Distributed Cross Layer Cooperative MAC Protocol for Multihop Wireless Networks

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***Abstract*—Extending the battery lifetime of energy constrained devices is a key issue in designing wireless adhoc networks. The existing works focus on using cooperative communications for improving network performance in terms of throughput, delay, spectral efficiency, etc. In this paper, we propose a distributed cross layer cooperative Medium Access Control (MAC) protocol for a multihop network environment that can improve the network lifetime and energy efficiency while not degrading the network throughput and end to end delay. The results show that the proposed protocol can improve the performance of the network in terms of network lifetime, throughput, end-to-end delay, and energy efficiency.**

Keywords–Wireless Ad hoc Networks; Cooperative Communication; Cross Layer; Energy Efficiency; Network Lifetime.

I. Introduction

Wireless communications have developed tremendously over the past few decades due to the large demand for mobile and wireless access. Compared to wired communications, the signals transmitted over the wireless channels may suffer from severe attenuation. The overall reliability of wireless communication can be significantly improved by transmitting multiple copies of the same signal over multiple independent fading channels. Multiple-Input-Multiple-Output (MIMO) systems achieve spatial diversity by deploying multiple antennas at the transmitter side and receiver side [1]. However, due to size, cost, and hardware limitations, mobile devices may not be able to support multiple antennas.

Recently, cooperative communication is widely used as a transmission strategy for wireless networks. It is a cost effective alternative to the MIMO systems. Here, wireless nodes work together to form a virtual antenna array to achieve diversity gains. It takes advantage of the broadcast nature of the wireless channel to allow communicating nodes to help each other [2]–[4]. Most cooperative transmission schemes involve two phases of transmission - a coordination phase and a cooperation phase. In the coordination phase, the nodes exchange their own source data and control messages with each other. In the cooperation phase, the nodes cooperatively forward their messages to the destination. Cooperative communication improves the network capacity, data transfer delay and Bit Error Rate (BER) performance, reduce battery consumption, and extend the coverage area [5].

When cooperative communication is employed at the physical layer, the receiving node can use physical layer combining to achieve diversity gain and this helps cooperative communication to achieve a higher signal-to-noise ratio (SNR) than the traditional Single-Input-Single-Output (SISO) systems. This SNR advantage can be used to reduce the power of transmitting nodes, which in turn, will increase the lifetime of the network. By using the concept of cooperative communications at the MAC layer, the transmitter (Tx) of a communication link can send the packet to the relay nodes instead of sending it to the receiver (Rx) of that link. Such a communication link is called a cooperative link. Usually, the nodes in between the Tx and Rx are selected as relay nodes. The transmit power or energy required to transmit a packet via cooperative link is comparatively lower than that of transmitting it via direct link. This will effectively improve the network lifetime. So, cooperative MAC can improve the lifetime of energy constrained devices and increase the network lifetime [6], [7].

A proper design of MAC protocols is necessary to exploit the advantages of cooperative diversity in a multiple user cooperative network. The cooperative MAC protocols developed in the past few years show how the MAC layer protocols can be modified to incorporate cooperation in the physical layer and the advantages of cooperative communication from a MAC layer perspective [6]–[12]. Depending on the channel condition, these protocols can apply two hop data transmissions in the MAC layer to achieve higher transmission rates. Most of these protocols aim to improve the overall system throughput and reduce the packet delay. Performance of the protocols in terms of energy efficiency or overall lifetime of the network are not discussed in these works.

The existing works on cooperative communications at physical layer focus on improving spectral efficiency, coverage area, BER, interference reduction, etc. The works on cooperative MAC protocols developed during the past years focus on improving network performance in terms of throughput, delay, and packet delivery ratio. Finally, the works on cooperative routing protocols use the relay nodes to find the energy or power efficient route. In most of the existing cooperative MAC protocols, the resources of the relay nodes (residual energy, queue size, etc.) are not considered while selecting the relay. For each destination, the best relay that can improve the network performance is used for transmitting all the packets generated by the source. This leads to over utilization of resources of some specific relay nodes, while the resources of the other relays are under utilized. In this paper, we propose a distributed cross layer cooperative MAC protocol that can efficiently utilize the resources of the nodes and improve the energy efficiency and network lifetime while maintaining a reasonable throughput and end to end delay.

