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Design and analysis of novel quorum-based sink location service scheme in wireless sensor networks

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Abstract Geographic routing in wireless sensor networks requires sources nodes to be aware of the location information of sinks to send their data. To provide the sink location service, quorum-based schemes have been proposed, which exploit crossing points between a quorum of a sink location announcement (SLA) message from a sink and a quorum of a sink location query (SLQ) message from a source node. For guaranteeing at least one crossing point in irregular sensor networks with void areas or irregular boundaries, the previous schemes however collect and flood the network boundary information or forward a SLA and SLQ message along the whole network boundary. In this paper, we design a novel quorum-based sink location service scheme that exploits circle and line quorums, which does not require the network boundary information and send a SLA and SLQ message along the whole network boundary. In the proposed scheme, a source node sends a SLQ message to the network center and sends another SLQ message to an edge node in the network boundary, thus generating a SLQ line quorum. On the other hand, a sink node sends a SLA message along a circle path whose center is the network center, thus forming a SLQ circle quorum. By this way, it is guaranteed that the SLQ and SLA quorums have at least one crossing point in irregular sensor networks. Both numerical analysis and extensive simulation results verify that the proposed scheme outperforms the existing schemes in terms of the delivery distance, the delivery hop count, and the energy consumption for providing sink location service.

Keywords Wireless sensor networks · Geographic routing · Sink location service · Energy efficiency

1 Introduction

Geographic routing [1] has been considered as an attractive approach since it only exploits pure local location information instead of global topology information to route data packets. This geographic routing makes it more efficient and scalable in Wireless Sensor Networks (WSNs) consisting of a large number of energy-restricted sensor nodes. However, geographic routing fundamentally requires three necessary conditions. First, each node must know its own location information. GPS devises [2] or other localization techniques [3, 4] can fulfill this requirement. Second, each node must know the location of its one-hop neighbor nodes. This requirement can be fulfilled by exchanging beacon messages [5]. Third, a source node must know the

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location of the destination (i.e. the sink in WSNs). In WSNs, source nodes and sinks can be deployed anywhere in the network and can even move. Some well-known geographic routing schemes [1–8] merely assume that source nodes can be aware of the location of sinks by location services. However, since the sink location service is not a trivial task, it is a challenging issue in WSNs.

Flooding [9] is the simplest method for providing source nodes with the sink location information. Specially, a sink globally floods its own location information throughout the entire network, thus all source nodes in the network can get the location of the sink. This flooding method consumes lots of network resources such as energy and bandwidth, and even worse when multiple mobile sinks are deployed in the network. To avoid the flooding overhead to the entire network, a local flooding scheme based on a grid structure, named TTDD [10] was proposed. In TTDD, a source node constructs a global grid structure to disseminate its location information while a sink locally floods its own location information only within about a grid cell size, thus making crossing points between the grid structure and flooding. However, although it reduces the scope of flooding region, it leads to high overhead for constructing a global grid structure.

To avoid the global or local flooding in sink location service, quorum-based sink location service schemes [11–13] have been proposed. The basic concept in these scheme is to support sink location service by providing crossing points between a quorum path of a sink location announcement (SLA) message from a sink and a quorum path of a sink location query (SLQ) message from a source. As shown in Fig. 1, the simplest quorum-based sink location service solution is the so-called column-row method that a sink sends a SLA message from its location in the vertical (i.e. north-south) direction while a source sends a SLQ message from its location in the horizontal (i.e. east-west) direction. However, in the real irregular sensor networks which can contain void (called hole or local minimum) areas [14] or have non-rectangle shapes (i.e. circle, ellipse, convex, and concave shape), the two SLA and SLQ quorums may be difficult to guarantee at least one crossing point. Thus, a network boundary information-based approach such as NELS [11] and a network boundary forwarding-based approach such as XYLS [13] have been proposed to guarantee at least one crossing point between the SLA and SLQ quorums in the irregular sensor networks. The network boundary information-based approach navigates SLA and SLQ messages by using the network boundary information to guarantee one crossing point. However, the network boundary information-based approach leads to much control overhead by collecting the network boundary information and flooding the collected information to the whole network. On the other hand, the network boundary forwarding-based approach forwards SLA and SLQ messages along the entire network boundary to guarantee one crossing point. However, the network boundary forwarding-based approach leads to much communication overhead by delivering the messages along the long network boundary. As a result, the two approaches have high energy consumption due to much control or communication overhead.

Therefore, to reduce the energy consumption for providing sink location service, we propose a novel quorum-based sink location service scheme that exploits a crossing point between circle and line paths. In the proposed scheme, a source node sends a SLQ message to the network center and a copy of the SLQ message to a node on the edge of the sensor network, thus generating a line quorum of a SLQ massage. On the other hand, a sink node sends a SLA message along a circle path whose center is the network center, and thus generating a circle quorum of a SLA message. By this way, it is guaranteed that the SLQ line and SLA circle quorums have at least one crossing point. Then, the sensor node located on the crossing point informs the source node of the sink location. We next present how the proposed scheme can accomplish this procedure in irregular sensor networks. Since the proposed scheme does not exploit any network boundary information and send any SLA or SLQ messages along the network boundary, it can reduce much control and communication overhead. Our numerical analysis and extensive simulation results have verified that the proposed scheme is more efficient than both NELS and XYLS in terms of the delivery distance, the hop count, and the energy consumption for sink location service in irregular sensor networks.

The rest of this paper is organized as follows: Sect. 2 reviews related works about sink location service schemes. We describe our novel quorum-based sink location service scheme based on circle and line paths in Sect. 3. Analysis and simulation results are given in Sects. 4 and 5, respectively. We discuss several issues related with the proposed scheme in Sect. 6. Section 7 concludes this paper.

2 Related works

In geographic routing for wireless sensor networks, sink location service schemes for providing the location information of sinks to sources can be categorized into two main approaches: a flooding-based approach and a quorum-based approach. The flooding-based approach provides the sink location to the sources by flooding the location at sinks and also can be divided into two approaches: full network flooding [9] and local network flooding [10]. The full network flooding [9] is that a sink consecutively informs its new location information to the entire network by flooding. This scheme ensures that any source in the network can be

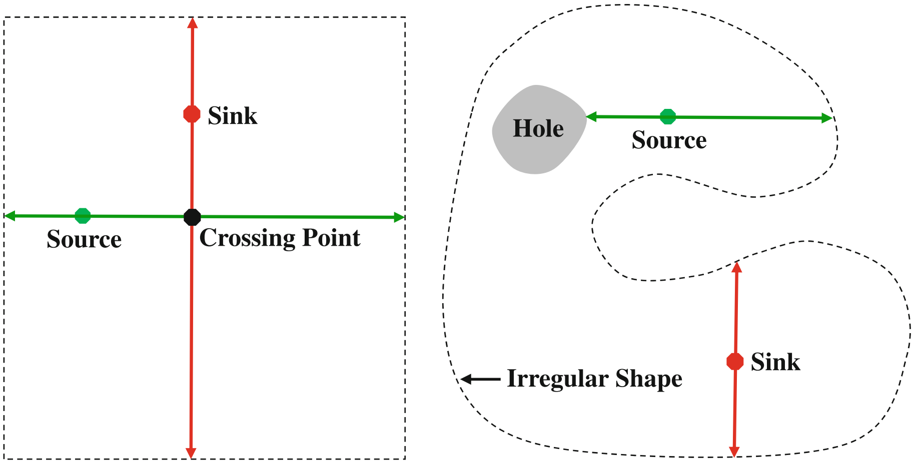

Fig. 1 The simplest quorum-based sink location service solution

provided with the sink location, but the full network flooding can lead to large energy consumption of the sensor nodes and collisions in wireless transmissions. The energy consumption of the full network flooding increases with the number of sinks. To avoid the full network flooding, the local network flooding, named TTDD [10] was proposed. A source in TTDD constructs a global grid structure from its location and disseminates its location information to sensor nodes on the grid structure. Then, a sink floods its own location information only within about a grid cell size to find a sensor node on the grid structure. The sensor node relays the location and query information of the sink to the source via the grid structure. Local flooding only within about a grid cell size is an efficient way. However, the bigger the cell size, the wider the flooding area, thus the more flooding overhead, while small grid size incurs more overhead for the grid construction. Moreover, per-source based global grid constructions also significantly generate additional overhead.

The quorum-based approach has been proposed to prevent the full and local network flooding. In the quorum-based approach, a Sink Location Announcement (SLA) message of a sink is sent to a subset (SLA quorum) of available sensor nodes, and a SLQ message of a source is sent to a potentially different subset (SLQ quorum). The two quorums are designed such that they have at least one crossing point between them. The simplest quorum-based scheme is the so-called column-row method that a sink sends a SLA packet from its location in the north-south direction while a source sends a SLQ packet from its location in the east-west direction. However, the simple column-row method can guarantee at least one crossing point only in the network of rectangle shape. Thus, the simple column-low method cannot provide at least one crossing point in the real irregular sensor networks which have void areas or are non-rectangle shapes such as circle, ellipse, convex, and concave shapes.

