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MAC protocol for cooperative networks, design challenges, and implementations: a survey

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Abstract

Cooperative communication has drawn considerable attention from the wireless research community given the efficient and optimal utilization of constraint resources in dynamic wireless networks. In this study, we conduct a review of extant literature based on protocol classification. We further classify existing cooperative medium access control (CMAC) protocols based on target objective orientation and show the relay selection robustness of these protocols to network requirements. Ultimately, we identify the design and implementation challenges facing CMAC protocols and present certain open research issues.

Keywords Cooperative networks · CMAC protocols · Cooperative gain · Relay selection · Mobility

1 Introduction

The dynamic nature of wireless broadcast networks has attracted the interest of the wireless research community. The exponential growth and deployment of mobile devices over the decade for different wireless applications have been requiring advancements in architectural networks for future use. A technology that has emerged over the decade was multiple-input multiple-output systems [1,2]. The high cost, implementation, and hardware complexities of deploying infrastructural multi-antenna systems have led to the emergence of small-sized, battery-powered, and low-cost single-antenna mobile nodes that cooperatively function in the virtual array to improve wireless network performance [3]. Research interest in cooperative communication [4–7], particularly the physical (PHY)-layer stack, has considerably increased in the last 2 decades.

Cooperative communication involves the introduction of a relay/helper node (the two terms are interchangeably used in this paper), which assists in retransmitting an overheard copy of transmitted data packets between the transmitting (source) and the receiving (destination) nodes to achieve a reliable communication. These helper nodes explore the broadcast nature of the wireless channel and create multiplexing and diversity gains [5]. The retransmission of a successfully overheard signal can be classified into non-regenerative and regenerative relaying. The non-regenerative type, that is, amplify-and-forward relaying, simply involves retransmitting the amplified noisy version of the signal, whereas the regenerative relaying can be further classified into decode-and-forward (DF) relaying, compress-and-forward (CF) relaying, and coded cooperation (CC). DF relaying involves the correct decoding of the transmitted signal at the relay node before retransmission to the destination node, whereas CF relaying involves quantizing and compressing the signal before retransmission. For CC, an incremental redundancy is added to the received codeword at the relay node through error correction capabilities. The destination node combines the received signal by using an optimal combining technique. The maximum ratio combining (MRC) technique is widely used by most researchers considering the optimal performance of this technique [4].

Moreover, high-layer stacks require considerable research, especially for the PHY-layer cooperative gain to be translated into a beneficial gain for the overall network performance [8–10]. Numerous research activities have been recently proposed to extend the PHY-layer cooperative gain to the medium access control (MAC) layer. This layer requires

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extending Legacy 802.11 MAC for cooperative network capabilities. The contributions presented in [10–12] have addressed the problems associated with the MAC layer and have created a new paradigm for MAC protocol design in wireless networks. Investigations have revealed that cooperative medium access control (cooperative MAC or CMAC) protocols in infrastructural and ad hoc wireless networks result in improvement in aggregate throughput and reduction in transmission delay. However, the cost of increasing demand, network resource constraints, and multi-objective capability of CMAC protocols still pose major challenges to network designers [13,14].

To the best of our knowledge, none of the reviewed literature has drawn the attention of the research community to classifying CMAC protocols into objective target orientation and has exploited the relay selection robustness to the wireless network dynamic characteristics despite numerous reviews that have been conducted in this area.

1.1 Motivation

In this study, we investigated the existing features and classification of CMAC protocols. The result shows that most reviews have classified CMAC protocols based on classifications to be discussed in Sect. 2.2. We discovered that classifying CMAC on previous classification bases after carefully examining the specific purpose of designing these CMAC protocols may not provide a true picture of an efficient and robust protocol design because each of the designed protocols is targeted at achieving a specific objective(s). Therefore, we reclassified existing CMAC protocols based on target objective orientation (i.e., single, dual, and multi-objective). This study classifies aggregated throughput and end-to-end (e2e) delay as a single objective given the reciprocal relationship between the two performance metrics.

Furthermore, we observed that most relay selection backoff schemes that are deployed in existing CMACs are deficient in appropriately adapting to the dynamics of wireless network requirements to achieve different target objectives at different points in time. These are some of the gray areas and challenges that CMAC protocol designers are facing. The design challenges and implementations are enumerated, and open research issues are provided accordingly.

1.2 Contribution

The contributions of the present study are highlighted as follows:

- This study investigates the existing CMAC protocols based on the dynamic characteristics of wireless networks by classifying their performance metrics based on the target objectives. Our findings indicate that most solutions are designed and deployed for a specific purpose, which hinder these protocol adaptation to ever-changing network characteristics and increases their inability to achieve certain target objectives outside of their sole objectives. Therefore, designing a multi-objective target CMAC protocol is a considerable challenge to achieve with few CMAC protocols in this category.
- This study also indicates that the robustness of relay selection plays an important role in achieving target network objectives. The use of numerous parameters may not necessarily result in multi-objective targets. Therefore, the appropriate and adaptive selection of network parameters could assist in achieving more than a single target objective, thereby constantly remaining as an important design challenge to resolve. These network parameters are included in the relay selection backoff procedure of the CMAC protocols for a specific network requirement at a specific instant.
- This study also demonstrates that security and hardware limitations and performances are crucial network characteristics that should be considered in CMAC protocol designs. Security and hardware limitations have been reported in most literature but have not been explored in many CMAC protocol designs. Security and hardware performances have received only a minimal attention in the PHY-layer information theory and require equal attention in the MAC layer stack because the duo can influence the performance of networks and require additional attention as an open area of research.

The remainder of this paper is organized as follows: Sect. 2 introduces the background of the MAC protocol for cooperative networks. Section 3 presents a review of existing CMAC protocol contributions. Section 4 provides insights into the CMAC protocol design challenges, implementation, and open research issues. Section 5 draws the conclusion.

2 MAC protocol for cooperative networks

This section provides a background study on the MAC protocol for cooperative networks. A brief overview of the Legacy 802.11 MAC protocol, and general classification of CMAC protocols. Furthermore, a review of an important study on the subject was discussed.

