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Distributed multi-hop cooperative communication in dense wireless sensor networks

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Abstract In this paper, we investigate the use of cooperative communications for high performance data dissemination in dense wireless sensor networks. We first identify the limitations of existing cooperative schemes. While we previously proposed a multi-hop cooperative data dissemination scheme, REER, to address these limitations, the construction of such structure relies on a pre-established reference path. The partially centralized approach makes REER unscalable when encountering network dynamics. To address this issue, this paper proposes a novel distributed multi-hop cooperative communication scheme (DMC), which is fully distributed and

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consists of two operation phases: (1) cooperative mesh structure (CMS) construction, and (2) CMS-based data dissemination, which includes random value-based scheme and distance-based scheme for forwarding node selection. Simulation results show that *DMC* performs well in terms of a number of QoS metrics, and fits well in large-scale networks and highly dynamic environments.

Keywords Cooperative communication · Wireless sensor networks · Data dissemination

1 Introduction

Wireless sensor networks (WSNs) have numerous potential applications, e.g., battlefield surveillance, medical care, wildlife monitoring and disaster response. In mission-critical applications, the wireless networks used for communications must ensure that data packets can be delivered to the data processing center reliably and efficiently. However, due to the dynamic nature of WSNs, time-varying wireless channel, and severe constraints on energy supply and communication bandwidth of battery-operated sensor nodes, providing high performance is a challenging issue, especially when deploying WSNs for multimedia surveillance.

One of recent technology for addressing this challenges is the use of cooperative communications, which have been proposed as a scalable, energy-efficient and error-resilient solution for data transmissions in wireless networks. Nodes in cooperative communication systems work cooperatively or relay data packets for each other, thus forming multiple transmission paths or virtual multiple-input–multiple-output (MIMO) systems to relay data packets to the destination without the need of multiple antennas at each node [1, 2]. By utilizing the broadcast nature of the wireless medium and spatial distribution of sensor nodes, cooperative communications can enhance the performance of WSNs, especially for improving network reliability.

Most previous work on cooperative communication is based on the following limitations:

- Nodes employ orthogonal channel access (FDMA, TDMA or CDMA),
- Channel states between sources and cooperative partners, sources and destinations, and cooperative partners and destinations are available at participating nodes,
- The destination node has full or partial knowledge of the cooperative assignments and the channel states between nodes.
- Most existing research has focused on the cooperation between a pair of users in one-hop communications [3–6]. Cooperations among multiple nodes are investigated in [5, 7]; however, the research is still limited to one-hop communications.

In order to apply cooperative communication in WSNs, the above limitations are needed to be addressed. In addition, practical sensor nodes employ time-division half-duplex transmissions, e.g., using the carrier-sensed multiple access with collision avoidance (CSMA/CA) protocol, so that they cannot transmit and receive signals simultaneously. Besides, due to the distributed nature of WSN applications, the sink node usually does not have knowledge of the channel states between the sensor nodes, as well as the cooperative partner selections and assignments.

As our previous solution, a cooperative communication scheme, REER [8], has been proposed for reliable and energy-efficient data dissemination in dense sensor networks. Based on geographical information, REER's design harnesses the advantages of high node density and relies on the collective efforts of multiple cooperative nodes to deliver data, without depending on any individual ones. It has the following features:

- The network can be easily extended to accommodate multi-hop communications.
- By utilizing the broadcast nature of the wireless medium and spatial distribution of sensor nodes, cooperative communications are used to improve the network performance of WSNs.
- No inter-node channel state information needs to be maintained.
- Dense senor network favors the scheme to yield enough cooperative nodes.

However, the construction of cooperative structure in REER relies on a pre-established reference path. The partially centralized approach makes it unscalable when encountering network dynamics. To address this issue, this paper proposes a novel distributed multi-hop cooperative communication scheme (DMC), which is fully distributed and optimal network performance can be achieved without the need of maintaining precise network state information and centralized control. It consists of two operation phases:

- *cooperative mesh structure (CMS) construction*: the source node initiates the construction by transmitting a prob message. Among the cooperative nodes at each hop, a master node will decide the cooperative nodes and another master node for its next hop. The construction will terminate when the sink receives the probe message.
- *CMS-based data dissemination*: data packets originated from the source are forwarded to the sink node by groups of cooperative nodes (denoted as *CNs*) relaying. In each group of *CNs*, a node will be elected as the forwarding node to forward the data packet to the adjacent group of *CNs* towards the sink node. We propose two simple schemes for forwarding node selection, i.e., random value-based scheme and distance-based scheme.

Simulation results show that *DMC* performs well in terms of a number of QoS metrics, and fits well in large-scale networks and highly dynamic environments. The rest of the paper is organized as follows. Section 2 presents related work. The problem is stated in Sect. 3. We present CMS construction and CMS-based data dissemination in Sects. 4 and 5, respectively. Our simulation studies are reported in Sect. 6. Finally, Sect. 7 concludes the paper and presents the future work.

