Scalable and Robust Data Dissemination in Wireless Sensor Networks

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Abstract— **Wireless sensor networks (WSNs) are appealing in obtaining fine-granular observations about the physical world. Due to the fact that WSNs are composed of a large number of low-cost but energy-constrained sensor nodes, along with the notorious timer-varying and error-prone natures of wireless links, scalable, robust, and energy-efficient data disseminating techniques are requisite for the emerging WSN applications such as environment monitoring and surveillance. To meet this challenging demand, we propose a hybrid data dissemination framework for WSNs in this paper. In particular, we conceptually partition a whole sensor field into several functional regions and apply different routing schemes to different regions in order to provide better performance in terms of reliability and fair energy usage. For this purpose, we also propose a novel zone flooding scheme, essentially a combination of geometric routing and flooding techniques. Our scheme features low overhead, high reliability, good scalability, and notable flexibility. Simulation studies are carried out to validate the effectiveness and efficiency of our scheme.**

I. Introduction

Wireless sensor networks (WSNs) are one of the most important technologies that will change the world [1] in that WSNs can furnish us with fine-granular observations about the physical world where we are living. Potential applications of wireless sensor networks include disaster rescue, energy management, medical monitoring, logistics and inventory management, and military reconnaissance, etc. While many research has focused on making sensor networks feasible and useful [2] [3], some important problems resulting from the error-prone and resource-constrained nature of WSNs are not well addressed yet. Of note are the issues associated with prolonging network lifetime, offering high reliability, and presenting good scalability.

This paper is targeted for realtime and continuous monitoring applications such as battlefield monitoring networks and volcano monitoring networks, where networking sensors are deployed in an ad hoc manner and the aforementioned nice features are desirable. Those sensors collaboratively accomplish the sensing task and forward the sensing data to the closest data processing centers or sink nodes through multi-hop wireless links. Traditional routing protocols proposed for ad hoc networks are unsuitable for the target applications owing to the substantial differences between ad hoc networks and sensor networks pointed out in [2]. In contrast, flooding, as a reactive technique with inbred reliability, seems to be a good candidate for sensor networks because it does not involve costly topology maintenance and complex route discovery algorithms. However, the main problems with flooding are that it typically causes unproductive and often harmful bandwidth congestion, as well as inefficient use of node resources such as energy that is scarce in resource-constrained sensor networks. This situation results in a high demand for scalable, robust, and energy-efficient data disseminating techniques. With this challenging demand in mind, we propose a hybrid data dissemination framework for WSNs in this paper. More specifically, we conceptually partition a sensor field into several functional regions and apply different routing schemes to each region. Moreover, we also propose a novel zone flooding scheme, essentially a combination of flooding and geometric routing techniques. Our rationale here is to offer the desirable reliability and routing simplicity with flooding and to mitigate the deficiency of blinding flooding with geometric routing.

The rest of this paper is structured as follows. We first detail our hybrid data dissemination framework in Section II, including the partition strategy of the sensor field and our novel zone flooding scheme. In Section III, simulation studies are carried out to evaluate the performance of our scheme. Finally, we summarize this paper in Section IV.

II. A Hybrid Data Dissemination Framework for Sensor Networks

A. System model

Here we use a WSN for habitat monitoring to illustrate our scheme. As shown in Fig. 1, we model the sensing task as a business behavior and conceptually divide the whole sensor field into several functional areas. In the *manufacture area*, some nodes such as those from A to J, are involved in generating raw data about the interested objects, i.e., birds in this case, while other nodes such as K, L, and P are responsible for data aggregation, i.e., consolidating the raw data and reducing the possible information overlap. The filtered data is fed into the *transportation area* to be collaboratively relayed by intermediate sensors to sink nodes. Since bursty traffic is prevalent in the sensor network for habitat monitoring, we introduce the *warehouse area* as a buffer area between the

