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DEC-MAC: delay- and energy-aware cooperative medium access control protocol for wireless sensor networks

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Abstract This paper deals with two critical issues in wireless sensor networks: reducing the end-to-end packet delivery delay and increasing the network lifetime through the use of cooperative communications. Here, we propose a delay- and energy-aware cooperative medium access control (DEC-MAC) protocol, which trades-off between the packet delivery delay and a node's energy consumption while selecting a cooperative relay node. DEC-MAC attempts to balance the energy consumption of the sensor nodes by taking into account a node's residual energy as part of the relay selection metric, thus increasing the network's lifetime. The relay selection algorithm exploits the process of elimination and the complementary cumulative distribution function for determining the most optimal relay within the shortest time period. Our numerical analysis demonstrates that the DEC-MAC protocol is able to determine the optimal relay in no more than three mini slots. Our simulation results show that the DEC-MAC protocol improves the end-to-end packet delivery latency and the network lifetime significantly compared to the state-of-the-art protocols, LC-MAC and CoopMAC.

Keywords End-to-end packet delay · Network lifetime · Cooperative communication · Process of elimination · Complementary cumulative distribution function

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1 Introduction

With the advancement of microelectromechanical systems technology, sensors are becoming increasingly small and economical. Since, they are typically battery-operated, thus it is very difficult to change battery from a tiny node and also difficult to replace a node from any hostile environment, making sensor nodes energy-constraint. Therefore, lifetime maximization is one of the primary concerns for wireless sensor networks (WSNs). End-to-end data packet delivery delay is another important constraint in many applications of wireless sensor networks [1, 2] such as tracking the target in a battlefield, critical patient monitoring in a hospital, and controlling temperature in industrial settings [3]. Hence, energy and data packet delay should be jointly considered in designing protocols for critical applications.

Interference and signal loss due to distance and fading severely reduce the data delivery performance of wireless networks. Multiple input multiple output (MIMO) is able to significantly improve the transmission quality [4]; however, it is not possible to design sensor nodes with MIMO ability due to their small size and power constraints [5, 6]. However, a cooperative communication technology is able to introduce this ability in very small wireless sensor networks. Cooperative communication exploits the wireless broadcast advantage by using neighbor nodes as relays [4]. A neighbor node acting as a relay node retransmits the packet in order to facilitate better reception at the destination end [5, 7]. There are two approaches for implementing cooperative communications: *proactive* and *reactive*. In the *proactive* approach, the relay is selected prior to the direct transmission; in *reactive* approach, the relay is selected only when a direct transmission has failed.

Network lifetime maximization is the primary issue, and metrics such as delay are the secondary issue [8, 9] in current wireless communications research. Most existing research efforts [4, 5, 8, 10] on cooperative wireless sensor networks have focused on approaches that attempt to maximize a network's lifetime. Other quality metrics, such as the delay, throughput, and jitter, have received little attention. A few research efforts [9, 11] have considered delay and energy, thus developing duty cycle-based medium access control (MAC) protocols; primary results show a wide range of trade-offs between delay and energy consumption. Both of the published papers provide solutions for lifetime maximization considering primary and secondary issues that apply traffic adaptive duty-cycle MAC.

The majority of the cooperative solutions [3–5, 12–14] select the relay on the basis of channel state information. All of these protocols focus solely on energy efficiency, causing the network to partition into multiple parts. Since nodes with better channel conditions frequently participate in cooperation, they finish their energy earlier, thus creating energy holes [15] in the network. Energy holes partition the network and hamper the ability to acquire critical data from the target location, causing an early network lifetime termination. Alternatively, the nodes with poor channel conditions, rarely participate in cooperation; energy may remain unused for those nodes resulting in unbalanced power consumption issues within the network. An analysis in [16] shows that energy left unused can reach up to 90 % of total initial energy of the network at the end of a network's lifetime for unbalanced power consumption.

Recently, some papers [17, 18] have proposed energy-aware cooperative MAC rather than using channel state information; selecting the relay with the highest residual energy helps to balance the energy consumption among the nodes. Therefore, their protocols reduce wasted energy and increase the network lifetime. However, delays may be incurred due to the poor channel conditions of the relay with the highest residual energy.

In this paper, the DEC-MAC protocol is designed with consideration for both delay and residual energy. Earlier discussions revealed that a relay having a higher residual energy might introduce additional delay; alternatively, the relay with better channel conditions forces a reduction in the network lifetime due to the network partitioning problem, thus creating a critical problem for the network. To overcome this problem, the DEC-MAC protocol seeks to optimize the trade-off between residual energy and delay; we developed a mechanism considering both the residual energy and delay in order to optimize the relay selection. This mechanism selects an optimal relay that enhances to keep balance the energy consumption among the nodes of network leading to longer network lifetime and less end-to-end delay.

No research has been conducted on cooperative MAC with consideration for both residual energy and delay. Our proposed DEC-MAC protocol maximizes the network lifetime and reduces the packet delivery delay, thus it is applicable in many real-time applications. The primary contributions of our research are summarized as follows:

- We consider a framework that enables balanced energy consumption among network nodes.
- We develop an algorithm to quickly select the optimal relay.
- We propose a cooperative MAC that increases the network lifetime.
- Finally, we simulate our proposed protocol and evaluate the performance of the network. Simulation results demonstrate that the proposed DEC-MAC protocol is able to significantly increase a network's lifetime.

The remainder of this paper is organized as follows. We first review related research in Section 2 and then discuss the network model and assumptions in Section 3. Our novel delay- and energy-aware medium access control protocol DEC-MAC is described in Section 4. Next, we analyze the number of required mini slots, end-to-end packet delivery delay, and network lifetime in Section 5. We present performance evaluation and simulation results in Section 6. Finally, we conclude the paper in Section 8 with some remarks and future scope of works.

2 Related research

Network lifetime maximization is a great challenge for very small energy-constrained sensor nodes. Alternatively, delay is another important issue in the timely delivery of data. A large number of MAC and routing protocols for WSNs aim to increase energy efficiency [4, 5, 7, 8, 10] and to decrease the end-to-end delay [1, 2, 19, 20]; the cited references either pay attention to energy efficiency or to delay minimization. Only a couple of studies reporting noncooperative protocols [9, 11] have included investigations of delay and energy together in WSNs; both of these protocols have trade-offs between energy efficiency and delay in order to optimize the lifetime and end-to-end packet delay.

Cooperative communication has the ability to provide better performance in the domain of energy efficiency and end-to-end packet delay. Cooperative protocols [4, 12, 13, 21] work on increasing throughput or reliability by selecting their relays on the basis of channel state information. The cooperative protocols in [5, 6, 17, 22] propose to maximize the lifetime on networks or to make more energy-efficient the protocol. All of these papers concentrate on improving the lifetime of networks and transmission energy. The cooperative protocols in [2, 20, 23] work with QoS in the domain of end-to-end delay or reliability. We propose a trades-off between energy consumption and end-to-end delay to maximize the network life time and optimize the end-to-end delay.

A cross-layer cooperative protocol is proposed in [24] where cooperative diversity at the physical layer reflects at the networking layer. Their investigation shows that end-to-end delay and throughput increase significantly due to their cross-layer cooperation. In [25], the authors propose two-relay-based cooperation where second relay is used as back-up relay. If the first relay fails to transmit the packet then the back-up relay retransmits it, thus decreases packet error probability. The paper shows that two-relay-based cooperation improves average delay and throughput considerably.

The cooperative MAC (CoopMAC) [4] is a highly cited cooperative wireless MAC protocol, which selects relay based on channel state information stored in CoopTable, i.e., a node providing good channel condition will be selected as the relay. Therefore, a single node might participate frequently in cooperation, causing nonuniform energy consumption among the nodes and therefore, the energy remains unused when the network expires. The CoopTable is updated overhearing the ongoing transmission only. Since the channel states vary over time, the CoopTable may not remain fully updated if some nodes do not transmit any packets for a while. Therefore, the best relay of CoopTable might not be the best when it is required. Moreover, when the sender seeks for help it might not be able to help due its poor performance for that moment. As for example, the relay might be under the interference range of a neighbor, but the sender has no knowledge about the interference. The relay cannot help while the neighbor's transmission is ongoing, although the helper is the best as per the CoopTable of sender. This effect increases the number of collisions and retransmissions and thus prolongs the average end-to-end packet delay.

Recently, an interesting single-phase cooperative protocol was proposed in link-utility-based cooperative (LC)-MAC [21] that considers both the throughput and energy consumption. In this protocol, the relay is selected based on a higher link rate and lower power consumption. In fact, both these criteria influence the selection of a relay with better channel conditions. The impact of this effect is to increase the leftover energy in the network when it expires. In addition, extra messages such as group indication (GI) and member indication (MI) as well as additional contention periods are used in relay selection. These extra overheads serve to increase the power consumption as well as exponentially increase the number of network collisions, thereby increasing the end-to-end delay.

