RRDD: Receiver-oriented Robust Data Delivery in Mobile Sensor Networks

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Abstract

Data forwarding in the wireless networks typically employs a sender-oriented approach in which the next hop node is pre-selected based on neighbor or network information. This method incurs large overhead when accurate information is needed for making the optimal forwarding decision. In this paper, a receiver-oriented robust data delivery scheme (RRDD) is proposed for mobile sensor networks. In RRDD, the sender does not appoint a specific forwarder proactively, but allows its neighboring candidates to dynamically contend for the data forwarding task based on local state information. In this way, the best-suited node is elected at each hop to provide robust and efficient delivery service to data packets. Comprehensive simulations show that RRDD exhibits superior transmission performance over all of the compared schemes.

1. Introduction

While extensive studies have been carried out in the past several years for wireless sensor networks, few of them have taken the node mobility into consideration. Actually, the sensor node may move together with the mobile element (e.g., animal, human and vehicle) to which it is attached for data gathering. As an example, in habitat monitoring [1] or environmental study [2], sensor nodes are deployed in the field as well as are equipped on free-ranging animals to be monitored. However, in mobile sensor networks, data delivery is more likely to be affected by link quality fluctuation and dynamic topology change. Therefore, the network should provide robust transmission mechanisms for the sensory data. Although some relevant issues have been studied extensively in the context of mobile wireless ad hoc networks, these works [3] are not well suitable for energy capability constrained sensor nodes. Thus, it is imperative to design a robust data delivery approach specifically for mobile sensor networks.

In this paper, we propose a novel 'receiver-oriented' robust data delivery scheme (RRDD) for mobile sensor networks. Instead of establishing the global end-to-end routing for data delivery, RRDD selects the forwarder at each hop through dynamic node contention. It works based on cross-layer design with the MAC layer as the anchor, operated under IEEE 802.11 MAC protocol, which has been proven effective in many prior works. Through the contention for the CTS reply, an intended receiver can be elected from the sender's neighboring nodes with a closer distance to the sink than the sender. This node will become the final forwarder if it receives the packet successfully. Otherwise, the nodes that have overheard the packet will contend again to elect a final forwarder. The final forwarder replies the ACK to the sender and then continues to relay the data packet. The contention for the ACK reply is applied so as to reduce unnecessary retransmissions and improve transmission efficiency. RRDD also takes the communication void problem [4] into account by adopting a stateless bypass mechanism to relay data packets along the void region border. Simulation result confirms that RRDD exhibits superior performance in presence of node mobility and link error.

The rest of this paper is organized as follows. Section 2 presents the proposed scheme in detail, while Section 3 discusses the performance evaluation of the proposed scheme. Section 4 summarizes the related works. Finally, Section 5 concludes the paper.

2. RRDD framework

2.1. Scenarios and assumptions

We first describe the basic application scenarios and assumptions:

1. This paper focuses on the mobile sensor network with a fixed sink, as well as a large number of sensor nodes which are static or move randomly with a slow speed. With various types of onboard

sensors, the node is capable to collect sensory data on the monitored targets, and transmit data through wireless multi-hop communication to the sink.

2. All sensor nodes have similar capabilities (energy, communication, etc.), and equal significance.
3. Each node is assigned a unique ID so that it can be identified from other neighboring nodes.
4. Each node knows its position (by GPS or other localization services [5]) and can estimate its own instantaneous motion state [6], i.e., direction and speed. The sink's location is pre-known to all nodes from pre-programmed information.
5. The radio is modeled as that in [7]: the probability p of successfully receiving a packet is:

   $$p(f) = (1 - P_e)^{8f} \quad (1)$$

   where f is the frame size, and P_e is the probability of bit error. From (1), the smaller a frame size is, the less likely the frame is to get dropped by nodes due to transmission errors. As a result, some control frames, i.e., RTS, CTS and ACK in MAC, can be considered as nearly error-free since their sizes can be neglected as compared with that of data frame.
6. In order to analyze conveniently as well as not to lose the basic characteristic of the wireless link, we adopts a simplified model derived in [8] to describe the relationship between p and the sender-receiver distance d, $p(d)$, as follows:

   $$p(d) = \min\left(\frac{(d_0 + D_t - d)}{D_t} u(d_0 + D_t - d), 1\right) \quad (2)$$

   where $u(t)$ is the step function, d_0 is the start point of the transitional region (the reception region with $0 < p < 1$), D_t is this region's width. The communication range R is defined as the region with $\varepsilon < p \leq 1$, while $\varepsilon > 0$ is the tolerable minimum reception rate that is dependent on the application requirement.