The rest of the paper is organized as follows. A brief description of the related works is given in Section II. Description about the distributed cooperative MAC is given in Section III. A simple expression for the saturation throughput of the proposed protocol is derived in Section IV. Simulation results are discussed in Section V. Conclusion and future work are presented in Section VI.

II. Related Work

In [7], the authors propose a cross layer distributed energy adaptive location based cooperative MAC protocol with the objective to improve the network performance in terms network lifetime and energy efficiency. In this protocol, the relay selection process is distributed and the best relay is selected based on location information and residual energy. An optimal cross layer power allocation scheme is designed that maintains a constant data rate to meet the desired outage probability requirement. The multi rate capability of 802.11 is not considered in this paper. The throughput of the proposed protocol is even lower than that of legacy 802.11 Distibuted Coordination Function (DCF).

In [13], the authors present a framework for extending the lifetime of energy constrained devices by exploiting cooperative diversity. The cooperation strategy used is based on decode-and-forward (DF) relaying protocol. They formulate an optimization problem with the goal of maximizing network lifetime under a BER constraint, and the solution gives which node to be selected as the relay and how much power to be allocated. The impact of cooperative communications in the higher layers of the protocol stack is not considered in this paper.

In [14], the authors propose an energy efficient cooperative MAC protocol to reduce energy consumption and increase network lifetime by power control. Also, they use a distributed utility based optimal helper selection procedure based on the residual energy and transmission power. They also propose a space and time combination backoff scheme to adjust the power level and contention window in the event of transmission failures. The data and control packets are transmitted using a single data rate. Request-To-Send (RTS) and Clear-To-Send (CTS) messages are transmitted at the highest power level and DATA and Acknowledgement (ACK) are transmitted at the minimum power level.

A low power receiver initiated cooperative MAC for wireless sensor networks is proposed in [15]. The authors compare the energy consumption between SISO, multi hop SISO, and cooperative relay systems for ideal and real MAC protocols to show the impact of MAC layer on the total energy consumption. The performance of the protocol in terms of network lifetime is not considered in this work.

Routing protocols which are based on cooperative communications are known as cooperative routing protocols. In [16], the authors propose cooperative routing protocols that can improve the network lifetime by selecting the energy efficient route. The problem of finding the minimum energy route is formulated as two seperate optimization problems. The first problem is to find the optimal transmission of information between two sets of nodes and the second problem is to decide the neighboring nodes to be selected to route traffic to the destination with minimum overall energy consumption.

A route that requires the minimum transmitted power while maintaining a certain end-to-end throughput is proposed in [17]. The proposed routing protocol makes full use of the cooperation communications to construct the minimum power route. The authors derive a cooperation based link cost formula, which represents the minimum transmitted power that is required to maintain the required end-to-end throughput.

TABLE I. RATE VS RANGE [for IEEE 802.11b]

Data Rate (Mbps)	11	5.5	2	1
Maximum Range (Meter)	60	120	180	250

In most of the existing cooperative MAC protocols, the resources of the relay nodes (residual energy, queue size, etc.) are not considered while selecting the relay. For each destination, the best relay that can improve the network performance is used for transmitting all the packets generated by the source. The protocols that take into account the resources of the relay for the relay selection process explicitly use power control while maintaining a constant data rate. While these protocols improve the network lifetime, the throughput and delay performance degrade to a large extent.

In this paper, we present the design and analysis of a cooperative MAC protocol named DCMAC, which considers the residual energy and the data rate (physical layer parameters)and queue size (total number of packets to be transmitted), of the nodes for the relay selection process. The results show that the protocol improves the performance of the network in terms of energy efficiency, throughput, end-to-end delay, and network lifetime.