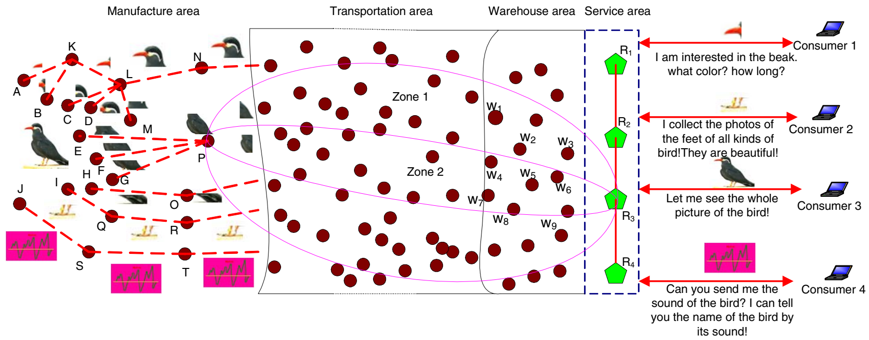

Fig. 1. System architecture for habitat monitoring

transportation area and the *service area* to reduce the possible traffic congestion and information implosion [2] problem at the sink nodes. The *service area* consists of sink nodes which can directly communicate with each other through fast and reliable links, either wired or wireless. The sink nodes perform collaborative reception of sensing events and offer different data items to end-users or consumers with different interests.

We assume that each node is aware of its own position and the positions of the sink nodes. For reasons of simplicity, we assume this location information is perfect at this time. We further assume all the nodes including common sensor nodes and sink nodes are identified by their geographic locations. The range of the aforementioned *manufacture area* is not fixed in that any node sensing the events of interest can form an *manufacture area* together with its neighboring nodes. So does the *transportation area* lying in the forward direction from the *manufacture area* towards the sink nodes. In contrast, the *service area* is determinate because of the invariable locations of sink nodes. Moreover, we define the *warehouse area* to be the area within sink nodes' $n-hop$ ranges, where *n* is a tunable design parameter. To form its *warehouse area*, one sink node just needs to broadcast a special request with the TTL value set to *n*. Any node receiving this request becomes a member of the *warehouse area* of the requesting sink node.

One of the novel features of our data dissemination paradigm is that we apply different data forwarding mechanisms to different functional areas, which are elaborated in the following sections.

B. Manufacture area

we assume that the nodes in the *manufacture area* are aware of their own missions. Each mission might represent a sensing task of the sensor network. In this example, the missions may be collecting the information of birds, such as the beak color, the feet length, or even the bird chirms. Due to the limitation of sensors' capabilities, each sensor may only sense part of the interested event so that they might locally exchange some sensing events and choose one node as an aggregation center to fulfill the data fusion task. For example, nodes *K*, *L*, and *P* in Fig. 1 are selected as aggregation centers. Since in most cases aggregation centers are only several hops away from the sensing nodes, the simplest way to forward the sensed raw data to aggregation centers is to broadcast packets with limited TTL values. For lack of space, we do not detail how to manage the sensing tasks and accomplish data aggregation in this paper.

Besides data fusion, each aggregation center takes a special role in our data dissemination framework. It needs to determine the transportation method for the filtered data, i.e, using single zone flooding or multizone flooding, and the proper transportation zone(s) through which the data will travel in the *transportation area*. For example, after finishing the aggregation of the raw data from nodes E, F, and G, node P makes the choice of using two flooding zones and then spreads the filtered data into two parts, both of which are labelled with their respective designated flooding zone. In the following subsection we will discuss how an aggregation center chooses appropriate flooding zones and how a node in the *warehouse area* processes a zone-flooded packet.

C. Transportation area

Sensor nodes in the *transportation area* undertake the task of relaying data to sink nodes. To avoid costly topology maintenance and complex route discovery algorithms, we propose a novel *zone flooding* scheme as the underlying routing protocol for the transportation area, which is a combination of geometric routing and flooding techniques. The basic idea is as follows: Once a node receives a packet carrying parameters that identify a flooding zone, it first needs to determine whether it is in the indicated zone or not through several simple calculations by using its own location information and the received zone parameters. Only when situated in the flooding zone could it rebroadcast the packet.