2.2. CTS reply contention

In RRDD, sensor nodes make forwarding decisions based on the location information. Thus, if a node has data to transmit, it has to notify the neighboring nodes of its existence by broadcasting the beacon message, which contains the node's location and motion state [9]. To save limited node energy resources, only the nodes that detected the transmission activities from neighbors will join the beacon exchanges.

Due to the broadcast nature of wireless medium, all neighboring nodes of the sender can overhear the RTS from the sender. It is possible that several nodes from them can become forwarder candidates. To break the tie and reduce collisions, candidate nodes respond to the sender after backoff time ΔT. Obviously, the node with the shortest backoff time will be the first one replying with a CTS. This node will be the intended receiver for the data packet. Since the carrier sensing range is normally larger than twice (e.g. 2.2 times) of the communication range, the CTS can be heard or sensed by the other neighboring nodes of the sender. Once other candidate nodes that are counting down the backoff timer hear of or sense the CTS, they stop competing for relay immediately. Thereafter, election for the intended receiver finishes.

To set a proper backoff time for each candidate, let us first consider several metrics that have to be taken into consideration by the scheme:

1. Node-to-sink distance: An ideal forwarder should be nearer to the sink with respect to the sender.
2. Node residual energy: In order to balance energy consumption, the node with more residual energy should be selected as the forwarder.
3. Distance-hop trade-off: If the scheme attempts to minimize the number of hops by maximizing the geographic distance covered at each hop (as in greedy forwarding [9]), it is likely to incur more retransmission on the unreliable long weak links. On the other hand, if the scheme attempts to maximize per-hop reliability by forwarding data only to close neighbors with good links, it may cover only a small geographic distance at each hop, which would result in more transmission hops for each packet to reach the sink. It has been recently suggested in [7] that the production of p and the sender-receiver distance d ($p \times d$) is an optimal metric for balancing distance-hop trade-off in lossy wireless networks.

To incorporate the above requirements, we define a combined function for the backoff delay of node i:

$$\Delta T_i = \left[w_1 \cdot \left(1 - \frac{d_{js} - d_{is}}{R}\right) + w_2 \cdot \left(1 - \frac{e_i}{E}\right) + w_3 \cdot \left(1 - \frac{p_{ij} \cdot d_{ij}}{R}\right) + w_4 \cdot Rand(0,1) \right] \cdot SIFS, \quad (3)$$

$$(e_i > 0, d_{js} > d_{is}, p_{ij} > 0, d_{ij} < R, \sum w_k = 1)$$

where $w_1 \sim w_4$ are weighting coefficients used to weight among the application requirements on the metrics ($w_4 < w_1, w_2, w_3$), e_i and E denotes the residual and initial energy of node i respectively, d_{ij} denotes the distance between node i and j, p_{ij} denotes the packet reception rate between node i and j, node j and s are the sender and the sink respectively. Thus, the backoff delay for a candidate node is no greater than Shorter Inter-Frame Spacing (SIFS).

To calculate the distances introduced above at node i, the estimated position of the sender j at time t, (x_j, y_j), is calculated as follows [6]:

$$
\begin{aligned}
x_j &= x_{beacon} + v_x \times \left(t - t_{beacon}\right) \\
y_j &= y_{beacon} + v_y \times \left(t - t_{beacon}\right)
\end{aligned} \tag{4}
$$

where x, y, v_x, v_y are node position and speed in the direction of the x-axis and the y-axis respectively, t is the current time, t_{beacon} is reception time of the latest beacon from node j.

2.3. ACK reply contention

Due to the broadcast nature of wireless medium, all neighboring nodes of the sender can overhear the data packet. It is possible that the intended receiver fails to receive the data packet from the sender while some of the candidate nodes in CTS reply contention overhear the transmission successfully (the failure probability of all links is much smaller than that of a single link). In this case, one of them can substitute for the intended receiver to become the final forwarder [10]. Intuitively, such a substitution can reduce the expected number of retransmissions from the sender while still keeping the geographical forwarding progress towards the sink.

In RRDD, the intended receiver is supposed to reply an ACK to the sender after γ*SIFS (γ < 0.5) if it has successfully received the data packet. Otherwise, the channel keeps silent during this interval. Then, the candidate nodes with the data packet copy can contend through ACK reply for becoming the final forwarder. The contention process here is much alike that of the CTS reply. The backoff delay for a candidate node is no greater than Shorter Inter-Frame Spacing (SIFS).