III. Distributed Cooperative MAC (DCMAC) Protocol

A. System Model

We consider an IEEE 802.11b/g based mobile ad hoc network where the node transcievers have multi-rate capability. The relationship between the transmission link distance and data rate is shown in Table I for the case of 802.11b transcievers. Two ray ground propagation model is assumed in getting this link length - data rate mapping. The wireless medium is shared among multiple contending mobile nodes. Depending on the distance between the Tx and Rx, a packet could be transmitted at different transmission rates. We assume no power adaptation, so each node transmits its packets using a constant transmission power. The wireless channel between the sender and the receiver is assumed to be almost symmetric. By applying the concept of cooperative communication at the MAC layer, slow one hop transmissions are replaced by fast two hop transmissions if suitable relays are available. Here, cooperative communication is employed only when the direct transmission rate is less than or equal to 2 Mbps and there exist relay nodes such that $\frac{1}{C_{TH}} + \frac{1}{C_{HR}} < \frac{1}{C_{TR}}$, where C_{TH}, C_{HR}, and C_{TR} denote the data rate from source to helper, helper to destination, and source to destination, respectively. In the case of a multi-hop network, Ad hoc On-Demand Distance Vector (AODV) [18] is used as the routing protocol. When a route is established, DCMAC protocol initiates cooperative transmission in a hop-by-hop manner by selecting the relay nodes.

B. DCMAC Protocol Description

DCMAC is based on the IEEE 802.11 DCF. We define one more control frame named Relay Ready To Cooperate (RRTC) to support MAC relaying in addition to the conventional control frames RTS, CTS, and ACK. RRTC is sent by the best relay node to indicate its willingness to act as a relay. The best relay (helper) is the node that can support the highest data rate

Frame Control	Duration	Source Address	Destination Address	Distance

Figure 1. RTS Frame Format

Frame Control	Duration	Source Address	Destination Address	Address 3	Sequence Control	Address 4

Figure 2. MAC PDU Header Format

between the Tx and Rx; and is one among the nodes which are within a routing pipe around the direct link between Tx and Rx, with residual energy above a given threshold, and with queue size below a given threshold. All the control frames are transmitted at the basic rate, i.e., 1 Mbps for 802.11b network and 6 Mbps for 802.11g network. The time duration for the transmission of RTS, RRTC, CTS, ACK, and DATA are denoted by T_{RTS}, T_{RRTC}, T_{CTS},T_{ACK}, and T_{DATA}, respectively.

1) Operations at the Sender:

a) When a sender has a packet to transmit, it first checks whether a cooperative link is beneficial or not. In the case of an IEEE 802.11b network, the cooperative link is beneficial if the data rate of the direct link is less than or equal to 2 Mbps. For an 802.11g network, a cooperative link is employed when the direct link data rate is less than or equal to 18 Mbps. *Distance* is a new field introduced in the RTS frame to support cooperative relaying. The format of RTS frame is given in Figure 1. If cooperative link is found beneficial, the node will copy the direct link length (distance in meters) to the destination in the distance field of the RTS message. Otherwise, this field is set to -1. The duration field denotes the time required to transmit the data frame which includes time for CTS, SIFS intervals, and ACK. Even if the sender decides to use cooperative communication, it does not know whether any helper exists to forward its packets. So the duration field in the RTS message is same for direct transmission and cooperative transmission. The duration field is given by

$$Duration = T_{SIFS} + T_{CTS} + \frac{8L}{C_{TR}} + T_{ACK} \tag{1}$$

where L denotes the payload length in bytes.

b) It then senses the channel to check if it is idle. If the channel is idle for DIFS, the node selects a random backoff timer between 0 and minimum contention window (CWmin). When the backoff counter reaches zero, the node sends an RTS to reserve the channel.

c) If the sender does not receive a CTS within $T_{RTS} + T_{SIFS} + T_{CTS} + 2\delta$, it will retransmit the RTS. Here δ denotes the propagation delay. Otherwise, the sender will wait for another $T_{maxbackoff} + T_{SIFS} + T_{RRTC} + \delta$, where $T_{maxbackoff}$ is the maximum backoff time for the relay nodes. If no RRTC is received within this time, it indicates that no relays are available to forward the data. The node will transmit the packet over the direct link and the ACK timeout is set as

$$\frac{8L}{C_{TR}} + 2\delta + T_{SIFS} + T_{ACK}. \tag{2}$$

d) If both CTS and RRTC are received, the sender will forward the data to the relay. The format of the MAC protocol data unit (MPDU) is shown in Figure 2. The sender stores the address of the relay in the destination field and the receiver address is stored in Address 3 field. In this case, the ACK timeout is set as

$$\frac{8L}{C_{TH}} + \frac{8L}{C_{HR}} + 3\delta + 2T_{SIFS} + T_{ACK} \tag{3}$$

The duration field denotes the time required to transmit the data including ACK and SIFS intervals. In the case of cooperative transmission, the value of the duration field in MPDU is given by

$$Duration = 2T_{SIFS} + \frac{8L}{C_{HR}} + T_{ACK} \tag{4}$$

In the case of direct transmission, the value of duration field in MPDU is

$$Duration = T_{SIFS} + T_{ACK} \tag{5}$$

e) If no ACK is received within the ACK timeout duration, the sender resumes the backoff procedure and contends for the channel again. When no ACK is received for cooperative transmission, the sender retransmits the packet directly to the receiver.

