Wireless Netw (2006) 12:465–479
DOI 10.1007/s11276-006-6546-x

A robust and energy-efficient data dissemination framework for 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 and energy-constrained sensor nodes, along with the notorious time-varying and error-prone nature of wireless links, scalable, robust and energy-efficient data dissemination techniques are needed for the emerging WSN applications such as environment monitoring and surveillance. In this paper, we examine this emerging field from the point of view of supply chain management and propose a hybrid data dissemination framework for WSNs. In particular, for each sensing task, the whole sensor field is conceptually partitioned into several functional regions based on the supply chain management methodology. Different routing schemes are applied to different regions in order to provide better performance in terms of reliability and energy consumption. For this purpose, we also propose a novel zone flooding scheme, essentially a combination of conventional geometric routing and flooding techniques. Our hybrid data dissemination framework features low overhead, high reliability, good scalability and flexibility, and preferable energy efficiency. Detailed simulation studies are carried out to validate the effectiveness and efficiency of our scheme.

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Keywords Sensor networks · Routing · Flooding · Supply chain management

1. Introduction

Recent advances in Micro-Electro-Mechanical Systems (MEMS) technology and wireless communications have resulted in the emergence of small, low-cost sensors with more and more powerful processing and networking capabilities, which makes Wireless Sensor Networks (WSNs) be identified as one of the most important emerging technologies [1]. Especially, wireless sensor networks can furnish us with fine-granular observation about the physical world we are living in. Potential applications include the remote sensing in nuclear plants, mines, and other hazardous industrial venues, real-time traffic monitoring, realtime weather monitoring, wild animal monitoring and tracking, disaster rescue, energy management, medical monitoring, logistics and inventory management, and military reconnaissance. While much research has been focused on making sensor networks feasible and useful [2, 3], some important problems resulting from the error-prone and resource-constrained nature of WSNs have not been well addressed yet. Notable are the issues associated with scalability, reliability and energy efficiency. For instance, since a WSN may consist of hundreds or thousands or even millions of sensor nodes, an efficient data dissemination technique should work well not only in small-scale sensor networks but also in large-scale ones. In addition, it should be robust against the harsh environmental effects and temporal or permanent failures of sensors and wireless links in between them, so that the functionality of the WSN can be sustained without any interruption. Moreover, it should have good energy efficiency in terms of both low average energy consumption per observation report and balanced energy usage instead of overburdening a small set of nodes in the network.

This paper targets at real-time and continuous monitoring applications such as battlefield monitoring networks and volcano monitoring networks, where sensors are deployed in an ad hoc manner and the aforementioned nice properties are desirable. Those sensors collaboratively accomplish the sensing task and forward the sensing data to the closest data processing centers or sink nodes through wireless links. Traditional routing protocols proposed for ad hoc networks may not be suitable for our target applications due 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, which is scarce in resource-constrained sensor networks. Though several data dissemination schemes have been proposed specifically for sensor networks [2, 3], research on finding a scheme that can strike a good balance among reliability, scalability, and energy efficiency is still lacking.

In this paper, we propose a hybrid data dissemination framework for WSNs that features low overhead, high reliability, good scalability and flexibility, and preferable energy efficiency. Our contributions in this paper are mainly three-fold. First of all, to the best of our knowledge, this is the first effort to study a wireless sensor network from the point of view of supply chain management. We introduce the notion of *supply chain* into the design of sensor networks and conceptually partition a sensor field into several functional regions according to the supply chain management methodology. Secondly, we apply different routing techniques to different regions in order to provide better performance in terms of reliability and energy consumption. Lastly, we propose a novel zone flooding scheme which is a combination of conventional flooding and geometric routing. Our rationale here is to offer the desired reliability and routing simplicity with flooding and to mitigate the deficiency of blind flooding with geometric routing.

The remainder of this paper is organized as follows. We start with discussing some basics of supply chains and the resemblance between supply chains and wireless sensor networks in Section 2. Then, we detail our hybrid data dissemination framework in Section 3. In Section 4, simulation studies are carried out to evaluate the performance of the proposed scheme. Section 5 describes the related work and the concluding remarks are given in Section 6.

2. Modelling sensor networks as supply chains

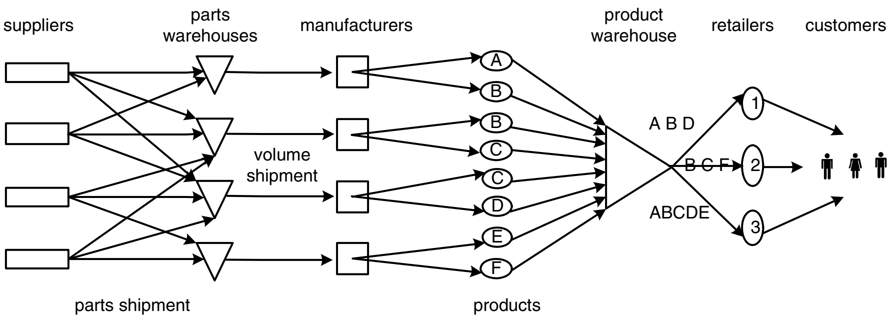
In this section, we first introduce some basics of supply chains and then discuss why and how we can model a WSN as a supply chain.

2.1. Introduction to supply chains

In the business world, a *supply chain* (SC) is a series of links and shared processes existing between suppliers and consumers, which involve all activities from the acquisition of raw materials to the delivery of finished goods to the end consumers [27]. Generally speaking, a supply chain consists of several components: raw material manufacturers, intermediate product manufacturers, end product manufacturers, wholesalers and distributors, and retailers. These components are connected by transportation and storage activities, and are integrated through information, planning, and integration activities. Figure 1 shows an exemplary SC, where raw materials or parts enter into a manufacturing organization via a supply system and are transformed into finished goods. The finished goods are then supplied to consumers through a distribution system.

Usually supply chains are operated with certain strategy to coordinate all the components' functions and to smooth the material and information flows in the supply chains.

Fig. 1 An exemplary supply chain



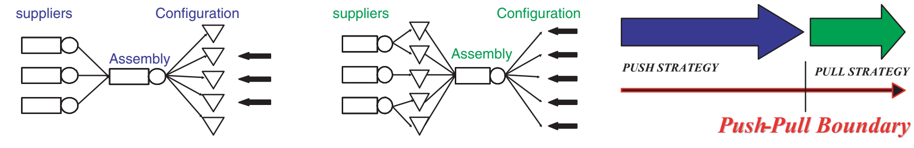
In the past 40 years, SC strategies have evolved from *push* strategies to *pull* strategies and finally to *push-pull* strategies [27]. In a push-type SC, production and distribution decisions are based on long-term forecasts. A manufacturer uses orders received from retailer warehouses to forecast demands. The decisions of consumers' orders are based on inventory rather than consumers' demands. Bullwhip effects such as excessive inventory, excessive production variability, and poor service levels, are very common in the push-type SC. In contrast, in a pull-type SC, production and distribution are demand-driven and are based on actual customer demands rather than forecasts. The firm no longer needs to hold any inventory and only responds to specific orders. However, in a pull-type SC, it is hard to leverage economies of scale. These advantages and disadvantages of push strategies and pull strategies have resulted in *hybrid* strategies: push-pull strategies. In push-pull strategies, push strategies are applied in the initial stages such as parts inventory, where production and distribution decisions are based on long-term demand forecasts by manufacturers on the basis of orders received from retailers; and pull strategies take effect in the final stages such as product assembly, where production and distribution are purely demand driven and rely on actual customer demands rather than forecasts. Usually a buffer inventory, such as a warehouse, is located at the push-pull boundary. Dell Computer, a giant computer manufacturer and retailer, is an excellent example of the push-pull-type SC. Dell keeps an inventory of components and assembles only when there is an actual order. Figure 2 shows those three different strategies.

