right|^2 d_{S,r_i}^{-v} d_{r_i,D}^{-v}}{(1-\alpha) N_o} \tag{6}$$

where $h_{r_i,D}$ is the gain of the channel between relay and destination, $d_{r_i,D}$ is the distance between relay r_i and destination D and N_o is the noise power which has similar value for all channel links.

2) POWER-SPLITTING BASED EH-CMAC

In the PSR approach in Figure 4(b), the portion of the received signal ϑP at the relaying terminal is employed for energy harvesting and the remaining power $(1-\vartheta) P$ is utilized for information detection, where $\vartheta \in (0, 1)$. The energy harvested available at the relay terminal is formulated as [11], [36], [37]

$$\psi_{r_i}^{PSR} = \eta\vartheta P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}\, {}^{T}\!/_{2} \tag{7}$$

Consequently, the relaying terminal transmitting power using the harvested energy in the retransmitting the decoded packet is written as [11], [36], [37]

$$P_{r_i}^{PSR} = \frac{\psi_{r_i}^{PSR}}{{}^{T}\!/_{2}} = \eta\vartheta P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v} \tag{8}$$

Also, the relay and destination terminals instantaneous received SNR for PSR are given as

$$\gamma_{S,r_i}^{PSR} = \frac{(1-\vartheta) P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}}{N_o} \tag{9}$$

$$\gamma_{r_i,D}^{PSR} = \frac{\eta\vartheta P_S \left|h_{S,r_i}\right|^2 \left|h_{r_i,D}\right|^2 d_{S,r_i}^{-v} d_{r_i,D}^{-v}}{N_o} \tag{10}$$

The outage probability for the DF reactive relaying (at the destination node) over Rayleigh fading channel for TSR and PSR schemes is formulated as [11], [36], [37]

$$\rho_{out}^{X} = \Pr\left(C_{S,r_i} < R_{th}\right) + \Pr\left(C_{S,r_i} \geq R_{th}, C_{r_i,D} < R_{th}\right) \tag{11}$$

where $X \in \{TSR, PSR\}$. Similarly, (11) can be expressed as

$$\rho_{out}^{X} = \Pr\left(\gamma_{S,r_i} < \gamma_{th}\right) + \Pr\left(\gamma_{S,r_i} \geq \gamma_{th}, \gamma_{r_i,D} < \gamma_{th}\right) \tag{12}$$

where $C_{S,r_i} = \frac{\omega}{2}\log_2\left(1+\gamma_{S,r_i}\right)$, $C_{r_i,D} = \frac{\omega}{2}\log_2\left(1+\gamma_{r_i,D}\right)$, R_{th} and $\gamma_{th} = 2^{R_{th}} - 1$ are the channel capacity at the relaying terminal, destination terminal channel capacity, transmission rate threshold and SNR threshold, respectively while $\omega = 1-\alpha$ for TSR and $\omega = 1$ for PSR.

D. POWER ALLOCATION

1) DIRECT TRANSMISSION

The direct transmission and cooperative DF reactive relaying allocated transmit power are derived from Shannon capacity theorem [38], [39]. For the Legacy 802.11 MAC of the proposed protocol, the allocated transmit power when there exists no assistant node to improve the network performance is given in [17], [20] is

$$P_t^D \geq -\frac{\left(2^{R_{th}}-1\right) N_o d_{S,D}^{v}}{\ln\left(1-\rho_{out}\right)} \tag{13}$$

where R and ρ_{out} are the transmission rate, and the outage probability needed to meet the chosen outage probability QoS requirement for direct transmission method respectively. For the direct transmit power allocation to satisfy the desired outage probability QoS requirement, the measured SNR between the source and destination nodes must be greater than the set threshold, and the CTS *flag_1* will be set equal to 0. If this condition is not met, then cooperative transmission is needed and the CTS *flag_1* is set to 1. Furthermore, the value in the CTS *flag_2* is very essential to decide the type of cooperation that suits the network requirement at that present of time. If the *flag_2* equals 0, the allocated transmit power for dual-hop transmission is required and the source node depends on the estimated allocated power at the relaying terminal (piggybacked in the HETF frame).

2) COOPERATIVE TRANSMISSION

For the traditional cooperative transmission to be activated, the craved outage probability QoS requirement must be met and the minimum allocated power is obtained from the outage capacity of dual-hop transmission as formulated in [39]. After several mathematical manipulations we obtained

$$\left(2^{2R_{th}}-1\right)\left(\gamma_{S,r_i}+\gamma_{r_i,D}\right) \leq \gamma_{S,r_i}\gamma_{r_i,D}\ \ln\left(1-\rho_{out}\right) \tag{14}$$

where $\gamma_{S,r_i} = \frac{P_S^C \left|h_{S,r_i}\right|^2}{d_{S,r_i}^{v} N_o}$ and $\gamma_{r_i,D} = \frac{P_{r_i}^C \left|h_{r_i,D}\right|^2}{d_{r_i,D}^{v} N_o}$ are the relay and destination terminals received SNR, respectively, and the reactive DF relaying outage probability is given as [20], [39]

$$\rho_{out} = 1 - \exp\left(-\gamma_{th}\left(\frac{1}{\gamma_{S,r_i}} + \frac{1}{\gamma_{r_i,D}}\right)\right) \tag{15}$$

The source terminal optimal allocated transmit power is obtained by solving (15) numerically which is then expressed as [22]

$$P_S^C \geq -\frac{\lambda_c P_{r_i}^C d_{S,r_i}^{v}}{\lambda_c d_{r_i,D}^{v} + P_{r_i}^C \ln\left(1-\rho_{out}\right)} \tag{16}$$

where $\lambda_c = \left(2^{2R_{th}}-1\right) N_o$. Eq. (16) has flexible solution and is based on the estimated optimal transmit power (at the helper node).