Our proposed DEC-MAC overcomes the problems with CoopMAC and LC-MAC. The relay node is selected in a distributed approach, unlike CoopMAC, and does not require any storage overhead. The relay can be selected dynamically using estimated metric value. In DEC-MAC, the potential candidates participate in a relay selection process, exchanging control messages that resolve intra-helper collisions and hidden node problems. The relay is selected by considering a weighted metric of residual energy and delay, whereas CoopMAC considers link quality and LC-MAC considers link rate and transmission power. Since the same relay may be repeatedly selected in CoopMAC and LC-MAC, unbalanced power consumption may occur in the network; the proposed DEC-MAC protocol provides balanced energy consumption as well as reduced end-to-end delay.

3 Network model and assumptions

We assume a large wireless sensor network where the nodes are uniformly distributed. We also assume that each source node has multi-hop routing paths to the destination sink. At each hop, a pair of communication nodes may exploit cooperative communication for performance improvement. In a single-hop environment, between a sender S and a destination D, multiple helper nodes exist that are able to participate in the cooperative process. When one node helps another node in a cooperative transmission process, we call that node a relay node.

Each node is able to compute its own weighted average metrics value from its own residual energy and measured average packet delay. The process of elimination algorithm is used to select an optimal relay shown in Algorithm 1. The node with the highest metrics value is considered to be the optimal relay. This optimal relay is selected by the receiving node D.

It is assumed that all of the nodes have an equal transmission range with an equal initial energy, $\mathscr{E}_{\text{ini}}$. The sink may reside anywhere within the network. Also, we assume that all of the packets are of equal size, and all of the nodes have buffers of equal size. A node is said to be dead when its residual energy becomes less than its threshold value $\mathscr{E}_{\text{thr}}$; in this case, the node is unable to acquire any data from the environment. One of the most important assumptions is that the entire network will expire when the first node becomes nonfunctional. In this paper, we assume that residual energy remains as leftover energy in m number of nodes out of η number of total nodes when the network expires. The residual energy in each of m number of nodes is greater than the threshold energy ($\mathscr{E}_{\text{res}} > \mathscr{E}_{\text{thr}}$) while the network remains functional.

We consider an additional queue, termed the relay queue, at the MAC layer of each node; the relay queue handles relayed packets at the node. In a cooperative network, since a node may act as both a source and a relay, problem arises when a node act as relay. This is because a new packet arrives that the node must relay before transmitting its own packet. In cooperative communication, a relay node should immediately retransmit (after one short interframe space (SIFS)) just after the transmission of sender to support the maximum ratio combining (MRC) technique [5] at the destination . If the relay node has its own packet at the head-of-the-line, in that case, it is unable to relay others packet immediately. In order to solve this issue, we consider the fact that each node maintains two transmission queues: one is the data queue for its own outgoing data and the other is the relay queue to buffer only overheard packets requiring relay when it is required. A higher priority is given to the helper queue such that the cooperative transmission can be executed at the required time.

4 Proposed DEC-MAC protocol

4.1 Basic concept

In this section, DEC-MAC protocol is proposed, which follows the design principle of IEEE 802.11. The proposed protocol considers two scenarios of communication. In the first scenario, a node having data to be transmitted operates in a two-phase cooperative transmission mode. In the first phase, an attempt is made to select a relay. If a relay is successfully selected, then the protocol proceeds to the second phase, the data transmission phase, wherein the sender S broadcasts the data packet, the relay overhears the packet, and the relay then retransmits the packet to the receiver D.

The second scenario depends on the first phase of the first scenario. If there is a failure to select a relay then the sender goes for the traditional direct transmission mode. For this case, the sender S receives a feedback message from the receiving node D at the end of first phase. In response, node S transmits directly to node D.

Sender S, when it has data to transmit, sends a request-to-send (RTS) message to the receiver D, and in response to that, D sends request-to-help (RTH) message. Here, each node knows its own weighted metrics value, as described in Section 4.2. The nodes, hearing RTS and RTH messages, compete as candidate relay nodes by sending an interested-to-help (ITH) message as part of the relay selection process. After completion of the relay selection process, the sender S sends the data packet to receiver D, and the relay overhears and then retransmits the data packet in the second phase. The basic steps are shown in Fig. 1.

The proposed protocol employs a judicious relay selection process in cooperative communication in order to maximize the network lifetime and minimize the end-to-end packet delivery delay. Relay selection is one of the critical issues in the design of a cooperative communication protocol. Which node is the best relay? How can the best relay be selected? How can the selection process time be decreased? These are the common challenges for cooperative communication. The following subsections address these issues in detail.

4.2 Metric design

In this section, an average weighted metrics (W) is formulated, consisting of the residual energy ($\mathscr{E}_{\text{res}}$) and the average delay $\mathscr{D}$ for successful packet transmission of a node in order to select the most optimal relay. Each node is able to calculate its own residual energy by subtracting the energy required for the immediate

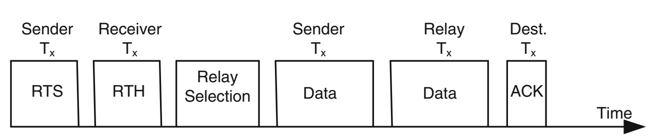

Fig. 1 Basic cooperative transmission process

transmission or reception based on the previous value of $\mathscr{E}_{\text{res}}$. The average packet transmission delay of a node can also be measured by using the link data rate, packet size, and link error rate.

In DEC-MAC, a source node S sends data to D through any relay r_n from n number of candidate relays. Different links exist from S to r_n and r_n to D. The transmission quality of a wireless link typically depends on shadowing, fading, interference, and noise; in particular, the error probability for a specific node significantly increases due to these parameters. Therefore, cooperative transmission delay $\mathscr{D}$ varies and is dependent on the links from S to r_n and r_n to D. Relay selection thus has a significant impact on single-hop delays.

$\mathscr{D}$ is calculated by summing the expected transmission time (ETT) from S to r_n, ETT_{Sr_n}, and that from r_n to D, ETT_{r_nD}, as given by Eq. 1:

$$\mathscr{D} = \text{ETT}_{Sr_n} + \text{ETT}_{r_nD} \tag{1}$$

The definition of ETT is given by

$$\text{ETT} = \text{ETX} \times \frac{\mathscr{S}}{\mathbb{B}} \tag{2}$$

where $\mathscr{S}$ is the packet size and $\mathbb{B}$ is the link data rate. The expected retransmission count ETX depends on packet error rate. The packet loss includes the packet drops for link errors. Thus, the ETX incorporates the effects of wireless link loss [26], and the increased link loss forces to increase the expected transmission time (ETT). This local delay has a significant impact on the end-to-end packet delay. Therefore, we incorporate ETT as a metric parameter that attempts to select a relay with lower link losses.

In the proposed DEC-MAC, a candidate relay node r_n, having the highest metric value W_n among the available candidate nodes n, is considered the optimal relay. The average weight W_n of an optimal relay is calculated such that

$$W_n = w_1 \frac{\mathscr{E}_{\text{res}}}{\mathscr{E}_{\text{ini}}} + w_2 \frac{\mathscr{D}^{\max} - \mathscr{D}}{\mathscr{D}^{\max}} \tag{3}$$

where w_1 and w_2 are smoothing factors for the sub-metric residual energy and delay, respectively, and $w_1 + w_2 = 1$, $0 < W_i \leq 1$. Determining the weighting values w_1 and w_2 is critical. By performing extensive simulation experiments, we were able to determine that better performance was achieved by setting $w_1 = 0.3$ and $w_2 = 0.7$.

In Eq. 3, the value of W_n will be at the maximum of $\mathscr{E}_{\text{res}}$, i.e., $\mathscr{E}_{\text{res}} = \mathscr{E}_{\text{ini}}$ and $\mathscr{D}$ will be the minimum, i.e., $\mathscr{D}^{\min} = 0$; $0 < \mathscr{D} \leq \mathscr{D}^{\max}$. In practice, the packet delay at any node r_n can never be equal to zero. The maximum packet delay $\mathscr{D}^{\max}$ will be when both of the expected transmission times for ETT_{Sr_n} and ETT_{r_nD} are at their respective maximum values. In fact, the maximum value for ETT is when the channel condition is very poor i.e., the link loss is very high, and the number of retransmissions (ETX) rises to a high value (maximum retry limit), which in turn decreases the metrics value W_n for the node. The proposed DEC-MAC protocol searches for the candidate having the highest value of W_n.

4.3 Relay selection

Relay selection is a vital issue for cooperative communication. It has been proven that a good helper is able to significantly improve network performance [14], in contrast to an inferior helper, which might considerably degrade the performance. In the following subsections, we present the DEC-MAC method of selecting the optimal relay within the shortest time period.