2 Related works

A large number of cooperative communication protocols have been proposed recently. Cooperation diversity gains, transmitting, receiving and processing overheads, are investigated by [9]. Cooperative issues across the different layers of the communication protocol stack, self-interested behaviors and possible misbehaviors are explored in [10]. Reference [11] proposed a cooperative relay framework which accommodates the physical, medium access control (MAC) and network layers for wireless ad hoc networks. In the network layer, diversity gains can be achieved by selecting two cooperative relays based on the average link signal-to-noise ratio (SNR) and the two-hop neighborhood information. A cooperative communication scheme combining relay selection with power control is proposed in [12], where the potential relays compute individually the required transmission power to participate in the cooperative communications. A variety of cooperative diversity protocols are proposed by [13], namely, amplify-and-forward, decode-and-forward, selection relaying, and incremental relaying. The performance of the protocols in terms of outage events and associated outage probabilities is evaluated respectively. Coded cooperation [14], integrated cooperation with channel coding and works by sending different parts of each user's code word via two independent fading paths. References [15, 16] implemented a cooperation strategy for mobile users in a conventional code division multiple access (CDMA) systems, in which users are active and use different spreading code to avoid interferences. In [17], distributed cooperative protocols, including random selection, received SNR selection and fixed priority selection, and are proposed for cooperative partner selection. The outage probability of the protocols is analyzed respectively. CoopMAC, a cooperative MAC protocol for IEEE 802.11 wireless networks, is presented by [18]. CoopMAC can achieve performance improvements by exploiting both the broadcast nature of the wireless channel and cooperative diversity. REER, a scalable, energy-efficient and error-resilient routing protocol for dense WSNs is proposed by [8]. To construct a multi-hop mesh cooperative structure, a set of nodes, termed as reference nodes (denoted as *RNs*) between the source node and the sink node (the source and the sink are also *RNs*) is first selected. The *RNs* are determined sequentially starting from the source to the sink, and the distance between two adjacent *RNs* is an application-specific value, which is a trade-off between reliability and energy efficiency. Once the *RNs* are determined, a set of nodes around each *RN* will be selected as the cooperative nodes (denoted as *CNs*), and thus, a multi-hop mesh cooperative structure is constructed in this phase. Data packets originated from the source will be forwarded to the sink by groups of *CNs* relaying, without depending on any individual ones.

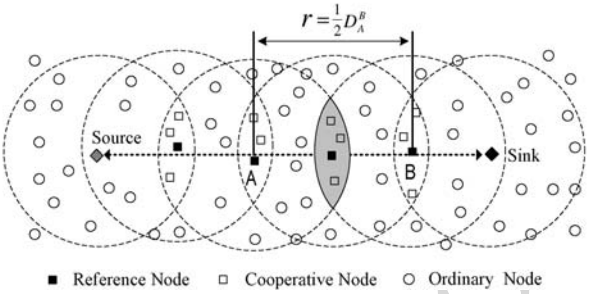
Our idea is also close to some works regarding opportunistic communication, such as GeRaF [19] and ExOR [20] where efficient methods of using multi-receiver diversity for packet forwarding are explored. However, unlike GeRaF and ExOR, the proposed scheme only uses a certain number of cooperative neighbors while achieving the application-specific requirement of reliability. The number of cooperative nodes can be flexibly adjusted to cope with network dynamics.

3 Problem statement

3.1 Architecture overview of REER

Figure 1 shows the architecture of REER scheme [8]. The sink node first sends an interest packet representing the application-specific requirements to the networks. When the interest packet is received by the source node, it starts generating reports on the detected events as specified. Before delivering the reports to the sink via multi-hop

Fig. 1 Illustration of REER scheme



routing, the source node initiates multi-hop mesh cooperative structure construction by sending a probe message towards the sink.

During the transmission of the probe message, a set of nodes, termed reference nodes between the source and the sink are first selected, such that the distance between two adjacent reference nodes is sought to be an application-specific value (denoted by r in Fig. 1).

REER considers the following facts regarding the introduction of r:

1. For any two reference nodes (e.g., A and B in Fig. 1) which are two hops away, nodes located in the area intersected by the two coverage circles centered around A and B can communicate with both A and B, as shown in the shadow area in Fig. 1.
2. If the distance (denoted by D_A^B) between A and B decreases, the size of the intersecting area increases, thus accommodating more nodes that can forward data packets cooperatively.
3. When more cooperative nodes are involved in the data dissemination, a higher reliability is provided.