3) TSR COOPERATIVE TRANSMISSION

a: OUTAGE PROBABILITY QoS REQUIREMENT TECHNIQUE

In order for EH-cooperative transmission to be initiated, the minimum transmit power to be allocated in EH-CMAC protocol can be achieved from (12). The lower bound outage probability is given by substituting (5) and (6) into (12) produces

$$\begin{aligned}\rho_{out}^{TSR} &= \Pr\left(P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v} < \lambda_c\right) + \Pr\left(P_S \left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}\right. \\ &\quad \left. \ldots \geq \lambda_c,\ 2\alpha\eta P_S \left|h_{S,r_i}\right|^2 \left|h_{r_i,D}\right|^2 d_{S,r_i}^{-v} d_{r_i,D}^{-v} < \lambda_c \left(1-\alpha\right)\right)\end{aligned} \tag{17}$$

where $\lambda_c = \left(2^{R_{th}} - 1\right) N_o$. Eq (17) can further be simplified by taking the cumulative distribution function (CDF) of the second term which then is expressed as

$$\begin{aligned}\rho_{out}^{TSR} &= \Pr\left(P_S < \frac{\lambda_c}{\left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}}\right) + \Pr\left(\min\left(P_S \leq \frac{\lambda_c}{\left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}}\right.\right. \\ &\quad \left.\left. \ldots, P_S < \frac{\lambda_c \left(1-\alpha\right) d_{S,r_i}^{v} d_{r_i,D}^{v}}{2\alpha\eta \left|h_{S,r_i}\right|^2 \left|h_{r_i,D}\right|^2}\right)\right)\end{aligned} \tag{18}$$

For further simplification, let the first and second terms of (18) be expressed as ρ_{out1}^{TSR} and ρ_{out2}^{TSR}, respectively such that $\rho_{out}^{TSR} = \rho_{out1}^{TSR} + \rho_{out2}^{TSR}$. Then, the outage probability for the source - relay hop can be formulated as

$$\rho_{out1}^{TSR} = 1 - \exp\left(-\frac{\lambda_c d_{S,r_i}^{v}}{P_S}\right) \tag{19}$$

Therefore, the source-relay channel link transmit power is given as

$$P_S = -\frac{\lambda_c d_{S,r_i}^{v}}{\ln\left(1 - \rho_{out1}^{TSR}\right)} \tag{20}$$

For the relay-destination channel link, the outage probability is expressed as

$$\begin{aligned}\rho_{out2}^{TSR} = \Pr\left(\min\left(P_S \leq \frac{\lambda_c}{\left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}},\right.\right. \\ \left.\left. P_S < \frac{\lambda_c \left(1-\alpha\right) d_{S,r_i}^{v} d_{r_i,D}^{v}}{2\alpha\eta \left|h_{S,r_i}\right|^2 \left|h_{r_i,D}\right|^2}\right)\right)\end{aligned} \tag{21}$$

Since our target at the destination node is to have the desired outage probability QoS requirement, then we have

$$\begin{aligned}\rho_{out2}^{TSR} &= \Pr\left(P_S < \frac{\lambda_c \left(1-\alpha\right) d_{S,r_i}^{v} d_{r_i,D}^{v}}{2\alpha\eta \left|h_{S,r_i}\right|^2 \left|h_{r_i,D}\right|^2}\right) \\ &= 1 - \exp - \left(\frac{\lambda_c \left(1-\alpha\right) d_{S,r_i}^{v} d_{r_i,D}^{v}}{2\alpha\eta P_S}\right)\end{aligned} \tag{22}$$

We obtained the retransmission power at the relay towards the destination node to be

$$P_S = -\frac{\lambda_c \left(1-\alpha\right) d_{S,r_i}^{v} d_{r_i,D}^{v}}{2\alpha\eta \ln\left(1 - \rho_{out2}^{TSR}\right)} \tag{23}$$

Substituting (20) and (23) into (17), we obtained the EH-CMAC with TSR protocol's minimum transmit power as

$$P_S = -\lambda_c d_{S,r_i}^{v}\left(\frac{1}{\ln\left(1 - \rho_{out1}^{TSR}\right)} + \frac{\left(1-\alpha\right) d_{r_i,D}^{v}}{2\alpha\eta \ln\left(1 - \rho_{out2}^{TSR}\right)}\right) \tag{24}$$

b: NETWORK LIFETIME OPTIMIZATION TECHNIQUE

The optimal allocation of the transmit power can be obtained by formulating an optimization problem of a network lifetime. In [12], the author reported the energy efficiency, transmission power, and network lifetime can be optimized that depends on the transmit power allocation. Thus, the optimization problem is formulated as

$$\begin{aligned}\max_{P_S \geq 0,\, \alpha}\ & \varepsilon_{r_i} + \psi_r^{TSR} \\ s.t\ & C \geq R_{th} \\ & \varepsilon_{r_i} + \psi_r^{TSR} \leq \varepsilon_o \\ & P_S \leq P_{t\ \max} \\ & P_{r_i}^{TSR} \leq P_S \\ & P_{r_i}^{TSR}, \quad P_S \geq 0 \\ & 0 \leq \alpha \leq 1\end{aligned} \tag{25}$$

The objective function of the formulated optimization problem is to maximize the network lifetime while constraining it to Shannon capacity such that $C = \min\left\{C_{S,r_i}, C_{r_i,D}\right\}$, the sum of the current residual and harvested energies must be equal to the initial energy that the battery capacity can accommodate. Also, transmit power and retransmission power are constrained to maximum transmit power and allocated power at the source terminal, respectively as well as the optimal value of the EH factor for TSR.

In order to solve the formulated problem in (25), we apply the Lagrange function given as

$$\begin{aligned}L&\left\{\lambda, \mu, q, \sigma, P_S, \alpha\right\} \\ &= \varepsilon_{r_i} + \psi_r^{TSR} - \lambda\left(R_{th} - C\right) \\ &\quad - \mu\left(\varepsilon_{r_i} + \psi_{r_i}^{TSR} - \varepsilon_o\right) - q\left(P_S - P_{t\max}\right) - \sigma\left(P_{r_i}^{TSR} - P_S\right)\end{aligned} \tag{26}$$

where $\lambda, \mu, q, \sigma \geq 0$ are the Lagrange multipliers with respect to the constraints given in (25). This optimal solution to the problem can be obtained by applying the Lagrange multipliers to update the solution of the transmitted power. According to the Karush Kuhn-Tucker (KKT) conditions [40] the optimal value of P_S is obtained by applying $\frac{\partial L\{\cdot\}}{\partial P_S} = 0$ which yields

$$P_S = \begin{cases} \left[\dfrac{\lambda\left(1-\alpha\right)}{2\ln 2\phi} - \dfrac{d_{S,r_i}^{v} N_o}{\left|h_{S,r_i}\right|^2}\right]^+, & if\ C_{S,r_1} < C_{r_i,D} \\ \left[\dfrac{\lambda\left(1-\alpha\right)}{2\ln 2\phi} - \dfrac{d_{S,r_i}^{v} N_o}{c_1}\right]^+, & if\ C_{S,r_1} > C_{r_i,D} \end{cases} \tag{27}$$

where $[\cdot]^+$ is the solution of the optimal allocated transmit power.