4.3.1 Relay selection algorithm

In the proposed DEC-MAC protocol, a proactive relay selection approach is used, where the relay is selected prior to the start of data transmissions. Proactive relay selection has been proven to be more energy-efficient than its reactive counterpart [12] since, in the former approach, only the selected candidate relay node needs to expend energy to overhear the transmission of the source.

We consider the fact that there are n candidate relay nodes in between sender S and receiver D. When sender S has data to transmit, it sends a RTS; in response to the RTS, the receiving node D sends a RTH after which the relay selection process starts. Active nodes, listening to the RTS and RTH messages, can compete as a relay. Each node n, based on its weighted metrics value W_n, participates in the relay selection process. In this process, a time slot $\mathscr{T}$ is assigned to transmit a single data burst, as shown in Fig. 2. Each time slot is divided into two parts: $\mathscr{T}_r$ and $\mathscr{T}_d$. The first

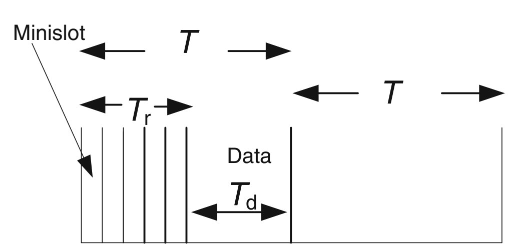

Fig. 2 Time slots for two data bursts

part $\mathscr{T}_r$ is used for relay selection; the second part $\mathscr{T}_d$ is used to transmit data packets. $\mathscr{T}_r$ is again divided into several mini slots (time slots). A candidate relay node n sends an ITH message at the beginning of a mini slot if its weighted metrics value W_n satisfies condition $W_{\mathrm{L}} \leq W_n \leq W_{\mathrm{H}}$, where W_{H} and W_{L} are the higher and lower thresholds of the metrics value defined by the receiving node D, respectively. In response, a feedback message FITH (feedback of ITH) is sent by the receiving node D in the same mini slot.

If there exists more than one candidate node whose weighted metrics value that remains within the range W_{L} and W_{H} in a slot, then an ITH message collision occurs in that slot; in this case, the receiving node increases the lower threshold W_{L}, as shown in Fig. 3, using function $W_{\mathrm{L}} = \mathrm{upper}(W_{\mathrm{L}}, W_{\mathrm{H}})$. This strategy reduces the collision probability and also increases the probability to find the optimal relay in the next mini slot. In order to make the relay selection process faster, the process of elimination (PE) is employed. In PE, if a node i hears an ITH message from any other node j and $W_i < W_j$, then the node i will not participate in the relay selection process for the subsequent mini slots, thus ensuring a further reduction in the collision probability.

If there is no candidate relay between W_{L} and W_{H}, meaning an empty slot, then the feedback message is $msg = empty$. Both of the values for W_{L} and W_{H} are lowered and new values are calculated such that $W_{\mathrm{H}} = W_{\mathrm{L}}$ and $W_{\mathrm{L}} = \mathrm{lower}(W_{\mathrm{lower}}, W_{\mathrm{L}})$, as shown in Fig. 3. Here, W_{lower} is the lower threshold above which certainly the optimal relay exists. If an empty slot is found after a single-node slot, it means that the optimal relay has been found, and the relay search process is terminated. If only one candidate node transmits in a mini slot, then it is called a single-node slot. In this case, a greedy strategy is followed in order to find an optimal relay. Here, we consider the possibility that a better candidate node might exist above the upper threshold. In this case, we assume that $W_{\mathrm{L}} = W_{\mathrm{H}}$ and $W_{\mathrm{H}} = 1$ for the next mini slot. If again it is found to be a single node-slot, then the relay of this mini slot is considered as an optimal relay and stop the relay searching process.

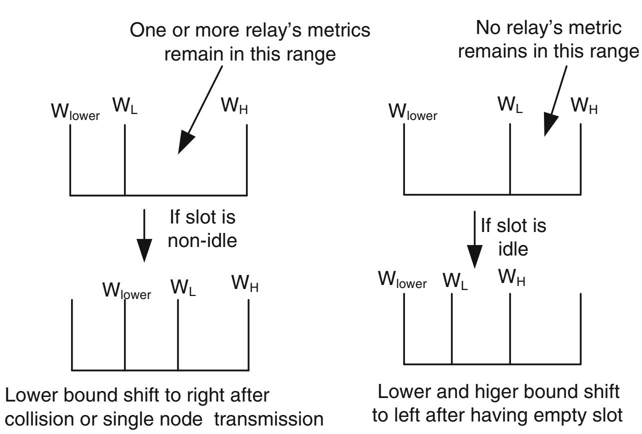

Fig. 3 Upper and lower threshold update procedure

The upper and lower threshold values can be determined by the following functions [27]:

$$\mathrm{upper}(W_{\mathrm{L}}, W_{\mathrm{H}}) = F_c^{-1}\left(\frac{F_c(W_{\mathrm{L}}) + F_c(W_{\mathrm{H}})}{2}\right)$$

and

$$\mathrm{lower}(W_{\mathrm{lower}}, W_{\mathrm{L}}) = F_c^{-1}\left(\frac{F_c(W_{\mathrm{lower}}) + F_c(W_{\mathrm{L}})}{2}\right)$$

The proposed optimal relay selection algorithm, DEC-MAC, is presented in Algorithm 1. If more than one candidate node transmits an ITH message, then a feedback message *multi* is sent back by D, indicating a collision. An *empty* message is sent when no node transmits any ITH message in a slot. The receiver D sends *msg_coop* when a relay is finally selected. If none of the relays is interested to help, then the feedback is *msg_dir* for direct transmission.

4.4 Terminology and challenges

Some terminology and determination process of few parameters are detailed in this section.

Mini slot A mini slot is a duration assigned to send ITH message by a candidate relay and to receive a feedback message from receiver. The duration of each mini slot β is equal to the round-trip time required for a node to transmit an ITH and receive a FITH message. If K mini slots are required to find a relay, then the total relay selection time is $\mathscr{T}_r = K\beta$.

Number of candidate relays Each node is able to compute its distance from a neighboring node using the Euclidian method [28]. The expected number of candidate relays can be expressed as $n = \xi\pi\left(\frac{\mathscr{R}}{2}\right)^2$, where ξ is the node density and $\mathscr{R}$ is the distance between the sender S and the receiver D.

Initialization We apply the complementary cumulative distribution function (CCDF) to determine the initial lower threshold W_{L} [27]. At first, we assume that the weight of only one node out of n nodes between S and D is above W_{L} and transmits with probability $1/n$ in the first mini slot. The weight of all of the other nodes

Algorithm 1 DEC-MAC algorithm

```
Initialization: Initialize flag = 0, W_L = F_c^{-1}(1/n), W_H = 1, W_lower = 0;
while W_H − W_L > constant do
  if msg = multi then
    W_lower = W_L; W_L = upper(W_L, W_H);
    if msg = single then
      flag = 1;
      W_L = W_H; W_H = 1;
      if msg = single then
        exit loop
      end if
    end if
  else
    if msg = empty then
      if flag = 1 then
        exit loop
      else
        W_H = W_L; W_L = lower(W_lower, W_L);
      end if
    end if
  end if
end while
if flag = 1 then
  Msg = msg_coop
else
  Msg = msg_dir
end if
```

are below the initial lower threshold W_{L}. The CCDF of the average weighted metrics of the nodes can be expressed as $F_c = P(W > W_{\mathrm{L}}) = \frac{1}{n}$. The value of W_{L} is determined by using inverse CCDF such that

$$W_{\mathrm{L}} = F_c^{-1}\left(\frac{1}{n}\right). \tag{4}$$

Upper threshold W_H Setting the value of the upper threshold W_{H} for each data burst is another challenging issue for the proposed DEC-MAC protocol. Initially, we assumed that if the weight of each candidate relay satisfies the condition $0 \leq W_n \leq 1$ then it immediately transmits an ITH message. According to Eq. 3, the initial upper threshold should be 1, if $\mathscr{E}_{\mathrm{res}} = \mathscr{E}_{\mathrm{ini}}$ and $\mathscr{D} = 0$. However, this is impractical since $\mathscr{E}_{\mathrm{res}}$ decreases over time, and the transmission delay can never be zero. Therefore, the value of W_{H} is much less than 1 as time goes on and hence, if we always set the upper threshold to 1, then the probability of an empty slot will increase over time. As a result, the required number of mini slots might be increased, thereby increasing the relay selection time ($\mathscr{T}_r$) . To solve this problem, the initial upper threshold is updated by each node according to the following equation:

$$W_{\mathrm{ini\_h}} = w_1 \frac{\max\left(\max\mathscr{E}_{\mathrm{res}}^{\mathrm{source}}, \max\mathscr{E}_{\mathrm{res}}^{\mathrm{dest}}\right)}{\mathscr{E}_{\mathrm{ini}}} + w_2 \frac{(\mathscr{D}_{\max} - \mathscr{D}_{\min})}{\mathscr{D}_{\max}} \tag{5}$$

The term $\max\mathscr{E}_{\mathrm{res}}^{\mathrm{source}}$ denotes the node having the highest residual energy in the transmission range of the source node. Similarly, the term $\max\mathscr{E}_{\mathrm{res}}^{\mathrm{dest}}$ denotes the node having the highest residual energy in the transmission range of the destination node. The entire term $\max(\max\mathscr{E}_{\mathrm{res}}^{\mathrm{source}}, \max E_{\mathrm{res}}^{\mathrm{dest}})$ represents the node containing the highest residual energy within the transmission range of both the source and destination. $\mathscr{D}_{\min}$ is the minimum transmission delay $\mathscr{T}_{\mathrm{SD}} = \mathscr{T}_{\mathrm{SD}}^{\min}$.

