Multi-Hop Mesh Cooperative Structure Based Data Dissemination for Wireless Sensor Networks

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***Abstract*—In this paper, we investigate the use of cooperative communications for reliable data dissemination in wireless sensor networks. We first identify the disadvantages of some existing cooperative schemes. While the previously proposed "multi-hop mesh cooperative transmission structure" addresses these disadvantages, it suffers from large end-to-end delays during data disseminations due to its random value-based forwarding node selection scheme. This paper proposes a novel distance-based forwarding node selection scheme that yields smaller end-to-end delays. We present extensive simulation results that verify the effectiveness of the proposed data dissemination scheme.**

I. 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 channels and interference from other users, providing reliable data delivery is a challenging issue.

In recent years, cooperative communications 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 by relaying 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, e.g., in terms of reliability and energy efficiency.

Most previous work on cooperative WSNs is based on the following assumptions:

- Sensor 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 sensor nodes,
- The sink node has full or partial knowledge of the cooperative assignments and the channel states between sensor nodes.

However, in practice 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 base station/sink node usually does not have knowledge of the channel states between the sensor nodes, as well as the cooperative partner selections and assignments.

In addition, most existing research has focussed on the cooperation between a pair of users in one-hop communications [3][4][5][6][7]. Cooperations among multiple nodes are investigated in [6][8]; however, the research is still limited to one hop communications. To solve the above problems, a novel mesh cooperative architecture has been proposed in [9], which has the following features:

- The network can be easily extended to accommodate multi-hop communications,
- Among the potential cooperative nodes, the data forwarding node is selected based on a random time value determined locally at each cooperative node without any negotiation between the nodes,
- No inter-node channel state information needs to be maintained.

However, in the data dissemination phase, the random value based scheme used in [9] to select the data forwarding node may cause large end-to-end delays. In this paper, we propose a novel distance based mechanism to set the value of the timer. The distance based mechanism can yield smaller end-to-end delays, facilitating reliable and fast packet delivery over an unreliable wireless networking environment. We present comprehensive simulation results that verify the effectiveness of the proposed data dissemination scheme.

II. Architecture Overview

Usually WSNs are deployed in harsh environments, and the wireless links and sensor nodes are failure prone. Thus, the multi-hop mesh cooperative structure has been proposed to address the reliability and energy efficiency issues [9]. We first give an overview of the construction of the multi-hop mesh cooperative structure in Section II-A. Based on the cooperative structure, the data dissemination method is described in Section II-B.

A. Multi-hop Mesh Cooperative Structure Construction

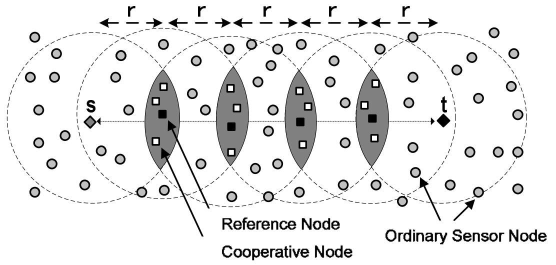

Fig. 1. Illustration of multi-hop mesh cooperative structure construction

In Fig. 1, The sink node (denoted by t) first sends an interest packet representing the application specific requirements. When the interest packet is received by the source node (denoted by s), it starts generating reports on detected events as specified. Before the reports are delivered to t via multi-hop routing, s initiates multi-hop mesh cooperative structure construction by sending a probe message toward t.

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).

We consider the following facts regarding the introduction of r:

1) For any two reference nodes (e.g., A and B) 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.
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 disseminations, a higher reliability is provided.

Thus, the main idea 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) [9]. 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. The reference node selection and forwarding node selection mechanisms are detailed in [9].

B. Mesh Cooperative Structure Based Data Dissemination

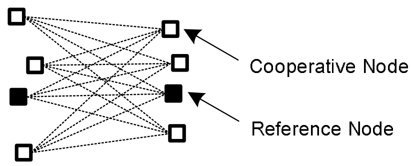

Fig. 2. Mesh structure between two cooperative groups

After the cooperative structure is built up, each data packet will be forwarded toward the sink node through group-by-group relaying. Fig. 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.

Note that reference nodes and cooperative nodes play the same role in data disseminations. 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.

III. Random Value-based and Distance-based Node Selection Schemes

A. 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 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. 3. 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.

B. Distance-based Scheme

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. 3, 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.

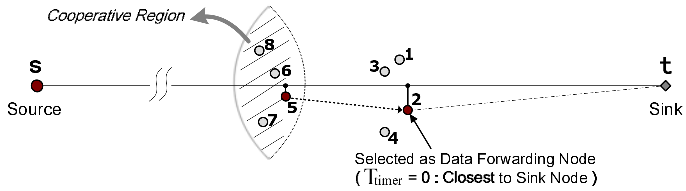

Fig. 3. Illustration of data forwarding node selection in distance-based strategy