On the other hand, *supply chain management* (SCM) is the act of optimizing all activities throughout the supply chain, so that products and services are supplied in the right quantity, to the right location, at the right time, and at the optimal cost. One of the fundamental concepts in SCM is that all the autonomous entities in the SC may have their own inner operations and management strategies, but they work in a cooperative fashion to achieve the management goal of the whole SC: satisfying the customer service requirements while minimizing the overall system cost and obtaining as much revenue as possible from the cooperations. Nowadays, SCM has been widely accepted in the business world as a vital factor for competitive advantage and sustainable business improvement.

2.2. How could supply chains help us?

Similar to supply chains, wireless sensor networks are designed to cooperatively transmit meaningful sensing data ("products") to the sinks ("retailers") with certain QoS requirements. For a designed sensing task, the sensors ("raw material manufacturers") sense the raw data ("raw materials") as suppliers and send them to some nodes ("product manufacturers") for further processing. These processed data ("products" or sometimes "intermediate products") are delivered hop-by-hop to sinks with the help from intermediate sensor nodes ("transporters"). In fact, supply chains and wireless sensor networks have many key components or functions in common. For example, the parts warehouse in Fig. 1 is designed to consolidate raw parts from different suppliers and it serves as a "multiplexer" to decouple the need from the availability. Its counterpart in sensor networks is the desirable functionality of "data aggregation", which is used to combine the data gradually at intermediate nodes enroute from different sensor nodes to the sink node. The objectives of the data aggregation are eliminating redundancy, minimizing the number of transmissions, and thus saving energy [4]. Further, the product warehouse close to retailers, ensuring low inventory, reduced transportation costs, and quick replenishment capability, acts a similar role as that of the mechanisms for reducing information implosion [2]. Vital to cost management of supply chains, transportation planning is equivalent in functionality to routing in sensor networks, whose major objective is to transfer sensing data from sensors to sink nodes as efficiently as possible. Moreover, both require all the entities in the system to work cooperatively for goals common in nature: providing good quality of service (QoS) and keeping the overall system cost as low as possible. In Table 1 we list the analogous components between supply chains and sensor networks. It is a rather "soft" matching in that not every sensor node can be absolutely or perfectly fit into a matching component in a supply chain architecture. A sensor may act as multiple roles under different scenarios. For example, one sensor may be a "*supplier*" of one communication, while be a "*transporter*" of another communication in the meantime. Intermediate nodes sometimes are also called "semi-manufacturers" or "parts warehouses" when performing data aggregation to reduce the data redundancy. What we emphasize here is the conceptual and technical motivations

Fig. 2 Supply chain strategies



Push Strategy: Make-to-stock model Pull Strategy: Assembly-to-order model Push-Pull Strategy: Hybrid model

Table 1 Analogue between supply chains and sensor networks

Items in supply chains	Counterparts in sensor networks
Raw materials or parts	Phenomena of interest, e.g., sound, images, and movements of observed objects
Suppliers or manufacturers	Sensor nodes generating sensing data
Transportation network	Intermediate sensor nodes
Distributors or retailers	Sink nodes
Finished products	Data processed by sink nodes
Consumers	End-users of the data offered by sink nodes

and the approaches leading to the viable solutions behind the two seemingly different systems.

Interestingly, we notice that two notable routing protocols for sensor networks, namely, directed diffusion [6] and SPIN [7], conform well with the SC methodology. In particular, directed diffusion can be viewed as a pull-type SC, in which the sink node propagates its interests throughout the sensor network and sensors possessing the data of interest respond with sensing data via intermediate sensors. Thus, directed diffusion is a pull-type SC in that *production is demand (interest) driven*. In contrast, SPIN with ADV-REQ-DATA handshaking is more like a push-type SC. It is designed for disseminating information to all nodes in a sensor network, where the nodes generating the data can be regarded as suppliers or manufacturers in a SC. Thus, SPIN is a push-type SC where *order decisions (REQ) are based on inventory (ADV)*.

The above resemblance between supply chains and sensor networks motivates us to model a WSN as a SC, thus we can apply the sophisticated knowledge of SCM in the business world to improve the performance of the sensor networks. More specifically, we know that it yields better performance and lower cost in SCM by partitioning the supply chain into several different components (*partition strategy*), applying different management mechanisms to different components (*hybrid strategy*), and designing cooperations among different components (*cooperation strategy*). Similar ideas can be introduced into sensor networks for solving reliability and efficiency problems.

3. A hybrid data dissemination framework for sensor networks

Inspired by SCM methodology, we design a novel hybrid data dissemination framework for wireless sensor networks. In this section, we first describe the system model and then detail the management strategies or routing techniques applied to different functional components.

3.1. System model

In what follows, we use a WSN for habitat monitoring as an example to illustrate our scheme. As shown in Fig. 3, for one specific sensing task, the whole sensor field is conceptually partitioned into several functional areas according to the aforementioned push-pull strategies of supply chains (see Section 2.1). In the *manufacture area*, some nodes such as those from *A* to *J*, are involved in generating the raw data about the objects of interest, 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 possible information overlapping. The filtered data is fed into the *transportation area* to be relayed by intermediate sensors to sink nodes. In addition, we introduce the *warehouse area* as a buffer area between the transportation area and the service