Feedback message In each mini slot, potential candidate relay nodes receive a FITH message from the receiver D. The feedback message contains the direction of action and the values of the upper and lower thresholds for the next mini slot.

Algorithm termination condition The loop will repeat until the condition $W_{\mathrm{H}} - W_{\mathrm{L}} >$ constant is satisfied. An appropriate constant is carefully selected in order to avoid having an excess number of mini slots or an infinity loop. It is evident that the lower the value of the constant is, the better the relay; however, the relay selection requires additional time. An optimal value of the constant is investigated based on simulation, i.e., *constant* $= 0.01$ but is not the main focus of our research.

4.5 Protocol operation

Figure 4 explains our proposed IEEE 802.11 distribution coordination function (DCF)-based DEC-MAC protocol operation details. A sender S initiates its transmission by sending a RTS packet after completing, its distributed inter-frame space (DIFS) and back-off periods . The receiver D responds by sending a RTH message in order to initiate cooperative communication; the relay selection process is started after the SIFS. The RTH message contains the initial lower (W_{L}) and upper thresholds (W_{H}) of the mini slot. A neighbor node n, hearing both RTS and RTH messages and satisfying $W_L < W_n \leq W_H$ sends an ITH message. The ITH message contains the node's ID and metrics value. After the ITH message, the candidate relays receive a feedback message from the receiver D.

At the end of the relay selection phase, the receiver node sends back either *msg_coop* or *msg_dir*. This final

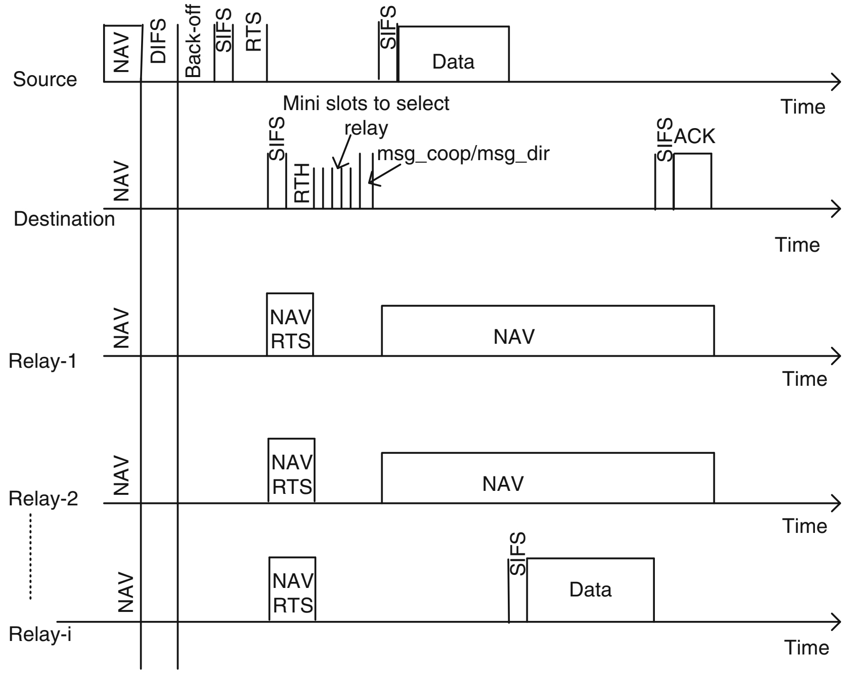

Fig. 4 DEC-MAC protocol operation diagram

feedback message is required by the sender to decide whether to transmit the data packet in cooperative mode or in direct transmission mode. The feedback message *msg_coop* from receiver *D* indicates that the optimal relay has been selected. This message is listened to by the sender *S* and all candidate relays. Thus, the other candidate relays stop their participation in the relay selection process. After receiving *msg_coop*, *S* sends data to receiver *D* after the SIFS interval. The relay node overhears and decodes this data and forwards it to *D* after another SIFS interval. Then, the node *D* sends an ACK message upon receiving data after an SIFS interval. The relay selection for a single packet might not be cost-effective because of the introduction of some overhead by the selection process. Therefore, the selected relay can continue its services as a helper for the consecutive continuous packets between *S* and *D* until its weight is reduced by a predefined threshold value, for instance 0.01. However, if the relay fails to hold the transmission performance as calculated at the time of relay selection process, it stops services and the protocol searches for a new relay.

The feedback message *msg_dir* means that a suitable relay is not available, and thus the sender *S* transmits its data directly to the receiver *D* after an SIFS interval. After another SIFS, *D* sends an ACK message upon successful data reception. The nature of this protocol is such that if a suitable relay is unavailable, then the sender uses a noncooperative transmission mode, also known as a traditional direct transmission mode.

The proposed DEC-MAC protocol has the ability to quickly switch from cooperative to noncooperative mode. When both the relay and the receiver fail to decode the sent data packet, then the receiver does not send an ACK message, and, hence, the sender retransmits the packet after a PCF interframe space (PIFS) (i.e., SIFS + slot time) time period. Similarly, when both the sender and relay transmit but the receiver is unable to decode, the packet is retransmitted by the sender after a PIFS time period.

5 Analysis

In this section, we derive analytical expressions for the expected number of mini slots required for relay selection. In addition, analyses for single-hop packet delay, power cost and network lifetime are accomplished.

5.1 Expected number of mini slots

Determining the number of mini slots required for finding the optimal relay is one of the key challenges for the proposed protocol. The overhead increases as the number of mini slots increases. Assuming that a slot is non-idle when one or more candidate helpers transmit in that slot, we can express the probability that the first j^{th} minislot is non-idle as $\binom{n}{k} p^k (1-jp)^{n-k}$, where $k \leq n$ is the number of candidate nodes transmitting an ITH message in a slot, and $p = \frac{1}{n}$ is the probability that a node will transmit an ITH message in any slot. Therefore, the average number of slots prior to the first non-idle slot is given by

$$E_1(X) = \sum_{j=1}^{n}\sum_{k=1}^{n}\binom{n}{k}p^k(1-jp)^{n-k}j. \tag{6}$$

Also, the average number of mini slots required to resolve the collision among k nodes is given by

$$E_2(X) = \sum_{j=1}^{n}\sum_{k=1}^{n}\binom{n}{k}p^k(1-jp)^{n-k}e(X_k). \tag{7}$$

Here, the term $e[X_k]$ denotes the number of mini slots that may be required to resolve the collision among k number of nodes. $e(X_k)$ is a recursive function and the value of $e(X_k)$ is given by [27]

$$e[X_k] = \frac{0.5^k \sum_{l=2}^{k-1}\binom{k}{l}e(X_k)+1}{1-(0.5)^{k-1}}, \quad \forall\, k \geq 1, \tag{8}$$

where $e[X_k] \leq \log_2(k)+1$ for all k. For simplicity, we can write the Eq. 8 as follows:

$$e[X_k] = \log_2(k)+1, \quad \forall\, k \geq 1. \tag{9}$$

Thus, the total number of mini slots required to find the optimal relay is given by

$$K = E_1(X) + E_2(X). \tag{10}$$

From Eqs. 6, 7, and 10, we can write

$$K = \sum_{j=1}^{n}\sum_{k=1}^{n}\binom{n}{k}p^k(1-jp)^{n-k}j + \sum_{j=1}^{n}\sum_{k=1}^{n}\binom{n}{k}p^k(1-jp)^{n-k}e(X). \tag{11}$$

Putting the value for $e[X_k]$ in Eq. 11, we have

$$K = \sum_{j=1}^{n}\sum_{k=1}^{n}\binom{n}{k}p^k(1-jp)^{n-k}j + \sum_{j=1}^{n}\sum_{k=1}^{n}\binom{n}{k}p^k(1-jp)^{n-k}(\log_2(k)+1). \tag{12}$$

We plot a graph of average number of required mini slots K vs. the total number of candidate relays n, as shown in Fig. 5. The graph reveals that the number of mini slots increases from 2 to 3.07 with the candidate relays ranging from 1 to 100. The number of mini slots remain close to 3.07 even though $n \to \infty$. The most noticeable finding is that the number of mini slots remains less than 3 ($K < 3$) until $n \leq 10$. Typically, for most of the cases, less than ten potential candidates remain in a transmission environment [12]. Therefore, we conjecture that three slots are required for finding the optimal relay.