Two quorum-based approaches have been proposed to guarantee at least one crossing points between SLA and SLQ quorums in the irregular wireless sensor networks: network boundary information-based approach [11, 12] and network boundary forwarding-based approach [13]. The network boundary information-based approach navigates SLA and SLQ messages by using the network boundary information to guarantee at least one crossing point. As shown in Fig. 2, NELS [11] collects the location information of network boundary nodes in a sensor network and selects anchor nodes among them. Then, NELS divides the anchor nodes into four parts, which are labeled as P1, P2, P3 and P4 in clockwise direction. Then, the location information of the anchor nodes is flooded in the sensor network. With the list information, a sink sends a SLA packet to a random anchor in each of P2 and P4, respectively. On the other hand, a source node sends a SLQ packet for a sink to a random anchor in each of P1 and P3, respectively. Thus, one crossing point is guaranteed in NELS. With the location information of network boundary nodes, SLS-IR [12] constructs an inner network of rectangle shape inside the whole sensor network to use the simple column-row quorum method and floods the location information of the inner rectangle network to the whole sensor network. Then, a sink construct a SLA quorum of east-west direction and a source construct a SLQ quorum of north-south direction inside the inner rectangle network. Thus, SLS-IR guarantees at least one crossing point in the inner rectangle network.

Instead of using the network boundary information, the network boundary forwarding-based approach forwards SLA and SLQ messages along the network boundary to guarantee at least one crossing point. As shown in Fig. 3, in XYLS [13], a sink sends a south-north quorum of a SLA message from its location to the network boundary. A source node sends an east-west quorum of a SLQ message from its location to the network boundary. Then, the SLA

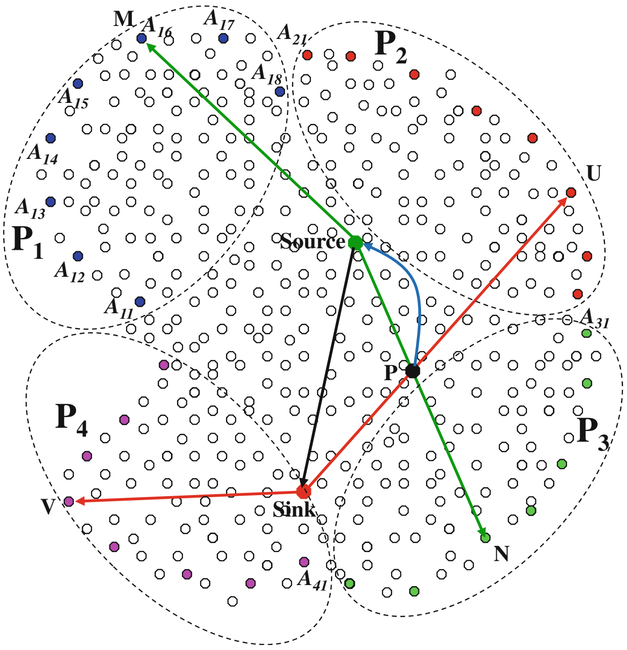

Fig. 2 NELS using the network boundary information-based approach

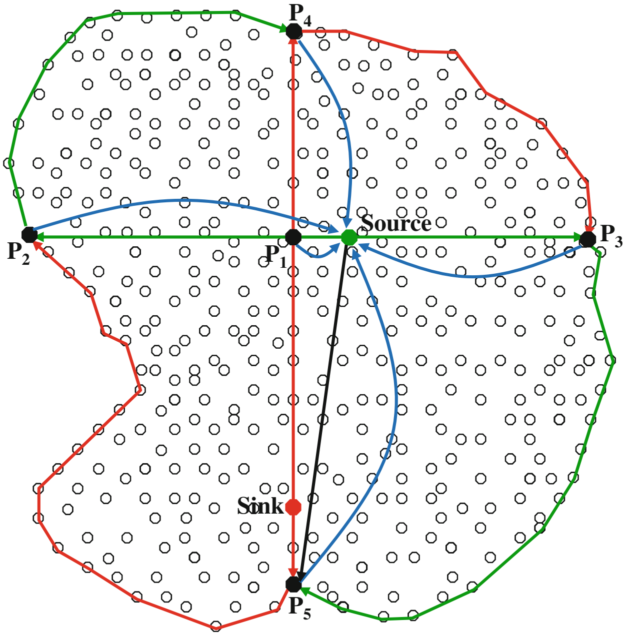

Fig. 3 XYLS using the network boundary forwarding-based approach

and SLQ messages arrive at the network boundary and then they are further forwarded along the network boundary with the clockwise direction to guarantee at least one crossing point between them. The authors in XYLS propose a variant, called CR+CR, of XYLS. In CR+CR, all of SLA and SLQ messages constructs both column and row quorums, that is, in both north-south and east-west directions, to provide more crossing points and fast sink location replies.

However, the network boundary information-based approach leads to much control overhead by collecting the network boundary information and flooding the information to the whole network. If the network size increases, it brings out more control overhead for collecting the network boundary information due to the increased network boundary length. If the number of sensor nodes increases, it also brings out more control overhead for flooding the network boundary information due to the increased number of sensor nodes. On the other hand, the network boundary forwarding-based approach leads to much communication overhead by delivering the messages along the long network boundary, and thus makes the network boundary nodes exhaust their energy fast. If the number of sinks and sources increases, it makes this problem more seriously due to delivering more SLA and SLQ packets along the network boundary. However, since energy-efficiency is one of the most important issues in wireless sensor networks [15–18], sink location service should be provided with less control and communication overheads. Thus, for energy-efficiency, the proposed sink location service scheme does not exploit any network boundary information and deliver any SLA or SLQ messages along the network boundary to guarantee at least one crossing point. The proposed scheme only uses the location information of the network center through embedding or programming it by network operators. With the network center location information, our scheme guarantees at least one crossing point between a SLA circle quorum and a SLQ line quorum. Thus, our scheme can reduce much control and communication overhead.

3 Design of the proposed scheme

We assume in this work that each node can get its own location information either by GPS [2] or localization schemes [3, 4]. Each node can get its one-hop neighbors list and their locations by periodically exchanging beacon messages [5]. A node can know whether it is located on the edge of a sensor network either by manual identification of network operators during network deployment, or by some automatic detection methods [19, 20] after network deployment. Every node can know the information of center location $C = (C_x, C_y)$ in the sensor network by programming or embedding from network operators before network deployment, because the network operators commonly know the region of sensor field to construct the sensor network in advance.

3.1 Network initialization

After network deployment of sensor nodes, a general sensor network may be shown as Fig. 4. Then, every node calculates a *Height* value from the center location $C = (C_x, C_y)$ as follows:

$$Height = \left\lceil \frac{L}{R} \right\rceil \tag{1}$$

where L is the distance from the center location to itself and R is the radio range of sensor nodes. Figure 5 shows the ideal result of this process, where the thick dotted curve line indicates the boundary of the sensor network, and the thin dotted circles are the traces of the sensor nodes which have the same *Height* value. To facilitate discussion, all general sensor nodes are not drawn out here. After the network initialization phase, every sensor node is aware of its *Height* value. By including the *Height* value in beacon messages [5] and exchanging them with neighbor nodes, all nodes can get the *Height* value information of their neighbor sensor nodes. The *Height* value information is used for navigating SLA and SLQ messages to their destinations for supporting our sink location service scheme.

3.2 Sink location service in regular sensor networks

In this section, we first describe our sink location service scheme in regular sensor networks. As shown in Fig. 5, when a sink S exists in the sensor network, it gets a *Height* value by querying a neighbor sensor node. Then, it initializes a SLA message that contains the following fields: *Sink_Location*, *Sink_Interest*, *Height*, and *Direction*. The *Sink_Location* field is set to the location of the sink *S*, the *Sink_Interest* field is set to the interest of the sink *S*, the *Height* field is set to the *Height* value obtained from the neighbor node, and the *Direction* field is set to a counter-clockwise. Then, the sink node *S* sends the SLA message to the farthest neighbor sensor node on the left side direction of itself, which has the same *Height* value. When the neighbor node receives the SLA message, it saves the location and interest information of the sink *S* to its sink information table, and then forwards the SLA message to its neighbor sensor node according to the same rule. This process repeats until the SLA message is eventually received by a sensor node which has forwarded it. The track of the SLA message forms a closed circle quorum as the solid circle shown in Fig. 5.

