

Adaptive Cooperative MAC with Energy Harvesting for Multi-Objective Performance in Wireless Ad-hoc Networks

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ABSTRACT: Energy harvesting (EH) offers a sustainable solution for powering energy-constrained wireless devices, reducing transmission costs, and extending network lifespan. However, existing cooperative medium access control (CMAC) protocols, which focus on single-objective optimization, struggle to balance critical trade-offs under dynamic network conditions. To address this limitation, an adaptive CMAC protocol, multi-objective energy harvesting cooperative medium access control (MOEH-CMAC), that integrates EH relaying to optimize multi-objective performance in wireless ad-hoc networks was proposed. A multi-objective optimization framework to jointly maximize spectral efficiency and network lifetime for EH-enabled relays using a power-splitting relaying (PSR) mechanism, while adhering to practical network constraints was formulated. The proposed solution was evaluated across diverse network scenarios to ensure efficient MAC-layer cooperation. Simulations in MATLAB environment revealed that the proposed MOEH-CMAC achieves 91.45% and 89.52% higher energy efficiency compared to energy-efficiency cooperative medium access control (EECMAC) and fair cooperative gain medium access control (FCGMAC), respectively. Additionally, it shows 31.73% and 56.36% improvements in network lifetime over energy harvesting medium access control (EH-CMAC) and EECMAC, respectively, along with a 5% increase in saturated throughput against EH-CMAC protocol.

KEYWORDS: CMAC protocol, Power splitting relaying, Relay selection, Multi-objective optimization.

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I. INTRODUCTION

Wireless ad-hoc networks are temporary, self-organizing networks created by wireless devices that connect directly to each other without relying on a central base station. These networks are popular in research due to their flexibility and ability to form spontaneously (Guo *et al.*, 2014). Consequently, it is used in diverse fields like disaster monitoring, military operations, traffic management, wildlife conservation, security, healthcare, and more (Engmann *et al.*, 2018). Next-generation networks, like 5G and IoT, aim to provide faster speeds, more efficient data use, wider coverage, lower latency, and reduced energy consumption and carbon emissions (Pan & Zhu, 2021). To meet the growing demands of billions of wireless devices with complex networks, cooperative communication is a promising solution. This involves mobile devices sharing their antennas to improve signal quality and efficiency. This helps overcome challenges like fading, shadowing, and path loss, which weaken signals and increase energy consumption in wireless networks (Laneman *et al.*, 2004).

Cooperative networks primarily employ two relaying strategies: amplify-and-forward (AF). In this strategy, relay

amplifies the received signal (including noise) and retransmits it to the destination. This method is simple and has low complexity, requiring fewer retransmissions. However, it is susceptible to noise amplification and propagation errors. In the decode-and-forward (DF) method, the relay decodes the received signal, re-encodes it, and then forwards it to the destination. This approach offers better performance but has higher complexity (Nosratinia *et al.*, 2004). According to Liu *et al.* (2019), relaying strategies can be reactive or proactive. Reactive relaying is used when the direct link is weak. Data is sent via the relay to conserve energy. Proactive relaying sends data via both the relay and the direct link, improving reliability but potentially shortening network lifetime. Relay terminals face energy constraints such as limited battery power and small buffer size; frequent charging/replacement is difficult in some environments (Tin *et al.*, 2020).

To address energy concerns in communication systems, radio frequency (RF) energy harvesting has emerged as a promising green solution. By capturing ambient radio waves, it offers a self-sustaining power source while simultaneously transmitting data. This approach surpasses traditional methods like solar, wind, and thermal harvesting in terms of reliability

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and efficiency, leading to improved communication quality with reduced energy consumption (Lin *et al.*, 2020; Nasir *et al.*, 2013). Two main methods for relaying in energy-constrained networks are time switching relaying (TSR) and power splitting relaying (PSR). TSR alternates between energy harvesting (EH) and information decoding (ID). PSR divides the received signal, using part for EH and the rest for ID. It generally outperforms TSR in terms of energy harvesting efficiency, leading to improved network performance (Nguyen *et al.*, 2015; Ojo *et al.*, 2020). Most research in this field have focused on the physical layer, but higher layers are now attracting significant attention.

The medium access control (MAC) layer, crucial for wireless network coordination, employs the IEEE 802.11 distributed coordination function (DCF) protocol, in which energy consumption for efficient packet delivery must be considered (Liu *et al.*, 2007). The cooperative medium access control (CMAC) protocol, an extension of Wireless MAC for cooperative networks, incorporates green communication principles. Green communication aims to minimize energy consumption, particularly when helper nodes assist in data transmission. This is achieved by prioritizing energy-efficient approaches when helpers utilize their own batteries. A few of the solutions in this category are presented therein. Sami *et al.* (2015) presented an energy-aware CMAC protocol for wireless ad-hoc networks to improve network lifetime and energy efficiency. Mousavi *et al.* (2018) proposed a fair CMAC protocol by exploiting the capacity of a helper terminal to improve the resource allocation of the network. In the work of Mahmud *et al.* (2019), the authors proposed an efficient CMAC protocol for wireless IoT networks using distance-aware data rate adaptability for reliable relay selection.

In the paper of Rafiee *et al.* (2021), a multi-objective CMAC protocol which focus on the use of full (multiple) relay selection (FCGCMAC) and partial (single) relay selection (EECMAC) was employed. The protocol utilized FCGCMAC for spectral efficiency performance while EECMAC was used for energy efficiency gain through a centralized look up table. Furthermore, for the CMAC protocols with cross layer design contributions, the work of Lin *et al.* (2020) proposed a cross-layer energy consumption optimization for cooperative multi-input single-output (CMISO) wireless sensor network (WSN) using carrier sense medium access/collision avoidance (CSMA/CA) scheme to improve the energy efficiency of the network. The authors in Peron *et al.* (2018) presented a CMAC protocol based on IEEE 802.11 in cooperative multi-input multi-output (CMIMO) networks to coordinate node cooperation and ensure energy efficiency improvement. These protocols are outdated due to their reliance on 'energy theft' (using the remaining energy of other devices), the increasing cost of power, and concerns about fairness and environmental impact in future networks (Akanke & Salleh, 2020; Xia *et al.*, 2020).

To this end, the radio frequency-energy harvesting (RF-EH) is deployed and has since been a promising solution in applications such as in wireless body area networks (WBANs) (Gu *et al.*, 2019), cognitive radio networks (CRN) (Sami *et al.*, 2016), WSNs (Kakria and Aseri, 2019), IoT (Esse *et al.*, 2021),

and so on to improve the throughput, network lifetime, and energy efficiency either as a single objective or dual objective manner. Some of these solutions, with RF-EH applied in conventional point to point wireless networks, are discussed. In Zhao *et al.* (2018), the protocol took advantage of the wireless broadcast nature and the rich ambient RF signal of the indoor wireless local area networks (WLAN) to ensure an uninterrupted power supply for low-powered wireless devices and improve network throughput through energy gleaning. In Ha *et al.* (2018), a harvest then transmits MAC protocol was proposed. The protocol arranged efficiently the data packets of wireless powered sensor networks (WPSNs). Presented in Zhao *et al.* (2016) is a carrier sense multiple access with collision avoidance (CSMA/CA) protocol that integrates data and energy transfer for indoor WLAN applications.