The rationale of REER is to adjust the value of $r = \frac{1}{2} \cdot D_A^B$ to provide a control knob to trade off robustness and energy efficiency (and latency). In order to achieve the required reliability while meeting the application-specific quality of service (QoS) requirements (e.g. reliability, and end-to-end latency bound), r is adaptively set by the source or sink node. The reference nodes are determined sequentially, starting from the source node. After a certain timer expires, the reference nodes determine a set of cooperative nodes around each of them based on the coverage of the probe messages they sent during the reference node selection period.

In the data dissemination phase, the data forwarding node is selected among the cooperative nodes at each hop through a receiver-oriented approach [21]. The reference node selection, cooperative nodes selection, and forwarding node selection mechanisms are detailed in [8].

3.2 Motivation of DMC proposal

In this section, we will illustrate the motivation to propose DMC, and present the DMC architecture in brief. Figure 2 shows a part of the mesh structure. Let V_h denote the n_{th} cooperative group; V_{h-1} denote V_h's adjacent group one hop closer to the source, while V_{h+1} denote V_h's adjacent group one hop closer to the sink. Let RN_{n-1},

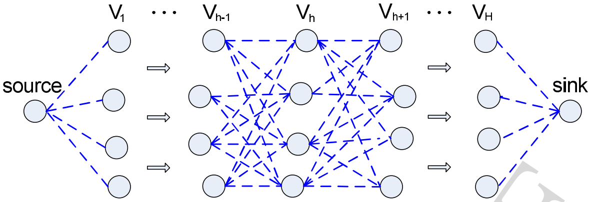


Fig. 2 Cooperation between adjacent groups of cooperative nodes

RN_n and RN_{n+1} denote the reference nodes for V_{h-1}, V_h and V_{h+1}, respectively. In order to construct an ideal multi-hop mesh cooperative structure, each node in V_h is connected with all the nodes in V_{h-1} and V_{h+1}.

Though the introduction of r provides REER a flexible control knob to trade off network performance, it has the following downfalls:

- According to the construction of its cooperative structure, REER can only guarantee the cooperative nodes in V_h are connected to RN_{n-1} and RN_{n+1}, but not all the nodes in V_{h-1} and V_{h+1}.
- It assumes that the density of sensor nodes can be deemed as a constant approximately. However, in practical wireless sensor networks, hole can be formed due to energy depletion of sensor nodes or other network dynamics. If hole exists in cooperative field, the number of cooperative nodes will decrease extensively, which causes the unbalance of the whole cooperative structure between the source and the sink node.
- The cooperative structure construction of REER relies on a pre-established reference path. Such partially centralized approach makes it further unscalable when encountering network dynamics and/or the changes of application-specific QoS requirements.

Thus, we are motivated to design a novel DMC algorithm to address the above downfalls. DMC realizes an ideal multi-hop mesh cooperative structure, and is fully distributed and decentralized and possesses the flexibility of adapting to the network dynamics and the specific QoS requirements. In DMC, the number of cooperative nodes in each cooperative group is the key parameter, which is set depending on the network size, node density and the trade-off between reliability and energy efficiency.

4 Multi-hop cooperative structure construction in DMC

4.1 Architecture overview

As an example in Fig. 1, the source node first selects a certain number of cooperative nodes (denoted by N) among its neighbor nodes. In the cooperative node list, the source further selects one as the reference node at next hop. Then, the source node creates a probe message with packet format as shown in Fig. 4. The main information included in the probe message are *CooperativeNodeList* and *NextReferenceNode*.[1]

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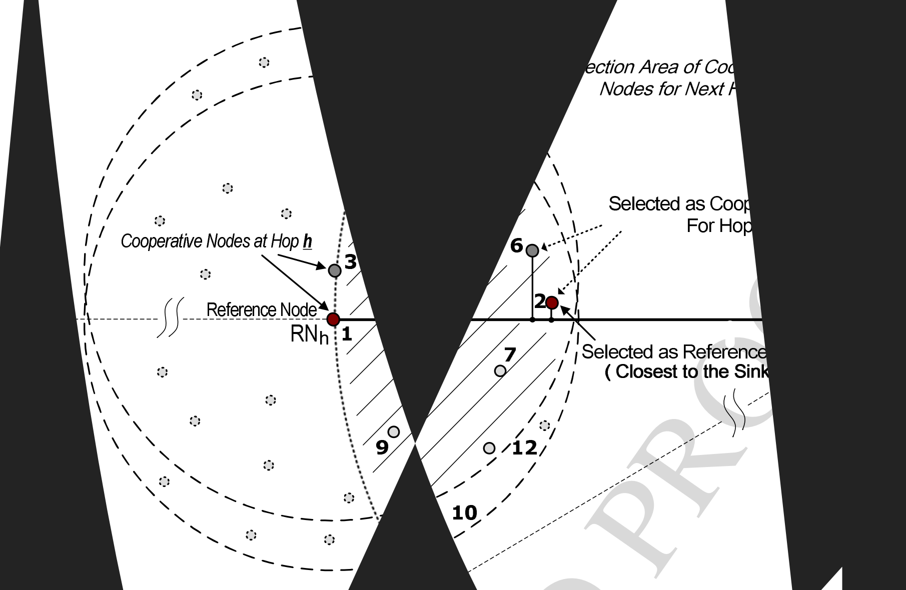
[1] The cooperative node selection and next reference node selection mechanisms are detailed in Sects. 4.3 and 4.4.