5.2 Delay analysis

The local single-hop delay has a great impact on the end-to-end packet delay. This local delay is defined as individual hop delay of a multi-hop network. We consider the following three parameters-expected transmission time, relay selection time ($\mathscr{T}_o$), and protocol operation overhead ($\mathscr{T}_r$) for calculating the total single-hop delay $\mathscr{D}_{SD}$ from node S to node D and can be expressed as follows:

$$\mathscr{D}_{SD} = \mathrm{ETT} + \mathscr{T}_o + \mathscr{T}_r. \tag{13}$$

Here, we have neglected propagation delay since it carries very small value. The measurement method of ETT has been discussed in Section 4.2. We assume that our cooperative communication method uses the

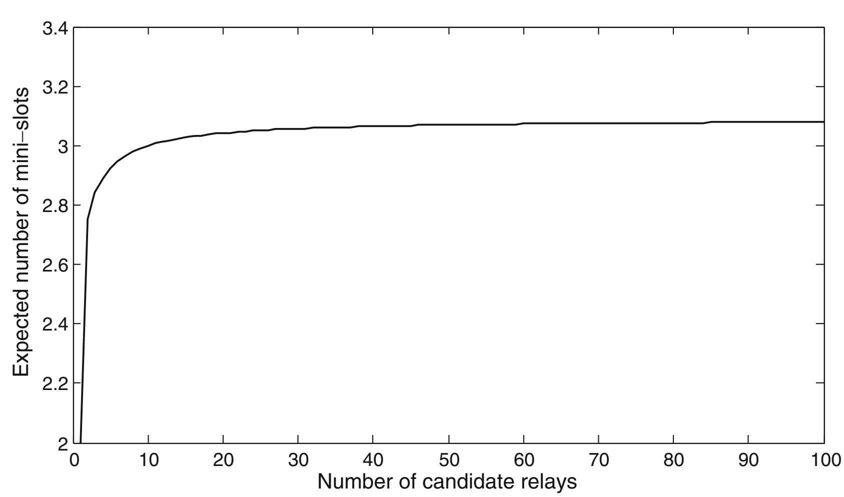

Fig. 5 Number of candidate relays vs. average number of mini slots

MRC technique at the receiving node D. Therefore, the total signal-to-noise ratio (SNR) value for decode and forward at the receiving node D can be written as

$$\Upsilon_{\text{coop}} = \Upsilon_{\text{SD}} + \Upsilon_{r_n D} \tag{14}$$

where Υ_{SD} is the SNR value at node D for the direct link SD and $\Upsilon_{r_n D}$ is the SNR value at D for the link $r_n D$. The probability of packet error for cooperative communication is given by [29]:

$$\delta_{\text{coop}} = \delta_{\text{SD}}\delta_{Sr_n} + (1 - \delta_{Sr_n})\delta_{Sr_n D} \tag{15}$$

where δ_{SD} and δ_{Sr_n} are the probabilities of packet errors for the links sender–receiver (SD) and sender-relay (Sr_n), respectively, and δ_{coop} is the probability of the packet error for the cooperative link $Sr_n D$. The first term of the right-hand side of Eq. 15 corresponds to the probabilities of packet error at the links sender–receiver and sender-relay. The second term corresponds to the probabilities of a successful reception at the relay for the sender-relay link and packet error at the receiver for the cooperative link $Sr_n D$. In terms of the SNR value, the probability of a packet error can be expressed as

$$\delta = 1 - \left(1 - \frac{1}{2}e^{-\frac{\Upsilon}{2}}\right)^{\mathscr{S}}$$

where $\mathscr{S}$ is the packet length. Therefore, the values for δ_{SD}, δ_{Sr_n}, and $\delta_{Sr_n D}$ of Eq. 15 can be calculated using the values Υ_{SD}, $\Upsilon_{r_n D}$, and Υ_{coop}, respectively.

Based on 802.11 DCF, the sender retransmits a packet if the original transmission is not successful, with a standard retry limit. Initially, we assume that the probability of the successful transmission of a packet from S to D, after φ attempts, can be written as

$$\delta_{\text{success}} = (\delta_{\text{coop}})^{\varphi-1}(1 - \delta_{\text{coop}}). \tag{16}$$

Finally, the expected number of retransmissions required to transmit a packet successfully from S to D can be written as

$$\text{ETX} = \sum_{\varphi=1}^{\infty} \varphi\delta_{\text{success}} \tag{17}$$

Therefore, using the value of ETX, we are able to determine the value of ETT such that

$$\text{ETT} = (\text{ETX})\frac{\mathscr{S}}{\mathbb{B}} = \frac{\mathscr{S}}{\mathbb{B}} \sum_{\varphi=1}^{\infty} \varphi\delta_{\text{success}} \tag{18}$$

If φ is the required number of retransmissions for the successful transmission of a packet, then we can find the delay $\mathscr{D}_{\text{SD}}^{\text{success}}$ for the hop SD using Eqs. 13 and 18 such that

$$\mathscr{D}_{\text{SD}}^{\text{success}} = \sum_{\varphi=1}^{\infty} \left(\frac{\mathscr{S}}{\mathbb{B}}\varphi * \delta_{\text{success}} + \mathscr{T}_{o,\varphi} + \mathscr{T}_{r,\varphi}\right) \tag{19}$$

Equation 14 demonstrates that $\text{SNR}_{\text{coop}} \geq \text{SNR}_{\text{dir}}$. Thus, the probability of a packet error with cooperative communication is less than with direct communication, $\delta_{\text{coop}} \leq \delta_{\text{dir}}$. Therefore, the required number of retransmissions φ for cooperative communication is less than the number required for direct communication. The result of Eq. 19 shows that the hop-by-hop delay is reduced. Our proposed relay selection algorithm also reduces the value of the relay selection overhead $\mathscr{T}_r$.

5.3 Power cost

The power cost in cooperative communication includes transmission cost by sender S is $T_{\text{tx,s}}$ and the receiving cost both by relay r_n and receiver D are $2P_{\text{rx}}$. A relay retransmits a packet at the cost $(P_{\text{tx,r}} + P_{\text{rx}})(1 - \delta_{\text{sr}})$, where, $(1 - \delta_{\text{sr}})$ is the probability that the relay decoded the packet correctly and then retransmitted. Thus, the power cost for cooperative transmission [29] is as follows:

$$P_{\text{coop}} = (P_{\text{tx,s}} + 2P_{\text{rx}}) + (P_{\text{tx,r}} + P_{\text{rx}})(1 - \delta_{\text{sr}}). \tag{20}$$

The power cost for direct transmission can be written as

$$P_{\text{dir}} = P_{\text{tx,s}} + P_{\text{rx}} \tag{21}$$

The required transmission energy for cooperative transmission is $E_{\text{coop}} = \frac{P_{\text{coop}}\mathscr{L}}{\mathscr{C}}$ and for direct transmission is $E_{\text{dir}} = \frac{P_{\text{dir}}\mathscr{L}}{\mathscr{C}}$. Here, $\mathscr{L}$ is the packet length and $\mathscr{C}$ is the transmission rate.

The expected number of retransmissions [22, 30] for one hop is given by $\text{ETX} = \frac{1}{1-\delta}$, where δ is the probability of a packet error. Thus, the required energy expected for successful transmission can be written as $E_{\text{coop}}^{\text{expected}} = \frac{E_{\text{coop}}}{1-\delta_{\text{coop}}}$ for cooperative transmission and $E_{\text{dir}}^{\text{expected}} = \frac{E_{\text{dir}}}{1-\delta_{\text{dir}}}$ for direct transmission. The packet error rate is inversely proportional to the SNR, $\delta \propto \frac{1}{\Upsilon}$. From Eq. 14, we find that $\Upsilon_{\text{coop}} \geq \Upsilon_{\text{dir}}$, where $\Upsilon_{\text{dir}} = \Upsilon_{\text{SD}}$. Therefore, the expected number of retransmissions for cooperative communication is $\text{ETX}_{\text{coop}} \leq ETX_{\text{dir}}$; ETX_{dir} is the expected number of retransmissions for direct transmissions. Thus, cooperative communication requires less transmission energy.