Here, the backoff delay of a node i can be given as:

$$
\Delta T_i^{'} = \left(1-\gamma\right)\cdot SIFS \cdot \left[w_5 \cdot \left(1 - \frac{d_{js} - d_{is}}{R}\right) + w_6 \cdot \left(1 - \frac{e_i}{E}\right) + w_4 \cdot Rand(0,1) \right] + \gamma \cdot SIFS \tag{5}
$$

$$
(e_i > 0, d_{js} > d_{is}, 0 < \gamma < 0.5, \sum w_k = 1)
$$

where w_5,w_6 are weighting coefficients ($w_4 < w_5$, w_6). If no ACK is heard, the sender will try to retransmit the data packet.

2.4. Communication void problem

The communication void problem [4] arises when a sender can't find a suitable neighboring node that is nearer to the sink. Some void regions are permanent, caused mainly by physical obstacles (e.g., a mountain). Thus, they can be detected, and handled by deploying static nodes around the void region and planning the routing a priori. For mobile sensor networks, however, the void region may be dynamic and temporary due to node motilities. One possible solution is to deploy as many sensor nodes as possible. Suppose sensor nodes move randomly in the area, the network topology can be deemed as random distributed at any moment. Then we can get a lower bound for the node density [11] that can probabilistically guarantee no void:

$$
Density \geq \frac{-\ln\left(1 - \sqrt[h]{1-\varepsilon}\right)}{\left(\frac{2}{3}\pi - \frac{\sqrt{3}}{2}\right) \times R^2} \quad \left(\varepsilon \to 0\right) \tag{6}
$$

where h is the hop count between the data source node and the sink, and the void probability is supposed to be upper bounded by ε. However, it may be impractical in many scenarios since the cost is too high. Thus, RRDD adopts a complementary approach, which is based on the well-known right-hand rule [10], to bypass the void region without requiring any a priori knowledge about the global network topology.

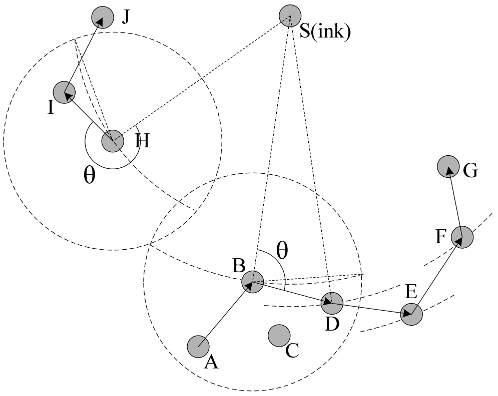

Fig.1. Bypass communication void region.

In RRDD, the void region is detected by the sender if it doesn't receive any CTS after sending the same RTS for several times (e.g., 2 times). Then the sender switches to the bypassing mode and sends out a new RTS (an additional binary bit in MAC frame header is used to identify the chosen mode). Following the right-hand rule, our goal is to select the bypassing nodes at one side (e.g., the right side) of the void region such that the packet will circumvent along that side of the void region border, as shown in Fig.1. The backoff delay of a bypassing node i is given as follows:

$$
\Delta T_i^{''} = \left[\frac{w_7 \cdot \theta_i}{\left(2\pi - \arcsin(R/d_{js})\right)} + w_8 \cdot \left(1 - \frac{e_i}{E}\right) + w_9 \cdot \left(1 - \frac{p_{ij} \cdot d_{ij}}{R}\right) + w_4 \cdot Rand(0,1) \right] \cdot SIFS, \tag{7}
$$

$$
(e_i > 0, p_{ij} > 0, d_{ij} < R, \sum w_k = 1)
$$

where θ$\theta_i \in \left(\arcsin\frac{R}{d_{js}}, 2\pi - \arcsin\frac{R}{d_{js}}\right)$ is the angle between $\overrightarrow{js}$ and $\overrightarrow{ji}$, w_7~w_9 are weighting coefficients ($w_7 > w_8, w_9, w_4$) and ($w_4 < w_7, w_8, w_9$). Since θ_i may be greater than π when the bypassing nodes is located at the left side of the sender (e.g. node I in Fig.1), only calculating through the cosine law is not enough to get its value correctly.