$$\phi = \frac{\eta\alpha \left|h_{S,r_i}\right|^2}{d_{S,r_i}^{v}}\left(\left(\mu - 1\right) T + \frac{2\sigma}{\left(1-\alpha\right)}\right) - \sigma + q, \quad \text{and}$$

$$c_1 = \frac{2\eta\alpha \left|h_{S,r_i}\right|^2 \left|h_{r_i,D}\right|^2}{\left(1-\alpha\right) d_{r_i,D}^{v}}.$$

Then, the Lagrange multipliers are updated by using the gradient method in an iterative manner with ξ chosen to be a small step size, which are formulated as

$$\begin{aligned}\lambda\left(1+I\right) &= \left[\lambda\left(I\right)+\xi\left(R_{th}-C\right)\right]^{+}\\ \mu\left(1+I\right) &= \left[\mu\left(I\right)+\xi\left(\varepsilon_{r_i}+\psi_{r_i}^{TSR}-\varepsilon_o\right)\right]^{+}\\ q\left(1+I\right) &= \left[q\left(I\right)+\xi\left(P_S-P_{t\ \max}\right)\right]^{+}\\ \sigma\left(1+I\right) &= \left[\sigma\left(I\right)+\xi\left(P_{r_i}^{TSR}-P_S\right)\right]^{+}\end{aligned}\tag{28}$$

4) PSR COOPERATIVE TRANSMISSION

a: OUTAGE PROBABILITY QoS REQUIREMENT TECHNIQUE

Using the same approach in (17), and substituting (9) and (10) for EH-CMAC with PSR. we obtained the lower bound outage probability to be

$$\begin{aligned}&\rho_{out}^{PSR}\\ &\quad= \Pr\left(P_S\left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}<\lambda_c\right)+\Pr\Big(\left(1-\vartheta\right)P_S\left|h_{S,r_i}\right|^2 d_{S,r_i}^{-v}\\ &\qquad\ldots\geq\lambda_c,\ \eta\vartheta P_S\left|h_{S,r_i}\right|^2\left|h_{r_i,D}\right|^2 d_{S,r_i}^{-v}d_{r_i,D}^{-v}<\lambda_c\Big)\end{aligned}\tag{29}$$

By solving (29), the minimum transmit power for EH-CMAC with PSR protocol is reduced as

$$P_S=-\lambda_c d_{S,r_i}^{v}\left(\frac{1}{\left(1-\vartheta\right)\ln\left(1-\rho_{out1}^{PSR}\right)}+\frac{d_{r_i,D}^{v}}{\eta\vartheta\ln\left(1-\rho_{out2}^{PSR}\right)}\right)\tag{30}$$

b: NETWORK LIFETIME OPTIMIZATION TECHNIQUE

Formulating similar optimization problem as given in (25), the optimization problem for EH-CMAC with PSR is given as

$$\begin{aligned}&\max_{P_S\geq 0,\,\vartheta}\ \varepsilon_{r_i}+\psi_r^{PSR}\\ &\ s.t\ C\geq R_{th}\\ &\qquad \varepsilon_{r_i}+\psi_r^{PSR}\leq\varepsilon_o\\ &\qquad P_S\leq P_{t\ \max}\\ &\qquad P_{r_i}^{PSR}\leq P_S\\ &\qquad P_{r_i}^{PSR},\quad P_S\geq 0\\ &\qquad 0\leq\vartheta\leq 1\end{aligned}\tag{31}$$

The Lagrange function is applied to (31) and the optimal transmit power using EH-CMAC with PSR is obtained according to KKT conditions [40] such that $\frac{\partial L\{\cdot\}}{\partial P_S}=0$ to be

$$P_S=\begin{cases}\left[\dfrac{\lambda}{2\ln 2\zeta}-\dfrac{d_{S,r_i}^{v}N_o}{\left(1-\vartheta\right)\left|h_{S,r_i}\right|^2}\right]^{+}, & \\ \qquad if\ C_{S,r_1}<C_{r_i,D} & \\ \left[\dfrac{\lambda}{2\ln 2\zeta}-\dfrac{d_{S,r_i}^{v}d_{r_i,D}^{v}N_o}{\eta\vartheta\left|h_{S,r_i}\right|^2\left|h_{r_i,D}\right|^2}\right]^{+}, & \\ \qquad if\ C_{S,r_1}>C_{r_i,D} & \end{cases}\tag{32}$$

where $\zeta=\frac{\eta\vartheta\left|h_{S,r_i}\right|^2}{d_{S,r_i}^{v}}\left(\sigma-\frac{T}{2}\left(1-\mu\right)\right)-\sigma+q$ with the Lagrange multipliers updated using similar equation as given in (28) to be

$$\begin{aligned}\lambda\left(1+I\right) &= \left[\lambda\left(I\right)+\xi\left(R_{th}-C\right)\right]^{+}\\ \mu\left(1+I\right) &= \left[\mu\left(I\right)+\xi\left(\varepsilon_{r_i}+\psi_{r_i}^{PSR}-\varepsilon_o\right)\right]^{+}\\ q\left(1+I\right) &= \left[q\left(I\right)+\xi\left(P_S-P_{t\ \max}\right)\right]^{+}\\ \sigma\left(1+I\right) &= \left[\sigma\left(I\right)+\xi\left(P_{r_i}^{PSR}-P_S\right)\right]^{+}\end{aligned}\tag{33}$$