Furthermore, the existing cross layer CMAC protocols with RF-EH includes the followings: In Akanke & Salleh (2019), a hybrid time-power splitting PHY layer-dependent CMAC protocol was proposed to improve the network lifetime and energy efficiency of wireless ad-hoc networks (WANETs). Also proposed in Akanke & Salleh (2020) is an EH-CMAC protocol with the ability to achieve multi-objective target-oriented performance using a PHY layer selective TSR-PSR mechanism. Nevertheless, most of these protocols have single objective performance and struggle to balance critical trade-offs under dynamic network conditions, while those with multi-objective performance result in high cost of energy consumption at the expense of a reliable transmission success.

To this end, an adaptive multi-objective energy harvesting cooperative medium access control (MOEH-CMAC) protocol, which uses an adaptive DF with PSR relaying strategy, ensures the accurate instantaneous network condition through an efficient relay selection process to provide a better network performance. Our contributions in this paper are listed as follows:

- i) We designed a new multi-objective protocol for wireless ad-hoc networks, which exhibits an adaptive cooperative DF-PSR relaying transmission strategy that relies on instantaneous channel conditions.
- ii) We formulated a multi-objective optimization problem consisting of spectral efficiency and network lifetime for energy-constrained relay nodes with PSR circuitry to harvest ambient RF energy from the source node. The multi-objective optimization problem is transformed into a single-objective problem, in which the weight determines the importance of the objective function. In addition, the optimal PSR factor as well as weighted values are obtained from the instantaneous channel condition to ensure a successful data packet transmission via the ready-to-send/clear-to-send (RTS/CTS) handshake.
- iii) We propose an efficient and adaptive power allocation method for a new relay selection algorithm, which is dependent on the optimal weighted value (spectral efficiency and network lifetime) for the proposed MOEH-CMAC protocol to select the best helper node to achieve a multi-objective network performance.

The remainder of this paper is organized as follows. Section II presents the system model, while Section III provides the proposed protocol, which includes protocol description, relay selection algorithm, wireless energy harvesting, power allocation, and PSR ratio optimization. Section IV presents the simulation results and performance comparison, while conclusions are drawn in Section V.

II. SYSTEM MODEL.

In this paper, a new MOEH-CMAC protocol is proposed, which comprises an adaptive cooperative transmission strategy. A wireless ad-hoc network is considered in Figure 1, which involves the source (S), destination (D), and N randomly distributed relay terminals, where $r_i: i \in \{1, \dots, N\}$ that are placed between the source and destination nodes. Adaptive cooperative transmission selects the best relay to help transmit data when direct communication is poor due to severe fading. This is determined after measuring the channel condition through the RTS/CTS handshake. Network terminals use omnidirectional antennas, operate in half-duplex mode, have adaptive DF strategy, and share the same wireless channel. More so, the source terminal is energy-unconstrained, uses maximum transmission power P_{Smax} to transmit its data packet while the relaying terminals are energy-constrained and possess PSR mechanism to harvest energy from the signals transmitted by the source. All control packets (RTS/CTS/HATS/ACK) are exchanged using 6.5 Mb/s constant transmission rate, while in traditional cooperation, transmission is done at higher rates. Also, the IEEE 802.11n multi-rate capability shown in Table 1 was employed. The relaying terminals deployed in the network can assist in retransmitting the successfully decoded data packet to the destination upon transmission by the source. The channel gains between the source and destination $h_{S,D}$, the source-relay link h_{S,r_i} and relay-destination link $h_{r_i,D}$ are assumed to be an invariant, independent, and identically distributed Rayleigh block fading channel, and cooperation can only be activated when the joint simultaneous wireless energy harvesting and information decoding are satisfied and guarantee a successful data packet retransmission. The distance of separation between the source-destination, the source-relay and relay-destination are denoted as $d_{S,D}$, d_{S,r_i} and $d_{r_i,D}$, respectively.

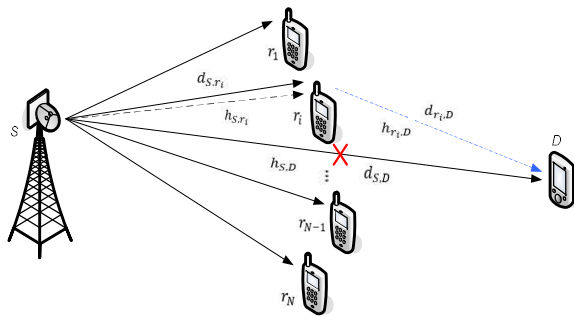


Figure 1. System model.

Table 1: Multi-rate capability of IEEE 802.11n

Data rate (Mb/s)	6.5	13	19.5	26	39	52	58.5	65
Range (m)	180	140	110	90	72	50	44	40

III. MATERIALS AND METHODS

This section presents the description of the proposed adaptive MOEH-CMAC protocol with PSR mechanism relay selection algorithm, and optimal power allocation.

A. Protocol Description

Figure 2 illustrates the control and data packet exchange for the proposed adaptive MOEH-CMAC protocol, which is backward compatible with IEEE 802.11 DCF. The proposed protocol extends the RTS/CTS frame with extra fields to determine destination distance and transmission requirements. The RTS and CTS frames differ in these extra fields and are similar to EH-CMAC (Akande & Salleh, 2020). A new "helper-able-to-send" (HATS) frame is introduced, broadcast by the best helper after backoff. The HATS frame includes the estimated harvested transmit power for the source's data transmission and resets other terminals' NAV to prevent interference. The proposed CMAC protocol uses fixed power for control frames and optimal power for data packets, adapting to channel conditions and network characteristics. This is measured by the instantaneous signal-to-noise ratio between the source-relay and relay-destination, which are denoted as γ_{S,r_i}^{DF} and $\gamma_{r_i,D}^{DF}$, respectively and compared with the threshold γ_{th} . Table 2 summarizes the transmission mode selection criteria.

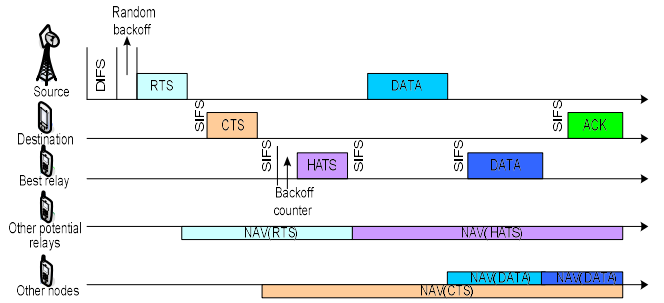


Figure 2: MOEH-CMAC protocol packet transmission.

Table 2: Transmission modes of the proposed adaptive MOEH-CMAC protocol

Transmission mode	Condition for transmission	CTS flag assignment
Direct	$\gamma_{S,D} > \gamma_{th}$	$flag1 = 0$
Cooperation without EH	$\min(\gamma_{S,r_i}, \gamma_{r_i,D}) > \gamma_{th}$	$flag1 = 1 \text{ \& } flag2 = 0$
Cooperation with EH	$\min(\gamma_{S,r_i}^{DF}, \gamma_{r_i,D}^{DF}) \geq \gamma_{th}$	$flag1 = 1 \text{ \& } flag2 = 1$

The operation of the proposed protocol at the source, helper and destination terminals is summarized in Algorithm 1 while the flowchart at the relay node is presented in Figure 3.