Fig. 1 shows an example our zone flooding scheme, in which ellipses are used to specify the flooding zones. Suppose one of the aggregation centers, say node P, has coordinates (x_1, y_1) in the cartesian plane of Fig. 2, and the intended sink node R_3 has coordinates (x_2, y_2). Besides the filtered data, each data packet sent from node *P* will carry four extra zone parameters: *AC_location* indicating the coordinates of the aggregation node *P*, *sink_location* indicating the coordinates of sink node R_3, and *Inner-SeminorAxis* and *Outer-SeminorAxis* used to denote the seminor of the inner and outer ellipses of the desired flooding zone respectively. Accordingly, when one node, say U with coordinates (x_3, y_3), receives such a data packet, the question whether it should rebroadcast the packet or not can be reduced to a simple geometric problem that, whether point U lies between two ellipses determined by end points P and R_3, and the *Inner-SeminiorAxis* b_1 and the *Outer-SeminiorAxis* b_2. Suppose the semiminor axis of an elliptic curve with two major-axis endpoints P and R_3 is b. Then the sum of the distance from point U to two fixed points F_1 and F_2 (the foci) can be expressed as $L(b) = D_1 + D_2$, where

$$D_1 = \sqrt{(\sqrt{\frac{(x_1-x_2)^2+(y_1-y_2)^2}{4}} - b^2 + (x_3 - \frac{x_1+x_2}{2}))^2 + (y_3 - \frac{y_1+y_2}{2})^2}$$

and

$$D_2 = \sqrt{(\sqrt{\frac{(x_1-x_2)^2+(y_1-y_2)^2}{4}} - b^2 - (x_3 - \frac{x_1+x_2}{2}))^2 + (y_3 - \frac{y_1+y_2}{2})^2}.$$

Therefore, node U needs to rebroadcast the packet after checking $L(b_1) < 2a < L(b_2)$ for $b_1 \neq b_2$, or $L(b_1) = L(b_2) < 2a$ for $b_1 = b_2$, where $a = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}/2$ is the semimajor axis of the ellipses with major-axis endpoints P and R_3. Otherwise, it will simply ignore the packet because it is not in the specified flooding zone for that packet.

Following the above procedures, sensor nodes ("transporters") in the *transportation area* can finally relay the data to the *warehouse area* through multihop wireless links.

We notice that two ellipses with the same endpoints can jointly determine six different flooding zones (see Fig. 2). To avoid the possible confusion about which zone should be used, we adopts a simple rule by using the positive value of the semiminor axis, e.g., b_1 or b_2, to denote the half part of an ellipse close to the positive direction in the shifted coordinate plane, while using the negative values of the semiminor axis to denote the half part close to the negative direction. For example, b_1 together with b_2 determines the zone I, while $-b_1$ and $-b_2$ jointly specify the zone III. In fact, by varying the values of seminimor axis, we can get physically separated or interleaved multipaths (multiple flooding zones) without incurring any additional costs. Such multipaths are well known for their use in increasing the reliability and security of data disseminations [6]. In fact, we can also utilize this multipath method to reduce the transmission delay of realtime data by chopping a large data into several portions to be simultaneously delivered to multiple sink nodes. Since sink nodes can communicate with each other through fast and reliable links, they can exchange the received portions and easily reconstruct the original data. Thus, the delay reduction can be expected.