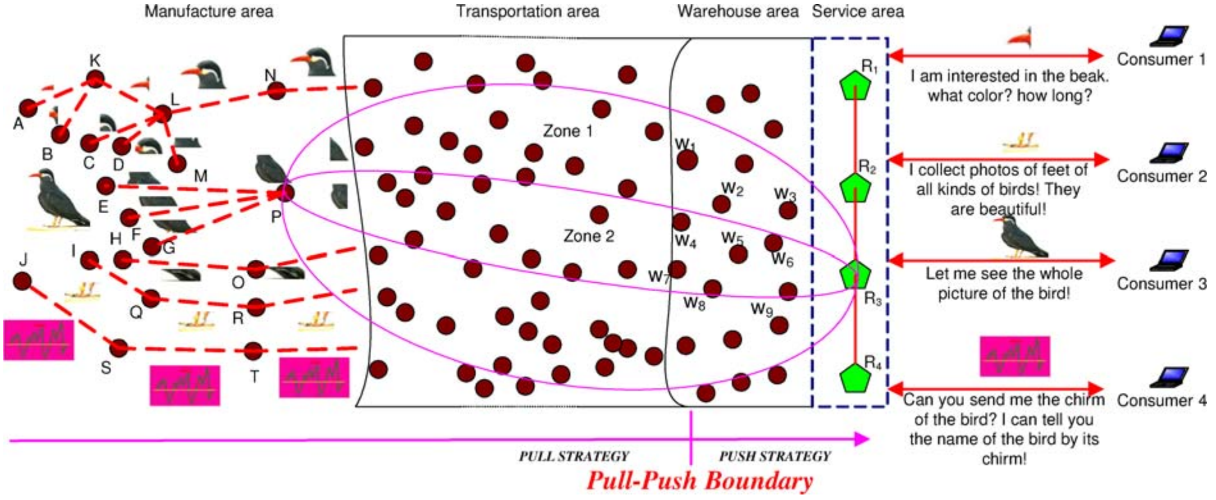


Fig. 3 System architecture for habitat monitoring

area to reduce the possible traffic congestion and information implosion [2] 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 has the knowledge of its own position[1] and the positions of the sink nodes, which is a reasonable assumption for many monitoring applications [2, 3]. We further assume that all the nodes including common sensor nodes and sink nodes are identified by their geographic information. We should emphasize here that the sensor field partition is only conceptual and application-dependent rather than a fixed one. Basically, various sensing tasks may have quite different partition instances. In particular, for each specific sensing task, those nodes sensing the events of interest can form a manufacture area together with their neighboring nodes just for that task. Accordingly, the transportation area lies in the forward direction from the manufacture area towards the sink nodes. In this paper, we assume that the sinks are far enough away from the manufacture area, and thus the transportation area does exist.[2] Moreover, we define the warehouse area to be the area within the sink nodes' n-hop range, where n is a tunable design parameter. To form its warehouse area, one sink node needs to simply broadcast a special request with the TTL value set to n. Any node receiving this request becomes a warehouse member (warehouse node) of the warehouse area of the requesting sink node. In fact, the value of n can be application-dependent, and various sensing tasks may have different values of n to reflect the diverse QoS requirements. In contrast to the above three areas whose locations and sizes are closely related to sensing tasks, the service area is determinate because of the invariable locations of sink nodes.

One of the novel features of our hybrid data dissemination paradigm is that we apply different data forwarding mechanisms in different functional areas. More specifically, local broadcasting in the manufacture area, a unicasting-based routing in the warehouse area, and a specially designed zone flooding, which is essentially a combination of conventional flooding and geometric routing, in the transportation area, are used respectively. With this hybrid data dissemination paradigm in place, a better balance between energy efficiency and reliability can be expected. In what follows, the hybrid data dissemination paradigm is elaborated in more detail.

3.2. Manufacture area

We postulate that the nodes in the manufacture area are aware of their own missions.[3] Each mission might represent a sensing task of the sensor network. In this example, the mission may be collecting the information of birds, such as the beak color, the feet length, or even the bird chirm. Due to the limitation of sensors' capabilities, each sensor may only sense part of the interested event so that they might need to locally exchange some sensing events and select among themselves one node as an aggregation center to fulfill the data fusion task. For example, nodes K, L, and P in Fig. 3 are selected as aggregation centers. Since aggregation centers, in most cases, 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 assumes a special role in our data dissemination framework. It is also responsible for determining the transportation method for the filtered data by itself, i.e., using single zone flooding or multi-zone 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 choice of using two flooding zones and then chops the filtered data into two parts, both of which are labelled with their respective designated flooding zone.

In fact, the operations in the manufacture area exhibit lots of flexibility during the selection of the transportation methods and the flooding zone(s). With proper selection, our scheme can strike a good balance between reliability and energy efficiency. For example, if the environment is good, an aggregation center can choose a single flooding zone instead of multiple flooding zones which are usually used in the face of harsh environment to forward the data. Moreover, if no warehouse area is allocated and the flooding zone is the whole sensor field, our zone flooding expands to blind flooding; on the other hand, if we can squash the flooding zone into an area containing only a single path, our zone flooding reduces to single path routing. For a bursty and bulky event report, an aggregation center can choose multiple flooding zones and split the report into several portions which are simultaneously delivered to multiple sinks through different flooding zones. Since sink nodes can communicate with each other through fast and reliable links, they can exchange the received portions and easily reconstruct the original event report. In this way, a reduction in the end-to-end delay can be expected. Such multipath approaches are also well known for

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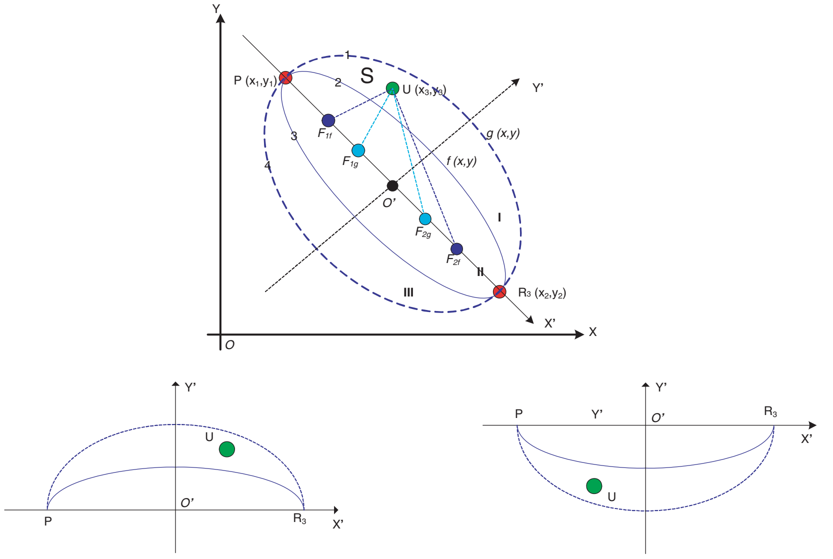
[1] Note that a node can obtain its location information at low cost from GPS or some localization system [13–17].

[2] For those sensing tasks close to the sinks, a modified partition method can be used where transportation area may not be necessary.

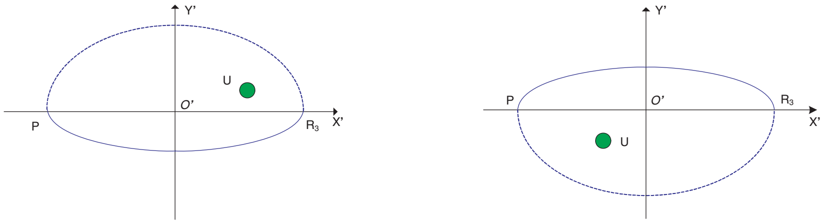
[3] Here we assume that certain mission allocation scheme is used during the deployment and initialization phases of sensor networks.

Fig. 4 The forwarding-decision-making process of nodes in the transportation area



Case 1: b_1, b_2 ($b_1 < b_2$).
Criteria: $y_3' = (y_3 - (y_1 + y_2) / 2) > 0$ and $L(b_1) < 2a < L(b_2)$.

Case 2: $-b_1$, $-b_2$ ($b_1 < b_2$).
Criteria: $y_3' = (y_3 - (y_1 + y_2) / 2) < 0$ and $L(b_1) < 2a < L(b_2)$.



Case 3: $-b_1$, b_2 ($b_1 < b_2$).
Criteria: $y_3' = (y_3 - (y_1 + y_2) / 2) >= 0$ and $L(b_2) < 2a$
or
$y_3' = (y_3 - (y_1 + y_2) / 2) < 0$ and $L(b_1) < 2a$.

Case 4: b_1, $-b_2$ ($b_1 < b_2$).
Criteria: $y_3' = (y_3 - (y_1 + y_2) / 2) >= 0$ and $L(b_1) < 2a$
or
$y_3' = (y_3 - (y_1 + y_2) / 2) < 0$ and $L(b_2) < 2a$.

their effectiveness in increasing the reliability and security of data disseminations [8]. Moreover, to combat the node or wireless link failures especially in a harsh environment, an aggregation center may introduce some redundancy by sending duplicate reports to the sinks through multiple flooding zones. We should note that, aggregation centers can vary the sizes and the locations of flooding zones with time in order to distribute the traffic load more evenly among sensors and thus avoid overburdening a small set of nodes. Besides, if proper scheduling is available, nodes can enter into wake or sleep modes zone by zone to save energy.