Algorithm 1: Proposed MOEH-CMAC protocol operation

Begin

- 1) A source node initiates a transmission only after a DIFS period of channel sensing to avoid interfering with other transmissions.
- 2) If the channel is currently unoccupied, a random backoff period begins. At the end of this period, the source node sends an RTS signal.
- 3) Upon receiving the RTS signal, the destination node transmits a CTS after a SIFS. This CTS includes flags (flag1 & flag2) to indicate the chosen transmission type.
- 4) Nodes receiving both RTS and CTS packets are potential helpers. These nodes then use Eq. (1) to determine and contend for the best relay role based on the flag1 & flag2 values in the received CTS frame.
- 5) *If* flag1 = 0, *then*
 Direct transmission mode is chosen
 elseif flag1 = 1 & flag2 = 1 *then*
 Due to the presence of relay nodes capable of harvesting RF energy, cooperative transmission with EH is necessary. Therefore, MOEH-CMAC is implemented, incorporating optimal power allocation.
 elseif flag1 = 1 & flag2 = 0 *then*,
 Cooperative transmission proceeds without EH when all potential relays have sufficient battery levels to preclude the need for harvested energy.
 end if
- 6) The source node attempts direct transmission to the destination if no relay responds, subsequently awaiting an ACK after a SIFS.
- 7) Otherwise, the best helper node will respond with the transmission of HATS after SIFS and relay backoff counter expire. Other nodes that received HATS broadcast quit and become inactive.
- 8) After a SIFS, the source node transmits its data packet to the best helper node. If the helper successfully decodes the packet, it re-encodes and retransmits it to the destination
- 9) The destination node sends an ACK if it receives the data correctly after a short waiting period. Otherwise, the transmission fails, and the source node tries again.

End

B. Relay Selection

This section outlines the relay selection algorithm for the adaptive MOEH-CMAC protocol. According to Al-Kahtani (2020), selecting the optimal helper terminal is crucial in impacting the network management decision. Previous relay selection methods for CMAC in multi-objective scenarios often use diverse selection criteria, leading to extended and inefficient contention periods. In contrast, protocols with a single target objective often select the same relay repeatedly

(Zhang *et al.*, 2017). This results in the relay's inefficiency and premature network lifetime expiration due to rapid energy depletion. Additionally, few existing multi-objective CMAC protocols consider the trade-off between spectral efficiency and network lifetime. Due to these limitations, a unified and adaptive distributed relay selection algorithm based on the instantaneous network condition is considered. This algorithm dynamically balances the spectral efficiency and network lifetime by adjusting weights ($\omega_1 + \omega_2 = 1$) using factors like link quality, residual energy after potential RF energy harvesting in choosing the optimal helper to improve network performance. The proposed relay selection process has its backoff utility value obtained as given in equation (1).

$$BU_{r_i} = \min \left(\left(\omega_1 \left(\frac{1}{R_{S,r_i}} + \frac{1}{R_{r_i,D}} \right) + \omega_2 \left(\frac{\varepsilon_o}{\varepsilon_{r_i} - \varepsilon_{r_i}^C} \right) \right), \beta \right) \quad (1)$$

where R_{S,r_i} and $R_{r_i,D}$ are the source-relay and relay-destination link data rate, respectively. ω_1 and ω_2 are the weighted values, ε_o is the initial energy and β is the threshold level to ensure a better network performance. The instantaneous residual energy, which is the sum of the current residual energy (ε_{r_i}) and the harvested energy (ψ_{r_i}) of the helper terminals, is expressed as

$$\varepsilon'_{r_i} = \begin{cases} \varepsilon_{r_i} + \psi_{r_i}, & \text{if } \psi_{r_i} \neq 0 \\ \varepsilon_{r_i}, & \text{if } \psi_{r_i} = 0 \end{cases} \quad (2)$$

For cooperation without EH, due to high residual energy level, helpers have their $\psi_{r_i} = 0$, while those that are able to harvest energy because they can contain the harvested energy have $\psi_{r_i} \neq 0$ and $\varepsilon_{r_i}^C$ is the estimated energy consumption for individual relay to participate in cooperation and is expressed by Akande & Salleh (2020) as

$$\varepsilon_{r_i}^C = (P_{S \max} + P_{rx} + P_{ct}) \times (T_{RTS} + T_{CTS} + T_{HATS} + T_{ACK}) + (P_S^X + P_{rx} + P_{ct}) \times \left(\frac{8L}{R_{S,r_i}} + \frac{8L}{R_{r_i,D}} \right) \quad (3)$$

where $P_{S \max}$, P_{rx} and P_{ct} are the maximum transmit power, receive power and processing power, respectively. $P_S^X \in \{P_S^C, P_S^{DF}\}$ is the optimal power allocation. T_{RTS} , T_{CTS} , T_{HATS} and T_{ACK} are the transmission time for RTS, CTS, HATS and ACK, respectively. L is the packet length. Intuitively, the helper with the lowest backoff utility value is elected the optimal helper among the possible helpers that contend the relay selection process. Hence, the backoff timer expires earlier than others and this helper will declare its emergence as the winner by broadcasting its HATS while other nodes in the network quit the backoff process.