2.1 Overview of legacy 802.11 MAC

The Legacy 802.11 MAC protocol was designed based on carrier sense multiple access (CSMA) for a single point-to-point communication link (direct transmission) to coordinate the activities of multiple nodes that share the same channel medium in wireless local area networks (WLANs) [12].

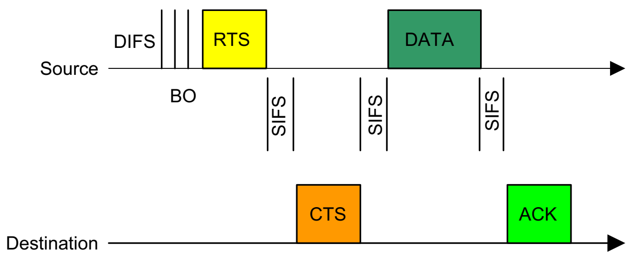

Fig. 1 Legacy 802.11 MAC packet transmission

The Legacy 802.11 standards were designed for a multi-rate PHY-layer with different modulation schemes for various channel conditions. The first standard was released in 1997 to operate at a 2.4 GHz band using direct sequence spread spectrum (DSSS) modulation with a maximum data transmission rate of 2 Mbps. Subsequently, two standards, namely, 802.11a and 802.11b, were released. The former operates in the 5 GHz band with a maximum data transmission rate of 54 Mbps by using orthogonal frequency division multiplexing (OFDM), whereas the latter operates in the 2.4 GHz band with a maximum data transmission rate of 11 Mbps using the DSSS modulation. The standards 802.11 g with maximum data rate of 54 Mbps and 802.11n with a maximum data rate of 150 Mbps were released in 2003 and 2009, respectively. The amendments to the standards resulted in an increase in throughput and improvement of data transmission rate in 802.11ac and 802.11ax. The adaptability of the direct rate protocols to multi-rate capability ensured high-quality direct transmission between the transmitter and the receiver. Owing to these advancements, the Legacy 802.11 standards, such as 802.15 and 802.16, are exploited for different applications. Figure 1 depicts the Legacy 802.11 MAC protocol.

The extension of the Legacy 802.11 MAC protocol with assisting helper node(s) for cooperative networks has drawn considerable research interests over the past decade. Virtual carrier sensing (VCS) mechanism has ensured the reduction in collision probability in the network. The VCS mechanism reserves a channel using the ready-to-send (RTS) and clear-to-send (CTS) handshake mechanism before transmitting the data packets. Transmitting nodes in the network sense the channel and transmit only when the channel is idle. Thus, a data packet transmission to other nodes at a certain time can differ by setting their respective network allocation vector (NAV). An acknowledgment (ACK) packet is transmitted upon successful reception at the receiver. For brevity, a detailed description of the Legacy 802.11 MAC protocol can be found in [15]. The existing state-of-the-art Legacy 802.11 MAC protocol is used as the baseline, and the appropriate extension to a high-layer stack is required to design the CMAC protocol.

2.2 General classification of CMAC protocols

The extension of the Legacy 802.11 MAC protocol is aimed at incorporating an assisting helper node to retransmit the data packet during transmission failure between the transmitter and the receiver in the MAC layer. This extension can be generally classified based on the following strategies:

1. *Network architecture* CMAC protocols are classified based on infrastructural and ad hoc networks [16]. In infrastructural networks, low-powered mobile devices (handset) rely on high-powered stationary terminals (base station) for a reliable communication connectivity. These infrastructural networks are applicable in cellular, satellite, and certain WLANs and require a high deployment cost and complexity. By contrast, ad hoc networks, also referred to as less-infrastructural networks, create seamless connectivity between low-powered mobile devices with few or no station that serves as the backbone of the network. This seamless connectivity is applicable to emerging wireless networks, amateur radios, wireless sensor networks (WSNs), mobile ad hoc networks, vehicular ad hoc networks, and wireless mesh ad hoc networks.
2. *Channel medium access method* An efficient CMAC protocol coordinates the sharing of the channel access and scarce radio spectrum among nodes in a network. This coordination can be central or distributed. Historical knowledge of potential nodes is required at either the transmitter, receiver, or relaying nodes [18] and requires a constant update of the schedule table, such as the CoopMAC table in [10], to coordinate the channel medium centrally [17]. Most reservation-based (contention-free) CMAC protocols fall into this category with each transmitting node allotted a specific time slot and ensure fair utilization of available resources in static networks. Time division multiple access (TDMA) [19–23] and reservation-based random access ALOHA [24–27] are techniques used given minimal transmission collision. By contrast, contention-based CMAC protocols do not require the historical information of the nodes [8,28–30]. The nodes that correctly overhear the transmitted packet from the transmitter are allowed to contend in a distributed manner to forward the packet to the receiver, thereby intuitively ensuring fairness among nodes [29,31,32]. Most CMAC protocols have adopted the contention-based technique because this technique easily adapts to ever-changing network configurations and leverages inherent overhead in selecting the optimal node and other transmission processes while maintaining the overall cooperative gain. However, contention-based CMAC protocols are faced with many design challenges, and extra work is still expected in this direction.