In what follows, we shall discuss how an aggregation center chooses appropriate flooding zones, what data structure a data packet "*manufactured*" by an aggregation center may use, and how a node in the warehouse area processes a zone-flooded packet.

3.3. Transportation area

Sensor nodes in the transportation area undertake the task of relaying data to possible multiple sink nodes. To avoid costly topology maintenance and complex route discovery algorithms, we propose a novel zone flooding scheme, which is a combination of conventional flooding and geometric routing techniques. The basic idea is as follows: a zone containing the source and the destination is specified by some geometric means; then, instead of network-wide omnidirectional flooding, the zone flooding is guided along the direction from the source to the destination and is restricted in the designated zone. Once a node receives a packet carrying parameters that identify a flooding zone, it first checks whether or not it is in the indicated zone through some trivial calculations based on its own location information and the received zone parameters. Only when located in the flooding zone would it rebroadcast the packet.

Figure 3 shows an example of the zone flooding scheme, in which ellipses[4] are used to specify the flooding zones. Suppose one of the aggregation centers, say node P, has the coordinates (x_1, y_1) in the cartesian plane of Fig. 4, and the intended sink node R_3 has the coordinates (x_2, y_2). We should mention that all the required information for zone flooding are embedded in the transmitted data packets rather than the control packets. Figure 5 shows the typical structure of a data

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[4] As we will see, ellipse can be represented with low overhead. More important, it is easy to manipulate.

<table>
<tr><td>AC_location</td><td>Sink_location</td><td>Inner-SeminorAxis</td><td>Outer-SeminorAxis</td></tr>
<tr><td colspan="2">Interest (event) Description
(location, time, type, ...)</td><td>Warehouse Flag</td><td>Other Control Fields
(multiple-zone flooding,
redundancy, ...)</td></tr>
<tr><td colspan="4">Payload</td></tr>
</table>

Fig. 5 An exemplary packet structure

packet "manufactured" by an aggregation node. 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 the sink node R_3, and *Inner-SemiminorAxis* and *Outer-SemiminorAxis* indicating the semiminors of the inner and outer ellipses[5] of the desired flooding zone respectively. The field "Warehouse Flag" is used to inform intermediate nodes whether this packet has ever been processed by a warehouse node. The usage of this field will be discussed in Section 3.4. In addition, based on the fields "Interest (event) Description" and "Other Control Fields", intermediate nodes and sinks can determine whether one received packet has already been processed, or it needs to assemble those partitioned packets belonging to the same interest, or to remove the possible redundancy added. The concrete use of these fields depends on specific applications, which is beyond the scope of this paper.

From the ellipse geometry, we know that when the two endpoints of the major axis are fixed (i.e., *AC_location* of P and *Sink_location* of R_3), a value of the semiminor axis can uniquely determine an ellipse. And two different semiminor values (i.e., *Inner-SemiminorAxis* b_1 and *outer-SemiminorAxis* b_2) will determine two ellipses as shown in Fig. 4, $f(x, y)$ and $g(x, y)$. Such ellipses can be used to specify multiple flooding zones. For example, the two ellipses with the same endpoints of the major axis can jointly determine three non-overlapping flooding zones—Zone I between curve 1 and curve 2, Zone II between curve 2 and curve 3, and Zone III between curve 3 and curve 4. In fact, any two of the four curves can specify a flooding zone, for example, a bigger zone determined by curve 1 and curve 3. We already know that, with the two endpoints of the major axis fixed, the semiminor axis uniquely determines an ellipse. But we need a means to differentiate the two curves constituting the ellipse - the upper half (above the X' axis, e.g., curve 1 and 2) and the lower half (below the X' axis, e.g., curve 3 and 4). In our design, we adopt a simple rule—we use the positive value, e.g., b_1 or b_2, to denote the upper half of an ellipse while using the negative value to denote the lower half curve of the ellipse in the shifted coordinate plane. For example, b_1 together with b_2 determines zone I, $-b_1$ and $-b_2$ jointly specify zone III, and $-b_1$ and b_2 select zone I + II. In particular, *Inner-SemiminorAxis* b_1 can be 0 to denote the X' axis as a special elliptic curve. Thus, a $\{(+/-)b_1,(+/-)b_2\}$ pair of real numbers can uniquely determine a flooding zone. Moreover, by varying the values of semiminor axis, we can easily get physically separated or interleaved multiple paths (multiple flooding zones) without incurring any significant additional costs. As discussed in Section 3.2, the multipath routing is a powerful technique to improve the reliability and security, among other system performance factors.

When one node, say U with coordinates (x_3, y_3), receives a data packet containing the above-mentioned zone parameters $\{(x_1, y_1), (x_2, y_2), (+/-)b_1, (+/-)b_2\}$, the question whether or not it should rebroadcast the packet is reduced to a simple geometric problem: whether or not point U lies between the two elliptic curves specified by the embedded parameters? Suppose the semiminor axis of an ellipse 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 $L(b) = D_1 + D_2$ [30], where

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

and

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

To determine whether a node itself is in the specified flooding zone, it needs to compare the distance to the foci of each ellipse with $2a$, where $a = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}/2$ is the semimajor axis of the ellipse with major-axis endpoints P and R_3. In Fig. 4 we give four possible cases and the corresponding decision criteria that a node may lie in the specified flooding zone. Therefore, for Case 1 where $b_1 < b_2 \neq 0$ in our example (Fig. 4), node U needs to rebroadcast the packet if $(y_3 - \frac{y_1+y_2}{2}) > 0$ and $L(b_1) < 2a < L(b_2)$. Otherwise, it will simply ignore the packet because it is not in the designated flooding zone for that packet. Following the above procedures, sensor nodes ("*transporters*") in the transportation area can finally relay a data packet to the warehouse area through multi-hop wireless links.

In our example, since we use two elliptic curves to specify one flooding zone, the "Flooding Zone Parameters" field only needs to include two values for the inner and the outer semiminor axes, respectively. Although any two noncrossing curves sharing the same two ends could be used to specify a flooding zone, we should cautiously 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

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[5] Here the "inner ellipse" means the ellipse with smaller semiminor axis, while the "outer ellipse" means the ellipse with bigger semiminor axis.

nodes. In this sense, arcs and ellipses are two promising candidates. Moreover, a flooding zone specified by two curves should be wide enough to have sufficient nodes to forward the packets while maintaining high energy efficiency in the meantime. To accomplish this, the aggregation center in our example, say node P, should properly choose the values of the semiminors of the two ellipses. Besides, to balance the nodal usage in the transportation area, aggregation centers should vary the flooding zones by using different and alternating negative and positive values for semiminor axes. By doing so, our scheme could achieve even load balance and fair energy usage without incurring any significant additional costs.

3.4. Warehouse area and service area

In the exemplary SC shown in Fig. 1, the warehouse near the retailers creates a break point in the movement of the products and acts as a buffer to reduce the cost of stock at the retailers, hence improving the flexibility of the retailers. The warehouse frequently updates its *inventory list* to the retailers, and the retailers can quickly get the products out of stock in the stores replenished from the warehouse. In addition, the warehouse may consolidate small shipments into a larger shipment to the same retailer to save transportation costs. We notice that such a warehouse component is also needed in sensor networks for realtime and continuous monitoring applications. In these applications, bursty and bulky traffic may be simultaneously transmitted to sink nodes, as a result of which notorious traffic congestion may happen frequently in the vicinity of sink nodes and thus cause the unfavorable loss of information and the waste of scarce network resources. Moreover, the redundant packets flooded towards sinks may result in the *information implosion* problem as well. Thus, the introduction of the warehouse area as a buffer area can decouple need (*interests*) from availability (*redundant event reports*) and hence help mitigate the above information implosion problem and possible traffic congestion.