As we mentioned above, we use two elliptic curves to specify a flooding zone, in fact, any two noncrossing curves sharing the same two ends could be used to specify a flooding zone. Nevertheless, we should choose those curves that not only can be represented with as few bytes as possible to reduce the communication overhead, but also can simplify the forwarding-decision-making processes of intermediate nodes. In this sense, arcs and elliptic curves are two promising candidates. Moreover, a flooding zone specified by two curves should be large enough to have sufficient nodes to forward the packets while maintaining high energy efficiency in the meantime. Therefore, in the above example, an aggregation center should properly

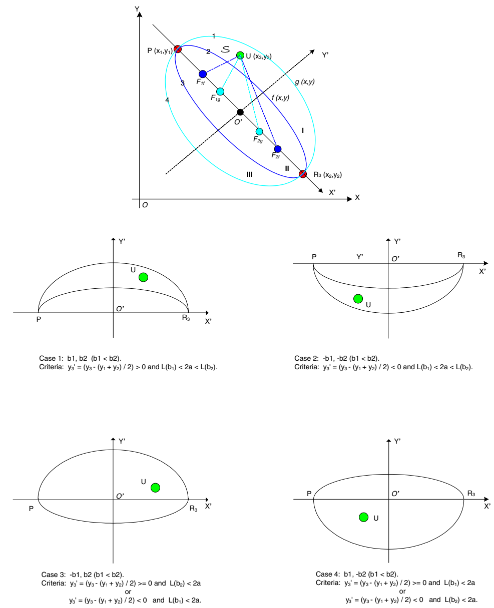

Fig. 2. The forwarding-decision-making process of nodes in the transportation area.

choose the values of the two semiminors of the two ellipses. Besides, to balance the nodal usage in the transportation area, aggregation centers should change the flooding zones with time by alternatively using different negative and positive values of semiminors. Therefore, our scheme achieves the evenly load distribution and the fair energy consumption without incurring any additional costs.

Furthermore, if wireless links are reliable enough, a redundancy elimination technique can be enabled to further optimize the packet flooding, which works as follows. Sensor nodes are required to keep track of redundant packets received over a short time interval, termed "Random Assessment Delay" (RAD) randomly chosen from a uniform distribution between 0 and T_{max} seconds, where T_{max} is the largest possible delay. Each node needs to rebroadcast one given packet if not receiving redundant ones during the RAD. This RAD method is designed to reduce the collisions among neighboring nodes and eliminate unnecessary transmissions for one packet.

D. Warehouse area and service area

As mentioned in Section II-A, for realtime and continuous monitoring applications of our interest, bursty and bulky traffic is often needed to be simultaneously transferred to the sink nodes. As a result, notorious traffic congestion may happen frequently in the vicinity of sink nodes and thus causes the unfavorable loss of information and the waste of scarce network resources. And the redundant packets flooded towards the sinks result in the *information implosion* problem.

The introduction of the *warehouse area* can help mitigate the above information implosion problem and reduce the possible data packet collisions. For the *warehouse area*, we use a modified version of SPIN [5] instead of the zone flooding as the underlying routing protocol. Of course, other routing

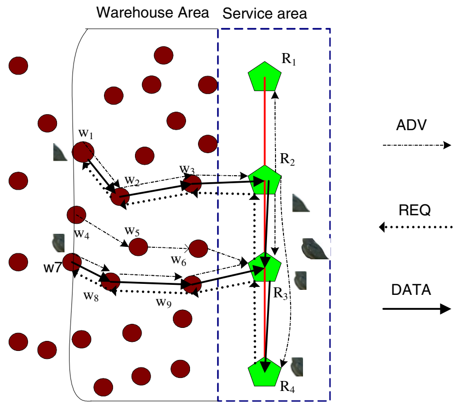

Fig. 3. The routing process in the warehouse area.

schemes are applicable to this area as well. Fig. 3 illustrates our routing strategy used in *warehouse area*. Once receiving data packets from sensor nodes out of the *warehouse area* of the targeted sink, a sensor node, say W_7 lying in both the flooding zone and the warehouse area, temporarily stores those packets. W_7 will unicast an ADV message, essentially an inventory list containing the descriptors of stored packets, to the targeted sink node R_3, either periodically or when the number of stored packets exceeds a threshold or on a per-packer basis. After that, R_3 will send a REQ message requesting for the data. Once seeing the REQ message, W_7 can unicast the data to R_3. The unicasting path could be established using the Destination-Sequenced Distance-Vector Routing protocol (DSDV) [7].