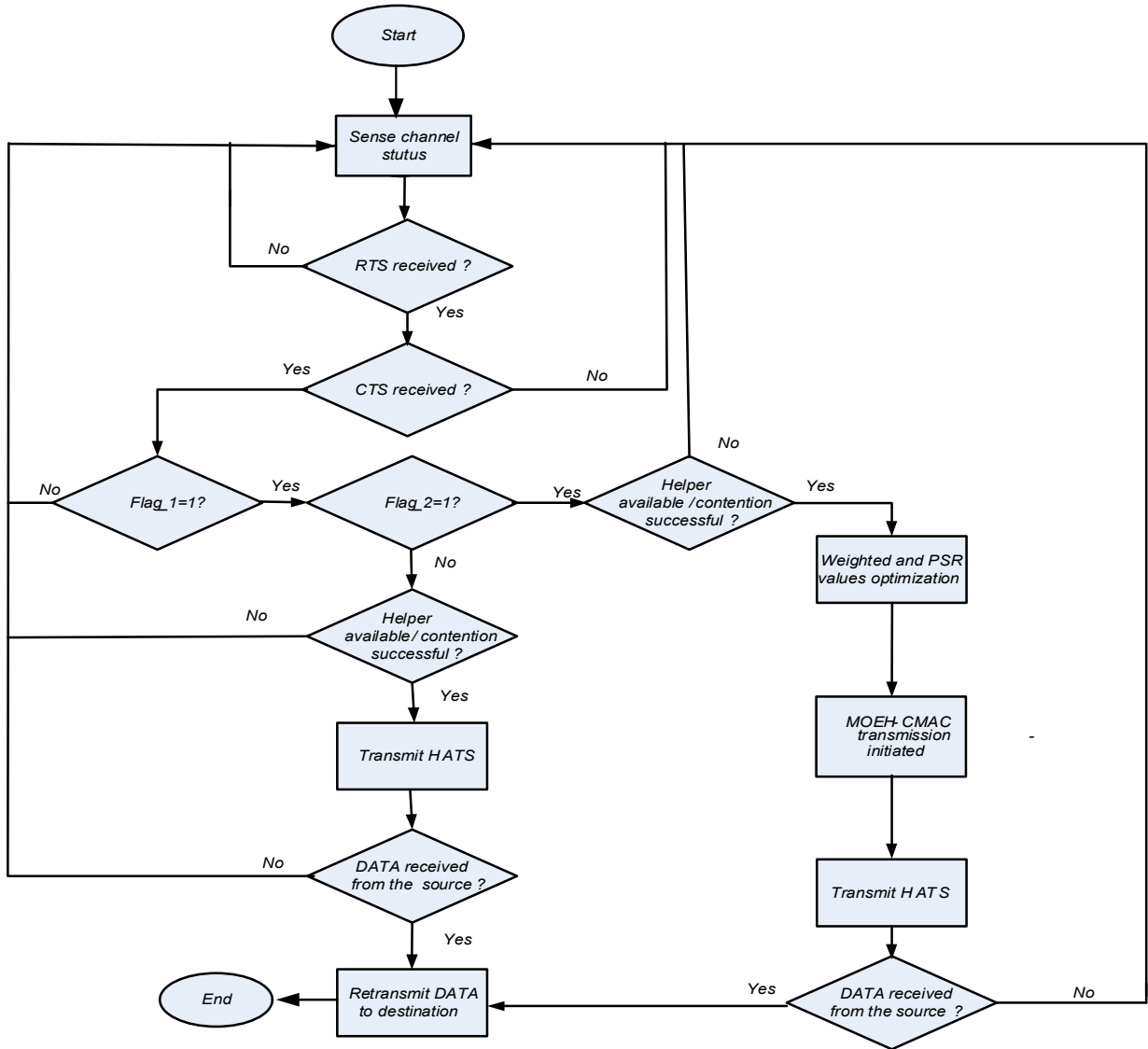


Figure 3: Flowchart of the relay terminal operation

C. Wireless Energy Harvesting Mechanism with PSR

The proposed CMAC is comprised of cooperative relaying protocol and DF-PSR model relaying. The PSR scheme depicted in Figure 4 has its frame structure with block length T which is divided into two portions. The first portion is further divided into two sub-portions where the first sub-portion of the received signal is used for energy harvesting and is designated as ϑP and the second sub-portion $(1 - \vartheta)P$ is used for information decoding at the relaying terminal, where the PSR factor is defined as $\vartheta \in (0,1)$.

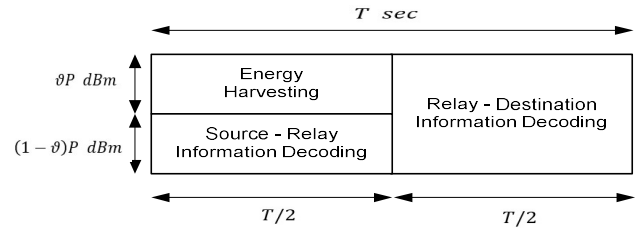


Figure 4: PSR energy harvesting and information processing frame structure.

The energy harvested at the relay terminal is given as

$$\psi_{r_i} = \frac{\eta \vartheta |h_{s,r_i}|^2 T}{2d_{s,r_i}^\alpha} \quad (4)$$

where $\eta \in (0,1)$ is the energy conversion coefficient, h_{s,r_i} is the source-relay link channel gain, d_{s,r_i} is the relay-

destination link distance of separation and v is the path loss exponent. Consequently, the harvested energy at the relaying terminal used for transmitting the decoded packet has its power written as

$$P_{r_i} = \frac{\psi_{r_i}}{T/2} = \frac{\eta \vartheta P_S |h_{S,r_i}|^2}{d_{S,r_i}^v} \quad (5)$$

Subsequently, the instantaneous received SNR at the relay and destination for DF relaying strategy are given as

$$\gamma_{S,r_i}^{DF} = \frac{(1-\vartheta)P_S |h_{S,r_i}|^2}{d_{S,r_i}^v N_o} \quad (6)$$

and

$$\gamma_{r_i,D}^{DF} = \frac{\eta \vartheta P_S |h_{S,r_i}|^2 |h_{r_i,D}|^2}{d_{S,r_i}^v d_{r_i,D}^v N_o} \quad (7)$$

respectively, where $h_{r_i,D}$ is the relay-destination link channel gain, $d_{r_i,D}$ is the relay-destination link distance of separation and N_o is the noise power, which is the same for all channel links. Subsequently, the channel capacity for a DF relaying with a maximum ratio combiner (MRC) at the destination is written as

$$C^{DF} = \frac{1}{2} \log_2(1 + \min(\gamma_{S,r_i}^{DF}, \gamma_{r_i,D}^{DF})) \quad (8)$$

D. Power Allocation for the Proposed MOEH-CMAC Protocol

Direct Transmission: This mode activates only when the channel between the source and destination is good enough to meet the desired outage probability QoS without requiring any cooperation. The allocated transmit power in this mode is given in Sami *et al.* (2015) as

$$P_S^D \geq -\frac{(2^R-1)N_o d_{S,D}^v}{\ln(1-\rho^{out})} \quad (9)$$

where R is the transmission rate and ρ^{out} is the outage probability for direct transmission mode.

Cooperative without EH: In this transmission mode, cooperative transmission without a direct link (reactive relaying) is activated. The power allocation for this transmission using the outage probability QoS requirement method can be obtained using the expression as given by Sami *et al.* (2016)

$$P_S^C \geq \frac{\xi P_{r_i}^C d_{S,r_i}^v N_o}{(2^{2R}-1) d_{r_i,D}^v + P_{r_i}^C \ln(1-\rho^{out})} \quad (10)$$

Cooperation with EH: This transmission optimizes power allocation by jointly considering spectral efficiency and lifetime. The destination selects the best transmission mode based on network conditions. Power allocation for each mode is found by optimizing a trade-off between spectral efficiency and network lifetime, which is a multi-objective problem. Therefore, a multi-objective optimization problem is formulated as

$$\begin{aligned} & \max_{P_S \geq 0, \vartheta} C^{DF} + (\varepsilon_{r_i} + \psi_{r_i}) \\ \text{s.t. } & c1: C^{DF} \geq R_{th}, \quad \forall i \in \{1, \dots, N\} \\ & c2: \varepsilon_{r_i} + \psi_{r_i} \leq \varepsilon_o, \quad \forall i \in \{1, \dots, N\} \\ & c3: P_S^{DF} \leq P_{max} \\ & c4: P_{r_i} \geq P_{r_i}^{min}, \quad \forall i \in \{1, \dots, N\} \\ & c5: P_S^{DF} \geq 0 \\ & c6: 0 \leq \vartheta \leq 1 \end{aligned} \quad (11)$$

The objective function of (11) is a maximization problem constrained in $c1$ to the channel capacity of the transmission mode with R_{th} being the transmission rate threshold. In $c2$, the capacity of the relaying batteries must be able to contain the addition of the current residual and harvested energies. Also, $c3$ and $c4$ involve the transmit power at the source constrained to maximum transmit power and harvested power allocated at the relay terminal constrained to the threshold harvested transmit power, respectively. $c5$ ensures that the power allocated at the source must not be 0 while $c6$ shows the optimal PSR ratio value. To simplify the problem formulated, the optimal value of ϑ^* to be shown later is first obtained alongside the weighted values introduced because of the weighted sum method applied to the objective function. This is achieved by assigning different weighted values to create a single objective function. This also allows for the introduction of another constraint with $0 \leq (\omega_1 \text{ or } \omega_2) \leq 1$. The optimal weighted values are obtained from the channel link measured between the source-relay during the exchange of RTS/CTS frames using the expression given as

$$\omega_1 = \frac{1}{I} \sum_{i=1}^I |h_{S,r_i}|^2 \quad (12)$$

The optimal solution is determined using the Pareto point (Rango *et al.*, 2012; Lari & Asaician, 2019) and Eq. (11) is therefore transformed now as

$$\begin{aligned} & \max_{P_S \geq 0, \vartheta} \omega_1 C^{DF} + \omega_2 (\varepsilon_{r_i} + \psi_{r_i}) \\ \text{s.t. } & c1, c2, c3, c4, c5, c6 \\ & c7: \omega_1 + \omega_2 = 1 \end{aligned} \quad (13)$$