For the warehouse area, we use a modified SPIN [7] instead of zone flooding as the underlying routing protocol. Different from the ADV-REQ-DATA exchange in SPIN that happens between neighbors, the ADV-REQ-DATA exchange in our scheme is between a warehouse node and a sink node several hops away and is realized by end-to-end unicast. The unicasting path could be established using the Destination-Sequenced Distance-Vector Routing protocol (DSDV) [9]. We note that only those warehouse nodes may participate in the routing maintenance activities. With a limited warehouse size, small overhead of routing maintenance can be expected. Of course, other routing schemes are applicable to this area as well. Figure 6 illustrates our routing strategy used in the *warehouse area*. Once receiving data packets from outside the warehouse area (by examining the field "Warehouse Field"), a warehouse member of the desired sink of the packets (cf. Section 3.1), say W_7 lying on the boundary of the warehouse area, first sets the field "Warehouse Flag" and temporarily stores the packets. Afterwards, W_7, the data holder, will unicast an ADV message, essentially an *inventory* containing the descriptors of stored packets, to the targeted sink node R_3, either on a per-packet basis or periodically or when the number of stored packets exceeds a threshold. Following the reception of the ADV message, R_3 will send a REQ message requesting the interested data. Upon receiving the REQ message, W_7 can unicast the requested data to R_3 via a DATA message. In case that R_3 does not receive the requested data in time after sending out a REQ, it can resend a REQ to the same data holder W_7 or another data holder who also sent to it an ADV containing the descriptors of the same data. Note that, just as what the warehouse does in the business SC, if a warehouse node has enough storage space, it can periodically consolidate several stored packets and send them in a volume shipment to the same sink, in which way energy savings can be expected.

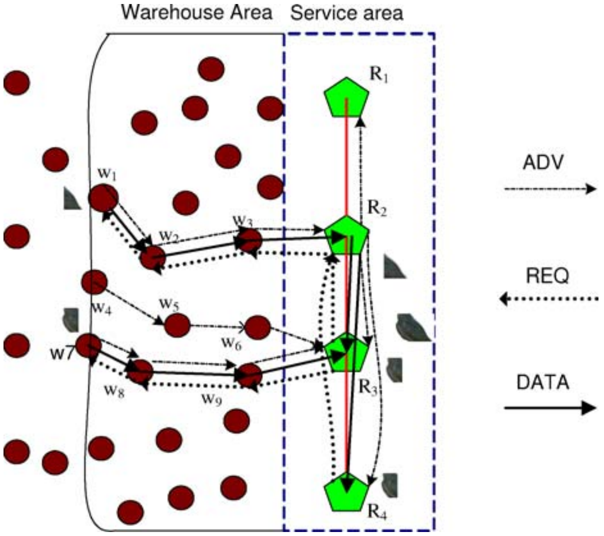


Fig. 6 The routing process in the warehouse area

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 both W_4 and W_7, which are located in the same flooding zone and the warehouse area of R_3. When no ADV-REQ-DATA exchange is used, depending on the routing protocol, both W_4 and W_7 will broadcast or unicast the packets for the same event to the sink R_3, which will lead to information implosion and energy waste owing to redundant packets, especially when numerous nodes send the same event report to the sink. However, using the proposed ADV-REQ-DATA procedure, both

W_4 and W_7 will send short ADV messages rather than relative long data packets to R_3. It is up to R_3 to make a decision on which data holder it should pull the data from based on certain criteria such as hop count 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 in 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 exchange.

Moreover, 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_2 to see if they need the provided data, though R_2 itself may not need it in some cases. Suppose R_4 needs the data, R_2 can help obtain the data from W_1 and send it to R_4. Such collaboration also helps a warehouse node deal with cases when the warehouse node has no unicasting route to the desired sink of the report due to node failures or other reasons. In such a case, the warehouse node may choose to send the ADV message to a nearest sink. For instance, in Fig. 6, W_1 is a common warehouse member of both sinks R_2 and R_3. For some reason, W_1 temporarily has no unicasting route to the reports' destination R_3 and thus it unicasts an ADV to R_2 instead. After receiving the ADV from R_2, R_3 may request R_2 to help collect the other portions of the information which are destined to R_3. After collecting all the portions, R_3 can reconstruct the original information "manufactured" by node P and serve consumers later.

3.5. Discussion

Our hybrid data dissemination framework is an open framework and allows different routing techniques to coexist in the same network. In fact, depending on the applications, a variety of routing protocols, not limited to the ones presented in this paper, can find their possible applications in this framework. In addition, similar to its support of scalability in database engineering [31], the partitioning strategy enables our scheme to be more scalable and flexible, and reduces the difficulty of designing a feasible overall routing scheme. The decision on how to partition the sensor field and what routing technique should be used for each functional area depends on the application requirements and sensor field features. For example, multipath routing could be used in the warehouse area if it is in a very harsh environment. Further, with more information about the sensor field, the flooding zones can be specified in an efficient and adaptive way. For example, some irregular curves can be used to avoid the physical obstacles in the field or to avoid the "dead zone" with sparse sensor nodes or empty of sensor nodes. As an another example, a flooding zone can be specified in a "smart" way such that it covers a relative small area where communications are of good quality, while covers a relative large area where communications are of bad quality.

Moreover, our zone flooding scheme does not exclude other flooding enhancement mechanisms. Note that our zone flooding scheme attempts to improve the energy efficiency of flooding by restricting the flooding range in the spatial domain. We can further improve the energy efficiency in the temporal domain. For example, 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 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 longest 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 to eliminate unnecessary transmissions for one packet.

Besides, energy information can be incorporated into the routing decision. For example, an energy-efficient cost metric can be used in the warehouse area to set up energy-efficient paths. In the above RAD enhancement, residual energy information can also be mapped into delays such that nodes with more energy can assume smaller delays than those nodes short of energy. Actually, energy efficiency can be further improved in other dimensions. For instance, if the flooding zone is properly chosen, we can make use of Gossiping-based flooding [20], probabilistic-based flooding [21, 22], and other controlled-flooding approaches to further improve the energy efficiency.

Considering the fact that some sensor nodes may have much more powerful capabilities in terms of energy and other important resources than common sensor nodes, more enhancement schemes can be proposed to make use of such heterogeneity to operate and manage the whole sensor network more effectively and efficiently. In some cases, such powerful nodes may perform data fusion and other management activities. They may even act as freight agencies as what UPS or Fedex does in the business supply chains. The aggregation centers can send their data to these freight agencies and further these agencies multiplex the data and ship the data in a manner of mass transportation through some high speed data link. In some circumstances, some mobile sensor nodes may be deployed in the field. In such cases, the mobile sensor nodes can perform as mobile data collectors, patrolling around some area and collecting data and carrying them to freight agencies or data processing agencies. These mobile nodes can greatly facilitate the data forwarding process. Moreover, in practice, it is possible to replace the depleted nodes near the sinks, or deploy some nodes with solar power supply in the field.