3. *Coding technique* The repetition- and space-time-based coding [4] are the major coding techniques that are used in cooperative communication. In the repetition-based algorithm, the relay nodes repeat either the amplified, compressed, stored, or fully decoded version of the overheard packet from the source nodes through individual orthogonal channels in frequency or time. However, the repetition-based algorithm is characterized by an extended delay time. For the space–time-based coding, the simultaneous transmission of a data packet on the same channel through coding schemes is allowed but requires high-level signaling schemes. The repetition-based coding is applicable to single-user scenarios, whereas the space–time-based coding is deployed in multiple user scenarios.
4. *Relaying methods* The CMAC protocol can be classified based on their relaying method, that is, proactive, reactive, and hybrid relaying methods [33]. In proactive relaying, transmission occurs simultaneously through a cooperative and direct path. In this method, the relay selection process precedes packet transmission from the transmitter, thereby reserving the channel for the relaying node. This process hinders other ongoing communication to the relaying node and limits the degree of a spatial frequency reuse of the radio channel. Proactive relaying is typically used at a small scale with limited mobility. In reactive relaying [31], a dual-hop transmission path is initiated through a relaying node when the transmission through the direct path fails. This method allows relaying nodes to participate in cooperation on demand, thereby reducing the channel reservation time. Periodic update due to dynamic network parameter is unnecessary, and energy consumption due to retransmission in case of severe channel conditions is drastically minimized. Reactive relaying is suitable for large networks that are characterized by a dynamic network topology. A hybrid relaying method allows using the proactive and reactive relaying methods to improve the overall network performance. This method is applicable to multi-hop and routing networks where the path to the receiver becomes relatively extended.
5. *User orientation* Another classification of the CMAC protocol based on diversity, which is used to achieve a high network performance, is user orientation. In a single-user orientation, only a single relaying node is selected as the optimal helper to retransmit the overheard packet to the destination. The complexity involved in this type of cooperation is minimal [10,34,35]. In the multiple-user orientation, multiple relaying nodes are selected as helpers to retransmit the source data packet, thereby increasing the cooperative gain [22,23,37,38]. In the MAC layer stack, if certain key issues are improperly addressed, then the high cooperative gain may be eroded and may further degrade the network performance as further relays increase the interference level and network complexity.

2.3 Existing surveys for CMAC protocol

The channel environment in the PHY-layer stack of a point-to-point wireless network system is characterized by scattering, multipath fading, attenuation, reflection, and refraction, thereby hindering the reliable reception of transmitted radio signals at the receiver. These effects result in retransmission and wastage of network resources. Cooperative relaying has become one of the viable solutions to alleviating these problems. This paradigm shift has its own associated cost [39]. Cooperation is activated by relaying node(s), which must eavesdrop/overhear the exchange of transmitted signals, and its benefit is assumed to be mutual to all nodes involved. From a MAC protocol designer perspective, numerous fundamental issues emerge in designing an efficient and effective MAC protocol for cooperative networks. Previous studies, such as [13,14,33,40–43], have addressed design challenges that are pertinent to all cooperative networks and have suggested different assumptions and perspectives to analyze the requirement for cooperation across the stacks. Different reviews on these studies focused on classifying CMAC protocols into transmission type, fundamental questions, helper selection initiation (i.e., source, helpers, or destination), channel medium access (i.e., contention- and reservation-based), channel coordination, architecture, complexity, and compatibility. The most recent review among these reviews was presented by Sadeghi et al. [43]. Their study indicated that CMAC protocols are operated in a reference framework, that is, the monitor, analyze, plan, and execute loops. The authors further classified CMAC protocols based on architecture, complexity, and compatibility. Table 1 summarizes several thorough surveys in this research interest. In this study, we corroborate on initiating/activating cooperation, as reported in [13], because three fundamental questions must be adequately addressed before an acceptable quality of cooperation can occur.

1. When to cooperate? For cooperation to be activated in the MAC layer, two important conditions must be satisfied; (1) availability of helper nodes, and (2) minimum transmission time. Also, cooperating nodes must accurately assume that its resulting gains are beneficial to the overall network [44]. In the PHY-layer, cooperation is used to mitigate the frequent variation in channel effects by exploiting spatial diversity through virtual antenna array without the necessity for high-cost multiple antenna systems to enhance high data rate, extend the coverage area and improve the system performance [4,5].

High-layer protocols, especially the MAC and network layers [45,46], should be considered to transform this PHY-

Table 1 Summary of cooperative MAC protocol survey

Authors	Classification	Open research issues	Comments
Zhuang and Ismail [40]	Potential benefit of cooperative transmission	Mobility, overhead, and cross-layer design routing metric and business models	A general review across the layer stacks
Ju et al. [14]	Fundamental question based, when to cooperate and whom to cooperate with? Helper selection initiation	Multiple relaying, mobility, energy, incentives and security	Comprehensive
Gomez-Cuba et al. [42]	Legacy 802.11 MAC transmission	Cooperative decision, neighborhoods mapping service, notification and agreement, and cooperative transmission designs	General and theoretical framework
Jamal and Mendez [33]	Relaying method for WLAN	Interference level, stability (mobility), overhead, multiple relay selection, power control and rate adaptation, implementation and multiple relay selection	For infrastructural networks
Zhuang and Zhou [41]	Similar to [14], with the addition of the third question, how to cooperate?	Cooperation metrics, cooperation gain, and cost, performance analysis, cross-layer design and multi-hop cooperation	WLAN and fully connected networks, and multi-hop networks
Mahmoud et al. [13]	Channel access method and application	Mobility, security, game theoretic, energy, fairness, spatial frequency reuse and multi-objective	Comprehensive
Sadeghi et al. [43]	Operational issues and transmission type (backoff target cooperation, minimum transmission, and cache and wait for failure)	Mobility, security, incentives, cross-layer, power control, and energy efficiency, performance bound and practical limitations	Framework

layer gain into beneficial cooperation completely. The realization of these benefits is complicated and challenging for the CMAC protocol because additional overhead is incurred (i.e., introducing new control packets); the interference area is enlarged [34,39,47], and the network energy consumption is increased, thereby possibly eroding the cooperative gain entirely if improperly checked. Furthermore, the effect of traffic schedule, node mobility, node density, and adequate update of the channel conditions may affect the requirement for cooperation considering coordination complexities, thereby resulting in poor overall network performance.

A large number of existing CMAC protocols are in accordance with the fact that cooperation is first initiated if the cooperative transmission time is less than the direct transmission time, that is, $\frac{1}{R_{s,h}} + \frac{1}{R_{h,d}} < \frac{1}{R_{s,d}}$.

2. Whom to cooperate with? This question is addressed after adequate satisfaction of the first question. The candidate helper nodes are then identified to assist in retransmitting the overheard packets in the MAC layer stack. These candidate set of helpers must fall within the high data multi-rate regions and possess the desired cooperative decision/criteria characteristics [34–39]. In a dense network scenario, the dynamics of mobile users can be predicted unlike in sparse networks. The probability/certainty of candidate helper nodes in the high data multi-rate region is high. However, works have constantly assumed the availability of candidate helpers in these regions between the source and the destination nodes to achieve the desired target objectives. A symmetric network scenario has been considered, particularly in the high data rate regions, to achieve a high cooperative gain. Most works focus on a single-hop scenario [10,32,34,35,48] and only a few works focus on a multi-hop scenario [37–39,49] given the complexity of designing a CMAC protocol, thereby resulting in high interference levels, energy consumption, and complexities.