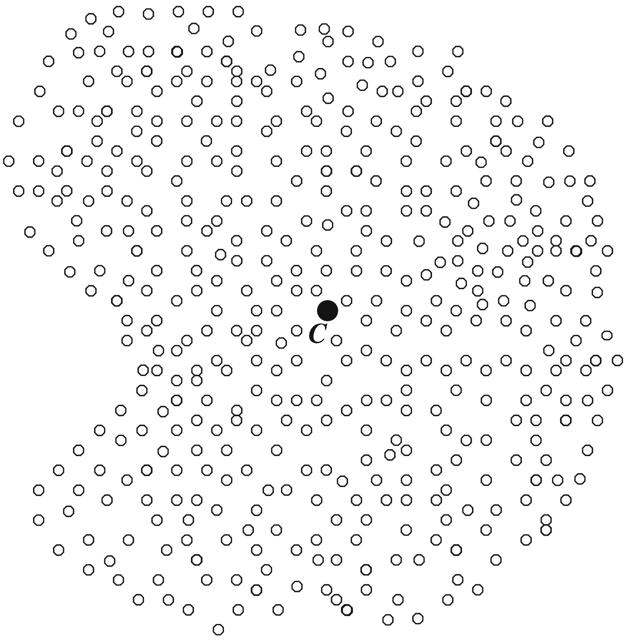

Fig. 4 A general sensor network after network deployment

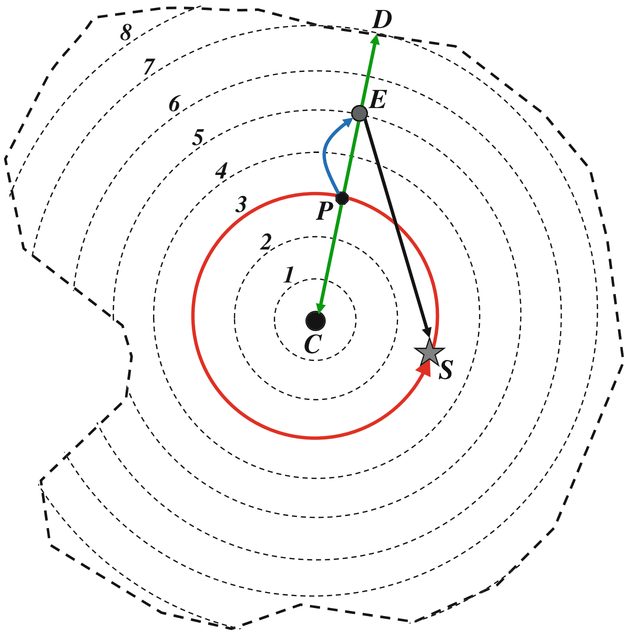

Fig. 5 Network initialization and the proposed sink location service scheme

When a sensor node detects an event and becomes a source node, e.g., the node *E* in Fig. 5, it initializes a SLQ message which contains the source node location and the detected event type. A copy of the SLQ message is sent to the center location *C* of the sensor network by geographic routing as the path shown in Fig. 5. All of the sensor nodes which have forwarded the SLQ message need to save the source node location and the event type in their source information table. The source node E also sends another copy of the SLQ message to the farthest neighbor sensor node whose *Height* value is 1 bigger than that of itself. When the farthest node receives the SLQ message, it saves the source node location and the event type in its source information table. Then, it also forwards the SLQ message to the farthest neighbor sensor node whose *Height* value is 1 bigger than that of itself. This process stops at a network edge node D which received the SLQ message. The network edge node should never reforward the received SLQ message in any case. The solid line $\overline{CED}$ in Fig. 5 shows the line quorum of the SLQ message.

For guaranteeing a crossing point between a SLA quorum and a SLQ quorum, our sink location service scheme is supported by following theorem:

Theorem *Given a circle and a line, if one end of the line is inside the circle and the other end of the line is outside of the circle, then the circle and the line have at least one crossing point.*

Proof As we can see from Fig. 5, one end of the SLQ line quorum is the center location C and is inside the SLA circle quorum, while the other end of the SLQ line quorum is the network edge node D and is outside the SLA circle quorum. Thus, the SLA circle quorum and the SLQ line quorum have at least one crossing point P.

From the theorem and proof, we can guarantee at least one crossing point P between a SLA message from a sink and a SLQ message from a source in our sink location service scheme. Thus, the sensor node which is located on the crossing point P received both SLQ and SLA messages becomes to know the source location and the event type from the SLQ message and the sink location and the sink interest from the SLA message. Then, if the event type matches the sink interest, the sensor node informs the source node of the sink location information as the solid curve line as shown in Fig. 5. After getting the sink location, the source node E sends data packets to the sink S by the geographic routing. This is the basic idea of the proposed sink location service scheme. In the Sect. 3.3, we discuss how our sink location service scheme guarantees one crossing point in irregular sensor networks.

3.3 Handling irregular profile sensor network

Most sensor networks have irregular profiles such voids [14] or non-rectangular shapes [11–13]. Thus, our sink location service scheme must work well in any irregular profile sensor networks. Figure 6 shows an irregular profile sensor network with three hole inside it and a non-rectangular shape. A sink node S sends a SLA message to announce its location and interest to the farthest neighbor sensor node on the left side of itself for constructing a SLQ circle path by the process described in the Sect. 3.2 When the sensor node M located on the edge of the hole receives the SLA message, since there is no sensor node located on the left side of itself with the same *Height* value, the node M sends the SLA message to a neighbor node whose *Height* value is 1 less then that of itself. When the neighbor node receives the SLA message, it tries to send the SLA message to the sensor node on the left side whose *Height* value is closest to the *Height* value encapsulated in the received SLA message. If there is no such a sensor node, it also sends the SLA message to a neighbor node whose *Height* is 1 less then that of itself. This process repeats until the SLA message was received by the sensor node N which has the same *Height* value as that encapsulated in the SLA message. Then, the SLA message is continuously forwarded until it was received by a sensor node U on the irregular edge as shown in Fig. 6. The subsequent process is similar to the process of bypassing the Hole as described above. By bypassing the irregular edge, the SLA message is received by another sensor node V on the irregular edge which has the same Height value as encapsulated in the SLA message. Then, the sensor node V sends the SLA message to the farthest neighbor sensor node on the left side of itself, which has the same *Height* value. This process repeats until the SLA message is eventually received by a sensor node which has firstly forwarded it. As shown in Fig. 6, although the path of the SLA message does not have a circle shape, it has a closed shape similar to circles.

When a source node E sends a SLQ message to the center location and a network edge in a irregular sensor network by geographic routing, the SLQ message can also meet a Hole. Thus, the SLQ message also need to bypass the Hole. When a copy of the SLQ message is sent from the source node to the center location by the greedy mode [1] in geographic routing, if it meets a Hole, a sensor node on the Hole received the SLQ

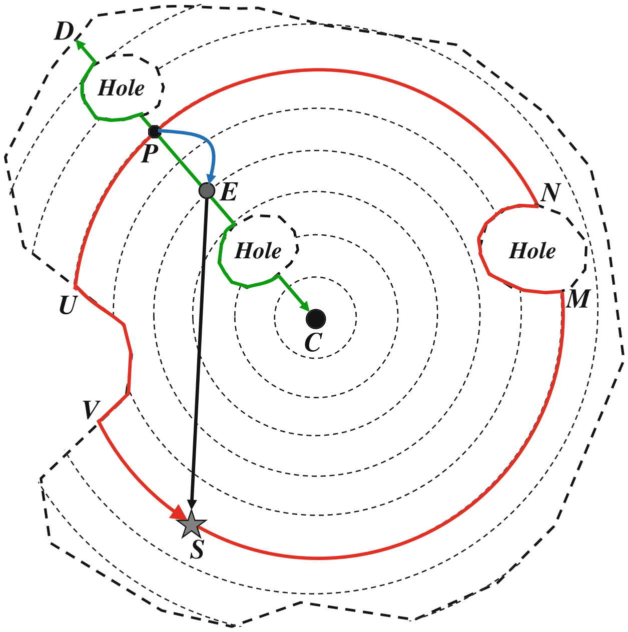

Fig. 6 The proposed sink location service scheme in any irregular profile sensor network

message changes the greedy mode [1] into the perimeter mode to bypass the hole. If the SLQ message bypasses the hole by the perimeter mode, it is also sent to the center location C by the greedy mode. By this process, the SLQ message is eventually forwarded to the center location. To forward a copy of the SLQ message to a network edge, the source node E sends the farthest neighbor sensor node whose *Height* value is 1 bigger than that of itself. However, since a sensor node on a Hole receives the SLQ message, it can have no any neighbor sensor node whose *Height* value is 1 bigger than that of itself. Then, it includes its *Height* value into the SLQ message and sends the SLQ message along the Hole in a counter-clockwise direction until a sensor node on the Hole, whose *Height* value is 1 bigger than that in the SLQ message, receives the SLQ message. This process continues until a network edge node D_2 receives the SLQ message. Thus, as shown in Fig. 6, a curve line $\overline{CED}$ is constructed between the center location C and the network edge D via the source node E.

From Fig. 6, we can see that, in the irregular profile sensor network, though the SLA delivery path is not a real circle and the SLQ delivery path is not a real straight line, our sink location service scheme can guarantee that the SLA path and the SLQ path have at least one crossing point, e.g., the sensor node P. If the Event Type in the SLQ message and the Sink Interest in the SLA message are matched, the sensor node P on the crossing point also sends the location information of the sink node S to source node E by geographic routing.