2) Operations at the Relay Nodes:

a) When an RTS message is received with the distance field set to -1, which is an indication that it is decided to use the direct link, the intermediate nodes will set their network allocation vector (NAV) to the duration specified in the duration field of the message.

b) If the distance field contains a non-negative value, the intermediate nodes check whether they can act as a relay. If they cannot act as a relay, they will set their NAVs. Otherwise, the relay nodes will wait for $T_{CTS} + T_{SIFS} + \delta$ duration. If no CTS message is received within this duration, the node will go back to idle state.

c) When the CTS message is received, all the potential relays contend to act as the best relay using the relay selection procedure described in Subsection III-C. The node whose cooperative backoff procedure expires first sends the RRTC message and when this message is heard by other potential relays, they abort the backoff procedure and will set their NAV duration and defer until the channel is idle. The format of RRTC message is given in Figure 3. The duration field denotes the time to transmit the data packet from transmitter to relay and from relay to destination. It also includes the time to send ACK and SIFS intervals. The duration field in the RRTC message is given by

$$Duration = 3T_{SIFS} + \frac{8L}{C_{TH}} + \frac{8L}{C_{HR}} + T_{ACK} \tag{6}$$

d) The best relay will wait for a duration equal to $T_{RRTC} + T_{SIFS} + \frac{8L}{C_{TH}} + 2\delta$ and if no data packet is received within this duration, it will go back to idle state. Otherwise, it will forward the packet to the

Frame Control	Duration	Source Address	Destination Address	Sequence Control

Figure 3. RRTC Frame Format

Frame Control	Duration	Source Address	Destination Address	Sequence Control

Figure 4. CTS Frame Format

destination. Before forwarding the packet, the value of the duration field in MPDU is changed to

$$Duration = T_{SIFS} + T_{ACK} \tag{7}$$

e) The relay waits for a duration of $T_{SIFS} + \frac{8L}{C_{HR}} + T_{ACK} + 2\delta$ to receive an ACK from the receiver. If no ACK is received within this duration, it will go back to idle state.

3) Operations at the Receiver:

a) When the Rx receives an RTS message it will send a CTS back to the source. The format of CTS message is shown in Figure 4. If the distance field is set to -1, the duration field of CTS is set to

$$Duration = 2T_{SIFS} + \frac{8L}{C_{TR}} + T_{ACK} \tag{8}$$

$$Duration = 3T_{SIFS} + T_{maxbackoff} + \frac{8L}{C_{TR}} + T_{ACK} \tag{9}$$

The destination will wait for $2T_{SIFS} + T_{CTS} + T_{maxbackoff} + \frac{8L}{C_{TR}} + 2\delta$ duration to receive either a data packet or an RRTC message. If no data packet or RRTC is recieved within the timeout interval, it will go back to idle state.

b) When a data packet is received, the Rx sends an ACK back to the Tx. If the packet is forwarded by a relay, a copy of the ACK is sent to the relay too.

C. Relay Selection Procedure

The existing cooperative MAC protocols mainly aim at improving network throughput or reducing the end-to-end delay by using cooperative communication. If the channel conditions remain the same, the same relay is selected by the source node every time it has a packet to be transmitted. The same relay may also be used by other source-destination pairs. In addition to this, the relay may also have some packets to be transmitted. These relay nodes run out of battery very quickly and may lead to network disconnection. At the same time, there may be other nodes in the network that are capable to act as relays. The energy consumption can be minimized if a portion of the traffic is relayed through each of the eligible relays. We propose a relay selection procedure to select the best relay based on its residual energy, queue size, and the data rate that it can support over the cooperative link.