5) ENERGY HARVESTING FACTOR OPTIMIZATION

a: TSR RATIO OPTIMIZATION

According to the assumption utilized in [41], [42] the optimal value for α_{opt} can be obtained under the condition that $C_{S,r_i}=R_{th}$ must be satisfied. The optimal value is obtained as

$$\alpha_{opt}=1-\frac{2R_{th}}{\log_2\left(1+\gamma_{S,r_i}\right)}=1-\frac{\varphi}{\Gamma\left(\left|h_{S,r_i}\right|^2\right)}\tag{34}$$

where $\Gamma\left(\left|h_{S,r_i}\right|^2\right)=\log_2\left(1+\gamma_{S,r_i}\right)$ and $\varphi=2R_{th}$. Since the dynamic nature of wireless channels result in random channel gain, the optimal value of TSR ratio can be expressed as

$$\alpha_{opt}=\begin{cases}1, & \Gamma\left(\left|h_{S,r_i}\right|^2\right)>\varphi\\ 1-\dfrac{\varphi}{\Gamma\left(\left|h_{S,r_i}\right|^2\right)}, & \Gamma\left(\left|h_{S,r_i}\right|^2\right)<\varphi\end{cases}\tag{35}$$

This implies that if the channel experiences an unfavorable channel condition i.e $\left(\alpha_{opt}=1\right)$, EH is not required to ensure a successful information decoding, therefore, no power is allocated for EH. On the other hand, if the channel condition is favourable, the optimal value is obtained when $\Gamma\left(\left|h_{S,r_i}\right|^2\right)<\varphi$ using both the requirement of outage probability QoS and optimization technique. The EH is allocated at $\alpha_{opt}=1-\frac{\varphi}{\Gamma\left(\left|h_{S,r_i}\right|^2\right)}$.

b: PSR RATIO OPTIMIZATION

Using similar approach adopted in [41], [42] the optimal value for ϑ_{opt} can also obtained provided that $C_{S,r_i}=R_{th}$ is satisfied. The optimal value is obtained as

$$\vartheta_{opt}=\frac{\left(2^{2R_{th}}-1\right)N_o d_{S,r_i}^{v}}{P_S\left|h_{S,r_i}\right|^2}=\frac{z}{\left|h_{S,r_i}\right|^2}\tag{36}$$

where $z=\frac{\left(2^{2R_{th}}-1\right)N_o d_{S,r_i}^{v}}{P_S}$. Also, this implies that the dynamic nature of wireless channel results in random channel gain and the optimal value of PSR ratio can be formulated as

$$\vartheta_{opt}=\begin{cases}1, & \left|h_{S,r_i}\right|^2\leq z\\ \dfrac{z}{\left|h_{S,r_i}\right|^2}, & \left|h_{S,r_i}\right|^2>z\end{cases}\tag{37}$$

The implication of this is that when the channel experiences an unfavourable channel condition i.e $\left(\vartheta_{opt}=1\right)$, power is

Algorithm 1 Proposed EH-CMAC Power Allocation

```
Begin
Initialize $N, I, P_{t\,\max}, v, \rho^{X}_{out}, R_{th}, N_o, \varepsilon_o, \eta$
set Lagrange multiplier $\lambda, \mu, q, \sigma \geq 0$ and $\xi$
for 1: length $(N)$ do
    randomly generate $d_{S,r_i}$ and $d_{r_i,D}$ such that relay node $i$ is located midway between $S - D$,
    randomly generate $\varepsilon_{r_i}$
    for 1: length $(I)$ do
        randomly generate $\left|h_{S,D}\right|^2$, $\left|h_{S,r_i}\right|^2$ and $\left|h_{r_i,D}\right|^2$ with Rayleigh fading channel
        compute the estimated $\gamma^{X}_{S,r_i}, \gamma^{X}_{r_i,D}$ and $\gamma_{S,D}$
        if $\varepsilon_{r_i} \approx \varepsilon_o$ &flag_2 $= 0$ then
            compute $P^{C}_{S}$ in (16) as a function of $P^{C}_{r_i}$ and the desired outage probability QoS requirement
        elseif $\varepsilon_{r_i} + \psi^{X}_{r_i} \leq \varepsilon_o$ & flag_2 $= 1$ then
            if $\Gamma\left(\left|h_{S,r_i}\right|^2\right) < \varphi$ then
                compute $\alpha_{opt}$ in (35)
                if QoS requirement then
                    compute $P_S$ in (24) as a function of the desired outage
                elseifOptimization technique then
                    compute $P_S$ in (27) and update Lagrange multipliers using (28)
                end if
            elseif $\left|h_{S,r_i}\right|^2 > z$ then
                compute $\vartheta_{opt}$ in (36)
                if outage QoS requirement then
                    compute $P_S$ in (30) as a function of the desired outage
                elseif Optimization technique then
                    compute $P_S$ in (32) and update Lagrange multipliers using (33)
                end if
            end if
        else
            no potential helper is available that satisfies cooperative transmission conditions
        end if
    end for
    obtain the optimal values of $P_S, P^{C}_{S}, P^{C}_{r_i}$ and $\psi^{X}_{r_i}$.
end for
End
```

Algorithm 2 Proposed EH-CMAC Relay Selection

```
Begin
Initialize $N, P_{t\,\max}, P_{rx}, P_{ct}, R_{S,D}, R_{Coop}, R_{X\_Coop}, \varepsilon_o, \varepsilon_{r_i}$ $P_S, P^{C}_{S}, P^{C}_{r_i}, \psi^{X}_{r_i}, L, L_H, T_{RTS}, T_{CTS}, T_{HETF}, T_{ACK}$
for 1: length $(N)$ do
    compute $\varepsilon^{C}_{r_i}$ in (2)
    if flag_1=0 & flag_2=0 then
        Compute the backoff utility function in (1) as
        $BU_{r_i} = \left(\frac{P^{C}_{t}}{P^{D}_{t}} \times \frac{R_{Coop}}{R_{S,D}} \times \frac{\varepsilon_o}{\varepsilon_{r_i} - \varepsilon^{C}_{r_i}}\right)$
    elseif flag_1=1 & flag_2=1 then
        Compute the backoff utility function in (1) as
        $BU_{r_i} = \tau \min\left(\left(\frac{P^{X}_{S}}{P^{D}_{t}} \times \frac{R_{X\_Coop}}{R_{S,D}} \times \frac{\varepsilon_{r_i} + \psi^{X}_{r_i}}{\varepsilon_o}\right), \beta\right)$
    else
        no available potential helper that satisfies cooperative transmission conditions.
    end if
    obtain the optimal helper with minimum $BU_{r_i}$
end for
End
```