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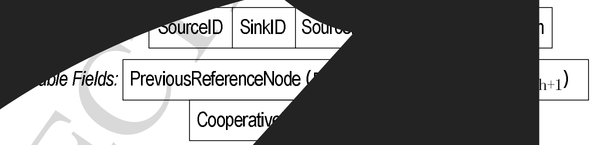

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Table 1 Pseudo-code for the determination of the cooperative node selection area at node RN_h

```
procedure SelectionAreaDetermination ($Q_h$)
begin
  $Q_h$ is the set of node $RN_h$'s neighbors in the forwarding area;
  $f_i$ is the flag indicating whether node $i$ ($i \in Q_h$) is included in the selection area;
  $R$ is the maximum transmission range;
for each neighbor $i$ in $Q_h$
  $f_i \leftarrow 1$;
  for each cooperative node $k$ in ($V_h - RN_h$)
    Calculate the distance between $i$ and $k$, $d_i^k$;
   if $d_i^k > R$
      $f_i \leftarrow 0$;
      break for;
   endif
  endfor
endfor
```

forwarding area[2] as the preliminary candidate nodes (denoted by Q_h). For each node in Q_h, the nodes that cannot be connected to all of the other cooperative nodes in V_h will be filtered. Given the example shown in Fig. 3, Q_h includes nodes 2, 4–11, and nodes 10, 11 are excluded because they cannot reach the other cooperative node (i.e., node 3). Table 1 shows the pseudo-code of the algorithm for determining the cooperative node selection area.

4.3 Cooperative node selection mechanism

Before RN_h determines the cooperative nodes at hop $h+1$, it first checks whether the sink node is within its one hop range. Should that be the case, it further checks whether the other cooperative nodes at hop h can reach the sink node. Only if all of nodes in V_h can be connected to the sink node, RN_h delivers the probe message to the sink without cooperative node selection. Otherwise, in the pre-determined cooperative node selection area, RN_h will select N nodes which are closest to the sink as the cooperative nodes for the next hop, as shown in Table 2.

4.4 Reference node selection mechanism

In global perspective, DMC algorithm is distributed. However, in order to facilitate the selection of cooperative nodes and delivery of the probe message, a reference node is still needed as a local coordinator for each hop. Table 3 shows the pseudo-code of reference-node-selection at node RN_h. Among the previously selected cooperative nodes in V_{h+1}, the next reference node is the one whose distance to the sink node is minimal. The selected reference node will continue to transmit the probe message, and so forth, until the sink node is reached.

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[2] In the forwarding area, the neighbors are closer to the sink node than RN_h.

Table 2 Pseudo-code for cooperative nodes selection at node RN_h

```
procedure CooperativeNodeSelection ($Q_h$)
begin
  $Q_h$ is the set of node $RN_h$'s neighbors in the forwarding area;
  $f_i$ is the flag indicating whether node $i$ ($i \in Q_h$) is included in the selection area;
if sink node is within one hop distance of all the cooperative nodes in $V_h$
  Send the probe message to the sink node;
else
  Among the nodes: $\{\forall i, f_i = 1 | i \in Q_h\}$
      Select $N$ nodes which are closest to the sink as $V_{h+1}$;
endif
```

Table 3 Pseudo-code for reference node selection at node RN_h

```
procedure ReferenceNodeSelection ($V_{h+1}$)
begin
  $V_{h+1}$ is the set of cooperative nodes selected by $RN_h$;
for each cooperative node $k$ in $V_{h+1}$
  Calculate the distance from $k$ to the sink node, $d_k^t$;
endfor
for each cooperative node $i$ in $V_{h+1}$
  if $d_i^t = \min\{d_j^t | j \in V_{h+1}\}$
    Select $i$ as NextReferenceNode;
    Break;
  endif
endfor
```

5 CMS-based data dissemination in DMC

After the cooperative mesh structure (CMS) is built up, each data packet will be forwarded towards the sink node through group-by-group relaying. Figure 2 shows all the possible wireless links between two consecutive cooperative groups. While the quality of each of the links varies over time, the mesh structure makes data transmissions robust to link dynamics; i.e., data broadcasting is exploited to attain high reliability. This strategy provides an effective trade-off between traditional multipath routing and single path routing schemes. That is, it has the advantage of error resilience as in multipath (or mesh) routing schemes, but without the associated overhead of sending multiple copies of the same packet.