3.4 Effects of multiple sinks and sources

Multiple source nodes and multiple sinks may exist in the sensor network simultaneously. In this case, the SLA circle path of any sink and the SLQ line path of any source can be surely guaranteed to have at least one crossing point. Once a sink sends a SLA message, all source nodes can get the location of the sink from the nodes located on corresponding crossing points; once a source sends a SLQ message, it can get the location information of all sinks form the nodes located on the corresponding crossing points. However, if the number of sinks or source nodes increases, the number of SLA and SLQ messages increases. Thus, sensor nodes consume more energy to deliver the increased SLA and SLQ messages. We evaluate how the number of sinks and source nodes can affect the proposed scheme through analysis and simulation in the Sect. 4 and 5.

4 Numerical analysis

In this section, we present numerical analysis for sink location service cost of Network Edge node-based sink Location Service (NELS) [11], XYLS [13], and the Proposed Scheme (PS). In all of sink location service schemes, since all of SLA, SLQ, and SLR messages are delivered by using geographic routing [1], we consider the delivery distance of all the messages as sink location service cost. This assumption is justified by the fact that the Euclidean distance in a dense and uniform wireless sensor network is approximately proportional to the hop count [21]. Furthermore, the energy consumption of sensor nodes is proportional to the hop count [22]. We note that such an energy model is also adapted by several power-efficient data communication protocols in wireless sensor networks [22, 23]. Thus, we numerically calculate the delivery distance for sink location service.

Sink location service consists of three messages: SLA, SLQ, and SLR messages. We first present the delivery distance of each of the three messages in each sink location service scheme in next three subsections, respectively. We next present the total delivery distance of each sink location services. We last present the hop count of each sink location service through the total delivery distance and the energy consumption of sensor nodes through the hop count. For numerical analysis of sink location service, we assume a sensor network whose shape is a circle with a radius Rm. The number of sinks and sources is a and b, respectively. The number of sensor nodes in the network is n.

4.1 Delivery distance of sink location announcement

A sink sends a SLA message with its location information according to sink location service schemes and thus constructs SLA quorums. In NELS, as shown in Fig. 2, a sink S delivers a SLA message from its location to a edge node U of part P_2 in the network boundary. When we assume for analysis that the sink locates around the center of the network, the length of line between S and U is almost same with the radius R. The sink also delivers a copy of the SLA from itself to a edge node V of part P_4. The length of the line between S and V also is almost same with the radius R. Therefore, the delivery distance D_{SLA_NELS} of a SLA message from a sink in NELS is calculated as follows:

$$D_{SLA\_NELS} = R + R = 2 \cdot R. \qquad (2)$$

In XYLS, as shown in Fig. 3, a sink sends a SLA message from its location to the network boundary both toward south and north, and thus constructing a vertical quorum in the network. Then, each of edge nodes in the network boundary of south and north sides received the SLA message sends the SLA message along edge nodes on the network boundary with the clockwise direction. Thus, the SLA message further constructs the SLA quorum to network boundary edge nodes on east and west sides in the east-west quorum of a SLQ message from a source node.

Therefore, the delivery distance D_{SLA_XYLS} of a SLA message from a sink in XYLS consists of a vertical quorum and two network boundary circle quorum of one-quarter, and is calculated as follows:

$$D_{SLA\_XYLS} = R + R + \frac{\pi \cdot R}{2} + \frac{\pi \cdot R}{2} = 2 \cdot R + \pi \cdot R. \quad (3)$$

In the proposed scheme, as shown in Fig. 5, a sink sends a SLA message from its location along a circle path whose radius is the distance from its location to the center of the network. When we assume that the sink averagely locates in the center between the network center and the network boundary, the radius of the circle path is half of the network radius R. Thus, the delivery distance D_{SLA_PS} of a SLA message from a sink in the proposed scheme is calculated as follows:

$$D_{SLA\_PS} = 2 \cdot \pi \cdot \frac{1}{2} \cdot R = \pi \cdot R. \quad (4)$$

4.2 Delivery distance of sink location query

A source queries the location information of the sink to send its data through geographic routing. In quorum-based sink location service schemes, a source sends a SLQ message with its location information by each sink location scheme and thus constructing SLQ quorums. In NELS, as shown in Fig. 2, a source E delivers a SLQ message from its location to a edge node M of part P_1 in the network boundary. When we assume for analysis that the source locates around the center of the network, the length of line between E and M is almost same with the radius R. The source also delivers a copy of the SLA from itself to a edge node N of part P_3. The length of the line between E and N also is almost same with the radius R. Therefore, the delivery distance D_{SLQ_NELS} of a SLA message from a source in NELS is calculated as follows:

$$D_{SLQ\_NELS} = R + R = 2 \cdot R. \quad (5)$$

In XYLS, as shown in Fig. 3, a source node sends a SLQ message from its location to the network boundary both toward east and west, and thus constructing one horizontal quorum in the network. Then, each of edge nodes in the network boundary of east and west sides received the SLQ message sends the SLQ message along edge nodes on the network boundary with the clockwise direction. Thus, the SLQ message further constructs the SLQ quorum to network boundary edge nodes on north and south sides in the north-south quorum of a SLA message from a sink. Therefore, the delivery distance D_{SLQ_XYLS} of a SLQ message from a sink in XYLS consists of a horizontal quorum and two network boundary circle quorum of one-quarter, and is calculated as follows:

$$D_{SLQ\_XYLS} = R + R + \frac{\pi \cdot R}{2} + \frac{\pi \cdot R}{2} = 2 \cdot R + \pi \cdot R. \quad (6)$$

In the proposed scheme, as shown in Fig. 5, a source sends a SLQ message from its location to the center of the network and a copy of the SLQ message to the network boundary, and constructing a quorum of one line between the network center and the network boundary via the source. Thus, the delivery distance D_{SLQ_PS} of a SLQ message from a source in the proposed scheme is calculated as follows:

$$D_{SLQ\_PS} = R. \quad (7)$$

4.3 Delivery distance of sink location reply

In quorum-based sink location service schemes, a sensor node on all crossing points between the quorums of SLA message of a sink and the quorums of SLQ message of a source sends a SLR message with the location information of the sink to the source. In NELS, as shown in Fig. 2, since a SLA message of a sink is sent toward part 1 and 3 of the network boundary and a SLQ message of a source is sent toward part 2 and 4 of the network boundary, one crossing point may be around the network center. When we assume for analysis that a source node averagely locates around the center between one among part 1 and 3 and the crossing point, the distance between the crossing point and the source is half of the network radius R. Thus, the delivery distance D_{SLR_NELS} of a SLR message in ALS is as follows:

$$D_{SLR\_NELS} = \frac{1}{2} \cdot R. \quad (8)$$

In XYLS, as shown in Fig. 3, a sink sends a SLA message to the network edges of both south and north. A source sends a SLQ message to the network edges of both east and west. Then, the SLA and SLQ messages are sent along the network boundary with the clockwise direction. Thus, five crossing points can be in the network. When we assume for analysis that a source locates around the center between the east boundary and the network center, one crossing point is the east boundary and the distance between the crossing point and the source is half of the network radius R. Another crossing point is the west boundary and the distance between the crossing point and the source is $\frac{3}{2} \cdot R$. Another crossing point is the north boundary and the distance between the crossing point and the source is the network radius R. Another crossing point is the south boundary and the distance between the crossing point and the source is the network radius R. When a sink averagely locates around the network center, the other crossing point is around the network center and the distance between the crossing point and the source is half of the network radius R. Thus, the delivery distance D_{SLR_XYLS} of a SLR message in XYLS is calculated as follows:

$$D_{SLR\_XYLS} = \frac{1}{2} \cdot R + \frac{3}{2} \cdot R + R + R + \frac{1}{2} \cdot R = \frac{9}{2} \cdot R. \tag{9}$$

In the proposed scheme, if a sink averagely locates in the center of the distance between the network center and the network boundary, it constructs a circle path of a SLA message in its location and thus the network is divided into two regions. A source constructs a SLQ quorum between the network center and the network boundary via itself. Thus, one crossing point happens. When a source averagely locates in the center of one among the two regions, the distance between the crossing point and the source is $\frac{1}{4} \cdot R$. Thus, the delivery distance D_{SLR_PS} of the SLR message in the proposed scheme is as follows:

$$D_{SLR\_PS} = \frac{1}{4} \cdot R. \tag{10}$$

4.4 Total delivery distance for sink location service

In this subsection, we calculate the total delivery distance for sink location service. The total delivery distance for sink location service is the sum of delivery distance of SLA, SLQ, and SLR messages. Thus, the total delivery D_T distance of NELS, XYLS, and the proposed scheme are as follows.