not allocated for PSR EH and all the time is allotted for information decoding. On the other hand, if the channel experiences a favourable channel condition i.e $\left(\vartheta_{opt} = z \big/ \left|h_{S,r_i}\right|^2\right)$, the optimal value is obtained for the power allocation for EH (for the desired outage probability QoS requirement and optimization technique). The power allocation and relay selection backoff procedures of the proposed EH-CMAC protocol are presented in Algorithm 1 and Algorithm 2, respectively.

IV. SIMULATION

The proposed EH-CMAC protocol is simulated using MATLAB software (v9.4, R2018a) and the performances are evaluated and then compared with EAP-CMAC [20] and TPSR-CMAC [12] protocols. In the simulation, the source node's buffer is assumed to be saturated with data packets that can transmit data at all times. Also, the network topology is assumed to be a 300m × 300m square area, where the source and destination terminals are placed 200m away and the relay terminals are uniformly distributed. In addition, we adopt a wireless channel model of having two-ray path loss propagation. The EH-CMAC and Legacy 802.11 MAC transmit their data packets at 1 Mbps fixed data-rate while CoopMAC transmits at a higher rate. Considering the aim of the proposed EH-CMAC is to accomplish a multi-objective target-oriented protocol, we evaluate the performance metrics in terms of transmission power, saturated throughput, energy efficiency, and network lifetime.

In this paper, saturated throughput is defined as the number of effectively received data bits at the destination terminal in a unit time. The end to end delay is defined as the time it takes a data packet ready to be transmitted until it is received successfully at the destination. Furthermore, the network lifetime is defined the time it takes for one of the nodes in the network to completely drain-out its battery energy, and energy efficiency is defined as the energy expended in transmitting a data packet to its expected destination successfully. The simulation was executed with nodes randomly generated using different seed values, and then averaged at 10^5 runs. Table 1 lists the parameters used in this simulation.

The proposed EH-CMAC protocol is assessed based on the outage probability QoS requirement and network lifetime optimization with the helper nodes located midpoint between the source and destination terminals. Figure 6 shows the plot of the transmitting power required (at different transmission methods of the protocol) versus outage probability

TABLE 1. Simulation parameters.

Parameter	Value	Parameter	Value
RTS/CTS	44/38 bytes	CW_{min}/CW_{max}	31/1023 slots
HRTC/ACK	38/34 bytes	Retry limit	6
MAC header	34 bytes	Unit time	0.1ms
PHY header	24 bytes	Initial energy	1 J
DIFS/SIFS	50/10 µs	Fixed transmit power	40 dBm
Data packet	1024 bytes	Receive power	20 dBm
Slot time	20 µs	Processing power	0 dBm
Basic rate	1 Mbps	η	0.9
$\alpha_{opt}, \vartheta_{opt}$	0.291, 0.486	Noise power	- 174 dBm

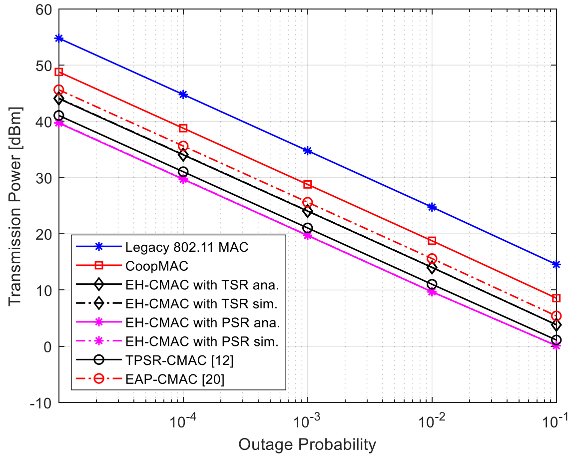

FIGURE 6. The transmission power against outage probability.

(decreasing). From the result, it can be observed that cooperative transmission with EH techniques always have better performances (in terms of lowest allocated transmit power) as compared to the Legacy 802.11 MAC and CoopMac. In particular, the EH-CMAC with PSR performs the best in terms of minimum allocated transmit power at the desired outage probability QoS requirement set to 10^{-3} and data-rate. It is imperative to note that the optimal value of the EH factors were obtained to be $\alpha_{opt} = 0.291$ and $\vartheta_{opt} = 0.486$ in (26) and (28), respectively. These values ensure the helper node successfully decodes the data packet at reduced total transmitting power.

Furthermore, the plot illustrates the merit of utilizing an EH-enabled assistant node in forwarding the discovered packet from the source terminal. This helps to avoid unpermitted energy usage, which is frequently happened in cooperative relaying. In the situation where EH is infeasible at the relay terminal because of the sufficiency of energy stored in the relay's battery, a cooperative transmission method as obtained from (16) is used, with a reduction in transmit power by 6.02 dBm against the Legacy 802.11 MAC to meet the chosen outage probability QoS requirement. The reason for utilizing this method at the helper node is to avoid energy spill-over because of the helper node's battery buffer cannot contain the energy harvested. Comparing the various transmission methods, EH-CMAC with PSR in (30) has a performance decreased in total transmit power by 1.32 dBm, 4.93 dBm, 8.78 dBm and 14.80 dBm against TPSR-CMAC, EH-CMAC with TSR in (24), EAP-CMAC, CoopMAC, and the Legacy 802.11 MAC, respectively, while the EH-CMAC with TSR performance better than the EAP-CMAC protocol by 1.25 dBm.