2) Solution to the Formulated Problem

The transformed equation in Eq. (13) is then solved using the Lagrange function which thus gives equation (14).

$$\begin{aligned} \mathcal{L}\{P_S, \lambda_1, \lambda_2, \lambda_3, \lambda_4\} = & \omega_1 C^{DF} + \omega_2 (\varepsilon_{r_i} + \psi_{r_i}) - \\ & \lambda_1 (R_{th} - C^{DF}) - \lambda_2 (\varepsilon_{r_i} + \psi_{r_i} - \varepsilon_o) - \lambda_3 (P_S^{DF} - P_{max}) - \\ & \lambda_4 (P_{r_i}^{min} - P_{r_i}) \end{aligned} \quad (14)$$

where the Lagrange multipliers in respect of the constraints in Eq. (14) are $\lambda_1, \lambda_2, \lambda_3, \lambda_4 \geq 0$.

To obtain the optimal solution of P_S for different cases of the weighted values, the Karush Kuhn-Tucker (KKT) optimality conditions in Boyd and Vandenberghe (2004) are applied using $\frac{\partial \mathcal{L}\{\}}{\partial P_S} = 0$ and Lagrange multipliers updated accordingly. The adaptive nature of the proposed protocol is analyzed in different scenarios.

Case 1 ($\omega_1 = 1$ and $\omega_2 = 0$): In this scenario, the spectral efficiency performance of the network is more important than the network lifetime. Therefore, the portion of the network lifetime in the objective function becomes zero, i.e., $\varepsilon_{r_i} + \psi_{r_i} = 0$. This implies that sufficient power storage is available and Eq. (14) becomes:

$$\mathcal{L}\{P_S, \lambda_1, \lambda_2, \lambda_3, \lambda_4\} = C^{DF} - \lambda_1(R_{th} - C^{DF}) - \lambda_2(\varepsilon_{r_i} + \psi_{r_i} - \varepsilon_o) - \lambda_3(P_S^{DF} - P_{max}) - \lambda_4(P_{r_i}^{min} - P_{r_i}) \quad (15)$$

By substituting Eqs. (4), (5), and (8) into Eq. (12) and applying the KKT condition with $\frac{\partial \mathcal{L}\{\cdot\}}{\partial P_S^{DF}} = 0$, and must satisfies $[\cdot]^+ = \min[P_S^{DF}, P_{max}]$. The optimal transmit power allocated then yields:

$$P_S^{DF} = \begin{cases} \left[\frac{1 + \lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{r_i,D}^v N_o}{(1-\vartheta) |h_{S,r_i}|^2} \right]^+, & \gamma_{S,r_i}^{DF} < \gamma_{r_i,D}^{DF} \\ \left[\frac{1 + \lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{S,r_i}^v d_{r_i,D}^v N_o}{\eta \vartheta |h_{S,r_i}|^2 |h_{r_i,D}|^2} \right]^+, & \gamma_{S,r_i}^{DF} > \gamma_{r_i,D}^{DF} \end{cases} \quad (16)$$

where $a = \frac{\eta \vartheta |h_{S,r_i}|^2}{d_{S,r_i}^v}$.

Case 2 ($\omega_1 = 0$ and $\omega_2 = 1$): In this scenario, the network lifetime performance of the network is prioritized over the spectral efficiency, and the portion of the spectral efficiency in the objective function is taken to be negligible. This implies that power storage is insufficient and requires that the lifetime needs to be sustained, then Eq. (14) becomes:

$$\mathcal{L}\{P_S, \lambda_1, \lambda_2, \lambda_3, \lambda_4\} = (\varepsilon_{r_i} + \psi_{r_i}) - \lambda_1(R_{th} - C^{DF}) - \lambda_2(\varepsilon_{r_i} + \psi_{r_i} - \varepsilon_o) - \lambda_3(P_S^{DF} - P_{max}) - \lambda_4(P_{r_i}^{min} - P_{r_i}) \quad (17)$$

Substituting Eqs. (4), (5) and (8) into Eq. (12) according to the KKT condition $\frac{\partial \mathcal{L}\{\cdot\}}{\partial P_S^{DF}} = 0$, the optimal transmitting power allocated yields:

$$P_S^{DF} = \begin{cases} \left[\frac{\lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{r_i,D}^v N_o}{(1-\vartheta) |h_{S,r_i}|^2} \right]^+, & \gamma_{S,r_i}^{DF} < \gamma_{r_i,D}^{DF} \\ \left[\frac{\lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{S,r_i}^v d_{r_i,D}^v N_o}{\eta \vartheta |h_{S,r_i}|^2 |h_{r_i,D}|^2} \right]^+, & \gamma_{S,r_i}^{DF} > \gamma_{r_i,D}^{DF} \end{cases} \quad (18)$$

and must satisfies $[\cdot]^+ = \min[P_S^{DF}, P_{max}]$.

Case 3 ($\omega_1 = \omega_2$ and $\omega_1 + \omega_2 = 1$): In this scenario, both the spectral efficiency and the network lifetime performances of the network of the objective function in the formulated problem are taken to be important and equal. This implies that the power storage is insufficient, which requires that the lifetime needs to be sustained, and the spectral efficiency is equally needed, then Eq. (14) becomes:

$$\begin{aligned} \mathcal{L}\{P_S, \lambda_1, \lambda_2, \lambda_3, \lambda_4\} &= \omega_1 C^{DF} + \omega_2 (\varepsilon_{r_i} + \psi_{r_i}) \\ &\quad - \lambda_1(R_{th} - C^{DF}) - \lambda_2(\varepsilon_{r_i} + \psi_{r_i} - \varepsilon_o) \\ &\quad - \lambda_3(P_S^{DF} - P_{max}) - \lambda_4(P_{r_i}^{min} - P_{r_i}) \end{aligned} \quad (19)$$

Substituting Eqs. (4), (5), and (8) into Eq. (19) according to the KKT condition $\frac{\partial \mathcal{L}\{\cdot\}}{\partial P_S^{DF}} = 0$, the optimal transmit power allocated yields,

$$P_S^{DF} = \begin{cases} \left[\frac{1 + \lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{r_i,D}^v N_o}{(1-\vartheta) |h_{S,r_i}|^2} \right]^+, & \gamma_{S,r_i}^{DF} < \gamma_{r_i,D}^{DF} \\ \left[\frac{1 + \lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{S,r_i}^v d_{r_i,D}^v N_o}{\eta \vartheta |h_{S,r_i}|^2 |h_{r_i,D}|^2} \right]^+, & \gamma_{S,r_i}^{DF} > \gamma_{r_i,D}^{DF} \end{cases} \quad (20)$$

and must satisfies $[\cdot]^+ = \min[P_S^{DF}, P_{max}]$.