3. How to cooperate/how can cooperation be stimulated? The relay selection process plays an important role in stimulating cooperation. A robust relay selection process must be time saving and energy efficient [47]. More network resources are consumed when cooperative transmission process involves relay selection and cooperative transmission than direct transmission. The relay selection process must be able to minimize collision and guarantee successful retransmission through an optimal helper node [38]. Several works have been proposed to guarantee an optimal helper node selection and effective cooperative transmission in address-

ing the hidden and exposed terminal problems [34–39]; however, no study has demonstrated the adaptability of its relay selection to suit the dynamics of network characteristics to achieve multi-objective orientation.

3 Review of existing CMAC protocol contributions

Essentially, a vast list of literature affirms that cooperation in the MAC layer can only be initiated if only cooperation can provide a certain degree of benefit/incentive for the entire network. Cooperation becomes unnecessary when no benefit/incentive can be achieved. The relay selection in the MAC layer is also an essential problem to identifying the best helper node(s) among potential helper nodes during the cooperative transmission process. To the best of our knowledge, no particular standard has been adopted for the CMAC protocol. The earliest landmark contributions are CoopMAC in [10] and relay-enabled distribution coordination function (rDCF) in [12] with the goal of improving the network throughput. Existing CMAC protocols, as listed in Table 2, have been proposed based on the success achieved by the previous contributions. Several recently proposed protocols are analyzed as follows:

3.1 Link-utility-based CMAC (LCMAC)

Zhou et al. [39] proposed a link-utility-based CMAC protocol for multi-hop networks using a hybrid relaying strategy in a distributed manner. In this protocol, the neighbor nodes that overhear the transmitted data packet in the previous hop may participate in cooperation in the current hop either as a partner or relay node. The partner has a copy of the transmitted packet, whereas the relay does not, thereby translating to different transmission modes. Each node is aimed at maximizing its own utility link by optimizing the measured transmission data rate, power, and transmission mode type (i.e., one-phase, two-phase, and direct transmissions) locally with a three-stage backoff relay selection scheme. The relay selection process comprises the inter-group contention, intra-group contention, and re-contention phases to ensure that the optimal helper node is selected. The destination node uses the MRC technique to combine the received data packets.

The results obtained show that the protocol exhibits a significant improvement in terms of network throughput and energy consumption over CRBAR and RBAR in [50,51], respectively.

3.2 Cooperative relaying MAC (CoRe-MAC)

In another interesting work by Adam et al. [31], a CoRe-MAC protocol based on CSMA/CA with RTS and CTS handshake mechanisms was proposed. The objective of this work was to improve the aggregated network throughput and reliability with a substantial focus on low energy capacity, off-the-shelf hardware, and backward compatibility. The protocol was also designed for easy integration into heterogeneous networks with other CoRe-MAC and existing CSMA/CA networks. In this protocol design, cooperation on demand with early retreat approach is initiated at the destination when the direct channel link between source and destination deteriorates. A relay selection process with early retreat and prioritized candidate set approach was applied to limit the number of neighboring nodes that overhear the data packet transmission to minimize the energy consumption given the additional energy incurred due to overhearing of frame exchange in the network.

The selection of the optimal helper node is based on three steps to ensure accuracy, efficiency, and reliability. The relay selection process commences once the destination fails to transmit the ACK after direct transmission. The three steps include the feedback, estimation, and contention steps. The feedback step involves information gathering of the availability of prioritized or new candidate set that has correctly received the transmitted data packet. The estimation step involves estimating the number of the available candidate set based on the contention window size. This step is optional given an increased transmission delay if the prioritized candidate set is available. However, a nonadaptive neighbor estimation is used to estimate the relay candidate cardinality when a new candidate set is to be selected. In the contention step, each candidate helper set in the previous step is selected randomly in a slot to transmit, in which their probability of non-collision is maximized.

The results obtained show that the original CoRe-MAC outperforms the CoRe-MAC-NE (without the candidate estimation step) and CoRe-MAC-NPC (without the candidate estimation step and prioritized candidate set) in terms of throughput at a high node density with increasing contention window sizes. The retransmission rate of CoRe-MAC also decreases while the node density increases, thereby making CoRe-MAC suitable for deployment in dense wireless networks. The cost incurred in cooperation has also been observed to be lesser in the original CoRe-MAC and CoRe-MAC-NE than the CoRe-MAC-NPC. However, this protocol may suffer throughput degradation given the high overhead and energy cost in severe channel conditions where a new candidate set should be selected for cooperative transmission, particularly in sparse networks.

3.3 Network coding-aware CMAC (NCAC-MAC)

A NCAC-MAC protocol based on reactive relaying for wireless ad hoc networks was proposed in [35] to enable the simultaneous retransmission of overheard data packets with