4. Performance evaluation

In this section, we evaluate the performance of our hybrid data dissemination framework through simulations. We first describe the simulation configurations, the performance metrics, and our simulation methodology. We then study the impact of some environment and control parameters on the performance of our scheme. We compare our scheme with flooding and directed diffusion [6] in terms of energy efficiency and reliability.

4.1. Methodology and metrics

To validate the effectiveness and efficiency of our proposed scheme (denoted by RRP), we have developed an evaluation environment within GlomoSim [28] and implemented our hybrid data dissemination paradigm, including the zone flooding scheme designed for the transportation area and the unicast-based ADV-REQ-DATA exchange for the warehouse area. 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 simulated network is shown in Fig. 7, where the sensor field is composed of the transportation area and the warehouse area only. The manufacture area and the service area are on the boundaries of the field and omitted for simplicity. Besides, each of the three sources generates a 128-byte data packet (event) destined to a randomly selected sink every 1.5 seconds, 1.0 second, and 2.0 seconds, respectively. Since our purpose is to study the routing performance of the hybrid data dissemination framework, with an emphasis on the zone flooding scheme, there is no data fusion and collaboration among sink nodes implemented in our simulation. Therefore, a source acts as both an event observer and a data aggregation center. Table 2 lists the configuration parameters of our simulation, where the transmission/reception power consumption of sensors are in line with those of Motes [29].

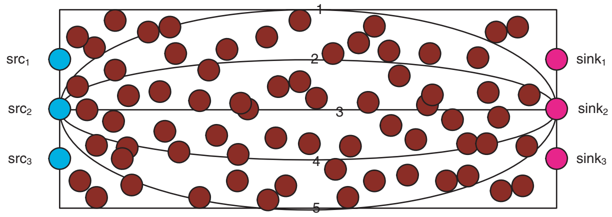


Fig. 7 The simulated sensor field

Table 2 Simulation configuration

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

In our simulation, we vary the size of the warehouse area, defined as the area within a sink node' n-hop range, to see its impact on RRP's performance. Besides, each source-sink pair uses equally-spaced elliptic curves to partition the entire sensor field into d (another control parameter) non-overlapping flooding zones. For example, Fig. 7 shows the curves used by source src_2 and $sink_2$ where $d = 4$. We evaluate the impact of the flooding zone size on RRP's performance by varying the value of d. Since the field size is fixed, the bigger the value of d, the narrower the flooding zone is. Furthermore, we introduce an environment parameter, namely, packet error rate (PER), to reflect the error-prone natures of wireless links in WSNs. For simplicity, we assume the error properties of all radio transmissions are independent but have the identical $PERs$ during one simulation run. Therefore, by varying the control parameters n and d, and the environment parameter PER, we can study the performance of our proposed RRP under different settings.

Moreover, we compare our RRP with flooding and directed diffusion [6] in terms of energy efficiency and reliability. In our implementation, directed diffusion uses delay as the criterion to select preferred neighbors during reinforcement. For our RRP, we use the ADV-REQ-DATA exchanges (cf. Section 3.4) and our proposed zone flooding (cf. Section 3.3) as underlying routing techniques for warehouse area and transportation area, respectively.

There are four performance metrics of interest to us. The **event delivery ratio (EDR)** reflecting the reliability is defined as the ratio of the total number of event reports (data packets) that are successfully delivered from the sources to the intended sinks over the total number of packets generated at the sources. The **normalized energy consumption** reflecting the energy efficiency is defined as the energy consumption per packet per node normalized by the energy consumption for one single packet reception. The **average event end-to-end delay** is defined as the average delay from when a packet (event) is generated and transmitted by the source till it is received by the sink. And the **average routing overhead** is defined as the average number of routing packets generated per data packet.

4.2. Simulation results

For the first set of figures (Fig. 8–Fig. 11), we fix the number of flooding zones to be 4, i.e., $d = 4$, and study the performance of RRP under different environment conditions, i.e., different values of packet error rate (*PER*), and with different warehouse size n.

Figure 8 compares the event delivery ratio of RRP, pure flooding, and directed diffusion under different PERs. As we can see, since directed diffusion maintains single path for each source-sink pair, its EDR is very sensitive to the change of PER, dropping almost linearly from 99% to 86% with the increase of PERs. In contrast, the EDRs of flooding always stabilize around 100%. This result is not surprising because of the inbred reliability of flooding techniques. Our RRP demonstrates a stable EDR greater than 99% under all five different warehouse sizes. This result indicates that our RRP, using zone flooding in the transportation area and unicasting in the warehouse area, has achieved the reliability comparable to that of flooding, but superior to that of directed diffusion. We can also observe the small degradation of EDR with the increase of n in RRP, which can be explained as follows: since our RRP uses unicasting in the warehouse area, data packets travelling in the warehouse area may suffer from packet dropping as in direct diffusion. Intuitively, the greater n is, the more hops a packet may travel in the warehouse area, hence increasing the dropping probability of packets. Fortunately, our ADV-REQ-DATA exchanges can compensate for such possible packet droppings by allowing sink nodes to receive ADVs from multiple data holders and retransmit REQs to a data holder if the expected DATA message is not received in time. Therefore, our RRP can still maintain a pretty high EDR comparable to that of flooding in the face of error-prone wireless links.

Figure 9 shows the normalized energy consumption of our RRP, flooding and directed diffusion. Compared with the other two schemes, directed diffusion demonstrates the minimum energy consumption because it uses low rate flooding for interest propagation and unicasting for data packets. Our RRP outperforms flooding because of the use of zone flooding instead of network-wide flooding. We observe that the greater n is, the less energy our RRP consumes. The reason is that zone flooding and unicasting are respectively used in the transportation area and the warehouse area. With the increase of the warehouse size n, more unicasting and less zone flooding will be involved and the former is known to be more energy efficient than the latter.

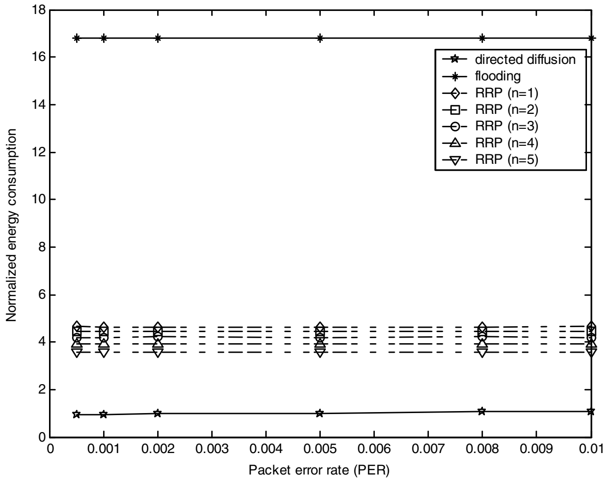


Fig. 9 Normalized energy consumption vs. packet error rate

Figure 10 gives the average event end-to-end delay of each scheme under different *PERs*. Since directed diffusion adopts minimum-delay paths, it has the shortest delay among the three schemes. For pure flooding, the network-wide pure flooding of data packets may result in much more collisions than our zone flooding and packets belonging to the same source-sink pair may follow different, quite unpredictable,