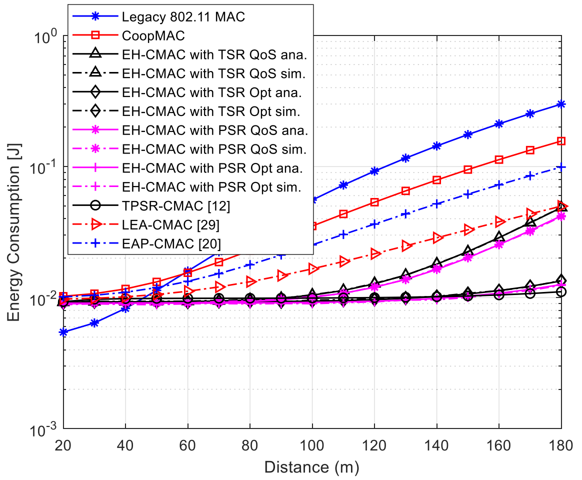

FIGURE 7. The energy consumption versus source-destination distances.

Figure 7 demonstrates the total energy consumption of the protocol with varying distances between the source and destination. The Legacy 802.11 MAC outperforms EH-CMAC with PSR and EH-CMAC with TSR at distance beneath 42m, and CoopMAC at distance shorter than 60m. With the distance increased after 42m, the EH-CMAC with PSR and EH-CMAC with TSR, using the requirement of outage probability QoS and network lifetime optimization technique at the optimal values of $\alpha_{opt} = 0.291$ and $\vartheta_{opt} = 0.486$ respectively show better performance against LEA-CMAC, EAP-CMAC and CoopMAC protocols.

It is important to note that the proposed protocol outperforms significantly the Legacy 802.11 MAC, LEA-CMAC and EAP-CMAC protocols since EH-CMAC with PSR (or EH-CMAC with TSR) can be employed whenever the direct transmission link cannot fulfill the chosen outage probability QoS requirement and data-rate or if EH becomes non-beneficial because of energy spill-over. More so, the plot also illustrates the significance of engaging EH helper terminal to help minimizing the energy consumption which leads to significant energy saving while trading off the network throughput. However, EH-CMAC protocol with network lifetime optimization suffers slight performance gain as compared to TPSR-CMAC protocol when the distance of separation is beyond 160m due to the optimized EH factor obtained in [12].

Figure 8 shows the energy efficiency against varying separation distances between the source and destination nodes. The result shows as the source and destination nodes are further apart, the energy efficiency deteriorates. It can be observed that the proposed EH-enabled cooperative transmission protocols outperform LEA-CMAC, EAP-CMAC, CoopMAC and the Legacy 802.11 MAC significantly but experience performance reduction. The helper

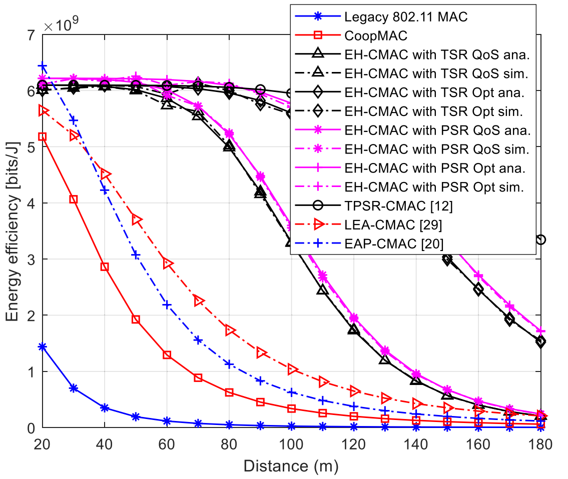

FIGURE 8. **The energy efficiency against distance between source-destination.**

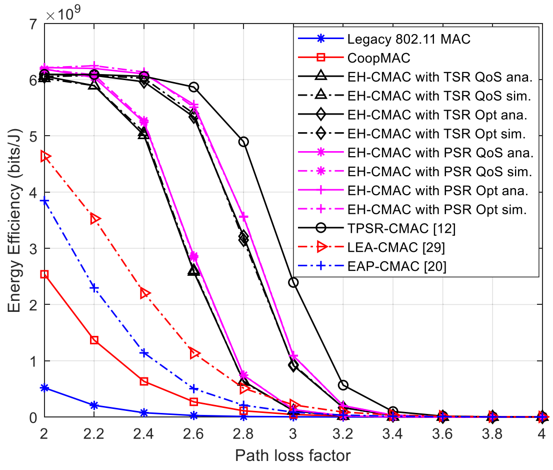

FIGURE 9. **The energy efficiency against distance between source-destination.**

node that uses RF-EH techniques requires minimal transmit power as compared to LEA-CMAC and EAP-CMAC. This is because the later techniques use their helper's energy which results in extra power consumption.

In addition, it is essential to mention that EH-CMAC with PSR using optimization technique slightly outperforms TPSR-CMAC protocol when the distance of separation is less than 90m but degrades when the distance is beyond 90m. While evaluating the energy efficiency of the proposed protocol transmission methods, it is observed that EH-CMAC with PSR preserves more energy as compared to EH-CMAC with TSR, CoopMAC and the Legacy 802.11 MAC by 11.09%, 90.71%, 99.29%, respectively at 100m (when outage probability QoS requirement technique is employed). The proposed protocol using network lifetime optimization shows an improvement of 37.67% over EH-CMAC with PSR using the outage probability QoS requirement technique.

Furthermore, as the distance of separation increased to 160m, EH-CMAC with PSR using optimization technique outperforms EH-CMAC with PSR using QoS requirement by 82.65%, EH-CMAC with TSR using optimization by 10.50%, EH-CMAC with TSR using QoS requirement technique by 85.39%, LEA-CMAC by 87.17%, EAP-CMAC by 92.77%. However, with the distance of separation increased to 180m, EH-enabled cooperation with network lifetime optimization significantly outperform that with outage probability QoS requirement techniques.

Figure 9 illustrates the performance result of energy efficiency against various path-loss factors with the condition that the relay node resides midway between the source and destination nodes. This plot shows that energy efficiency deteriorates as the path-loss factor increases. EH-enabled cooperation performs better at a reduced value of path-loss factor that is ($v < 3$) when outage probability QoS requirement is utilized. However, as the path-loss factor above 3, that is ($v > 3$), the performance diminishes significantly due to the increased in energy consumption resulting from the prominent effects of multipath fading. The result also shows that EH-enabled cooperative transmission can only be valuable at lower path-loss values that is ($v \leq 3$) with outage probability QoS requirement technique is employed. In addition, from Figure 9, the path loss factor should be less than 3.4 for energy to be preserved in the network which indicates that the use of network lifetime optimization technique is beneficial.