$$\begin{aligned} D_{SLS\_NELS} &= D_{SLA\_NELS} + D_{SLQ\_NELS} + D_{SLR\_NELS} \\ &= 2 \cdot R + 2 \cdot R + \frac{1}{2} \cdot R = \frac{9}{2} \cdot R \end{aligned} \tag{11}$$

$$\begin{aligned} D_{SLS\_XYLS} &= D_{SLA\_XYLS} + D_{SLQ\_XYLS} + D_{SLR\_XYLS} \\ &= (2 \cdot R + \pi \cdot R) + (2 \cdot R + \pi \cdot R) + \frac{9}{2} \cdot R \\ &= \frac{17}{2} \cdot R + 2 \cdot \pi \cdot R \end{aligned} \tag{12}$$

$$\begin{aligned} D_{SLS\_PS} &= D_{SLA\_PS} + D_{SLQ\_PS} + D_{SLR\_PS} \\ &= \pi \cdot R + R + \frac{1}{4} \cdot R = \frac{5}{4} \cdot R + \pi \cdot R \end{aligned} \tag{13}$$

The number of sinks and source nodes affects the total delivery distance for sink location service. Thus, we calculate the total delivery distance of sink location service for the number of sinks and sources. The number of sinks affects the number of SLA and SLR messages, and the number of source nodes affects the number of SLQ and SLR messages. When the number of sinks is a, the number of SLA and SLR messages increases a times, respectively. When the number of source nodes is b, the number of SLQ and SLR messages increases b times, respectively. When the numbers of sinks and source nodes are a and b, the total delivery distance D_T of ALS, XYLS, and the proposed scheme are as follows.

$$\begin{aligned} D_{SLS\_NELS}^{Sink=a;Source=b} &= a \cdot D_{SLA\_NELS} + b \cdot D_{SLQ\_NELS} \\ &\quad + a \cdot b \cdot D_{SLR\_NELS} \\ &= a \cdot 2 \cdot R + b \cdot 2 \cdot R + a \cdot b \cdot \frac{1}{2} \cdot R \\ &= \left(2 \cdot a + 2 \cdot b + \frac{1}{2} \cdot a \cdot b\right) \cdot R \end{aligned} \tag{14}$$

$$\begin{aligned} D_{SLS\_XYLS}^{Sink=a;Source=b} &= a \cdot D_{SLA\_XYLS} + b \cdot D_{SLQ\_XYLS} \\ &\quad + a \cdot b \cdot D_{SLR\_XYLS} \\ &= a \cdot (2 \cdot R + \pi \cdot R) + b \cdot (2 \cdot R + \pi \cdot R) \\ &\quad + a \cdot b \cdot \frac{9}{2} \cdot R \\ &= \left(2 \cdot a + \pi \cdot a + 2 \cdot b + \pi \cdot b + \frac{9}{2} \cdot a \cdot b\right) \cdot R \end{aligned} \tag{15}$$

$$\begin{aligned} D_{SLS\_PS}^{Sink=a;Source=b} &= a \cdot D_{SLA\_PS} + b \cdot D_{SLQ\_PS} \\ &\quad + a \cdot b \cdot D_{SLR\_PS} \\ &= a \cdot \pi \cdot R + b \cdot R + a \cdot b \cdot \frac{1}{4} \cdot R \\ &= \left(\pi \cdot a + b + \frac{1}{4} \cdot a \cdot b\right) \cdot R \end{aligned} \tag{16}$$

4.5 Total hop count for sink location service

In the subsection, we calculate the total hop count for sink location service in NELS, XYLS, and the proposed scheme. The total hop count are calculated by the total delivery distance in the Sect. 4.4. Given the total delivery distance, if an average single hop progress $Single\_Hop\_Pro_{ave}$ is given, the total hop count can be calculated. The $Single\_Hop\_Pro_{ave}$ is defined as the expected value of the difference between the before-hop distance (between the sender node and the destination node) and the after-hop distance (between the next-hop node and the destination node) [24]. As the $Single\_Hop\_Pro_{ave}$, we use a value calculated by the equation (14) in [24] where ρ is the average number of neighbors within the transmission range r of the sender and is given by $\rho = \pi \cdot r^2 \cdot \lambda$ where λ is the expected number of nodes within a unit area. Figure 7 shows the average single hop progress for average number of neighbor sensor nodes in [24]. As shown in Fig. 7, if the average number of neighbor sensor nodes is small, the average single hop progress has very small value. However, if the average number of neighbor sensor nodes increases, the average single hop progress increases sharply first and slowly later. Thus, given the $Single\_Hop\_Pro_{ave}$,

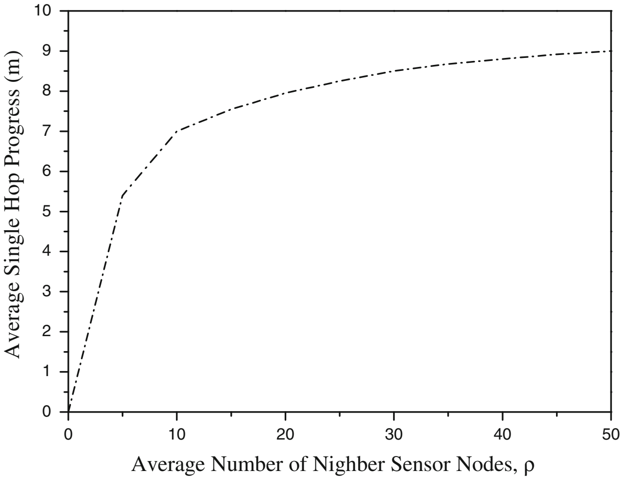

Fig. 7 Average single hop progress for average number of neighbor sensor nodes in [24]

the total hop count H_T for sink location service in NELS, XYLS, and the proposed scheme are calculated as follows.

$$
\begin{aligned}
H^{Sink=a;Source=b}_{SLS\_NELS} &= D^{Sink=a;Source=b}_{SLS\_NELS}/Single\_Hop\_Pro_{ave} \\
&= \left(2\cdot a + 2\cdot b + \frac{1}{2}\cdot a\cdot b\right) \\
&\quad \cdot R/Single\_Hop\_Pro_{ave}
\end{aligned} \tag{17}
$$

$$
\begin{aligned}
H^{Sink=a;Source=b}_{SLS\_XYLS} &= D^{Sink=a;Source=b}_{SLS\_XYLS}/Single\_Hop\_Pro_{ave} \\
&= \left(2\cdot a + \pi\cdot a + 2\cdot b + \pi\cdot b + \frac{9}{2}\cdot a\cdot b\right) \\
&\quad \cdot R/Single\_Hop\_Pro_{ave}
\end{aligned} \tag{18}
$$

$$
\begin{aligned}
H^{Sink=a;Source=b}_{SLS\_PS} &= D^{Sink=a;Source=b}_{SLS\_PS}/Single\_Hop\_Pro_{ave} \\
&= \left(\pi\cdot a + b + \frac{1}{4}\cdot a\cdot b\right) \\
&\quad \cdot R/Single\_Hop\_Pro_{ave}
\end{aligned} \tag{19}
$$

4.6 Total energy consumption for sink location service

In this subsection, we calculate the total energy consumption for sink location service in NELS, XYLS, and the proposed scheme. The total energy consumption is calculated through multiplying the total hop count by the sum of transmitting and receiving power in one-hop transmission of sensor nodes. If we assume that the transmitting and receiving energy consumption rates are E_t and E_r, respectively, the total energy consumption for sink location service in NELS, XYLS, and the proposed scheme are calculated as follows.

$$
\begin{aligned}
E^{Sink=a;Source=b}_{SLS\_NELS} &= H^{Sink=a;Source=b}_{SLS\_NELS}\cdot(E_t + E_r) \\
&= \Bigg(\left(2\cdot a + 2\cdot b + \frac{1}{2}\cdot a\cdot b\right) \\
&\quad \cdot R/Single\_Hop\_Pro_{ave}\Bigg)\cdot(E_t + E_r)
\end{aligned} \tag{20}
$$

$$
\begin{aligned}
E^{Sink=a;Source=b}_{SLS\_XYLS} &= H^{Sink=a;Source=b}_{SLS\_XYLS}\cdot(E_t + E_r) \\
&= \Bigg(\left(2\cdot a + \pi\cdot a + 2\cdot b + \pi\cdot b + \frac{9}{2}\cdot a\cdot b\right) \\
&\quad \cdot R/Single\_Hop\_Pro_{ave}\Bigg)\cdot(E_t + E_r)
\end{aligned} \tag{21}
$$

$$
\begin{aligned}
E^{Sink=a;Source=b}_{SLS\_PS} &= H^{Sink=a;Source=b}_{SLS\_PS}\cdot(E_t + E_r) \\
&= \Bigg(\left(\pi\cdot a + b + \frac{1}{4}\cdot a\cdot b\right) \\
&\quad \cdot R/Single\_Hop\_Pro_{ave}\Bigg)\cdot(E_t + E_r)
\end{aligned} \tag{22}
$$