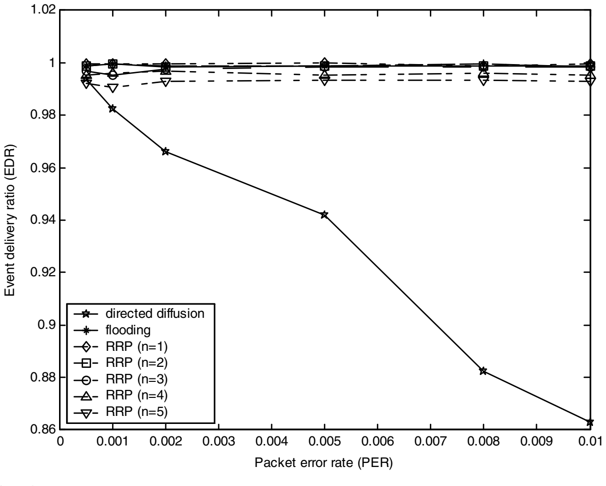


Fig. 8 Event delivery ratio vs. packet error rate

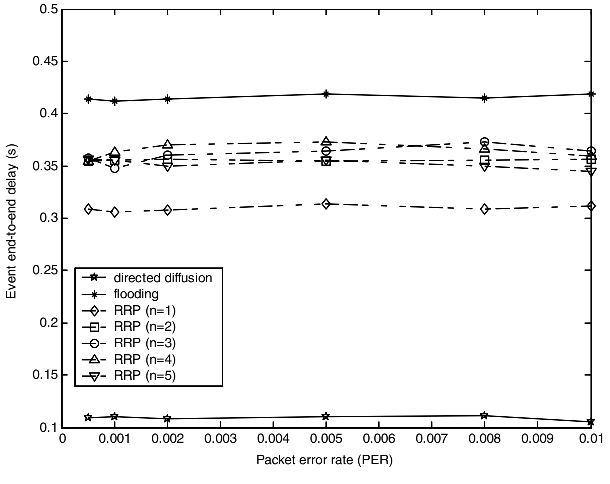


Fig. 10 Average event end-to-end delay vs. packet error rate

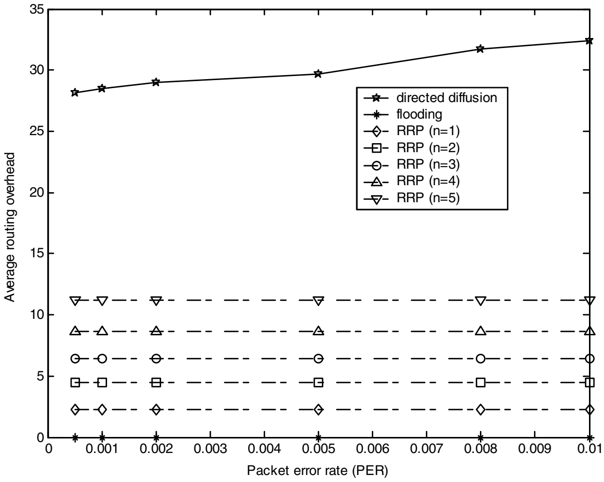


Fig. 11 Average routing overhead vs. packet error rate

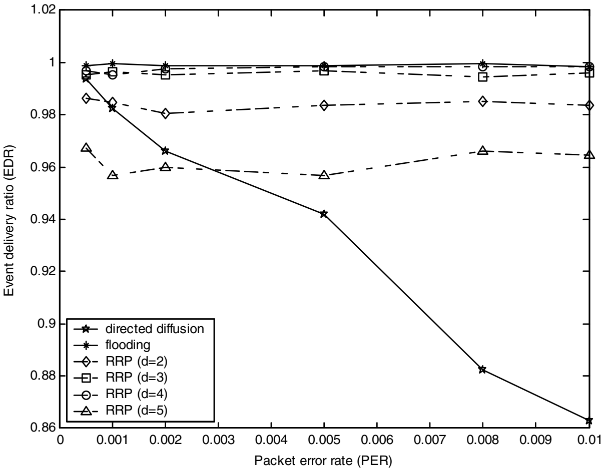


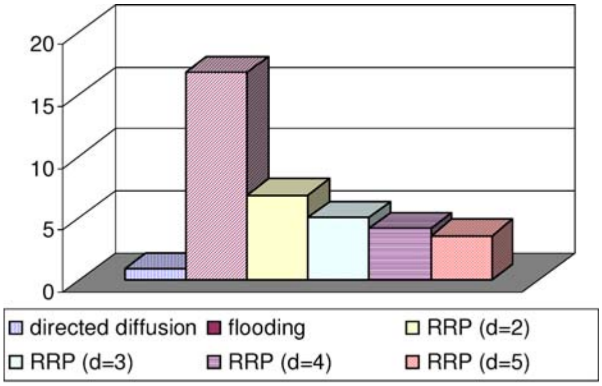
Fig. 12 Event delivery ratio vs. packet error rate

and possibly very long routes. Therefore, pure flooding experiences longer average event delay than that of our RRP. For our RRP, since an event report first travels through the transportation area and then the warehouse area, there are two sources contributing to the delay. One is the zone flooding in the transportation area, and the other is the ADV-REQ-DATA exchanges in the warehouse area. The average delay coming from zone flooding decreases with the increase of n, while the average delay coming from ADV-REQ-DATA exchanges increases with the increase of n. An interesting observation here is that the delay performance is not monotone with regard to n. Our RRP achieves smallest delay when $n = 1$, followed by $n = 5$ and $n = 2$, the other two are very close and not easy to tell them apart. This observation suggests a tradeoff between zone flooding and warehouse routing should be made to achieve a desired latency.

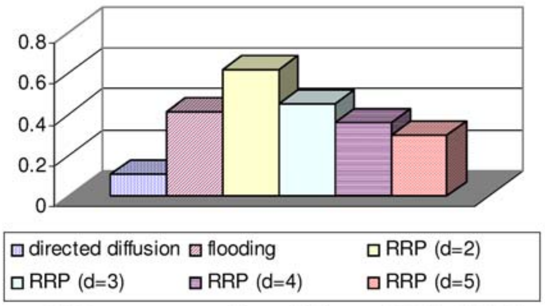
Figure 11 presents the average routing overhead of each scheme. Among the three schemes, directed diffusion requires sinks to periodically flood *interests* to maintain the gradients, as a result of which it encounters the largest routing overhead. For our RRP, the routing overhead comes from the routing maintenance in the small warehouse area. Therefore, its routing overhead is much smaller than that of directed diffusion but larger than that of pure flooding which is supposed to have zero routing overhead. Besides, since the overhead of RRP mainly comes from the routing maintenance in the warehouse area, it is of no surprise that we observe the overhead of RRP increases with the increase of n, i.e., the warehouse size.

In the second set of figures (Fig. 12–Fig. 13), we present our results on the RRP performance with a fixed warehouse size $n = 3$ but different *PER*s. We also vary the control parameter d to study the impact of different flooding zone sizes.

Figure 12 shows the event delivery ratio with different d. We observe that the size of flooding zone has significant impact on the performance of RRP. When $d = 2$, the EDR of RRP is nearly 98%, but when d increases to 3 or 4, the EDR of RRP becomes better and is comparable to that of pure flooding. However, the larger d does not always imply better EDR. As we can see, when d increases to 5, the EDR drops to 96%. This observation can be interpreted as follows. When d is small, meaning a large flooding zone, the collisions in the zone may occur quite often and result in relatively



(a)Normalized energy consumption vs. d (PER=0.0005).



(b) Average evernt end-to-end dlay vs. d (PER=0.000.5)

Fig. 13 Energy consumption and event end-to-end delay of RRP with different d

lower EDR. Though pure flooding suffers from collisions as well, flooding has higher probability to receive a copy of the original data packet because it is flooded in the whole field rather than in a zone. With the increase of d and thus the decrease of the flooding zone size, packet collisions may decrease, leading to a better EDR. However, the flooding zone size should be reasonably wide to have enough nodes to relay packets. However, our RRP outperforms directed diffusion in most cases even when the flooding zone is small.