To solve this problem, we establish a new virtual coordinate system *X'Y'* by the transformation [12] (i.e., translation and rotation) of the real coordinate system. The direction of positive x-axis in the new coordinate system is the same as the direction of $\overrightarrow{js}$, as shown in Fig.2. If the virtual coordinates of node *i* is denoted by $(x_i^{'}, y_i^{'})$, we can notice that the value of θ_i is related to $y_i^{'}$ and can be calculated by (8) and (9):

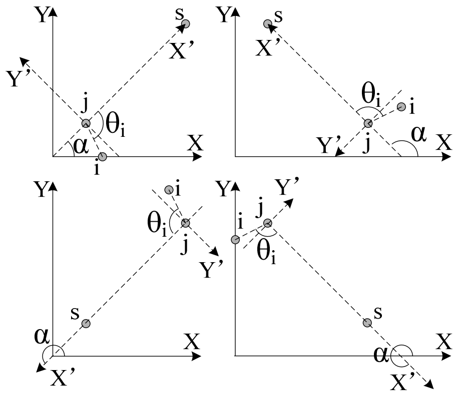

Fig.2. Virtual Coordinates

$$\theta_i = \begin{cases} \arccos\left(\dfrac{d_{js}^2 + d_{ij}^2 - d_{is}^2}{2d_{js}d_{ij}}\right) & y_i^{'} < 0 \\ \pi & y_i^{'} = 0 \\ 2\pi - \arccos\left(\dfrac{d_{js}^2 + d_{ij}^2 - d_{is}^2}{2d_{js}d_{ij}}\right) & y_i^{'} > 0 \end{cases} \qquad (8)$$

where

$$y_i^{'} = (y_i - y_j)\cos\alpha - (x_i - x_j)\sin\alpha$$
$$= \frac{(y_i - y_j)(x_s - x_j) - (x_i - x_j)(y_s - y_j)}{d_{js}} \qquad (9)$$

The node with the shortest backoff time will become the final forwarder while other nodes are suppressed (this node is also required to stay in the communication range of the sender for data transmission). To prevent routing loops, the sender keeps track of the ID of the bypassing node, and will not respond to its RTS for a small period of time.

It needs to be noted that ACK reply contention can not be adopted in the bypassing mode, since direction factor (θ_i) is considered as a metric for bypassing node selection. Link-layer retransmission is the only choice for error recovery in the bypassing mode.

3. Performance evaluation

In this section, we present simulation results of our scheme RRDD along with GPSR [9] and AODV [13] in NS-2. AODV is a representative of reactive ad hoc routing scheme designed with mobile wireless services in mind. Totally *N* sensor nodes move randomly in a 200*m* ×200*m* area, and the radio communication range and interference range are 30m (d_0 =10*m*) [8] and 66*m* respectively. The 1Mbps 802.11 DCF model is used as MAC layer (physical carrier sensing with exponential backoff and retransmission at link-layer are enabled). Radio energy dissipations during transmission and reception are 660*mW* and 395*mW* respectively. The size of data packet and MAC control packets are set as 250 bytes and 10 bytes respectively [14]. Flows are randomly initiated in the network, and each source sends packets at a rate of 25 packets/s. We measure the packet delivery ratio, the per-hop packet delay, and the energy consumption per packet.

Fig.3 shows the packet delivery ratio with respect to different degree of node density (maximal node speed = 6m/s). Since the other two routing protocols both try to find the routing path with shortest hops (AODV) or distances (GPSR), the link quality is always very poor. RRDD experiences the least packet loss rate among the three because it selects the links with relatively higher quality. The ACK reply contention in RRDD further improves the packet delivery rate of RRDD when the node density is high.

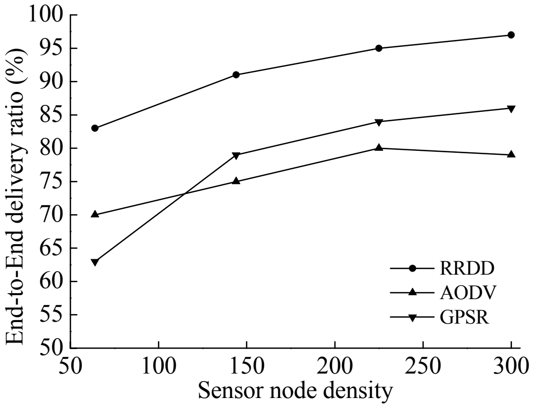

Fig.3. Delivery ratio vs. node density

RRDD also performs better than AODV and GPSR in terms of the per-hop packet delay, as shown in Fig.4. This is mainly attributed to a considerable decrease in the number of retransmissions. The two contentions for the forwarding right in RRDD increases the probability of successful hop-wise packet delivery, thus leading to fewer time-outs for link-layer retransmissions. AODV is an on-demand routing protocol. A data packet has to wait until transmission links are discovered available by control message exchanges, so it will experience longer delay than in GPSR and in RRDD, especially when node speed is high.