When an RTS message is received with the distance field set to a non-negative value, all the neighboring nodes other than the destination check whether they are eligible to act as relays. A node is eligible only if its residual energy is more than 25% of the initial battery level and the following condition is satisfied:

$$\frac{1}{C_{TH}} + \frac{1}{C_{HR}} < \frac{1}{C_{TR}}.$$

All the nodes that satisfy the above condition will start a backoff timer to contend for the optimal relay. The backoff utility function is defined as

$$Backoff = Min\left(\left(\frac{\frac{1}{C_{TH}} + \frac{1}{C_{HR}}}{\frac{1}{C_{TR}}}\right)^{\alpha}\left(1 - \frac{E_r}{E_i}\right)^{\beta}\left(\frac{q_c}{q_{buf}}\right)^{\gamma}, \tau\right) \tag{10}$$

where E_r and E_i denote, respectively, the residual energy and initial energy at the relay node. The terms q_c and q_{buf} denote the number of packets in the queue and the buffer size, respectively. The value τ is used so as to limit the backoff time within an acceptable range. We fix the value of τ in such a way that the backoff time does not exceeds the time to transmit any of the control messages. The variables $\alpha, \beta, and \gamma$ are the weight factors associated with data rate, energy, and queueing parameters. For the results reported in the next section, we give equal weight to all the three parameters.

IV. DCMAC Analysis

In this section, we derive a simple expression for the saturation throughput of DCMAC. A simplified form of the system model presented in III-A is considered for analysis. We consider a single hop network in which all the source-destination pairs are separated by a distance between 120 to 180m. We assume that there exist two helpers between every source-destination pair that can support data rates of (11,5.5) and (5.5,5.5) between the source to helper, and helper to destination, respectively. Only 25% of the total nodes generate traffic and the remaining nodes act as destination and relays. The performance analysis of the IEEE 802.11 DCF presented in [19] and the analysis of CoopMAC [6] are used for analysing the performance of the proposed protocol.

Let Ts denote the transmission time for one packet and L denotes the size of the packet in bytes. For DCMAC protocol, Ts is defined as

$$T_s = (P_{11,5.5} + P_{5.5,5.5})\, T_{DCMACOH} + \frac{8LP_{11,5.5}}{R_{11}} + \frac{8LP_{11,5.5}}{R_{5.5}} + \frac{16LP_{5.5,5.5}}{R_{5.5}} \tag{11}$$

where $T_{DCMACOH}$ denotes the DCMAC overhead, $P_{11,5.5}$ and $P_{5.5,5.5}$ denote the probability to transmit the packets through the relays that support data rates of (11,5.5) and (5.5,5.5) between the source to helper, and helper to destination, respectively. These probabilities are obtained through numerical approximation.

$$T_{DCMACOH} = 2T_{PLCP} + 5T_{SIFS} + T_{RRTC} + T_{DIFS} + T_{RTS} + T_{CTS} + T_{ACK} + T_{maxbackoff} \tag{12}$$

In the case of EECO MAC protocol [14], Ts is defined as

$$T_s = T_{EECOOH} + \frac{16L}{R_2} \tag{13}$$

where T_{EECOOH} denotes the EECO MAC overhead and it is defined as

$$T_{EECOOH} = 2T_{PLCP} + 5T_{SIFS} + T_{HTS} + T_{DIFS} + T_{RTS} + T_{CTS} + T_{ACK} + T_{eecomaxbackoff} \tag{14}$$

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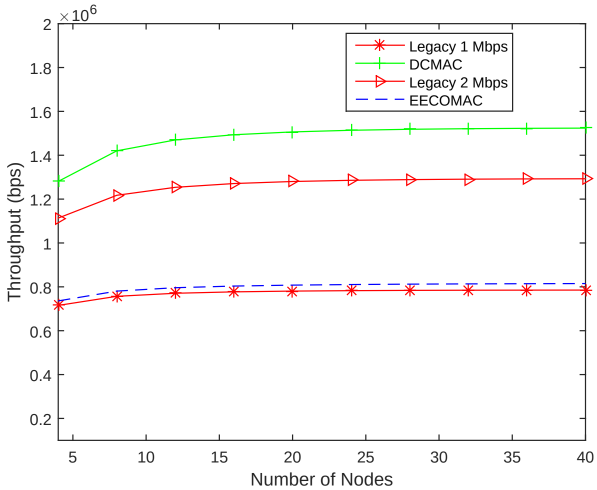