Case 4 ($\omega_1^* \neq \omega_2^*$ and $\omega_1^* + \omega_2^* = 1$): In this scenario, both the transmission rate and the network lifetime performances of the network are important but not equal as compared to that of case 3. This implies that the sustainability of lifetime and the spectral efficiency are unequally allotted, then Eq. (14) becomes:

$$\mathcal{L}\{P_S, \lambda_1, \lambda_2, \lambda_3, \lambda_4\} = \omega_1^* C^{DF} + \omega_2^* (\varepsilon_{r_i} + \psi_{r_i}) - \lambda_1(R_{th} - C^{DF}) - \lambda_2(\varepsilon_{r_i} + \psi_{r_i} - \varepsilon_o) - \lambda_3(P_S^{DF} - P_{max}) - \lambda_4(P_{r_i}^{min} - P_{r_i}) \quad (21)$$

Substituting Eqs. (4), (5), and (8) into Eq. (21) according to the KKT condition $\frac{\partial \mathcal{L}\{\cdot\}}{\partial P_S^{DF}} = 0$, with the optimal transmit power allocated yields:

$$P_S^{DF} = \begin{cases} \left[\frac{\omega_1^* + \lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \omega_2^* \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{r_i,D}^v N_o}{(1-\vartheta) |h_{S,r_i}|^2} \right]^+, & \gamma_{S,r_i}^{DF} < \gamma_{r_i,D}^{DF} \\ \left[\frac{\omega_1^* + \lambda_1}{2 \ln 2 \left(\left(\lambda_2 \frac{T}{2} - \omega_2^* \frac{T}{2} - \lambda_4 \right) a + \lambda_3 \right)} - \frac{d_{S,r_i}^v d_{r_i,D}^v N_o}{(1-\vartheta) |h_{S,r_i}|^2 |h_{r_i,D}|^2} \right]^+, & \gamma_{S,r_i}^{DF} > \gamma_{r_i,D}^{DF} \end{cases} \quad (22)$$

and must satisfy $[\cdot]^+ = \min[P_S^{DF}, P_{max}]$.

Then by applying the gradient method the optimal power allocation solutions for the MOEH-CMAC protocol in Eqs. (16), (18), (20), and (22) are updated through the Lagrange multipliers in an iterative manner with a chosen step-size μ given as

$$\begin{aligned} \lambda_1(I + 1) &= [\lambda_1(I) + \mu(R_{th} - C^{DF})]^+ \\ \lambda_2(I + 1) &= [\lambda_2(I) + \mu(\varepsilon_{r_i} + \psi_{r_i} - \varepsilon_o)]^+ \\ \lambda_3(I + 1) &= [\lambda_3(I) + \mu(P_S^{DF} - P_{max})]^+ \\ \lambda_4(I + 1) &= [\lambda_4(I) + \mu(P_{r_i}^{min} - P_{r_i})]^+ \end{aligned} \quad (23)$$

3) PSR Ratio Optimization

The PSR ratio plays a very important role for the optimal power allocation of the proposed adaptive MOEH-CMAC protocol. It is assumed that for any cooperative transmission to be successful, the channel capacity between the source-relay channel link must be greater or equal to that of the threshold rate, i.e. $C_{S,r_i}^{DF} \geq R_{th}$. This implies that the relaying terminal must be able to decode correctly the overheard signal from the source. To obtain the optimal value using the generalized expression of the weighted values, the KKT optimality conditions is applied using $\frac{\partial \mathcal{L}\{\}}{\partial \vartheta} = 0$ and Lagrange multipliers updated accordingly.

$$\mathcal{L}\{\vartheta, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5\} = \omega_1 C^{DF} + \omega_2 (\varepsilon_{r_i} + \psi_{r_i}) - \lambda_1 (R_{th} - C^{DF}) - \lambda_2 (\varepsilon_{r_i} + \psi_{r_i} - \varepsilon_o) - \lambda_3 (P_S^{DF} - P_{max}) - \lambda_5 (\vartheta - 1) \quad (24)$$

The optimal solution for PSR ratio yields

$$\vartheta^* = \left[1 - d_{S,r_i}^v N_o \left(\frac{\lambda_1 - \omega_1}{2 \ln 2 (\lambda_3 - (\lambda_2 + \omega_2) \eta P_S^{DF} |h_{S,r_i}|^2 \tau)} - 1 \right) \right]^+ \quad (25)$$

where $\tau = \frac{1}{2 d_{S,r_i}^v N_o}$. Due to the unpredictable wireless channel nature, the channel gain between the source-relay link which is modeled as a random variable, ω_1 and ω_2 play a vital role in determining the optimal value for the cases discussed earlier. The optimal power allocation and relay selection for the proposed adaptive MOEH-CMAC protocol is presented in Algorithm 2 and Algorithm 3, respectively.

Algorithm 2: MOEH-CMAC power allocation.

- 1) *Begin*
- 2) Initialize the network's parameters: $P_{s,max}, R_{th}, N_o, v, \varepsilon_o, \rho^{out}, \eta, d_{S,D}, I, N$.
- 3) Set Lagrange multiplier $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \geq 0$ and μ
- 4) Set $P_{r_i}^{min}$
- 5) *for* $i = 1$ *to* N , *do*
- 6) randomly generate d_{S,r_i} and $d_{r_i,D}$ such that the relays are located midway between the source and destination
- 7) randomly generate ε_{r_i}
- 8) *for* $i = 1$ *to* I , *do*
- 9) randomly generate $h_{S,D}, h_{S,r_i}$ and $h_{r_i,D}$ with Rayleigh fading channel characteristics
- 10) compute the estimated $\gamma_{S,D}, \gamma_{S,r_i}, \gamma_{r_i,D}, \gamma_{S,r_i}^{DF}$ and $\gamma_{r_i,D}^{DF}$.
- 11) *if* $(\varepsilon_{r_i} \approx \varepsilon_o)$ & $(flag1 = 1)$ *then*
- 12) *if* $(\min(\gamma_{S,r_i}, \gamma_{r_i,D}) > \gamma_{th})$ *then*
- 13) compute P_S^C and $P_{r_i}^C$ in (11)
- 14) *elseif* $(\varepsilon_{r_i} + \psi_{r_i} \leq \varepsilon_o)$ &
- 15) $(flag1 = 1 \text{ \& } flag2 = 0)$ *then*
- 16) determine ω_1 and ω_2 .

- 17) *if* $C_{S,r_i}^{DF} \geq R_{th}$ *then*
- 18) determine ϑ^* in Eq. (25)
- 19) *end if*
- 20) *If* $(\min(\gamma_{S,r_i}^{DF}, \gamma_{r_i,D}^{DF}) > \gamma_{th})$ &
- 21) $(flag1 = 1 \text{ \& } flag2 = 1)$ *then*
- 22) compute P_S^{DF} in Eqs. (16), (18), (20)
- and
- Lagrange
- multipliers with Eq. (23)
- 23) *end if*
- 24) *end if*
- 25) *else*
- 26) potential helper not available for cooperation, so compute P_S^D in Eq. (9)
- 27) *end if*
- 28) *end for*
- 29) obtain the optimal values of allocated powers P_S^{DF*}
- 30) *end for*
- 31) *End*

Algorithm 3: MOEH-CMAC relay selection.