5.4 Lifetime analysis

The network lifetime is defined as the duration of the network operating time up until the first node fails due to battery depletion [10, 18]. This is a meaningful measurement in the sense that failure of the first node is an indication of the remaining limited network lifetime; in some applications, the first node failure can cause a network to become partitioned and additional services can be interrupted. In general, the lifetime (LT) of any node i with initial energy $\mathcal{E}_{\text{ini}}$ can be expressed as

$$\text{LT}_i = \frac{\mathcal{E}_{\text{ini}}}{e_i}, \forall i = 1, 2, \ldots \eta \tag{22}$$

where e_i is the average energy consumed per unit time.

First, we assume that all of the network energy is used in transmitting, receiving, processing, idle, and listening modes. Therefore, the virtual lifetime of the network is defined as $\text{LT}^{\text{vir}} = (\eta \mathcal{E}_{\text{ini}})/e_i$ where no energy remains leftover in the network. In reality, however, some energy remains leftover in the network when the network expires. Let each of a m number of nodes have residual energy $\mathcal{E}_{\text{res,i}}$, where the total number of nodes is η. This leftover residual energy is treated as wasted energy. The average amount of wasted energy in a network can be expressed as

$$\mathcal{E}_w = \sum_{i=1}^{m} \mathcal{E}_{\text{res,i}}, \quad t \geq \text{lifetime} \tag{23}$$

The network lifetime can be written in terms of wasted energy $\mathcal{E}_w$ such that

$$\text{LT} = \frac{\eta \mathcal{E}_{\text{ini}} - \mathcal{E}_w}{e_i} \tag{24}$$

In Eq. 24, η and $\mathcal{E}_{\text{ini}}$ are constants for a network; thus, the network lifetime depends on $\mathcal{E}_w$. In [8], it is reported that the network lifetime depends not only on the average consumed energy but also on the residual energy left after the network lifetime expires. Therefore, in order to maximize the network lifetime, the protocol should reduce the wasted energy $\mathcal{E}_w$ to a minimum value $\min\mathcal{E}_w$. Thus, the network lifetime is increased to its maximum as max LT and given by

$$\max\text{LT} = \frac{\eta \mathcal{E}_{\text{ini}} - \min\mathcal{E}_w}{e_i} \tag{25}$$

Since our protocol searches for an optimal relay having a higher residual energy and shorter delay, it influences the balance of energy consumption among all of the nodes, which decreases the leftover wasted energy, thereby increasing the network lifetime.

6 Performance evaluation

6.1 Simulation environment

We evaluated the performance of the proposed DEC-MAC using simulation experiments conducted on NS-2 [31] and compared the results with those of CoopMAC [4] and LC-MAC [21]. The configuration of the simulation environment parameters is listed in Table 1. The data traffic bursts from three randomly chosen events, listed in Table 2, are considered in the performance studies. Each data point shown in the graphs are the results of the average of ten simulation runs.

6.2 Performance metrics

6.2.1 Average end-to-end packet delay

The end-to-end delay of a single packet is measured as the time difference between when the packet is

Table 1 Configuration of parameters

Deployment	Area size	2,000 × 2,000 m
	Deployment type	Uniform random
	Network architecture	Homogeneous flat
	Number of nodes	2,000
	Sink	(1,000, 1,000)
	Initial node energy	100 J
	Buffer size	50
	Sources in one event	15 nodes
	Radio range	100 m
	Link layer trans. rate	512 kbps
	Transmit power	$7.214e^{-3}$ W
	Rcv. signal threshold	$3.65209e^{-10}$ W
	PHY error model	Uniform random
	Link failure rate	0.30
Task	Application type	Event-driven
	Packet size	64 bytes
	Traffic type	CBR, 3 pkts/s
DEC-MAC	MAC header	272 bits
	PHY header	192 bits
	RTS	128 bits
	RTH	128 bits
	ACK	112 bits
	ITH	112 bits
	FITH	112 bits
	SIFS	10 μs
	DIFS	32 μs
	aCWMin	31 slots
	aCWMax	1,023 slots
	Retry limit	5
Simulation	Time	200 s

Table 2 Events and bursts description

	Event 1 (s)	Event 2 (s)	Event 3 (s)
Burst 1	10∼40	20∼50	30∼60
Burst 2	90∼120	100∼130	110∼140

received at the sink from and its the time it is generation generated time at the source node. Delays experienced by individual data packets are averaged over the total number of individual packets received by the sink. The lower the value is, the better the performance is.

6.2.2 Network lifetime

The network lifetime is defined as the length of time from the network's deployment until the point in time when the first of its nodes is fully drained of energy and becomes nonfunctional.

6.2.3 Per-packet energy consumption

Energy consumption per packet is measured as the ratio of the total amount of energy dissipated by all source and forwarding nodes during the simulation period to the number of packets received by the sink, e.g., the average amount of energy expended for each successful packet reception.

6.2.4 Standard deviation of residual energy levels

The standard deviation of residual energy levels at sensor nodes defines the average variance between the residual energy levels at all nodes and is measured by Eq. 26,

$$\sigma = \sqrt{\frac{1}{\mathcal{N}} \sum_{i=1}^{\mathcal{N}} (\mathscr{E}_{\mathrm{res,i}} - \mu_{\mathrm{res}})^2}, \tag{26}$$

where $\mathscr{E}_{\mathrm{res,i}}$ and μ_{res} are the residual energy of node i and the mean residual energy for all nodes, respectively. The value of σ indicates how well the energy consumption is distributed among the sensor nodes; the smaller the value, the better the capability of DEC-MAC to balance the energy consumption.

6.2.5 Protocol operation overhead

In order to compare the protocol operation overhead incurred by the control packets, the following are counted during the entire simulation period: the number of bytes in RTS, RTH, ITH, FITH, and ACK control packets transmitted by DEC-MAC; the number of bytes in RTS, HTS, CTS, and ACK packets transmitted by CoopMAC; and the number of bytes in RTS, CTS, GI and MI messages, RTH and RC (recontention) messages, and ACK packets transmitted by LC-MAC. The lower the values are for the number of bytes, the higher the protocol's performance.

6.3 Simulation results

6.3.1 Impacts of node density

In this section, we show the impacts of node density on the performance of the protocols. The graph of Fig. 6 shows that average end-to-end delay of DEC-MAC has significantly improved over CoopMAC and LC-MAC. Although initially end-to-end delay of Coop-MAC is lower than DEC-MAC, it increases with the node densities. Since, the helpers in CoopMAC do not exchange any message before transmission, so the neighbors might start to transmit data while the transmission of helper is ongoing. Therefore, collision increases in CoopMAC as node density increases and hence average end-to-end delay also increases.

Measuring the lifetime of a sensor network in a simulation environment is a tedious task, typically ranging from several months up to 2 years. It depends upon the initial energy of the nodes, the amount of traffic, and the MAC and routing protocols employed in the network. We executed simulation runs for varying node densities, with an initial energy of 20 J for each node, in order to compare the performances of the protocols. Figure 7 shows that the network lifetime of DEC-MAC is significantly increased compared to that of LC-MAC and CoopMAC. The reason behind this interesting

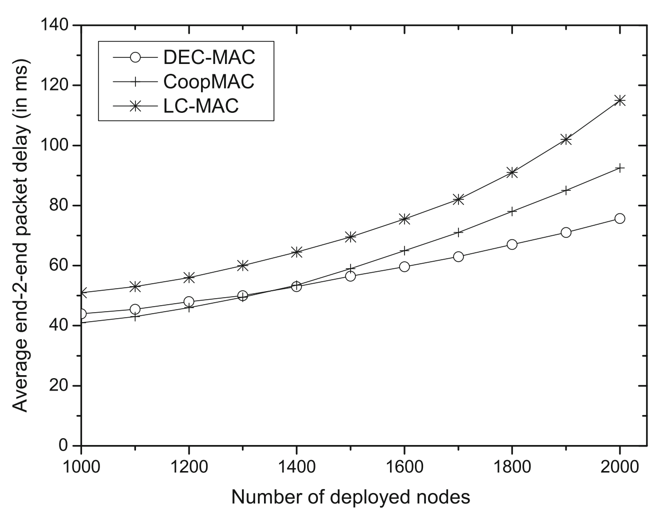

Fig. 6 Average end-to-end delay vs. number of deployed nodes

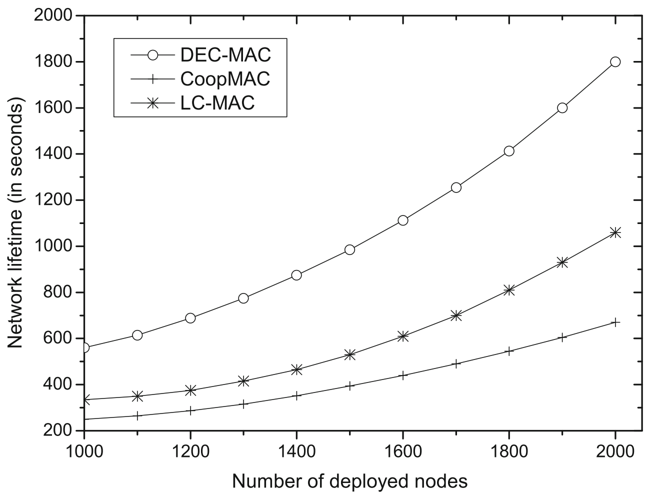

Fig. 7 Network lifetime vs. number of deployed nodes

result is that residual energy is considered in the relay selection in DEC-MAC, which implements balanced energy consumption among the nodes. Therefore, less leftover energy remains when a network dies out. LC-MAC and CoopMAC do not consider the residual energy when selecting a relay node; thus, the better helper nodes frequently participate in cooperation and die earlier. As a result, a significant amount of energy remains unused as leftover energy in the network.