However, since NELS carries out the collection and the flooding of the network boundary information in the network initialization phase for navigating SLA and SLQ messages, the control overhead for these two processes must be included in the total energy consumption for sink location service. For the process of the network boundary information collection, a boundary edge node sends a Boundary Information Collection (BIC) message along the network boundary. Thus, the delivery distance of the BIC message is same to the circumference length of a circle with a radius R. Thus, the energy consumption for sending the BIC message along the network boundary is $(2\cdot\pi\cdot R/Single\_Hop\_Pro_{ave})\cdot(E_t + E_r)$. For the process of the network boundary information flooding, the boundary edge node floods a Boundary Information Announcement message to all sensor node in the network. Then, for flooding the BIA message to all sensor nodes, every sensor node receives the BIA message once and sends the BIA message once. Thus, the energy consumption for flooding the BIA message is the number n of sensor nodes times $(E_t + E_r)$, namely $n\cdot(E_t + E_r)$. Thus, the control overhead E_{CO_NELS} for the network initialization is calculated as follows,

$$
\begin{aligned}
E_{CO\_NELS} =& (2\cdot\pi\cdot R/Single\_Hop\_Pro_{ave})\cdot(E_t + E_r) \\
& + n\cdot(E_t + E_r).
\end{aligned} \tag{23}
$$

Therefore, the total energy consumption for sink location service in NELS is recalculated as:

$$\begin{aligned} E_{T\_NELS}^{Sink=a;Source=b} &= E_{SLS\_NELS}^{Sink=a;Source=b} + E_{CO\_NELS} \\ &= \left(\left(2\cdot a + 2\cdot b + \frac{1}{2}\cdot a\cdot b\right)\cdot R/Single\_Hop\_Pro_{ave}\right) \\ &\quad \cdot (E_t + E_r) + (2\cdot \pi \cdot R/Single\_Hop\_Pro_{ave}) \\ &\quad \cdot (E_t + E_r) + n\cdot (E_t + E_r) \\ &= \left(\left(\left(2\cdot a + 2\cdot b + \frac{1}{2}\cdot a\cdot b + 2\cdot \pi\right)\right.\right. \\ &\quad \left.\left.\cdot R/Single\_Hop\_Pro_{ave}\right) + n\right)\cdot (E_t + E_r) \end{aligned} \tag{24}$$

As shown in the Eqs. (21), (22) and (24), the performance of NELS, XYLS, and the proposed scheme is influenced by the network size R, the sink number a, the source number b, and the sensor node density n. Thus, we evaluate how they can affect the performance of the three schemes through analysis and simulation results in the Sect. 5.

5 Performance evaluation

5.1 Simulation environments

We compare the performance of the Proposed Scheme (PS) with those of NELS [11] and XYLS [13]. We implemented these three schemes in Network Simulator Qualnet 4.0 [25]. The models of sensor nodes follow the specification of MICA2 [26]. The radio range r of sensor nodes is 10 m and their transmitting and receiving energy consumption rates are 49 and 29 mW, respectively. As default setting, we consider a sensor network of circular shape with a radius 100 m where 2,000 sensor nodes are uniformly distributed. Thus, the $Single\_Hop\_Pro_{ave}$ is about 7.9 m by the equation (14) in [24] because the average neighbor node number ρ of a sensor node is 20. In our simulation, one sink and one source are randomly located in the network every 100 s. In every scheme, the source and the sink send SLQ and announcement messages every 100 s. We define every 100 s as a sink location service round. The simulation time is 1,000 s. We use three performance evaluation metrics, the total delivery distance, the total hop count, and the total energy consumption for sink location service. Each point of the plots is the average of 10 instances with a 95 % of confidence interval.

5.2 Simulation results for network size

In this section, we compare the performance of NELS, XYLS, and the proposed scheme for the network size R. We vary the network size 100–600 m at an interval of 100 m. Figures 8, 9 and 10 show analysis and simulation results of the delivery distance, the delivery hop count, and the energy consumption for sink location service, respectively. If the network size increases, the delivery distance of SLA, SLQ, and SLR messages for sink location service increases by the Eqs. (2)–(10). Thus, as shown in Fig. 8, the delivery

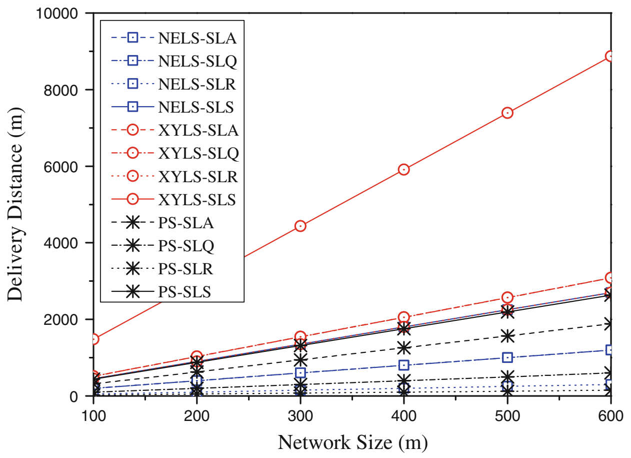

Fig. 8 Delivery distance for network size

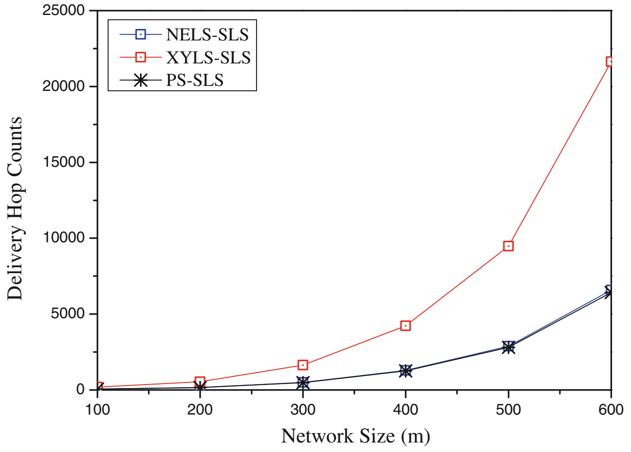

Fig. 9 Delivery hop count for network size

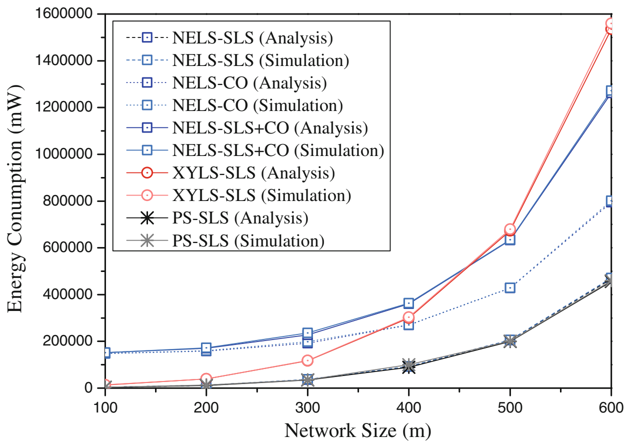

Fig. 10 Energy consumption for network size

distance, namely, the sum of the delivery distance of SLA, SLQ, and SLR messages, for sink location service also increases by the Eqs. (11)–(13). The delivery distance of XYLS is the longest, the second longest to that of NELS, and the shortest to that of the proposed scheme, because the increased network size makes SLA and SLQ messages in XYLS be forwarded along the increased network boundary.

The delivery distance for sink location service is proportional to the delivery hop count for sink location service by the Eqs. (17)–(19). However, the delivery hop count is inverse proportional to the $\mathit{Single\_Hop\_Pro}_{ave}$. The $\mathit{Single\_Hop\_Pro}_{ave}$ is also inverse proportional to the network size because average number of neighbor sensor nodes is inverse proportional to the network size when the number of sensor nodes is fixed. Thus, Fig. 9 shows that the delivery hop count of XYLS is the most, the second most to that of NELS, and the smallest to that of the proposed scheme. If the network size increases, they exponentially increase their delivery hop count.

Figure 10 shows the energy consumption for the network size. The energy consumption for sink location service is similar to the delivery hop count for sink location service, because the energy consumption is proportional to the delivery hop count by the Eqs. (20)–(22). However, since NELS needs the control overhead for collecting the network boundary information and for flooding the information to the whole network by the Eq. (23), total energy consumption of the sink location service and the control overhead in NELS is very high by the Eq. (24). Thus, the energy consumption of NELS is higher than that of XYLS. However, if the network size is bigger than 600 m, the energy consumption of NELS is lower than that of XYLS, because for the increased network size, the increased control overhead of NELS is smaller than the increased energy consumption by forwarding SLA and SLQ messages along the network boundary of XYLS. Figure 10 shows that our numerical analysis result is similar to our simulation result.