Also, at a maximum distance of separation greater than 180m with $v = 3$, EH-CMAC protocol suffers a performance reduction of around 25% against LEA-CMAC protocol which employs outage probability QoS requirement technique but outperforms EAP-CMAC protocol by about 35.74%. In addition, EH-CMAC with network lifetime optimization technique performs better than its outage probability QoS requirement technique by about 80%. However, TPSR-CMAC protocol which tradeoff the energy and throughput outperforms the proposed EH-CMAC protocol by over 4.62% when $v > 2.6$.

Figure 10 presents the performance of the protocols' saturated throughput against a various number of nodes for the desired outage probability QoS requirement and network lifetime optimization, at $L = 1024$ bytes. In analyzing the proposed protocol, for an assistant node to engage in cooperation, the data-rate between itself, the source and destination node must exceed that of the direct transmission data-rate. It can be seen from the result that CoopMAC protocol outperforms all other transmission methods in the proposed EH-CMAC protocol. This is because the EH enabled cooperative transmission methods leverage their network throughput for energy conservation. For instance, if the relays are unable to harvest the RF energy due to the full status of their batteries, CoopMAC protocol is activated with the relays utilizing their own energy to retransmit for the source. Therefore, throughput is enhanced by utilizing the multi-rate characteristics of the IEEE 802.11b PHY at the expense of energy consumption. However, if there exist helper nodes that can harvest the RF energy, any of TSR or PSR can be activated

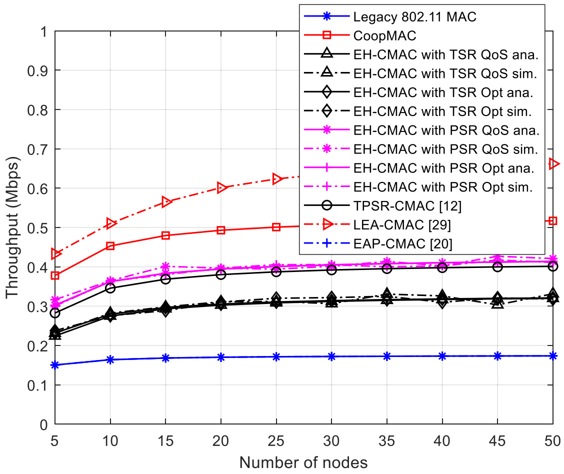

FIGURE 10. **The throughput against number of nodes.**

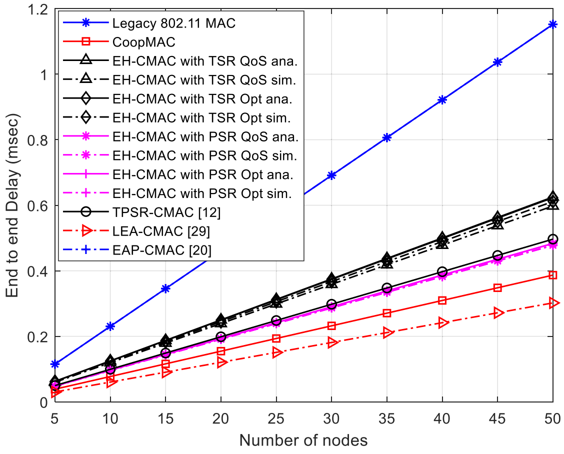

FIGURE 11. **The end to end delay against number of nodes.**

based on the EH factor (that is attained the optimal value in (35) and (37) first) in order to guarantee timely relay selection process.

Figure 11 presents the end to end delay performance of the proposed protocol and is compared with other protocols. In the result obtained, the end to end delay of the protocols degrades with an increase in the number of terminals. It can be observed from the result that CoopMAC has a better end to end delay reduction as compared to other transmission methods in the proposed protocol. This is because the transmission rate for CoopMAC is higher than that of the other transmission methods but with more energy consumption. Besides, EH-CMAC with PSR slightly outperforms TPSR-CMAC and EH-CMAC protocols by an average of 0.008ms and 0.0615ms, respectively. Nonetheless, the LEA-CMAC protocol outperforms the proposed protocol due to its asymmetric transmit power policy, high data rate region, and utilized its relay selection backoff procedure.

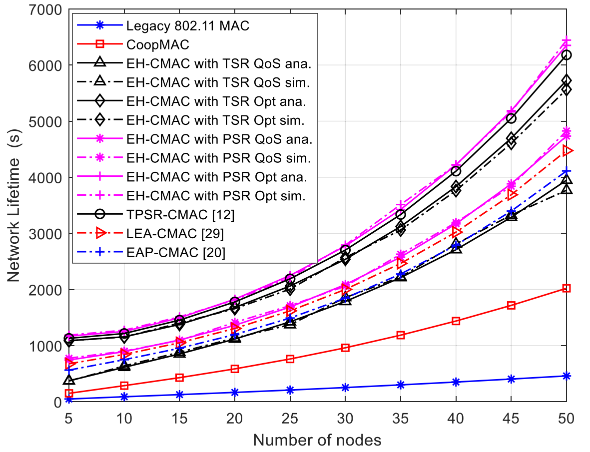

FIGURE 12. **The network lifetime against number of nodes.**

The network lifetime performance of the proposed protocol is demonstrated in Figure 12. It can be observed that the network lifetime increases with the increase in the number of nodes. Since there is the raised in the accessibility of possible assistant nodes, EH-enabled cooperation significantly outperforms the CoopMAC and Legacy MAC (except LEA-CMAC protocol) at the desired outage QoS requirement and data-rate. Furthermore, the result obtained shows that utilizing network lifetime optimization based EH-CMAC has a better network lifetime in comparison to EH-CMAC with outage probability QoS requirement technique and other protocols as the number of nodes increases. At $N = 25$, EH-CMAC with PSR using QoS requirement technique shows a slight performance gain over LEA-CMAC which is dependent on the helper node's battery by about 5.10% and EH-CMAC with TSR using similar technique by 8.86%.