Figure 13(a) shows the normalized energy consumption of our RRP with regard to d, where $PER = 0.0005$. The results of pure flooding and directed diffusion are shown for reference only. We observe that the larger d is, the less energy each packet consumes. This result is reasonable because the larger d is, the narrower the zone is, the fewer nodes are involved in the flooding, and hence the less the energy is consumed. Considering the impact of d on both EDR and energy consumption, it clearly indicates that the flooding zone size d is an important parameter in RRP and should be well chosen to strike a good balance between reliability and energy efficiency.

Figure 13(b) shows the average event end-to-end delay of our RRP with regard to d with *PER* equal to 0.0005. We can see that the event latency decreases with the increase of d. When d is small, meaning a large flooding zone, packets received by a sink may travel along unpredictable paths, leading to a longer average delay. In contrast, when d is large, meaning a small flooding zone and fewer nodes involved in the packet forwarding, packets received by a sink may travel along more predictable paths limited by the small zone, which results in a shorter average delay. We can further expect a small latency comparable to that of directed diffusion if we carefully choose a small enough flooding zone.

To sum up, our simulation results show that flooding and our zone flooding techniques are less sensitive to the link failures thereby provide more robust packet delivery service. However, pure flooding suffers from inefficient energy usage and long end-to-end packet latency. By choosing appropriate warehouse size and flooding zone size, we can adjust the energy consumption, the event end-to-end latency, and the routing overhead of RRP to competitive levels while maintaining nearly perfect reliability. Therefore, our RRP provides a good solution to balance the reliability and energy efficiency requirements in sensor networks.

5. Related work

How to efficiently deliver the information in densely deployed sensor networks is a very challenging task. Directed diffusion [6], and SPIN [7] are two exemplary data dissemination paradigms for sensor networks. SPIN adopts meta-data negotiation to eliminate the redundant data transmission, and it is suitable for the scenarios where an individual sensor disseminates its observations to *all* the sensors in a network. As a *data-centric* approach, directed diffusion employs low rate flooding to establish gradients and uses gradual reinforcement of better paths to accommodate certain levels of network and sink dynamics. Recently, two variations of directed diffusion were proposed in [26], in which the authors advocated the importance of matching dissemination algorithms to application performance requirements. Besides the above schemes, the cluster-based LEACH [18] and hierarchical-based TTDD [19] are also available in the literature. In LEACH, nodes are organized into clusters, each of which has a randomly selected cluster header. Sensor nodes send their observations to affiliated cluster headers and request cluster headers to forward their reported data to a base station. As the authors mentioned, their scheme was designed for applications where a sensor node is able to transmit data to a far away base station with higher transmission power. In TTDD, each data source first builds a grid structure, based on which the sink's query and sensing data are forwarded through this grid structure and further flooded in a local grid cell. TTDD can accommodate the existence of mobile sinks. We notice that the above approaches need lots of overhead to be workable, e.g., they need exchange a lot of information with neighbors to build routing tables or to form and propagate the cluster/grid structures. In addition, reliability in the presence of the error-prone wireless links is another constraint of the above approaches like [6, 18, 19] because they usually maintain only a single route for each source-sink pair. Though the multipath extension of [6] was reported in [25], it is quite different from our approach. Particularly, the alternative paths are only used when some node failures occur along the primary path. Moreover, the multipath extension of directed diffusion is still not able to deal with other transmission failures due to the wireless links. In contrast, our RRP inherits the inbred reliability of flooding and is robust against transmission failures coming from both node failures and wireless link impairment.

As a reactive technique with inbred reliability, flooding seems to be a good candidate for sensor networks because it does not involve costly topology maintenance and complex route discovery algorithms. In view of this, quite a few research efforts have been done to optimize the use of flooding in terms of reducing the unproductive and often harmful bandwidth congestion, as well as inefficient use of nodes resources caused by flooding. Gossiping [20], probabilistic-based flooding [21, 22], and other controlled-flooding approaches [23] belong to this category. In contrast, our zone flooding scheme utilizes the node location information instead of a probabilistic method to control the flooding range. Furthermore, based on the partition strategy and applying different routing strategies to different functional regions, our data dissemination paradigm can well balance the reliability and the energy efficiency and achieve good scalability and notable flexibility.

Geographic routing is another potential candidate for sensor networks. It uses nodes' locations as their addresses based on which packets are forwarded towards the destination in a greedy manner. Several approaches have been proposed to improve the efficiency and accuracy of the geographic routing. In GPSR [12], a detour algorithm was proposed to overcome the possible dead ends with the greedy method. In addition, LAR [10] uses restricted area flooding to reduce the cost of discovery. Moreover, in DREAM [11], each node obtains its geographic location through external devices such as GPS, and periodically transmits its location coordinates to other nodes in the network. A source sends a data packet to a subset of its neighbors in the direction of the destination. Unlike the above approaches that require a mass of location information exchange among neighboring nodes or require a node to be aware of the locations of all the other nodes, our zone flooding scheme only requires a node to learn the locations of its own and sink nodes, and to make a forwarding decision based on its own location and the flooding zone information carried in received packets. Therefore, our scheme demonstrates good scalability. Besides, our scheme provides the option of multi-zone flooding and hence is more resilient to node or route failures. Another notable work in geographic routing is the trajectory based routing (TBF) proposed in [24]. TBF embeds a trajectory in each packet and intermediate nodes around the trajectory collaboratively forward a given packet. Different from TBF, our zone flooding scheme uses two curves to specify a flooding zone and all the nodes in the specified zone will participate in forwarding a given packet in an autonomous way. Hence our approach is more reliable than TBF. More important, our approach is completely loop free, while trajectory based forwarding still risks possible routing loops in some scenarios like other geographic routing.

Our data dissemination framework demands the location information of nodes, which is indispensable for many applications, such as target tracking and environment monitoring [5], and is fundamental for many geographic routing schemes ([10–12]). There is a rich literature in ad hoc networks on how to retrieve the location information as accurate as possible. For example, several approaches based on time difference of arrival (TDOA) [13], angle of arrival (AOA) [15], or signal strength [14] have been proposed for the scenarios without GPS devices. More recently, two novel approaches have been proposed specifically for sensor networks [16, 17]. We believe that the location information should be effectively utilized to provide better performance in wireless sensor networks, the more accurate the location information is, the more benefit we can get.

6. Conclusion

In this paper, we introduce the concept of supply chain into wireless sensor networks and propose a hybrid data dissemination framework based on the supply chain management methodology. We conceptually partition a whole sensor field into several functional regions and apply various routing schemes to different regions in order to provide better performance in terms of reliability and efficient energy usage. For this purpose, we also propose a novel zone flooding technique which is a combination of geometric routing and flooding. On top of our scheme, physically separated or interlaced multipath routing can be easily implemented without incurring any significant additional costs. Our hybrid data dissemination framework features low overhead, high reliability, good scalability, and notable flexibility. The effectiveness and efficiency of our scheme are validated through simulation studies. We demonstrate that our scheme can strike a good balance between reliability and energy efficiency with proper sizes of the warehouse area and flooding zones.

Acknowledgments This work was supported in part by National Science Foundation Faculty Early Career Development Award under grant ANI-0093241 and the Office of Naval Research Young Investigator Award under grant N000140210464.

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