- 1) *Begin*
- 2) Initialize $\varepsilon_o, \varepsilon_{r_i}, R_{S,r_i}, R_{r_i,D}, P_S^{DF*}, \psi_{r_i}, \omega_1^*, \omega_2^*, \beta, P_{t,max}, P_{rx}, L, P_{ct}, T_{RTS}, T_{CTS}, T_{HATS}, T_{ACK}$.
- 3) *for* $i = 1$ *to* N , *do*
- 4) compute ε_{r_i}' in Eq. (2)
- 5) compute $\varepsilon_{r_i}^C$ in Eq. (3)
- 6) *if* $(flag1 = 1 \text{ \& } flag2 = 0 \mid 1)$ *then*
- 7) compute BU_{r_i} in Eq. (1)
- 8) *else*
- 9) potential helper not available for cooperation
- 10) *end if*
- 11) obtain the optimal helper terminal with BU_{r_i}
- count
- down first.
- 12) *end for*
- 13) *End*

D. Simulation

In this section, the evaluation of the proposed adaptive MOEH-CMAC protocol is performed and then compared with other related existing CMAC protocols such as CoopMAC, FCGMAC and EECMAC and EH-CMAC. MATLAB R2020a software was used in simulating the protocols using a two-ray path loss propagation wireless channel model. In the simulation, it was assumed that data packets are transmitted from the buffer of a saturated source terminal. Also, the source and destination are separated at 180m using the IEEE 802.11n multi-rate capability standard. The topology of the network is of dimension $300 \times 300 m^2$ with the relay terminals distributed uniformly within the dimension. The IEEE 802.11n standard packet data rates were used for CoopMAC and FCGMAC and EECMAC while a fixed data rate was used for the proposed MOEH-CMAC and EH-CMAC transmissions. The performance metrics used are saturated throughput defined as the number of successfully received bits in a unit of time at the destination. Network

lifetime is the time it takes one of the nodes in the network to completely run out of power stored in its battery. Lastly, energy efficiency is the energy required to successfully transmit a data packet to its destination. The simulation parameters are as shown in Table 3. Since the proposed protocol is based only on PSR technique, the optimal value of ϑ^* used for the simulation is obtained according to Eq. (25) as 0.479.

IV. RESULTS AND DISCUSSION

Figure 5 shows that transmission power increases as the separation distance between source and destination terminals increases. This reduction in the proposed MOEH-CMAC protocol was achieved by harnessing RF signals at the relay, unlike traditional data packet transmission methods that rely on energy from the selected relay terminal. The weighted values and optimal PSR ratio play a critical role in successful data packet exchange, ensuring different target objectives outcomes for optimal power allocation. Case 1 consumes the highest transmission power, while case 2 shows the least. In case 1, the saturated throughput is prioritized over network lifetime, resulting in higher allocated transmit power at the expense of energy savings. In cases 3 and 4, transmission power allocation shows no significant difference, as the optimal values were obtained through simulation using Eq. (13). The reason was that the optimal $\omega_1^* = 0.4593$ and $\omega_2^* = 0.5407$ from Eq. (13) show no significant difference compared to when $\omega_1 = \omega_2 = 0.5$. However, EH-CMAC outperforms the proposed MOEH-CMAC protocol only in case 1 because it does not consider the tradeoff between throughput and network lifetime.

Figure 6 depicts total energy consumption versus source-destination distance. Energy consumption generally increases with distance, as observed in DCF, CoopMAC, FCGMAC, and EECMAC. While EH-CMAC and MOEH-CMAC exhibit similar trends initially, MOEH-CMAC shows slight energy consumption variations beyond 130 m. This was attributed to the multi-objective nature of MOEH-CMAC, which considered both network lifetime and spectral efficiency, unlike EH-CMAC, which primarily focused on lifetime. The optimal weight values in MOEH-CMAC played a crucial role in achieving this balance.

Table 3: Simulation parameters

Parameter	Value	Parameter	Value
RTS/CTS	44/38 bytes	CW_{min}/CW_{max}	31/1023 slots
HATS/ACK	38/34 bytes	Retry limit	6
MAC header	34 bytes	Unit time	0.1 ms
PHY header	24 bytes	Initial energy	1 J
$DIFS/SIFS$	50/10 μ s	Fixed transmit power	30 dBm
Data packet	1024 bytes	Receive power	20 dBm
Slot time	20 μ s	Processing power	10 dBm
Basic rate	1 Mb/s	η	0.9
ϑ^*	0.479	Noise power	-174 dBm

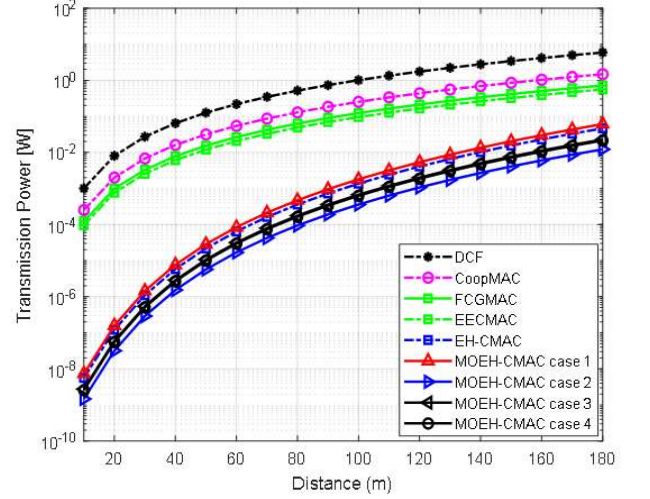


Figure 5. Transmission power of the protocols against source-destination distance.

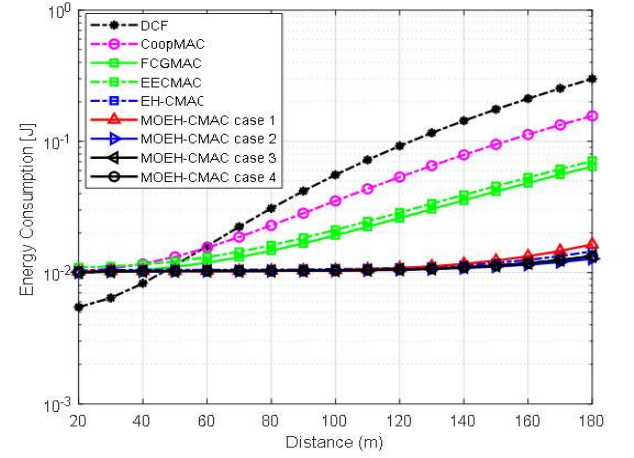


Figure 6. Energy consumption of the protocols against distance.

Figure 7 illustrates the decline in energy efficiency across all protocols as the source-destination distance increases. RF-EH relay-based protocols generally outperformed traditional relaying due to reduced energy consumption. The proposed MOEH-CMAC protocol significantly improved the energy efficiency compared to EH-CMAC in most scenarios. However, its performance degraded more in case 1 at longer distances (e.g., 140 m), likely due to increased transmission power requirements. Cases 2, 3, and 4 in MOEH-CMAC consistently outperform EH-CMAC. Notably, case 3, with equal importance targets, demonstrated the highest energy conservation among all protocols, surpassing EECMAC and FCGMAC by 91.45% and 89.52%, respectively, at 180 m.

Figure 8 illustrates that energy efficiency degrades as the pathloss exponent increases. The proposed MOEH-CMAC outperformed the existing CMAC protocols for path loss exponents below 2.8. However, the performance converged with increasing pathloss, likely due to worsened channel conditions and higher energy consumption at greater

distances. Case 2 of MOEH-CMAC (network lifetime objective) achieved the best energy efficiency at a pathloss exponent of 3. Compared to EECMAC, the proposed MOEH-CMAC in cases 1-4 showed energy efficiency improvements of 56.09%, 79.89%, 75.93%, and 75.77%, respectively.