Figure 5. Throughput vs Number of Nodes

R_{11}, $R_{5.5}$, and R_2 represent 11 Mbps, 5.5 Mbps, and 2 Mbps, respectively. From [19], the saturation throughput is defined as,

$$S = \frac{P_s P_{tr} L}{(1 - P_{tr})\sigma + P_s P_{tr} T_s + P_{tr}(1 - P_s)T_c} \tag{15}$$

where P_s is the probability for successful transmission, P_{tr} is the probability that at least one station transmits in a given slot, σ is the slot time, and T_c is the collision time. P_s and P_{tr} are obtained through the Discrete Time Markov Chain (DTMC) analysis of Bianchi [19]; and $T_c = T_{RTS} + T_{DIFS} + \delta$.

Figure 5 compares the saturation throughput performance of the proposed protocol with the legacy DCF that transmits packets at 1 Mbps and 2 Mbps, and EECO-MAC [14]. The throughput of the proposed protocol is higher than that of legacy DCF and EECO-MAC. In the proposed protocol, the packets are forwarded using the relays that support (11,5.5) and (5.5,5.5) data rates in both directions. But in the case of EECO-MAC, the packets are forwarded through the relays at a rate of 2 Mbps.

V. Simulation Results

The proposed DCMAC protocol described in the previous section is implemented in the NS2 network simulator [?]. A network topology of 600 x 600m^2 is considered. Nodes are uniformly and independently distributed at random locations. Two ray ground reflected model is considered for wireless channel and IEEE 802.11b parameters are used for the experiments. The data rates for different transmission ranges as per IEEE 802.11b are shown in Table I. The simulation parameters are listed in Table II. EECO-MAC [14] protocol was developed to improve the network lifetime. So, the performance of the proposed protocol is compared with that of EECO-MAC. We also compare the performance of the proposed DCMAC with the legacy 802.11 DCF that transmits packets at a rate of 1 Mbps. 10% of the total nodes are considered as source nodes generating CBR traffic and their destinations are selected randomly.

Figure 6 shows the relationship between the number of nodes and the overall throughput at a fixed payload size (512 bytes). For EECO-MAC and DCMAC protocols, as the

TABLE II. SIMULATION PARAMETERS

MAC Header	272 bits
PHY Header	192 bits
RTS	352 bits
CTS	304 bits
RRTC	304 bits
ACK	304 bits
Data Rate for MAC Header	1 Mbps
Slot Time	20 μs
SIFS	10 μs
DIFS	50 μs
CWMin	31 Slots
CWMax	1023 Slots
Retry Limit	6

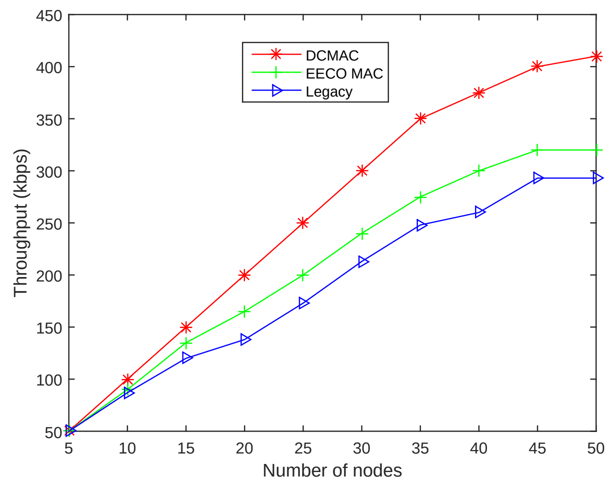

Figure 6. Throughput vs Number of Nodes

number of nodes increases, the availability of helpers for forwarding data packets increases and hence these protocols have better throughput compared to 802.11 DCF. This increase in throughput is due to the increase in availability of helper nodes which results in faster two hop transmission instead of single one hop transmission. The proposed DCMAC protocol has significantly higher throughput than the EECO-MAC. This is because EECO-MAC transmits data at a fixed rate of 2 Mbps.

Figure 7 shows the relationship between the number of nodes and delay.The delay performance is also better in the case of DCMAC protocol. This is because in EECO MAC, the transmission time is doubled when cooperative communication is employed. In addition to this, the sender node has to wait for a certain amount of time to receive the HTS message. In the case of DCMAC, the source node has to wait for a certain amount of time to get the RRTC message. If cooperative transmission is used, the data is transmitted at higher rates.