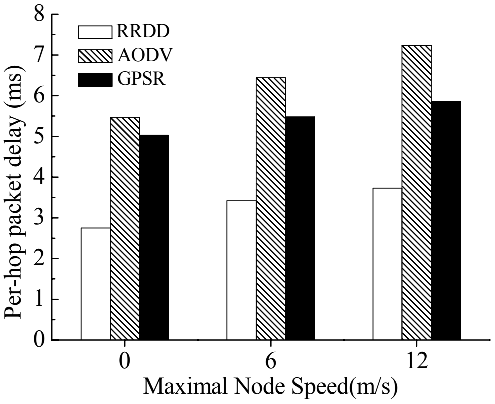

Fig.4. Effect of node mobility on per-hop delay ($N = 150$)

RRDD is the most energy efficient among the three as shown in Fig.5. The underlying reason is that it incurs fewer retransmissions and beaconing overhead in the network. The energy consumption of GPSR is less correlated with node mobility than AODV because the periodically beaconing does not change too much with node mobility. However, the energy consumption of AODV increases fast with node mobility because frequent topology changes lead to heavy overhead for the path recovery. This justifies the application of our RRDD in energy constrained mobile sensor networks.

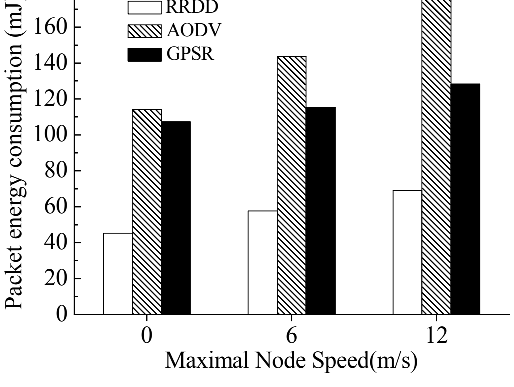

Fig.4. Effect of node mobility on per-hop packet energy consumption ($N = 150$)

4. Related works

In literature, many data delivery protocols have been proposed for mobile wireless ad hoc networks [3]. To deal with link unreliability, usually a large amount of overhead is generated for maintaining routing path and network state, thus consuming much precious energy and bandwidth. Meanwhile, much of the prior research has been based on the extremely idealized assumptions on wireless channels, e.g., the binary disk model [7], which are far away from that in realistic situations. As a result, these works aren't readily applicable to mobile sensor networks.

Several recent studies try to improve transmission performance for the basic geographic greedy routing mechanism [9] in wireless sensor networks. In [6], Son et al. use the mobility prediction technique to solve the problems caused by node or sink mobility. Zamalloa et al. [7] find that the product of the packet reception rate and the distance improvement towards destination is a highly suitable metric for geographic forwarding in lossy wireless networks. TPGF [15] adopts a two-phase greedy forwarding algorithm to explore one or more near shortest void-bypassing paths in wireless multimedia sensor networks. SIF [16] introduces the idea of receiver-based forwarding into greedy routing by cross-layer design between MAC and routing layer, but gives no consideration to the reliability metric. Ge et al. [17] proposes to explore cooperative geographic forwarding in coalition-aided wireless sensor networks. These prior works have helped us to understand more clearly about the problems of geographic forwarding in the context of mobile sensor networks.

The Delay/Fault-Tolerant mobile sensor network is a special type of opportunistic network, in which the connectivity between mobile nodes is too poor to form a well connected mesh network for data transmission. Replication is the only choice for data delivery in order to achieve certain success ratio [18]. However, RRDD is designed specifically for the well-connected network.

5. Conclusions

This paper proposes the novel RRDD scheme that employs a receiver-oriented approach and combines the tasks of routing and MAC via cross-layer design, to achieve robust and efficient data delivery in the mobile sensor network. Through dynamic node contention, the best-suited node is selected for data packet forwarding. RRDD has shown to be a promising deliver scheme for the mobile sensor network. In future work we intend to integrate RRDD with multipath data delivery to further enhance robustness. We also hope to implement and experiment our scheme on real mobile sensor network platforms.

Acknowledgements

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