5.1 Random value-based scheme

In random value-based scheme, one cooperative node will be selected as the data forwarding node using a time-based mechanism as follows. Initially, every cooperative node starts a so-called Forwarding-Node-Selection-Timer (FNS-Timer), which

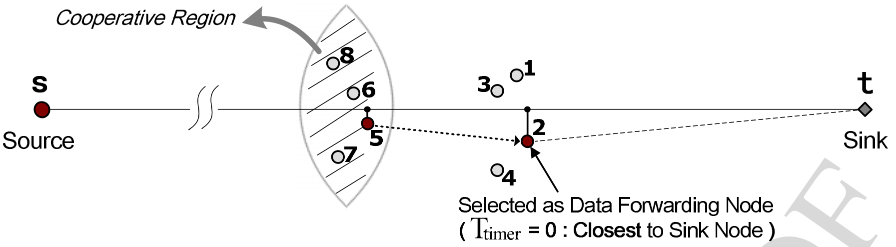


Fig. 5 Illustration of data forwarding node selection in distance-based strategy

is set to a random value. The cooperative node whose FNS-Timer expires first will be selected as the data forwarding node; i.e., a smaller timer value indicates that the corresponding cooperative node has a higher eligibility. The winning node broadcasts an election notification message within the cooperative region, as shown in Fig. 5. When other cooperative nodes within the same cooperative region receive the notification message, they will cancel their FNS-Timers. Next, the data forwarding node will broadcast data packet towards the sink node, and so forth.

5.2 Distance-based scheme

5.2.1 Calculating minimum and maximum distances to sink node

We assume that each sensor node i knows its cooperative nodes' positions (including its own position), and the sink's location (x_t, y_t). For example, in Fig. 5, node 1 knows the positions of nodes 1, 2, 3 and 4, while node 5 knows the positions of nodes 5, 6, 7 and 8.

Let V_h be the set of node i's cooperative nodes in the hth hop's cooperative region. Node i can compute the distance between any cooperative node and the sink node as

$$D_t^k = \sqrt{(y_t - y_k)^2 + (x_t - x_k)^2}, \tag{1}$$

where $k \in V_h$, and (x_k, y_k) is the location of node k.

Then, node i can figure out which cooperative node is the closest one to the sink, and which one is the farthest one from the sink. Let $D_{\min}$ and $D_{\max}$ denote the minimum and maximum distance between the sink and cooperative nodes in V_h.

5.2.2 Time-based next-hop-election

Let T_{timer} denote the value of the FNS-timer. T_{timer} has been set by the current cooperative node to elect itself for next-hop data forwarding during the data dissemination. Let $T_{\max}$ denote the maximum possible value of the FNS-timer.

Based on $D_{\min}$, $D_{\max}$ and node i's own distance to sink D_t^i, node i can calculate its timer value by (2):

$$T_{\text{timer}}^i = \frac{D_t^i - D_{\min}}{D_{\max} - D_{\min}} \cdot T_{\max}. \tag{2}$$

Table 4 Pseudo-code for setting time value for FNS-timer

```
procedure NextHopSelection ($V_h$)
    $V_h$ is the set of cooperative nodes in the $h$th
    hop's forwarding area;
  $i$ is one of the cooperative nodes in $V_h$;
  $D_{\min}$ is the minimum distance between sink
    and cooperative nodes in $V_h$;
  $D_{\max}$ is the maximum distance between sink
    and cooperative nodes in $V_h$;
begin
  calculate $D_{\min} = \min\{D_t^k | k \in V_h\}$
  calculate $D_{\max} = \max\{D_t^k | k \in V_h\}$
  calculate $T_{\mathrm{timer}}^i$ according to Eqn. (2);
  Set $T_{\mathrm{timer}}^i$ to node $i$'s FNS-timer;
end
```

In the case that node i is the closest cooperative node to the sink (e.g., nodes 2 and 5 in Fig. 5), T_{timer}^i will be equal to 0. Furthermore, if node i receives a data packet broadcast by its previous hop node successfully, it will forward the data packet due to its FNS-timer expiring before those of the other cooperative nodes in V_h.