Figure 8 shows that DEC-MAC is more energy efficient than LC-MAC and CoopMAC. This is based on the fact that the number of successful transmission of data packets in the simulation period is higher with DEC-MAC than with the other protocols. Therefore, per data packet energy consumption is lower in DEC-MAC. The per data packet energy consumption is higher in CoopMAC and LC-MAC due to the lower number of successful packet transmissions resulting from the higher number of collisions during the simulation period. Energy efficiency increases as node density increases; along with the node increase is an increase in cooperative diversity, which leads to an improved chance of having a better helper node.

Figure 9 shows the standard deviation of the residual energy in different protocols with varying node densities. The figure reveals that the proposed DEC-MAC performs quite well in terms of energy load balancing among the network nodes. Even at very low node densities, DEC-MAC outperforms LC-MAC and CoopMAC. This is due to the use of an energy-aware relay selection mechanism in DEC-MAC, which is absent in LC-MAC and CoopMAC.

Figure 10 compares the operational overhead of the different protocols. The graphs indicate that the operational overhead of DEC-MAC is significantly lower than that of LC-MAC and CoopMAC. Initially, the operational overhead is higher than that of CoopMAC since the number of control packets in CoopMAC is lower than that in DEC-MAC. However, with an increase in node density, the number of collisions and retransmissions increases in CoopMAC and thus the protocol's operational overhead also increases. The use of extra GI and MI messages, along with the common control messages in LC-MAC, also serves to increase the protocol's operational overhead; LC-MAC's operational overhead increases exponentially as collisions increase with increases in node density.

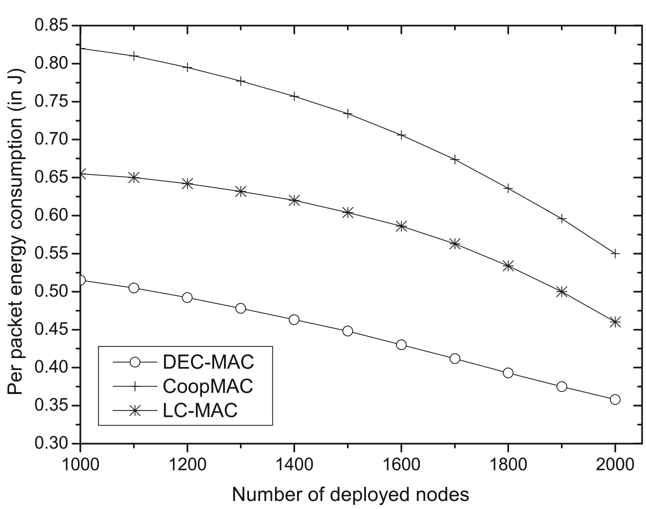

Fig. 8 Per-packet energy consumption vs. number of deployed nodes

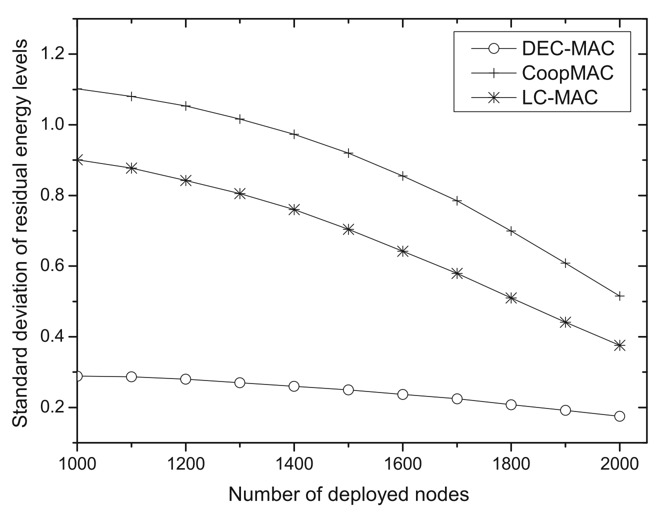

Fig. 9 Standard deviation of residual energy vs. number of deployed nodes

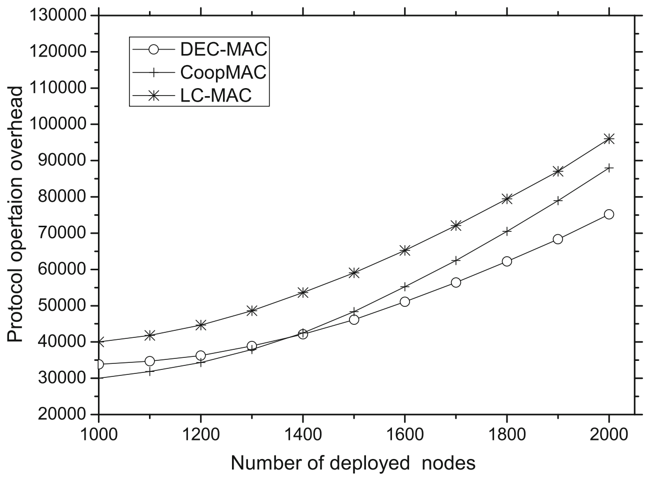

Fig. 10 Protocol operation overhead vs. number of deployed of nodes

6.3.2 Impacts of link failure rate

This section discusses the impacts of different channel conditions on the performance of the protocols. The more link failures in a unit of time, the more unstable a wireless network will be [32]. In this paper, we express the channel condition in terms of link failure rate f and we vary the value of f from 0.05 to 0.50 in increments of 0.05; all other parameters in Tables 1 and 2 are fixed.

The simulation results in Fig. 11 show that DEC-MAC has a better average end-to-end packet delay than the other protocols at higher link failure rates. Since the number of control messages for CoopMAC is lower than that for DEC-MAC, so initially CoopMAC has a lower end-to-end packet delay. However, the end-to-end packet delay of CoopMAC is higher than that of DEC-MAC at higher link failure rate. This is because, in CoopMAC and LC-MAC, relays are selected based on the transmission rate; however, the node with a better transmission rate always might not be a better helper due to its heavy traffic load. Therefore, DEC-MAC has less end-to-end packet delay than CoopMAC and LC-MAC at higher link failure rates.

The graphs in Fig. 12 reveal that DEC-MAC provides a more than 60 % higher lifetime as compared to CoopMAC and LC-MAC, even with a 50 % link failure rate. This is due to the uniform distribution of the energy consumption among the nodes, even with a higher link failure rate. This strategy reduces the leftover energy in a network when it dies out. As a result, the network lifetime of DEC-MAC is much higher than that of the other protocols, even with a higher link failure rate.