Here we want to explain how the *warehouse area* can help reduce the information implosion. Suppose packets describing the same event for sink R_3 arrive at W_4 and W_7 respectively, which are situated in the same flooding zone and the *warehouse area* of R_3. Using the above procedure, both W_4 and W_7 will send ADV messages to R_3. It is up to R_3 to make a decision on which one should send the data based on some criterions such as hop counts or delay. Suppose W_7 is chosen, R_3 will send a REQ to W_7 and accordingly W_7 can unicast the requested data via a DATA message to R_3. After a certain period, W_4 may delete the stored stale data. From this example, we can see that redundant packets can be successfully eliminated by the means of ADV-REQ-DATA exchanges.

Sink nodes in the *service area* perform collaborative reception in the sense that they could communicate with each other through fast and reliable means, e.g., wired links or separate wireless channels. For example, if sink R_2 receives an ADV message from node W_1, it can contact other sink nodes far from W_1 to see if they need the provided data, though R_2 itself may not need it. Suppose R_4 needs the data, R_2 can help obtain the data from W_1 and sends it to R_4.

III. Performance Evaluation

To validate and justify the effectiveness and efficiency of our proposed scheme, we have developed an evaluation environment within Glomosim [8] and implemented our hybrid data dissemination paradigm, including the zone flooding scheme. We simulate a sensor field consisting of 606 sensor nodes. We have 3 independent equally-spaced sources at the left boundary of the sensor field and 3 independent equally-spaced sinks at the right boundary of the sensor field. The other 600 sensors are uniformly deployed in the sensor field. The sensor field topology is shown in Fig.4, where the sensor field is composed of transportation area and the warehouse area only, while the manufacture area and the service area are on the boundaries of the field. In this sense, these sources function as both raw data collectors and data aggregation centers. In addition, we define the warehouse area to be the area within sinks' 2-hop range.

To study the performance of the zone flooding scheme alone, there is no data fusion and collaboration among sink nodes in our simulation. Besides, each of three sources generates a data packet destined to a random sink every 1.5 seconds, 1.0 seconds, and 2.0 seconds, respectively. In our simulation, each source-sink pair uses five equally-spaced elliptic curves to specify the flooding zones. Fig. 4 shows the curves used by source src_2 and $sink_2$. And src_2 always chooses two consecutively numbered curves to specify a flooding zone.

We compare our scheme (denoted by RRP) with pure flooding (denoted by Flooding), and directed diffusion [4] (denoted by Directed Diffusion) in terms of energy efficiency and reliability. The metrics of interest include average packet delivery ratio (PDR) or reliability, average energy consumption per packet, average packet end-to-end delay, and normalized routing overhead. The packet error rate (PER) at each node varies from 0.0005 to 0.01. Moreover, each simulation is executed for 15 simulated minutes. In sum, Table I lists the configuration parameters of our simulation, where the transmission/reception power consumption of sensors are in line with those of Motes [9].

Fig. 5 compares the packet delivery ratios with different PERs. As we can see, since directed diffusion uses single path for each source-sink pair, its PDR is very sensitive to the change of PER, dropping almost linearly from 99% to 86% with the increase of PERs. In contrast, the PDRs of our scheme RRP and flooding always stabilize around 100%. This result is not surprising because flooding-based routing techniques bear innate reliability. From this comparison, we can see that by using zone flooding in the *transportation area* and unicasting in the warehouse area, RRP has comparable reliability to flooding, but is superior to directed diffusion.