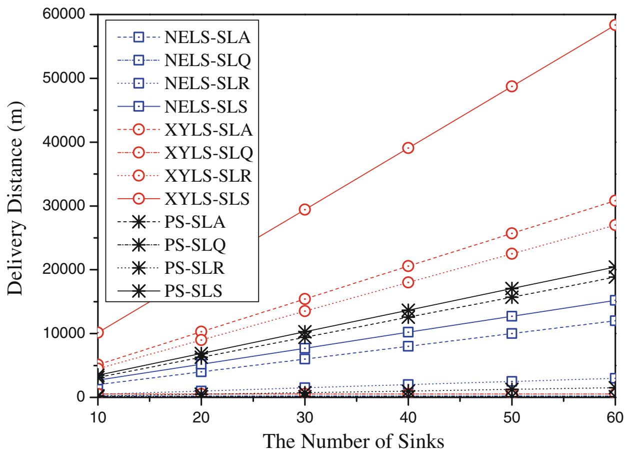

Fig. 11 Delivery distance for the number of sinks

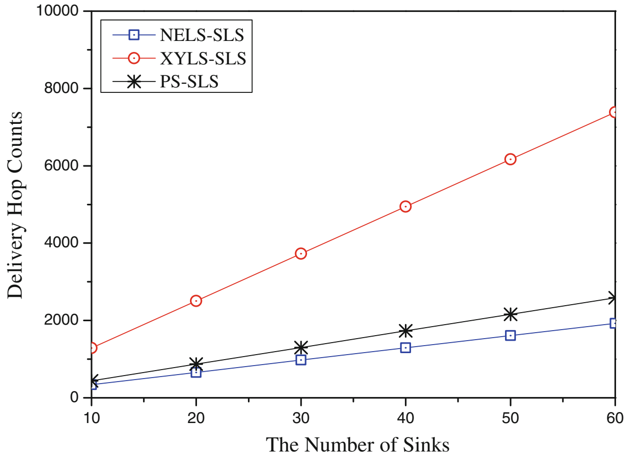

Fig. 12 Delivery hop count for the number of sinks

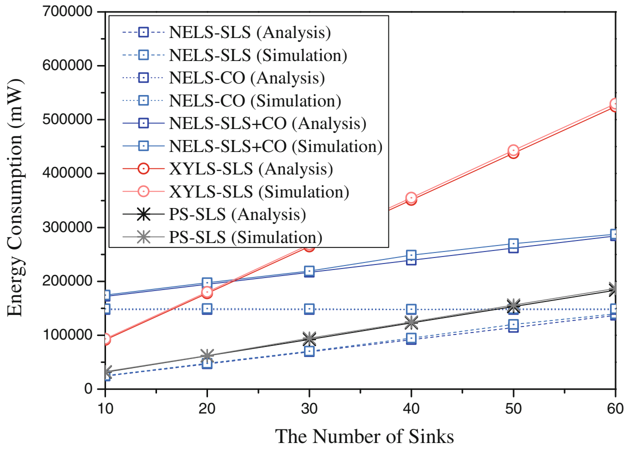

Fig. 13 Energy consumption for the number of sinks

5.3 Simulation results for the number of sinks

In this section, we compare the performance of NELS, XYLS, and the proposed scheme for the number of sinks. We vary the number of sinks 10–60 at an interval of 10. Figures 11, 12 and 13 show the delivery distance, the delivery hop count, and the energy consumption for sink location service, respectively. If the number of sinks increases, the numbers of SLA and SLR messages is the same with the number of sinks, respectively. As shown in Fig. 11, the delivery distances for sink location service of NELS, XYLS, and the proposed scheme all increase as large as the sum of the delivery distance of SLA and SLR messages by the Eqs. (14)–(16). However, each sink in NELS makes a SLA line quorum of the length $(2 \cdot R)m$, and each sink in the proposed scheme makes a SLA circle quorum of the length $(\pi \cdot R)m$, and each sink in XYLS make a SLA line quorums of the length $(2 \cdot R)m$ and network boundary quorum of length $(\pi \cdot R)m$. Thus, XYLS has the longest delivery distance, the proposed scheme the second longest delivery distance, and NELS the shortest delivery distance.

Figure 12 shows the delivery hop count for the number of sinks. The delivery hop count for sink location service is proportional to the delivery distance for sink location service by the Eqs. (17)–(19). When both the network size and the number of sensor nodes are static, the average single hop progress is also static. Thus, Fig. 12 has a similar pattern to Fig. 11.

Figure 13 shows the energy consumption for the number of sinks. The energy consumption for sink location service is proportional to the delivery hop count for sink location service by the Eqs. (20)–(22). Thus, the energy consumption for sink location service in Fig. 13 has a similar pattern to that in Fig. 12. However, NELS has the energy consumption for the control overhead by collecting the network boundary information and flooding the information to the whole network. Thus, NELS has higher energy consumption than XYLS. However, if the number of sinks is more than about 23, NELS has lower energy consumption than XYLS, because a lot of sinks in XYLS make line quorums and network boundary quorums. Figure 13 shows that our numerical analysis result is similar to our simulation result.

5.4 Simulation results for the number of sources

In this section, we compare the performance of NELS, XYLS, and the proposed scheme for the number of sources. We vary the number of sources 10–60 at an interval of 10. Figures 14, 15 and 16 show the delivery distance, the delivery hop count, and the energy consumption for sink location service, respectively. If the number of sources increases, the numbers of SLQ and SLR messages is the same with the number of sources, respectively. As shown in Fig. 14, the delivery distances for sink location service of NELS, XYLS, and the proposed scheme all increase as large as the sum of the delivery distance of SLQ and SLR messages by the Eqs. (14)–(16). However, each source in NELS makes a SLQ line quorum of the length $(2 \cdot R)m$, each sink in XYLS makes a SLQ line quorum of the length $(2 \cdot R)m$ and a SLQ network boundary quorum of length $(\pi \cdot R)m$, and each source in the proposed scheme makes a SLQ line quorum of the length $(\frac{1}{2} \cdot R)m$. Thus, XYLS has the longest delivery distance, NELS the second longest delivery distance, and the proposed scheme the shortest delivery distance.

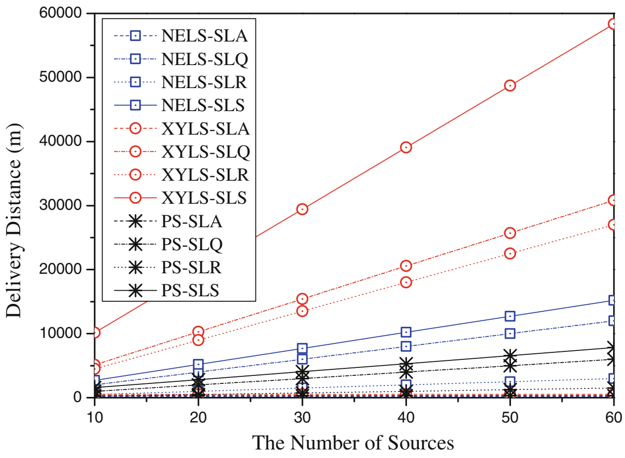

Fig. 14 Delivery distance for the number of sources

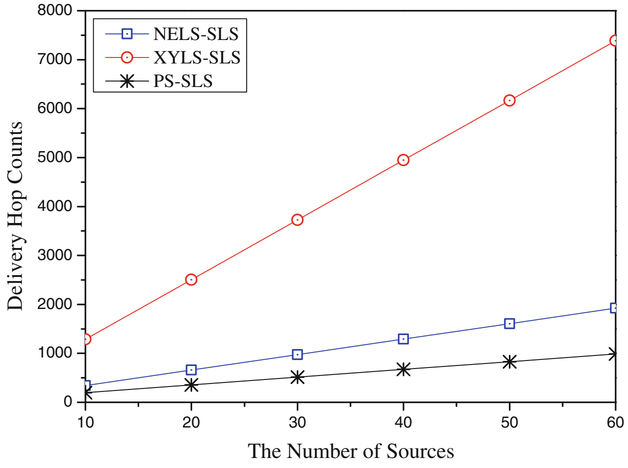

Fig. 15 Delivery hop count for the number of sources

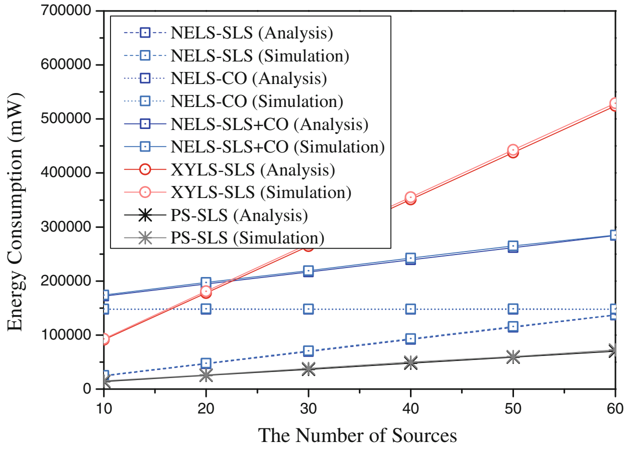

Fig. 16 Energy consumption for the number of sources

Figure 15 shows the delivery hop count for the number of sources. The delivery hop count for sink location service is proportional to the delivery distance for sink location service by the Eqs. (17)–(19). When both the network size and the number of sensor nodes are static, the average single hop progress is also static. Thus, Fig. 15 has a similar pattern to Fig. 14.