Table 2 Summary of some existing cooperative MAC protocols

Protocols	Cooperative condition	Research objective(s)	Classification			Drawbacks	Comment
			SO	DO	MO		
CoopMAC [10]	Transmit time	Throughput	√	–	–	Accurate and up-to-date information about the helper may suffer in a fast time-varying environment	Mostly adopted benchmark for CMAC protocols
rDCF [12]	Helper availability	Throughput and delay	√	–	–	Best helper selection not guaranteed, long relay selection time	Support any rate higher than direct transmission
ADC MAC [55]	Threshold SNR	Throughput	√	–	–	A direct link was not considered	Relay selection is performed at the PHY layer
CLMAC [8]	Availability of helper in a distinct region	Throughput	√	–	–	Accurate synchronization is required among the helpers	May not be feasible in real network scenario
RRS-MAC[56]	Transmit time	Throughput	√	–	–	The relay selection process may result in retransmission failure, due to the helper node energy levels	Energy efficiency of the protocol was not considered
2rcMAC [57]	Transmit time	Throughput and delay	√	–	–	Reserve the channel for long period of time. Signal interference increases	Energy efficiency not considered and reduces spatial reuse
LCMAC [39]	Joint transmit rate and power	Throughput and energy efficiency	–	√	–	Prolong relay selection process due to complex signaling	A more efficient relay selection process is required to minimize the contention period. Long relay selection period reduces network lifetime
NCCARQ-MAC [58]	Incorrect reception of packet at the destination	Energy efficiency	√	–	–	Multi-rate capability not exploited. The source-helper and helper-destination link are assumed to be error-free	Perfect channel assumption is not a true reflection of practical networks
CoRe-MAC [31]	Signal strength	Throughput and reliability	√	–	–	Extra overhead and energy consumption due to a long period of the relay selection process in event of new candidate set	Requires a reduced relay selection phase and fairness in term of energy if the prioritized set is always available
DEL-MAC [34]	Transmit time	Energy efficiency and network lifetime	√	–	–	Suffers degradation in sparse networks with no helper nodes in the vicinity of the source and destination nodes	Lower throughput and higher delay with respect to legacy 802.11 DCF hence require a trade-off
SRcoop MAC [51]	Transmit rate	Throughput and reliability				Reserve the channel for long period of time. Signal interference not considered	Interference between the nodes needs to be taken into consideration
NCAC-MAC [35]	SINR threshold	Throughput and delay	√	–	–	Suffers transmission delay due to inaccurate up-to-date information and prolong relay selection process	Same as LCMAC [39]. High risk of data packet insecurity
EECO-MAC [48]	Joint transmit power and rate	Energy efficiency	√	–	–	May suffer retransmission due to the selection of relay before CTS transmission	Suitable for densely populated network scenario

Table 2 continued

Protocols	Cooperative condition	Research objective(s)	Classification			Drawbacks	Comment
			SO	DO	MO		
EAP-MAC [53]	Transmit power	Network lifetime and energy efficiency	√	–	–	Higher computational complexity and not robust in sparse networks	Trade-off is required to improve throughput
DCMAC [38]	Transmit time	Network lifetime, throughput, delay, and energy efficiency	–	–	√	Signal interference may arise in single hop networks. Suffers computational complexity	It assumes that helpers are always available in the regions considered
PO-MAC [37]	Transmit power and transmit time	Network lifetime, throughput and energy efficiency	–	√	–	Signal interference may arise arises with no definite rate region	The effect to signal interference need to be considered
COMAC [36]	Transmit power and target bit error rate (BER)	Energy efficiency and reliability	–	√	–	Deployed only for indoor static WSNs	The need to address the network lifetime is very important

SO single objective, *DO* dual objective, *MO* multi objective

that of the assisting helper node. The work focused on enhancing network throughput, reducing transmission delay, and improving the packet delivery ratio of the network. This design considered the drawbacks discussed in [52], including unguaranteed coding opportunity, unexploited multi-rate capability, and queuing conditions associated with the potential helper candidates. This design also introduced a connectivity table for each node to store its own connectivity and predict the conditions of its neighboring nodes in a single-hop manner.

The NCAC-MAC protocol consists of two collateral relay selection approaches based on the utility backoff function, namely, network coding-supported cooperative retransmission (NCS-CR) and pure cooperative retransmission (P-CR). The relay selection strategy for selecting the relay candidates in the NCS-CR focuses on coding opportunity, whereas the PC-R focuses on the queuing condition of the relay nodes to enhance the network throughput and reduce transmission delay. In this protocol, four distinct scenarios arise at the destination node during frame exchange. In Scenario 1, the payload is considered successfully decoded, thereby ending the current transmission process after receiving an ACK at the source. In Scenario 2, the payload is regarded as corrupted while the received signal-to-interference-plus-noise ratio (SINR) is above the set threshold. In this case, the destination node replies with the transmission of negative acknowledgement (NACK), which contains the SINR_FLAG assigned with the value of 1. This case indicates the requirement for cooperative support for the coded retransmission using NCS-CR.

All of the nodes that hear the NACK and have successfully decoded the packet are selected as the relay candidates. In Scenario 3, the payload is considered corrupted and the received SINR is below the set threshold. Thus, the destination node sends the NACK frame, which contains the SINR_FLAG assigned with the value of 0. Coded retransmission is unsupported given the low SINR. Therefore, traditional cooperative retransmission is performed based on the P-CR. In Scenario 4, if the payload and header are corrupted, then the header is considered totally lost and becomes infeasible for the destination to identify the source and request for retransmission. In this case, the source node starts a new transmission after its timeout.

The group contention-based relay selection (GC-RS) and splitting algorithm-based relay selection (SA-RS) algorithms were proposed to select the best helper node accurately. These algorithms are modified approaches to the relay selection process in [39].

The results obtained indicate that the aggregated throughput, transmission delay, and packet delivery ratio of the proposed protocol outperforms that of Legacy 802.11 MAC and Phoenix [52]. The comparison of the original NCAC-MAC and the two relay selection algorithms (GC-RS and

SA-RS) show that the performance was the same for aggregated throughput, but the energy consumption at varying packets increases in the order of original NCAC-MAC, NCAC-MAC with GC-RS, and NCAC-MAC with SA-RS. However, the work does not show the energy consumption analysis of the protocol and compare with that in [52].

3.4 Distributed energy-adaptive location-based MAC (DEL-MAC)

Wang and Li [34] proposed a cross-layer DEL-MAC protocol to improve the energy efficiency and network lifetime of MANETs given their constraint energy capability. Energy consumption during transmission, processing, and reception was considered in cooperative transmission. The protocol also introduced two new control frames, namely, eager-to-help and interference indicator (II), to broadcast the selected helper node and enhance the network spatial reuse. In this protocol, a proactive relaying strategy is used in which nodes that overheard the exchange of transmitted control packets between the source and the destination are selected as capable relay candidates.

The protocol was designed based on the location information and residual energy of the node in the vicinity of the source and destination nodes. Subsequently, the helper nodes that are capable of achieving energy efficiency explore contention using their residual energy and transmit power to select the optimal helper node. The selected helper broadcasts its II frame with its optimal transmitting power to reconfirm its interference range before forwarding the data packet to enhance the spatial frequency reuse of the network.