The network lifetime and the average energy consumption for different network sizes are shown in Figures 8 and 9, respectively. In EECO MAC, the transmit power is lowered when cooperative communication is used. This leads to a decrease in the total energy consumption and increases the network lifetime. In DCMAC, the relay nodes are selected based on the residual energy level; and as the residual energy of a relay node decreases, other nodes are selected as relays and this leads to an increase in the overall network lifetime. But, in DCMAC, all messages are transmitted with fixed transmit

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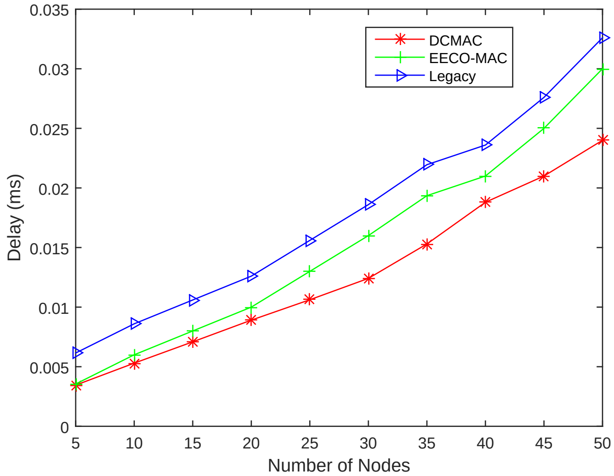

Figure 7. Delay vs Number of Nodes

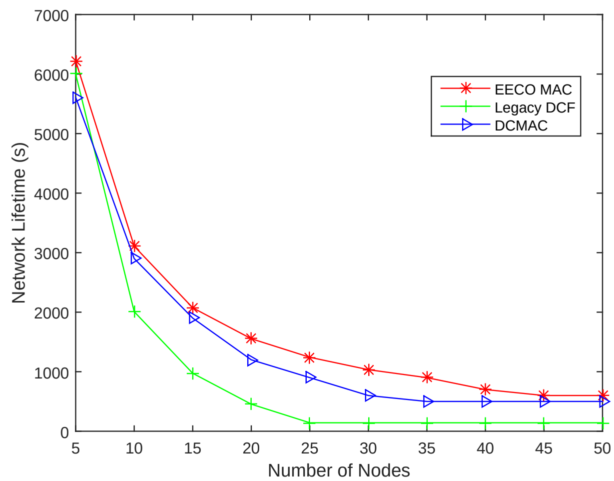

Figure 8. Network Lifetime vs Number of Nodes

power and therefore the energy efficiency and network lifetime is slightly reduced when compared to EECO MAC.

VI. Conclusion

In this paper, we have proposed a distributed cross layer MAC protocol for multihop networks by employing cooperative communication. The relay selection process is distributed and the optimal relay is selected by considering the residual energy, queue size, and location of the potential relays. The simulation results show that the network lifetime and energy efficiency can be improved in multihop networks by using cooperative communication in the MAC layer. The results also show that the proposed protocol can improve the network lifetime and energy efficiency without degrading the network throughput and delay performance.

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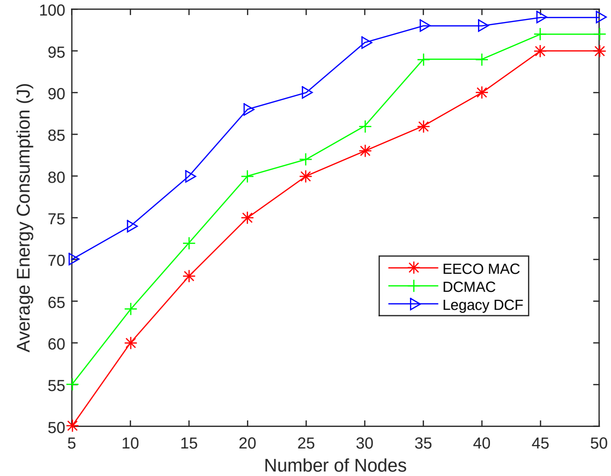

Figure 9. Average Energy Consumption vs Number of Nodes

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