In addition, at $N = 25$, EH-CMAC with PSR using network lifetime optimization has a gain of about 7.80% over EH-CMAC with TSR using same technique, 25.70% over EH-CMAC with PSR using outage probability QoS requirement technique, 1.04% over TPSR-CMAC using transmit power optimization, 28.98% over LEA-CMAC, 37.56% over EAP-CMAC and 41.02% over CoopMAC protocol. These results exhibit the effect of utilizing EH helper node in forwarding the successfully decoded data packets as against the traditional cooperation to elongate the network lifetime.

Figure 13 illustrates the performance comparison of the protocols' energy efficiencies with each profile depends on the number of nodes. The figure shows that the profiles of protocols' energy efficiencies degrade as the number of nodes in the network increases. It can be observed that the energy efficiency achieved by utilizing network lifetime optimization based EH-CMAC with PSR outperforms all other transmission methods in the proposed protocol. EH-CMAC with PSR using network lifetime optimization has an average energy efficiency gain of 2.66% over TPSR-CMAC, 7.78% over EH-CMAC with TSR using the same technique, 25.69% and 41.14% over EH-CMAC with PSR and with TSR, respectively using outage probability QoS requirement technique. While LEA-CMAC performance is better than EH-CMAC with TSR protocol using outage probability QoS requirement technique at an average of 25.10%. In the physical layer (PHY) stack, energy efficiency maximization is of significant importance in EH-enabled relaying. The MAC layer

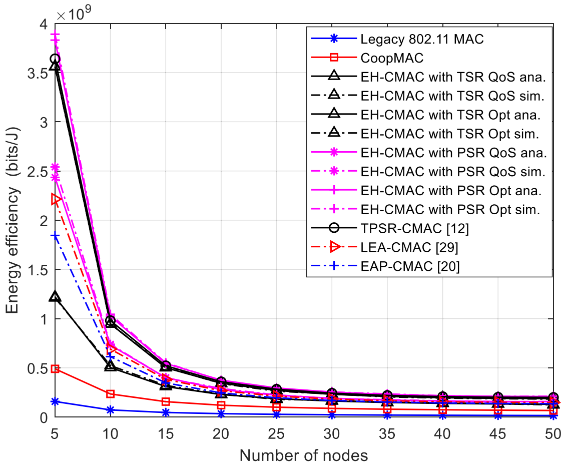

FIGURE 13. **The energy efficiency against varying number of nodes.**

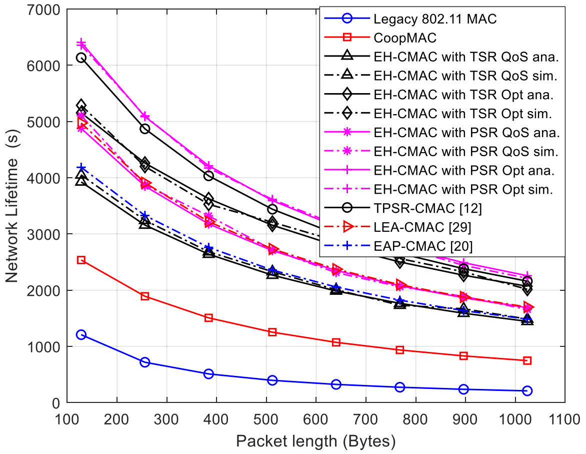

FIGURE 14. **The network lifetime against varying packet length at N = 25.**

performance shows that energy efficiency of the proposed EH-CMAC protocol can remarkably enhances the network efficiency over traditional CoopMAC protocol due to the EH capability, robust and adaptive relay selection backoff process in both network lifetime optimization and outage probability QoS requirement technique, respectively at their respective optimal values.

Finally, Figure 14 presents the performance of the proposed protocol in terms of network lifetime against packet length. The figure shows that the network lifetime of all the protocols degrade as the packet length increases. In this simulation, the data packets are trasnmitted at varying packet length with N is set to 25. The result indicates that using EH-enabled cooperation can prolong network lifetime but at a reduced transmission rate as compared to traditional cooperation. This implies that the throughput performance is traded off for lesser energy consumption that translates to an improved network lifetime.

The comparison made in terms of average packet length shows that EH-CMAC with PSR employing network lifetime optimization recorded a performance gain of 3.66%, 10.62%, 25.15%, 26.61%, 36.21%, 37.81% and 66.37%, respectively over TPSR-CMAC [12], EH-CMAC with TSR using optimization and outage probability QoS requirement techniques, LEA-CMAC, EAP-CMAC and CoopMAC protocol, respectively. Comparing the performance of EH-CMAC with PSR with optimization and EH-CMAC with PSR using QoS requirement technique shows that the former prolongs the network lifetime by 22.75% at packet length of 512 bytes and 25.10% at packet length of 1024 bytes ($N = 25$) respectively, where these results are obtained based on the optimal values of energy harvesting factors.

V. CONCLUSION

In this paper a cross layer cooperative medium access control (CMAC) protocol that harnesses the RF ambient energy harvesting (EH) is proposed. The EH-CMAC protocol exploits the location, current leftover energy and EH information of relaying nodes to enhance the network performance and realize a multi-objective target oriented protocol through the instantaneous network condition. We also proposed a distributed and dynamic relay selection algorithm to choose the best helper node to retransmit the successfully decoded packet if EH becomes necessary or otherwise and ensure fairness to assisting relays. In addition, our protocol significantly reduced the allocation of transmit power at the source terminal using optimization technique over the outage probability QoS requirement technique and significantly increase the reuse of the spatial frequency of the network.

Furthermore, our proposed protocol has clearly demonstrated a significant improvement in the overall network performance in terms of network lifetime, energy efficiency, end to end delay and a better network throughput at the desired data-rate and QoS requirement. The simulation shows our protocol that utilized ambient RF-EH techniques in the MAC layer stack result in multi-objective target oriented protocol. In future work, several issues would be investigated such as energy efficiency optimization. In addition, the deployment of beamforming techniques in RF EH nodes would be considered to further enhance energy preservation and minimize interference which are still, open issues in cooperative MAC layer designs will be explored.

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