6 Performance evaluations

We implement our protocols and perform simulations using OPNET Modeler. The sensor nodes are uniformly random;y deployed over a 1000 m × 500 m field. To verify the scaling property of mesh cooperation-based schemes, we select a large-scale network scenario with 800 nodes. The source nodes are deployed at the left side of the field and one sink is located on the right side. The sensor application module consists of a constant-bit-rate source, which generates 1024 bits every 100 ms. As in [22], we use IEEE 802.11 Distributed Coordinate Function as the underlying medium access control (MAC), and the radio transmission range (R) is set to 60 m. The data rate of the wireless channel is 1 Mb/s. All messages are 64 bits in length. We assume both the sink and sensor nodes are stationary. For consistency, we use the same energy consumption model as in [22]. The transmit, receive and idle power consumptions are 0.66 W, 0.395 W, and 0.035 W, respectively. The initial energy of each node is 12 Joules. We account for energy consumption in the simulations, in terms of transmissions, receptions, overhearing, collisions and other unsuccessful transmissions, MAC layer headers, retransmissions, and control frames such as RTS/CTS/ACKs. The following performance metrics are considered:

- *Packet delivery ratio*: It is the ratio of the number of data packets delivered to the sink, to the number of packets generated by the source nodes.
- *Average End-to-end Packet Delay*: including all possible delays during data dissemination, caused by queuing, channel access delay, retransmission due to packet collision and loss, and packet transmission time.

- *Average Communication Energy*: the total communication energy consumption, including transmitting, receiving, retransmissions, overhearing and collision, over the total number of distinct reports received at the sink.
- *Average Hop Counts*: It is the number of hop counts of a path from the source to the sink.
- *Lifetime*: the time when the first node exhausts its energy.

Figure 6 shows the snapshot of an OPNET simulation, which illustrates the result of mesh cooperative structure construction. The OPNET animation can be referred to [23]. At each hop, one of the cooperative nodes elects itself successfully to forward the data packet.

6.1 Impact of cooperative node number on the performance of DMC

In this section, we denote N as the number of cooperative nodes in each cooperative group. We change N from 2 to 6. In each group of experiments, we change link failure ratio from 0.05 to 0.55 by the step size of 0.05. Random value-based scheme is used in the data dissemination phase.

Let P denote the packet delivery ratio. Let $H(N)$ denote the hop counts between the source and the sink when N cooperative nodes are used at each hop. Let f be the

Fig. 6 A snapshot of simulation animation

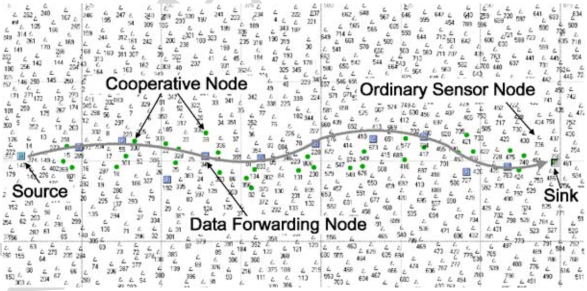
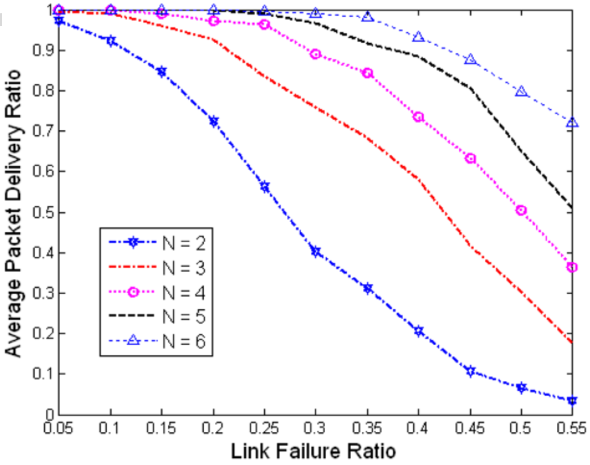


Fig. 7 The comparison of average packet delivery ratio



failure probability of each link/node. Let p denote the successful delivery probability of data packet at each hop. Then,

$$P = p^H = \left(1 - f^N\right)^H (N). \tag{3}$$

According to (3), the larger is N, the higher reliability can be obtained, which is observed in Fig. 7. When N is up to 6, the packet delivery ratio keeps higher than 95% if link failure ratio is smaller than 35%. By comparison, P is much lower (i.e., 30%) when N is equal to 2. It is expected that P is lower in traditional shortest path scheme.

Figure 8(a) shows the curves of delay performance. When N is equal to 6, the delay is the lowest. Note that the setting of the maximum backoff delay plays an important role in the delay performance, since random value-based scheme is adopted in our experiments.

As shown in Fig. 8(b), the average communication energy per successful data delivery is increased when link failure ratio becomes larger. The energy in $N = 2$ case increases exponentially with link failure ratio increasing. It is because the packet delivery ratio is very low when the number of cooperative nodes is not sufficient in unreliable environments.[3]

Figure 8(c) shows the comparison of hop counts when different N is used. As described in Sect. 4.2, the larger is N, the smaller is the cooperative selection area, thus causing hop distance shorter and hop count larger. Thus, the superior performance with more cooperative nodes involved in the data dissemination is compromised by a larger hop count. As shown in Fig. 8(c), the $N = 6$ case uses about three more hops than $N = 2$ case. However, such trade-offs are valuable in unreliable and dynamic environments.