The results obtained show a major improvement in the energy efficiency and network lifetime with respect to Legacy 802.11 MAC and CoopMAC. However, network throughput degradation occurs. The protocol works efficiently in static and mobile networks. Therefore, the required network throughput improvement can only be deployed in mobile networks, with the main objective of extending the network lifetime.

3.5 Energy efficient CMAC (EECO-MAC)

In [49], the authors proposed an EECO-MAC protocol with power control in MANETs. The primary goal of this work was to enhance the energy efficiency and improve the lifetime of networks by incorporating additional helper nodes into its transmission. The work also investigates two types of backoff algorithms, namely, space–time and time–space; these algorithms are involved in selecting the optimal helper node to achieve its set objective.

The results obtained in this work indicate that the EECO-MAC outperforms the Legacy 802.11 MAC and CoopMAC in terms of energy efficiency and network lifetime. However, these protocols undergo degradation in terms of network throughput with respect to CoopMAC in the dense and sparse network scenarios. The time–space backoff-based EECO-MAC was determined to be more efficient than the space–time backoff.

3.6 Energy-aware cross-layer CMAC (EAP-MAC)

Mahmoud et al. [53] proposed an energy-aware cross-layer CMAC protocol for ad hoc networks with the integration of PHY-layer network coding (PNC). A two-way transmission network model was adopted. This model allows the source and destination nodes to transmit their data packets to each other simultaneously through an intermediate helper and maps the superimposed electromagnetic signal into a network-coded packet to enhance the spectral efficiency, minimize the energy consumption, and extend the network lifetime.

The protocol encompasses three transmission modes with backward compatibility, namely, Legacy 802.11 MAC, traditional cooperation, and PNC-based cooperation transmission, thereby making the protocol adaptable to varying wireless channel conditions. A major contribution of the protocol was developing a 3D discrete time Markov chain model with a focus on saturated and imperfect channel conditions.

The results obtained in this work denote that the energy efficiency and network lifetime of the EAP-CMAC outperform that of Legacy 802.11 MAC and CoopMAC but undergo network throughput degradation with respect to CoopMAC. Therefore, throughput improvement by trading off with energy consumption should be considered when the PNC transmission mode is activated to strengthen the protocol.

3.7 Power optimized CMAC (PO-MAC)

The protocol proposed in [37] was designed for WSN; this protocol was aimed at minimizing energy consumption and extending the network lifetime of extensive working energy-limited nodes efficiently. The work mainly focused on network lifetime and data packet delivery in different traffic load situations. Lifetime extension transmission power optimization and greedy algorithm were introduced to balance the energy consumption and improve the energy utilization of different nodes in the network in a distributed manner.

The nodes that satisfy the optimization solution (i.e., high channel gain and residual energy) were selected as the optimal helper group. A dynamic contention access and collision resolution procedure was also adopted to ensure that the optimal group of helper nodes is selected to retransmit their overheard data packet to the destination simultaneously with their estimated optimized power to avoid unnecessary contention access delay.

The results obtained showed that the network lifetime and data packet delivery in the uniform and nonuniform traffic load situations of PO-MAC outperform Legacy 802.11 MAC and EE-CR [54]. However, signal interference might degrade the network performance because no definite multi-rate regions are considered. The proposed PO-MAC disregards the overhead incurred in transmitting the control packet, which consumes extra energy with a high number of helpers.

3.8 Distributed CMAC (DCMAC)

The distributed CMAC protocol was proposed by Shamna and Jacob [38] to extend the network lifetime, improve the throughput, and minimize the transmission delay of cooperative networks using optimization techniques.

The system model used was a modification of that used by Liu et al. [10], with emphases on three high data rate cooperative regions, that is, (5.5,5.5), (11,2), and (2,11) Mbps based on the multi-rate capability of the Legacy 802.11 MAC protocol. The work indicated that two relays can be used in a distributed manner to balance the energy consumption among nodes in the network, rather than employing a single relaying node for forwarding the data packets to the destination. The assumption was that an assisting node constantly exists in the region under consideration.

The results obtained in this work resolved the throughput, network lifetime, e2e delay, and energy consumption problems and outperformed EECO-MAC in terms of throughput, e2e delay, packet delivery ratio, and energy efficiency but exhibited poor performance in network lifetime. However, this assumption may not apply in a sparse and mobile network scenario. In a practical and realistic network scenario, finding assisting nodes that possess the desired node resources, such as sufficient residual energy, high data rate, and good queue scheduling, in the area under consideration might become impractical.

4 CMAC protocol design and implementation challenges, and open research issues

4.1 Resource allocation

Wireless communication is characterized by scarce and under-utilization of allocated network resources such as the spectrum [16,59,60] which hinders optimal network performance. Ubiquitous networks have experienced tremendous growth in the past decade given the ever-increasing wireless access, thereby providing seamless connectivity with easy access to daily life activities. The dynamic and efficient sharing of the spectrum has become imminent to manage these scarce resources and cater to the hundreds of billions of users. The development of a robust and intelligent MAC protocol for the MAC layer stack has also become necessary [61], as indicated in [10]. CSMA/CA was developed in the Legacy 802.11 MAC protocol to reduce collision probability caused by hidden and exposed nodes (near and far effects) that resulted in retransmission (traffic congestion). The addition of a cooperative helper node has further aggravated these problems, thus resulting in high energy consumption, e2e delay, design complexities, and adaptation to the existing legacy technology.

CMAC protocol designs have significantly improved the efficient utilization of constrained wireless bandwidth and facilitated the simultaneous/orthogonal transmission of data packets, which have effectively increased the bandwidth efficiency [7], achieved a high data rate with low transmission delay, and improved the network coverage [38,39]. The effect of other resources has received minimal attention because most protocols focus on improving the network performance through aggregated throughput or energy efficiency. Future wireless networks will realize a high demand and complex network scenario, which will considerably degrade the network performance. The design of intelligent CMAC protocols that can easily predict the dynamic nature and constraint network resources of complex heterogeneous wireless networks requires adequate attention and an open research area to be explored.