As the link failure rate increases, the throughput decreases, and the end-to-end packet delay increases, thereby increasing the per-packet energy consumption. Figure 13 shows that the per-packet energy consumption of all protocols increases as the link failure rate increases. However, the per-packet energy consumption for DEC-MAC is much lower than for CoopMAC. This is because CoopMAC select a relay based on CoopTable which updates overhearing the neighbor's transmission, so it is less dynamic. If the link failure rate increases, then the probability to select a relay with poor-linked path increases. In turn, this fact increases the retransmissions and thus increases transmission energy. On the other hand, in LC-MAC, it has higher protocol overhead and higher susceptible to collision than DEC-MAC. Thus, the per-packet energy consumption

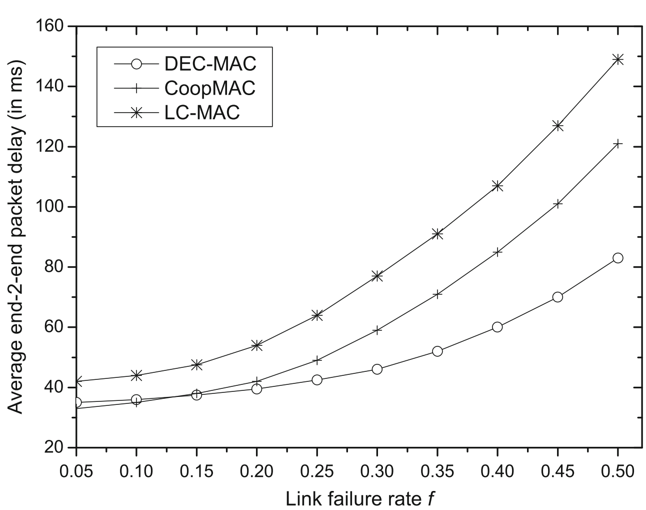

Fig. 11 Average end-to-end delay vs. link failure rate

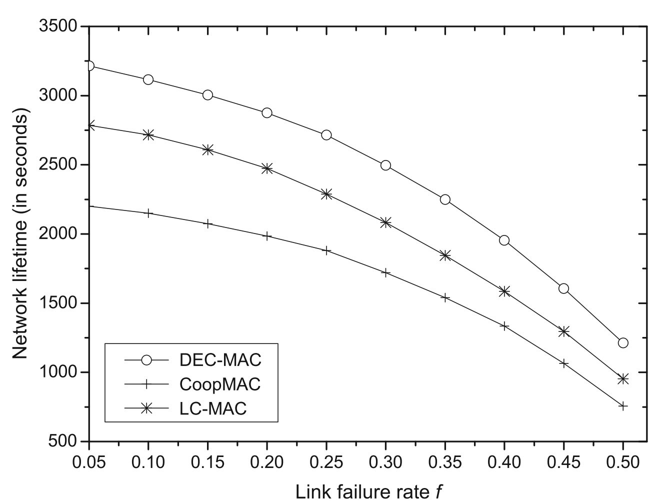

Fig. 12 Network lifetime vs. link failure rate

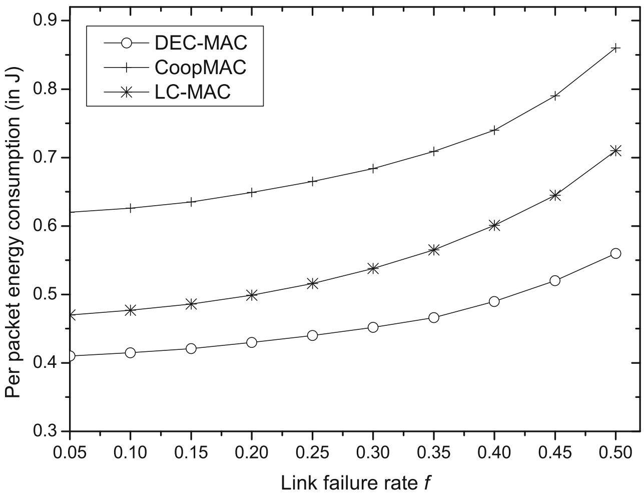

Fig. 13 Energy efficiency vs. link failure rate

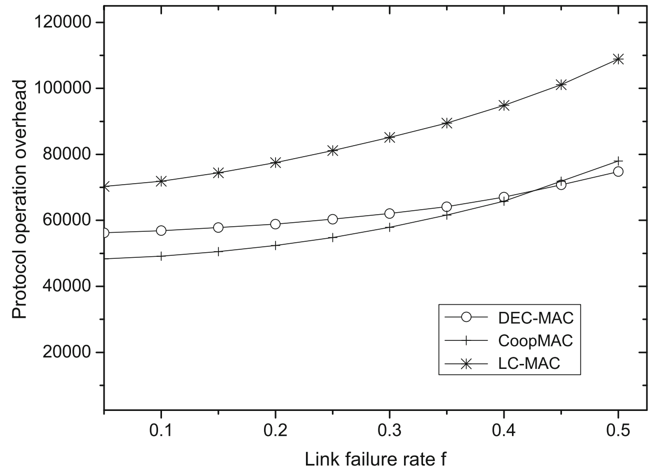

Fig. 15 Protocol operation overhead vs. link failure rate

in DEC-MAC is much lower than LC-MAC. This proves that the proposed DEC-MAC protocol, with its higher link failure rate, is more energy-efficient than LC-MAC and CoopMAC.

A desirable result is found for the standard deviation of residual energy against link failure rate, as shown in Fig. 14. The graphs of Fig. 14 show that there is little change in the standard deviation of the residual energy in DEC-MAC even with an increasing link failure rate. This is because DEC-MAC selects an optimal relay having a lower delay and higher residual energy, causing the power consumption among the nodes to remain balanced. Alternatively, the standard deviation of LC-MAC and CoopMAC changes considerably with the rate of link failures, thus proving that DEC-MAC provides a better distribution of energy consumption among the sensor nodes.

Figure 15 shows the changes in a protocol's operation overhead as a function of the link failure rate. Initially, the operation overhead of DEC-MAC is higher than that of CoopMAC. The graphs in Fig. 15 reveal that the increasing rate of operation overhead for DEC-MAC is much lower than for CoopMAC and LC-MAC. Therefore, DEC-MAC, with a higher link failure rate, achieves lower operation overhead than either LC-MAC or CoopMAC. The reason for this is that the increasing rate of collision between the relay and neighbor in DEC-MAC is lower than that of CoopMAC and LC-MAC.

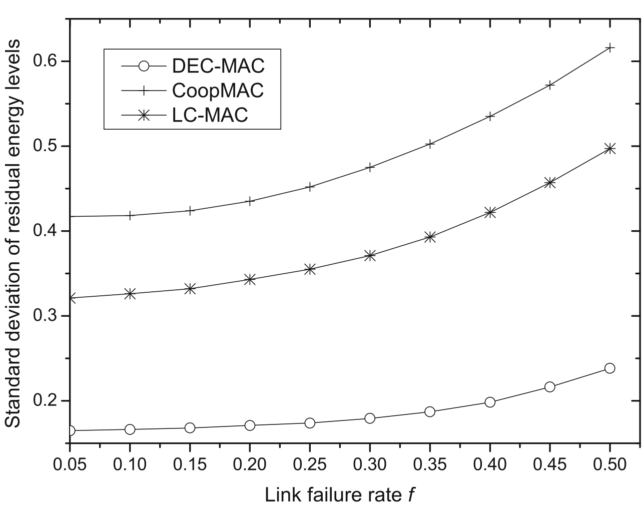

Fig. 14 Standard deviation of residual energy vs. link failure rate

7 Discussion

In this section, we would like to direct the readers' attention to the discussions on the limitations and weaknesses of our paper.

In the relay selection mechanism, we use PE and the CCDF to select the most optimal relay. However, if two or more potential relays have equal average weighted metric (W) value, then the required number of mini slots for relay selection goes to infinity. Thus, the relay selection time also goes to infinity. One of the possible solutions for such situation is as follows. The relays that send ITH message after fourth mini slot, all are selected as optimal relays to break the tie. This is because average number of required mini slots is 3.07, thus if more than one relays transmit ITH messages at fifth mini slot, then all the respondents of fifth mini slot will be selected as optimal relays. After selection of the relays, sender transmits to relays and then relays transmit together to receiver. Since, the relays transmit same data at the same rate to the destination node, thus it does not result any collision there [25].

Relay selection is an important part for cooperative transmissions to improve the network performance. In our scheme, we select a relay which has higher residual energy and lower data delivery delay. If we select a relay with highest residual energy but with poor channel condition, it increases packet error rate as well as transmission energy and thus increases per-packet energy consumption. In contrast, if we select a relay which has lowest data delivery delay, then particular relay may participate in cooperation frequently. Thus, it finishes its energy early and may partition the network which reduces the network lifetime. Therefore, we do trade-off between delay and energy consumption to optimize end-to-end delay and network lifetime. Due to these facts, end-to-end delay does not increase sharply like other protocols such as CoopMAC and LC-MAC shown in Fig. 6. On the other hand, per-packet energy consumption does not decrease sharply like other protocols such as CoopMAC and LC-MAC shown in Fig. 8. However, network lifetime of DEC-MAC improves significantly over the protocols CoopMAC and LC-MAC as shown in Fig. 7. This is because our relay selection mechanism balances the energy consumption among the nodes and reduces the leftover energy when the network dies out.

8 Conclusion

The proposed DEC-MAC protocol provides significant service differentiation in relay selection and network lifetime domains. Our relay selection algorithm contributes to find the most optimal relay in reduced number of time slots. For the lifetime domain, our methodologies help the network to maintain balanced energy consumption among the nodes, thereby increasing the network lifetime significantly.

Like other cooperative protocols, our DEC-MAC also has relay selection and additional transmission overheads. Furthermore, relayed transmission might interfere transmissions from other hidden or exposed nodes. In the future, we work on methodologies that could diminish the relay selection overheads and the interferences.

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