6.2 Comparison of random-based and distance-based schemes for data dissemination in DMC

As shown in Fig. 9, the end-to-end packet delay of the distance-based scheme is always much lower than that of the random value-based scheme. When there is no link failure, the cooperative node with the least FNS-timer value will forward the data packet. In the distance-based scheme, the cooperative node which is the closest to the sink node will win the election, and thus there is no backoff time before data forwarding under a good channel condition. By comparison, the backoff time at hth hop in the random value-based scheme [8] is equal to

$$T_{\text{backoff}} = \min\left\{T_{\text{timer}}^k \mid k \in V_h\right\} \tag{4}$$

where $T_{\text{timer}}^k = \text{rand}(0, T_{\max})$. The delay performance depends on the setting of the maximum backoff time value $T_{\max}$. Large $T_{\max}$ helps to reduce the possibility of simultaneous data broadcasting, while a small value of $T_{\max}$ decreases the data latency.

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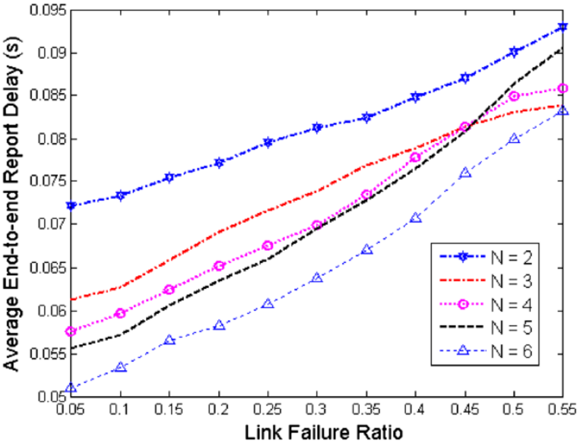
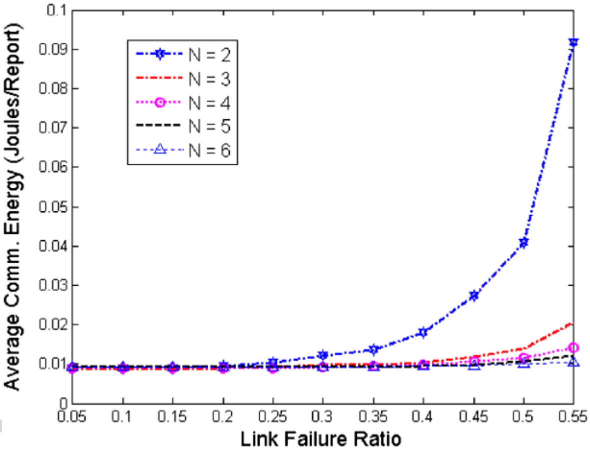
[3] The average communication energy is equal to the network energy consumption divided by the number of successful data packet deliveries.

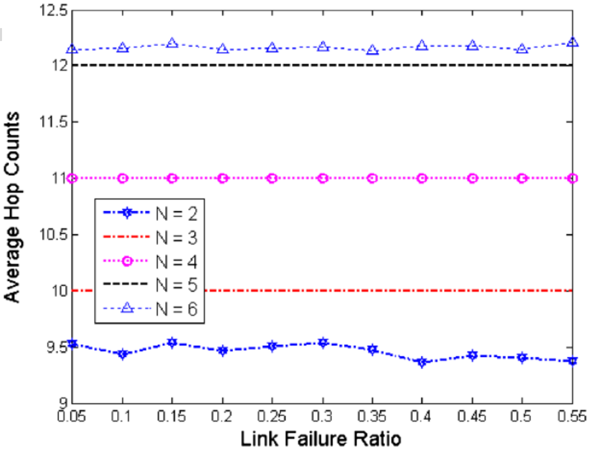
Fig. 8 Impact of cooperative node number on the performance of DMC in unreliable environments



(a) The Comparison of Average End-to-end Packet Delay



(b) The Comparison of Average Communication Energy



(c) The Comparison of Average Hop Counts

Table 5 Comparison of lifetime for random value-based scheme and distance-based scheme

Scheme	$f = 0$	$f = 0.2$
Random value-based:	7.92 (minutes)	10.9 (minutes)
Distance-based:	8.98 (minutes)	11.4 (minutes)