Table II compares average energy consumption, average packet delay, and the routing overhead, where the PER is set to 0.0005 with which all three compared schemes appear high reliability. Since directed diffusion uses low rate flooding for interest propagation and unicasting for data packets, it demonstrates the minimum normalized energy consumption, defined as the ratio of the total energy consumed for the transmission and reception of data and routing messages in the simulation time, to the energy consumed for one single data reception. In addition, our scheme outperforms pure flooding because of the use of zone flooding instead of network-wide flooding. We note that we can further improve the energy

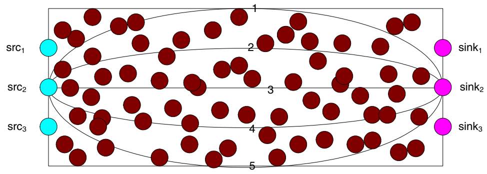

Fig. 4. The simulated sensor field.

TABLE I
SIMULATION CONFIGURATION

Simulation Area	$500m \times 300m$
Number of Nodes	606
Transmission Range	$40m$
Initial Energy	$60J$
Transmit Power	$81mW$
Receive/Idle Power	$30mW$
Radio Bandwidth	$2Mbps$
Data packet	$128Bytes$
Directed Diffusion interests	$36Bytes$
ADV/REQ	$12Bytes$

efficiency of our RRP by properly choosing the size of the flooding zones. The investigation on this issue is ongoing.

In addition, since directed diffusion adopts minimum-delay paths, it has shorter packet delay than that of our RRP. For pure flooding, the network-wide pure flooding of data packets may result in much more collisions than the zone flooding. In addition, packets between a source-sink pair in pure flooding may follow quite unpredictable and possibly very long routes. Therefore, our RRP demonstrates shorter packet delay than that of pure flooding.

In terms of the routing overhead, directed diffusion requires sinks to periodically flood *interests* to maintain the gradients, as a result of which it displays the largest routing overhead among others. For our RRP, the routing overhead comes from the maintenance of the small *warehouse area*. Therefore, it has slightly larger routing overhead than that of pure flooding that is assumed to have zero routing overhead.

To sum up, our hybrid data dissemination paradigm inherits the simpleness and reliability of pure flooding, while mitigating the unproductive and often harmful bandwidth congestion, as well as inefficient use of node resources such as energy caused by pure flooding.

IV. CONCLUSION

In this paper we propose a hybrid data dissemination framework for WSNs. We conceptually partition a whole sensor field into several functional regions and apply different routing schemes to different regions in order to provide better performance in terms of reliability and fair energy usage. For this purpose, we also propose a novel zone flooding technique which is a combination of geometric routing and flooding techniques. On top of our scheme, physically separated or interleaved multipath routing can be easily implemented without incurring any significant additional costs. Our scheme features low overhead, high reliability, good scalability, and notable flexibility. The effectiveness and efficiency of our scheme are validated through simulation studies.

As for the future work, we plan to study the impact of varied sizes of warehouse on the system performance, and investigate how to choose optimal flooding zones to strike a good balance between reliability and energy efficiency.

TABLE II
SIMULATION RESULT WHEN PACKET ERROR RATE IS 0.0005

	RRP	Flooding	Directed Diffusion
Avg. Energy Consumption (per packet per node)	8.1030	20.4258	3.4854
Avg. Packet End-to-end Delay (s)	0.5263	0.6237	0.2482
Avg. # of routing overhead per packet	4.47	0	27.9836

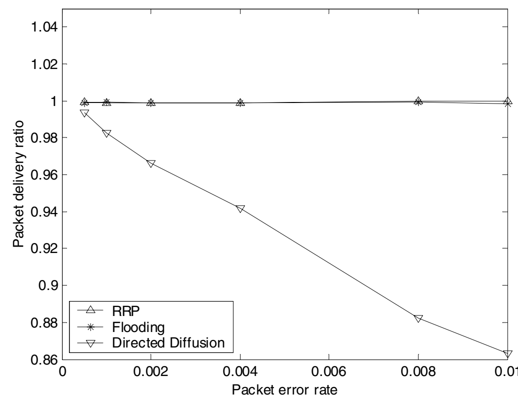

Fig. 5. The packet delivery ratio vs. packet error rates.

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