4.2 Power adjustment and energy issues

Power adjustment/control has a direct effect on constrained wireless networks and allows communicating mobile nodes to adjust their power level based on the distance, link quality conditions, interference, signaling scheme, and network lifetime. These ever-changing channel characteristics affect the energy capacity profile of power-constrained wireless networks [32,39,62]. Power-aware protocols are categorized as follows: (1) fixed transmit power, in which the transmit power of mobile nodes is fixed in all network conditions, thereby increasing the interference range [48,53] and minimizing the network lifetime; (2) varying transmit power, which allows mobile nodes to adapt its transmit power to changing network requirements with limited interference and conserve energy [34,37].

In the MAC layer stack, other factors that affect cooperative gain in addition to those mentioned previously include number of cooperative nodes (user orientation), relay selection schemes, and residual energy of nodes. These factors require adequate consideration to leverage the additional overhead incurred and total energy consumption [34,48]. Recently, network lifetime and energy harvesting have received increasing attention; these aspects are important for achieving energy efficiency. Other important aspects that jointly improve the network performance remain an open research area. The CMAC protocols that focus on power adjustment and energy issues are summarized in Table 3. A robust backoff algorithm for the CMAC protocols should be optimally designed to boost the overall network performance, with emphases on additional network resources. However, this robust backoff algorithm presents high cost and complexities and requires tradeoffs.

4.3 Relay selection

The selection criteria for the choice of the best helper node(s) among the potential nodes for cooperative transmission are one of the crucial challenges in the MAC layer design. The fundamental question "Whom to cooperate with?" is addressed based on the desired network target objective(s). Several researchers have proven that the optimal helper selected is not the best node(s) for beneficial cooperative gain in the MAC layer.

This finding can be attributed to the difference in the network target objectives. Several protocols on link quality conditions focus on preselecting the helper node before the transmission process begins, thereby relying on historical knowledge of the previous transmission. In this case, the preselected helper may not possibly be the best as the information becomes outdated given the varying network resource characteristics [10,55,64]. Several protocols have been designed to prioritize the nodes that have previously contended and participated in cooperation [31,65]; this finding may not possibly result in a reliable performance unless the network dynamics are adequately predicted for all network resources.

A robust relay selection process must consider the cross-layer design or the high percentage of network characteristics or possibly adapt/switch its helper selection criteria based on instant network requirements. The helper selection processes that fall into this category are few and pose a major challenge to CMAC protocol designers, hence resulting in an open research direction. Table 4 lists existing CMAC protocols with their selection characteristics.

4.4 Nodes mobility and density

The distributed nature and dynamic topology of wireless nodes make the design of wireless networks a difficult task. From the PHY layer perspective, a high diversity gain equates to a large number of relaying nodes. However, the interference area increases, and the frequency of spatial reuse decreases, thereby significantly degrading the network performance [34,35].

For the MAC layer, the deployment of additional nodes can erode the benefits of cooperation caused by high overhead, high collision probability, and extended backoff and helper(s) selection time, thereby resulting in bandwidth and energy wastage. Most designs have focused not only on single-user cooperation but also on the requirement to harness the advantage of multiple helper nodes [37,38] and exploit the multi-rate network capability. The dynamics of the node and its density create uncorrelated links that minimize the effect of deep fading, thus enhancing the network performance.

Fairness among the nodes is also equally important in network resource sharing. Prioritizing certain sets of nodes given their previous transmission successes deprives other nodes of the opportunity to access the channel. If the CMAC protocols are improperly designed with node mobility and density in mind, then collision probability may increase, thus resulting in misuse of scarce network resources and shortened network lifetime. In the case of multiple cooperative nodes, several protocols have demonstrated that multiple nodes that were allowed to aid in retransmitting the packet data can perform better than a single relaying node but is only feasible if the protocols are properly designed to select an optimal number of helper nodes by locally optimizing certain parameters (such as SNR, energy consumption, and interference range) with low computational complexity.

4.5 Spatial frequency reuse

The degree of spatial reuse of the constrained wireless spectrum is an important factor for the efficient management of network resources in the MAC layer. Many problems can lead to the deterioration of spatial frequency reuse. One major problem is associated with the interference range of cooperative networks. Transmission at fixed or high power restricts other neighboring nodes from transmitting and therefore results in adverse effects of the hidden and exposed terminal problems the interference area of the participating helper nodes enlarges the expected cooperative transmitting range. The high collision probability increased the channel resource consumption and reduced the degree of spatial reuse of the spectrum, thereby subsequently degrading the overall network performance [52]. Most protocols mainly focus on aggregated network throughput or energy-saving approach with minimal emphasis on spatial frequency reuse. Khalid et al. [57] considered a two-helper relaying scenario, with the second helper serving as a backup during an adverse channel condition. In their work, the interfering region of the two helper nodes was disregarded, although cooperative diversity gains translated into an enhanced network aggregated throughput. The degree of spatial frequency reuse was completely neglected, which can result in bandwidth inefficiency in a situation when nodes are near one another. However, the appropriate setting of the NAV in [34] reduced the interference area by appropriately adjusting the transmit power during the interference indication and data transmis-

Table 3 CMAC protocols with power adjustment and energy issues

Protocols	Backoff characteristics	Coordination	Layer of helper selection	Advantages	Disadvantages
LCMAC [39]	Power control	Distributed	MAC	Improves throughput and saves energy	It does not take into consideration the helper nodes resources (residual energy)
EAP-MAC [53]	Residual energy and location information	Distributed	Cross-layer	Improves network lifetime and energy efficient in dense and high mobility networks due to reduced packet error	Suffers throughput degradation
DEL-MAC [34]	Residual energy and power control	Distributed	PHY and NET	Improves network lifetime, energy efficient and improves spatial reuse	Suffers throughput degradation
EECO-MAC [49]	Residual energy and power control	Distributed	PHY and MAC	Enhance throughput, energy efficient and suitable for sparse networks	Throughput only improves at higher network density
PO-MAC [37]	Residual energy and power control	Distributed	PHY and NET	Rely on the shortest path between the source and destination nodes via the helper	Consumes more energy in severe channel condition, no analytical backoff expression
COMAC [36]	Power control	Distributed	PHY and MAC	Balances the tradeoff between reliability and energy cost	Deplorable for static WSN only. Network lifetime nit considered
DCMAC [38]	Residual energy, link quality, and queue size	Distributed	PHY and MAC	Maximizes network lifetime improves throughput and reduces delay when compared to Legacy MAC	Not energy efficient as compared to EECO-MAC