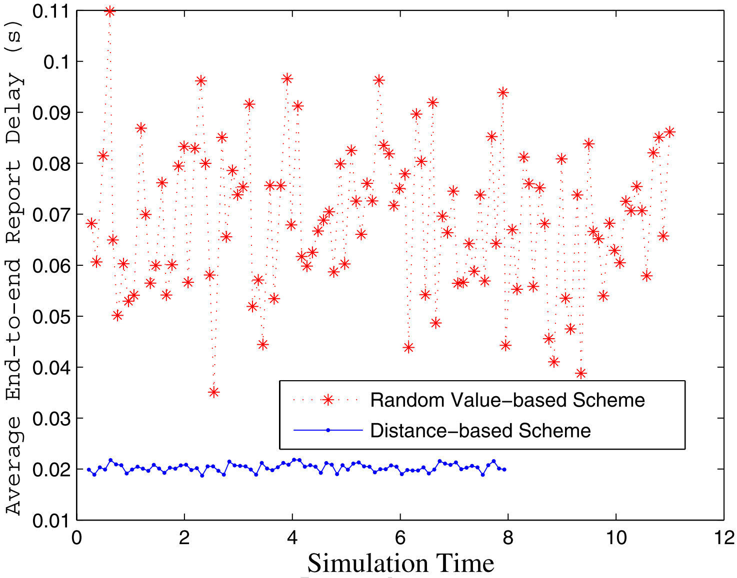


Fig. 9 Comparisons of end-to-end delay with link failure ratio = 0

In our simulations, we set $T_{\max}$ according to the average number of cooperative nodes in the cooperative region [8].

Figure 10 shows the comparison of end-to-end delays when the link failure ratio is equal to 20%. The end-to-end packet delay of the random value-based scheme is larger than that of the distance-based scheme in most cases. Comparing Fig. 9 to Fig. 10, the end-to-end packet delays of the distance-based scheme are larger when the link failure ratio increases. When the cooperative node with $T_{\text{timer}} = 0$ fails to receive the broadcast data in an unreliable environment, extra backoff delay will be introduced.

The lifetime results in Table 5 show that the random value-based scheme has 38% more lifetime than the distance-based scheme under good channel conditions. And the random value-based scheme has 27% longer lifetime than the distance-based scheme when the link failure ratio is equal to 0.2. It is because the traffic load is more evenly distributed among the cooperative nodes in the random value-based scheme, while the distance-based scheme tends to select the cooperative nodes closer to the sink. Thus, the random value-based scheme achieves better load balancing than the distance-based scheme. We will address the load balancing issue in our future work. A hybrid criterion which combines the features of both distance-based and energy-

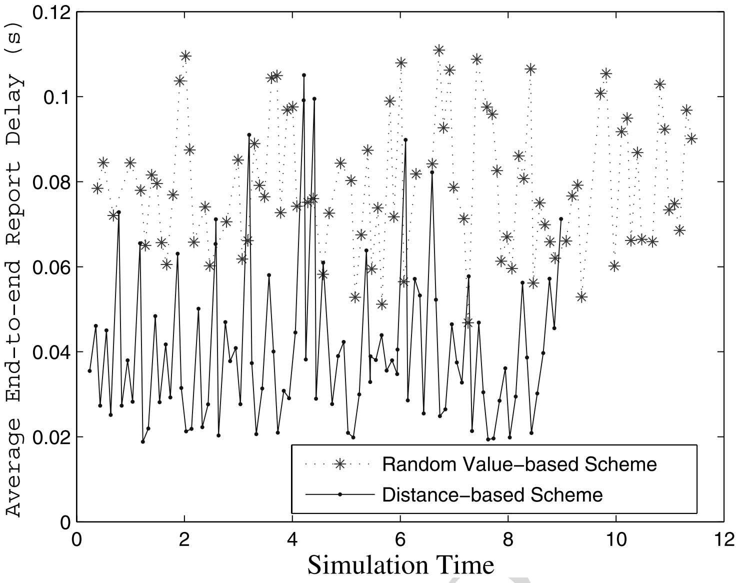


Fig. 10 Comparisons of end-to-end delay with link failure ratio = 0.2

based criteria, will be proposed in order to facilitate load balancing, reliability and fast packet delivery in an unreliable environment.

7 Conclusion

The use of cooperative communications for reliable data dissemination is appealing in wireless sensor networks. However, some disadvantages exist in previous cooperative schemes. This paper considers the construction of "multi-hop mesh cooperative transmission structures" to address these disadvantages, and propose a novel distributed multi-hop cooperative communication scheme for data dissemination in dense sensor networks. Simulation results show that the proposed scheme scales well in handling difference network dynamics. Appealing performance is achieved when a sufficient number of cooperative nodes is used in unreliable environments. We will consider the more challenging case of utilizing multi-radio multi-channel technique to further improve the network performance in our future work. In order to guarantee the bandwidth requirement for multimedia transmission over wireless sensor networks, concurrent multipath transmission strategy will also be considered by exploiting the proposed multi-hop mesh cooperative transmission structures.

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