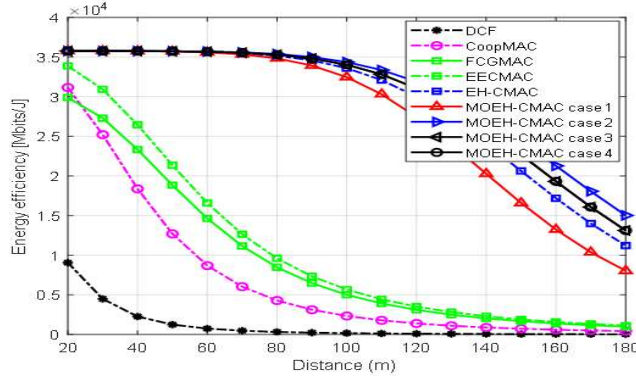


Figure 7. Energy efficiency of the protocols against distance.

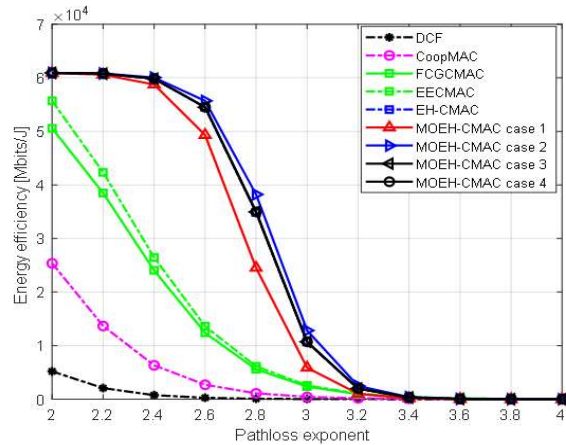


Figure 8. Energy efficiency of the protocols against path loss factors.

Figure 9 shows how saturated throughput changes with the number of nodes for different protocols. The proposed MOEH-CMAC protocol, with its varying transmission modes, generally performed well, especially in case 1 where it maximized the throughput performance against EHCMAc by 5% improvement. However, it is outperformed by FCGMAC, EECMAC and CoopMAC in most scenarios. Compared to CoopMAC, FCGMAC and EECMAC, the proposed protocol in case 1 exhibited lower throughput, because they are single objective performance protocols and the superiority of FCGMAC was due to the use of multiple relays at the expense of high energy consumption.

Figure 10 shows that network lifetime generally increases with the number of nodes. The proposed MOEH-CMAC protocol, with its relay selection and energy harvesting (EH) capabilities, significantly extended network lifetime. Case 2 (lifetime priority) achieved the best lifetime, surpassing EH-CMAC and EECMAC by 31.73% and 56.36%, respectively. Case 4 (unequal weights)

outperformed cases 3 and 1 by 6.4% and 38.79%, respectively. Case 1 (spectral efficiency priority) still improved by 19.53% over FCGMAC and demonstrated the benefits of RF-EH and the multi-objective optimization.

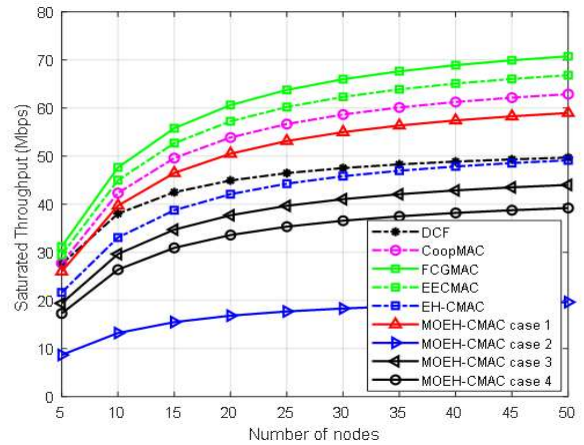


Figure 9. Saturated throughput of the protocols against number of nodes.

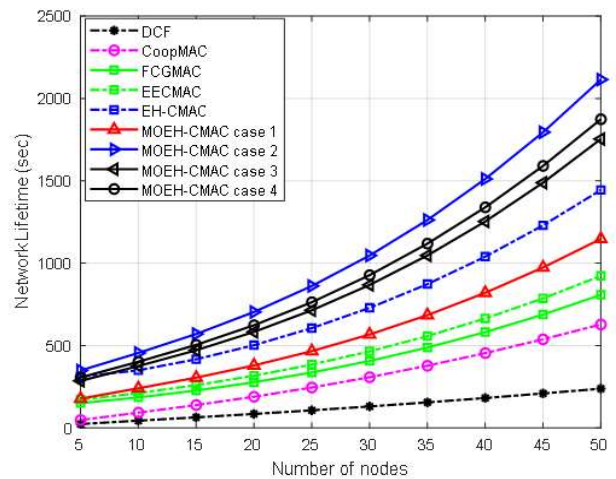


Figure 10. Network lifetime of the protocols against number of nodes.

Figure 11 shows that energy efficiency generally decreases as the number of nodes increases for all protocols. MOEH-CMAC in case 2 consistently achieved the highest energy efficiency. While EH-CMAC initially outperformed MOEH-CMAC in some cases, its efficiency dropped significantly with more nodes. Compared to other protocols prioritizing lifetime extension, MOEH-CMAC in case 2 showed significant energy efficiency gains. When compared with spectral efficiency-focused protocols, MOEH-CMAC in case 1 also demonstrated substantial energy efficiency improvements. Finally, MOEH-CMAC in cases 3 and 4, which balance spectral efficiency and lifetime, showed a 6.86% energy efficiency improvement by using unequal weights compared to equal weighting. This highlights the practicality and realism of the MOEH-CMAC approach in case 4.

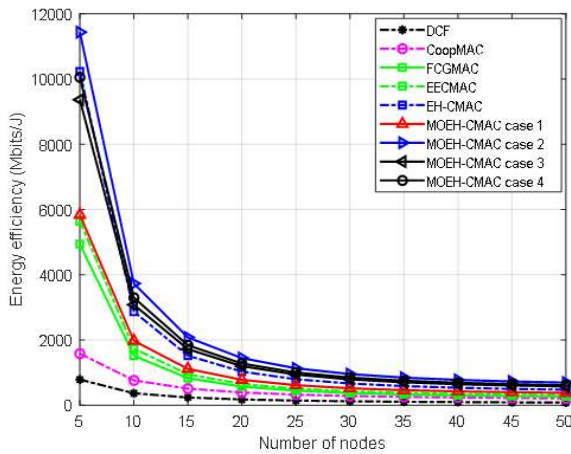


Figure 11. Energy efficiency of the protocols against number of nodes.

V. CONCLUSION

In this paper, an adaptive MOEH-CMAC protocol that harnesses RF ambient energy harvesting (EH) has been proposed. The MOEH-CMAC protocol took advantage of the DF-PSR strategy at the relay terminal for predictable, sustainable, and reliable packet transmission. Multi-objective optimization was exploited to leverage on the performance of the spectral efficiency and lifetime of the network to achieve a multi-objective protocol through different transmission modes. Also proposed is a new distributed and robust relay selection algorithm to select the optimal relay terminal through instantaneous network chosen weighted values to achieve multi-objectives performance. Through extensive simulation, the proposed MOEH-CMAC protocol exhibited significant improvement over existing CMAC protocols in throughput, energy efficiency, and network lifetime.

AUTHOR CONTRIBUTIONS

D. O. Akande: Conceptualization, Methodology, Simulation & Writing - Original draft. **F. K. Ojo** Methodology, Writing – review & edited. **O. F. Oseni** Writing – editing, while **S. I. Ojo** Simulation.

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