TABLE I
PSEUDO-CODE FOR SETTING TIME VALUE FOR FNS-TIMER

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procedure NextHopSelection(V_h)
  V_h is the set of cooperative nodes in the hth
      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 ∈ V_h}
 calculate D_max = max{D_t^k | k ∈ V_h}
 calculate T_timer^i according to Eqn.(2);
 Set T_timer^i to node i's FNS-timer;
end
```

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

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

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 to the sink. Let D_{min} and D_{max} denote the minimum and maximum distance between the sink and cooperative nodes in V_h.

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).

$$T_{timer}^i = \frac{D_t^i - D_{min}}{D_{max} - D_{min}} \cdot T_{max} \quad (2)$$

In the case that node i is the closest cooperative node to the sink (e.g., nodes 2 and 5 in Fig. 3), 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.

IV. PERFORMANCE EVALUATIONS

We implement our protocols and perform simulations using OPNET Modeler. The sensor nodes are uniformly random deployed over a 1000m × 500m field. To verify the scaling property of mesh cooperation based schemes, we select a large scale network scenario with 800 nodes. The source nodes is 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 100ms. As in [10], we use IEEE 802.11 Distributed Coordinate Function as the underlying medium access control (MAC), and the radio transmission range (R) is set to 60m. 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 [10]. 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:

- *Lifetime*: the time when the first node exhausts its energy.
- *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.

Fig. 4 shows the snapshot of an OPNET simulation, which illustrates the result of mesh cooperative structure construction. The OPNET animation can be referred to [11]. At each hop, one of the cooperative nodes elects itself successfully to forward the data packet.

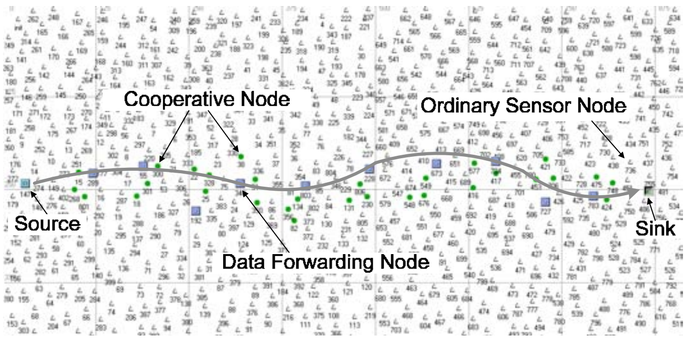

Fig. 4. A snapshot of simulation animation

As shown in Fig. 5, 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 [9] is equal to:

$$T_{backoff} = min\{T_{timer}^k | k \in V_h\} \quad (3)$$

TABLE II
COMPARISON OF LIFETIME FOR RANDOM VALUE-BASED SCHEME [9] AND PROPOSED 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)

where $T^k_{timer} = \text{rand}(0, T_{max})$. 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. In our simulations, we set T_{max} according to the average number of cooperative nodes in the cooperative region [9].

Fig. 6 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. 5 to Fig. 6, the end-to-end packet delays of the distance based scheme is larger when the link failure ratio increases. When the cooperative node with $T_{timer} = 0$ fails to receive the broadcast data in an unreliable environment, extra backoff delay will be introduced.

The lifetime results in Table II 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 achieve better load balancing than the distance base 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 based criteria, will be proposed, in order to facilitate load balancing, reliability and fast packet delivery in an unreliable environment.

V. 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 distance-based scheme for forwarding node selection. Simulation results show that the proposed scheme performs well in large scale WSNs (up to 800 sensor nodes), and yields smaller end-to-end delays than the existing random value-based scheme.

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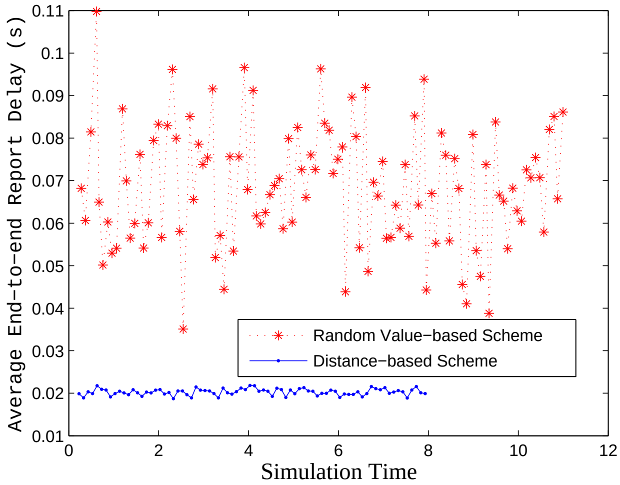

Fig. 5. Comparisons of End-to-end Delay with link failure ratio = 0

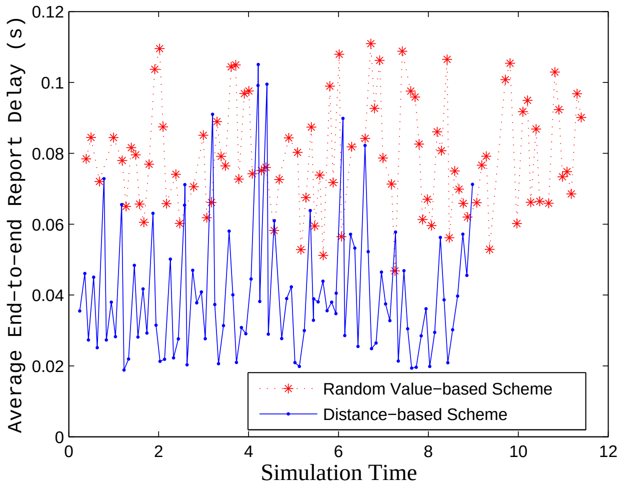

Fig. 6. Comparisons of End-to-end Delay with link failure ratio = 0.2

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