Table 4 Relay selection information parameters

Protocols	Relay selection backoff parameters							Target objective		
	LQI	EI/PI	LI	SII	REI	QSI	NCI	SO	DO	MO
CoopMAC [10]	√	–	–	–	–	–	–	√	–	–
LCMAC [39]	√	√	–	–	–	–	–	–	√	–
2rcMAC [57]	√	–	–	–	–	–	–	√	–	–
CoRe-MAC [31]	√	–	–	–	–	–	–	√	–	–
DEL-MAC [34]	-	√	√	√	√	–	–	√	–	–
NCAC-MAC [35]	–	√	√	√	–	–	√	√	–	–
EECO-MAC [48]	√	√	–	–	√	–	–	√	–	–
EAP-MAC [53]	–	–	√	–	√	–	√	√	–	–
RRS-MAC [56]	√	–	–	–	–	–	–	√	–	–
DCMAC [38]	√	–	–	–	√	√	–	–	–	√
NCCARQ-MAC[58]	–	–	√	–	–	–	√	√	–	–
SRcoop MAC [47]	√	√	√	-	-	-	-	-	√	–
COMAC [36]	√	√	–	–	–	–	–	–	√	–
PO-MAC [37]	√	√	–	–	√	–	–	–	√	–

LQI link quality information, *EI/PI* energy/power information, *LI* location information, *SII* signal interference information, *REI* residual energy information, *QSI* queue schedule information, *NCI* network coding information

sion phases, thereby essentially increasing the degree of spatial reuse and network lifetime.

In [31], relaying on demand with early retreat significantly reduced the number of participating helper nodes in the network. A prioritized set of helper nodes engage in cooperation if the best helper node is found available, thereby resulting in a high degree of spatial frequency reuse and vice versa. However, most of these works have assumed that the helper node is single and static during the period of cooperative transmission, thus an open area of research for protocols that can fit into the practical wireless network scenario and performance metric definition.

4.6 Security

A solution to the rampant vulnerability of data information systems has become increasingly important, especially in the present world. Several spates of illegitimate activities or misbehaviors, such as hacking, spying, unsolicited obstructions, and selfish/malicious handling [66], constitute serious threats to data packet transmission in cooperative networks [41]. These threats/attacks could possibly result in denial of service (i.e., deliberate dropping/jamming) or spoofing (i.e., falsifying, replaying, and cheating) of the overheard packet before retransmission [67]. These threats are characterized by different misbehaviors, especially in distributed wireless networks [68].

Robust and dynamic attack detection schemes (that can scan neighboring nodes or new entrants with threat capability) and network security measures that can be adopted across the layer stack with authenticity, authorization, integrity, confidentiality, and non-repudiation properly implemented at the MAC layer [68] are important to adequately protect the originality of retransmitted data packets. However, this feat is difficult because an extra overhead associated with implementing cryptographic techniques results in high e2e transmission delay and energy consumption. This issue poses a considerable challenge because the helper node not only requires correctly decoding the overheard data packets of channel errors but also possess requisite digital signatures (keys) required to ensure the authenticity, confidentiality, and integrity of the retransmitted data packet.

Few works that have analyzed the vulnerabilities of feasible security threats to CMAC protocol design include [69,70] with different arguments. Several researchers have contended that helper nodes that portend security threats to transmitted signals be completely blocked to ensure fairness in network resource sharing to legitimate helper nodes. Other researchers believed that adequate punishment (such as blacklisting) be meted on such malicious nodes to prevent these nodes from further participation [41]. However, most CMAC protocols have disregarded the effect of implementing cryptographic capability with neighbor nodes and new entrant scanning assessment. In fact, most existing protocols have assumed perfect decoding at the helper node. The last two fundamental questions are reposed as “How secured are overheard/eavesdropped signals in cooperation?” This question remains unanswered and requires a serious practical solution, hence a critical open research area that should be explored to address security threat adequately.

4.7 Multiple metric-oriented protocols

For the efficient design of the CMAC protocols, the ever-changing network requirements require adequate adaption and multiple metric-oriented protocols [13], which play an important role in accurately identifying the cooperative opportunities. Additional CMAC protocols are expected to drift in this direction to stimulate the benefits of cooperation to the overall network because only a few works fall into this category, as presented in Table 4.

4.8 Incentives

The CMAC protocols that are designed based on game theory [71] are subject to the possibility of creating incentives for the helper nodes through repeated gaming. Helper nodes that cannot acquire gain/benefit for itself are removed from cooperation. Advertisements become necessary to identifying such nodes; this advertisement also incurs additional overhead and consumes extra energy. Other gaming methods, such as incomplete, auction, and Bayesian, can be found in [61,72]. This gaming concept is a growing area of study and remains open for in-depth research.

4.9 Hardware limitation and performance

The practical implementation of the CMAC protocols into the existing network infrastructure is the endpoint of communication network deployment. The design and fabrication of hardware play a vital role in this regard. Most designs have practically assumed the ideal cases of the hardware without considering their level of impairments. To the best of our knowledge, the performance limits of transceiver hardware impairment on the MAC layer protocols have not been exploited. Several studies of information theory of the PHY layer stack in [73–75] show that hardware distortion effects, such as phase noise, in-phase/quadrature imbalance, and high-power amplifier nonlinearities, affect the network performance in implementing practical cooperative networks. These hardware distortion effects adversely affect the energy consumption and quality of service of networks, thereby remaining as an important open area of study in the practical deployment of MAC protocols for cooperative networks.

5 Conclusion

Cooperative communication has received considerable research attention in the PHY layer stacks and requires a high or cross-layer design. The deployment of an efficient and robust CMAC protocol is a prerequisite for standardizing this technique and remains a major contribution. In this study, we classify existing CMAC protocols based on target objectives, that is, single, dual, and multi-objective. Moreover, we present their relay selection backoff robustness to ever-changing network requirements. The design challenges, implementation, and open research issues facing the effective deployment of the CMAC protocol were identified and discussed appropriately.

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