Figure 16 shows the energy consumption for the number of sources. The energy consumption for sink location service is proportional to the delivery hop count for sink location service by the Eqs. (20)–(22). Thus, the energy consumption for sink location service in Fig. 16 has a similar pattern to the delivery hop count in Fig. 15. However, NELS has the energy consumption for the control overhead by collecting the network boundary information and flooding the information to the whole network. Thus, when the number of sources is small, NELS has higher energy consumption than XYLS. However, if the number of sources is more than about 23, NELS has lower energy consumption than XYLS, because a lot of sources in XYLS make SLQ line and network boundary quorums. Figure 16 shows that our numerical analysis result is similar to our simulation result.

5.5 Simulation results for the number of sensor nodes

In this section, we compare the performance of NELS, XYLS, and the proposed scheme for the number of sensor nodes (that is, the node density). We vary the number of sensor nodes 1,000–6,000 at an interval of 1,000. Figure 17 shows the energy consumption for the number of sensor nodes. If the number of sensor nodes increases, because the average number of neighbor sensor nodes increases, the single hop progress ($Single\_Hop\_Pro_{ave}$) increases and thus the delivery hop count slowly decreases. As a result, the energy consumption for sink location service of all of NELS, XYLS, and the proposed protocol decreases. However, If the number of sensor nodes increases, the energy consumption for the control overhead of NELS increases with the number of sensor nodes because more sensor nodes are included for collecting the network boundary information and flooding the information. Thus, the energy consumption for both sink location service and control overhead of NELS is very high.

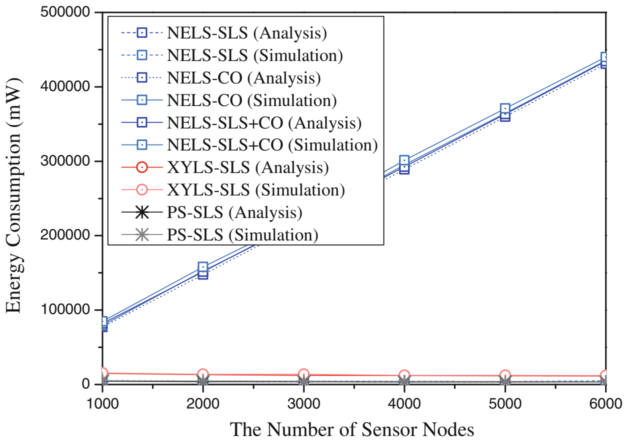

Fig. 17 Energy consumption for the number of sensor nodes

5.6 Simulation results for network irregularity

In this section, we compare the performance of NELS, XYLS, and the proposed scheme for the network irregularity. The network irregularity is considered in terms of two cases, the irregularity degree of network boundary and the number of void areas. Figure 18 shows the energy consumption for the irregularity degree of network boundary. The irregularity degree of network boundary is defined as the ratio of the total boundary length of real network to the total boundary length of network of circle. In the simulation, we consider the network of circle with a radius 1,000 m. As shown in Fig. 18, when the irregularity degree of network boundary increases, all of NELS, XYLS, and the proposed scheme increase the energy consumption. In terms of sink location service, NELS is hardly affected by the network boundary irregularity because SLA and SLQ quorums are not constructed in the network boundary. However, in terms of control overhead, if the irregularity degree of network boundary increases, NELS increases the energy consumption for collecting the network boundary information due to the increased network boundary length. Since the proposed scheme makes some sinks construct SLA circle quorums along some parts of network boundary, it slowly increases the energy consumption for the increased network boundary irregularity. However, since XYLS make all sinks and sources constructs SLA and SLQ quorums along the network boundary, it sharply increases for the increased network boundary irregularity.

Figure 19 shows the energy consumption for the number of void areas in the sensor network. We consider circle regions of radius 5 m as the size of void areas. As shown in Fig. 19, if the number of void areas increases, all of ALS, XYLS, and the proposed scheme increase the energy consumption for sink location service because SLA, SLQ,

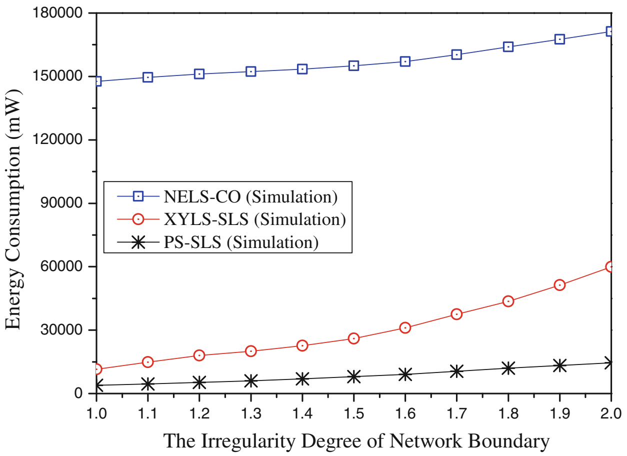

Fig. 18 Energy consumption for the irregularity degree of network boundary

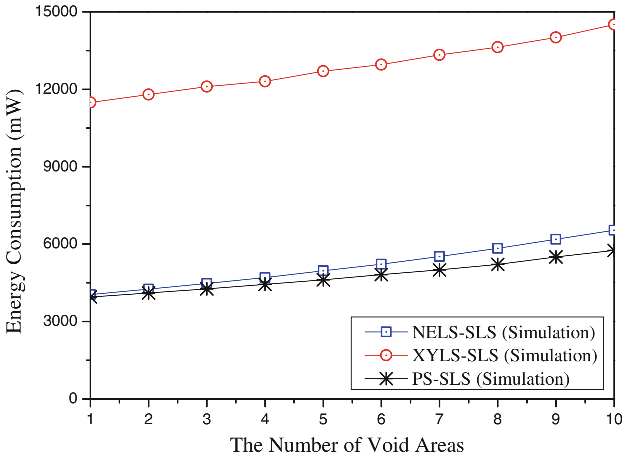

Fig. 19 Energy consumption for the number of void areas

and SLR messages can meet much more the void areas and thus must detour the void areas. Since the total delivery distance of SLA, SLQ, and SLR messages in XYLS is longest as shown in the Eqs. (11)–(13), it has the most energy consumption because it is most affected by the void areas. NELS has the second most energy consumption. The proposed protocol has the least energy consumption because it has the shortest total delivery distance of SLA, SLQ, and SLR messages.

6 Discussions

In this section, we discuss several issues related with our quorum-based sink location service scheme.

6.1 Location information of the network center

In the proposed scheme, the location information of the network center is a very important element for conducting two purposes. As one purpose, every node uses the information to calculate a Height value. As the other one, a source uses the information as a destination to send a SLQ message. For the two purposes, a network operator can embed the location information of the network center to sensor nodes by programming and then deploy them in an interesting sensor field. However, the location information of the network center embedded in nodes can be different from that in the sensor network actually deployed by sensor nodes. Thus, the difference will affect the performance of the proposed scheme. In the proposed scheme, a sink sends a SLA message to make a circle path quorum consisting of sensor nodes with the same *Height*. Then, since the difference between two network center locations can request a sink to make a circle path quorum with higher *Height*, the circle path quorum becomes longer.

6.2 Realistic sensor networks

As sensor nodes are densely and uniformly deployed in sensor networks, the hop count between any two nodes may be proportional to the distance between them. However, realistic sensor networks can be organized with sensor nodes that are sparsely and randomly deployed. Thus, the realistic sensor networks may have irregular network shapes and void areas. In the realistic sensor networks, the proportional relation between the distance and the hop count of any two nodes cannot be fully true. The reason is because any two nodes can have irregular network shapes and void areas between them in the realistic sensor networks. Thus, an approximate hop count between any two nodes is very difficult to be derived by the distance between them. However, we think because all of NELS, XYLS, and the proposed scheme use a geographic routing, they are equally influenced by irregular network shapes and void areas. As a result, they have longer delivery distance and thus higher energy consumption in realistic sensor networks. Actually, this comment is underpinned by our simulation results 18 and 19.

6.3 Number of crossing points

In quorum-based sink location service, the most important issue is to guarantee at least one crossing point between SLA and SLQ quorums. Figures 2, 3 and 5 show the overviews of NELS, XYLS, and the proposed scheme, respectively. As shown in the figures, NELS and the proposed scheme can have only one crossing point, but XYLS can have 1–5 crossing points. If any network failures such as link and node failures happen to crossing points, XYLS is more robust than NESL and the proposed scheme because it can have more crossing points. Thus, the number of crossing points may be related with the robustness of sink location service.

6.4 Location of crossing points

When we see Figs. 2, 3 and 5, we can intuitionally expect where crossing points locate in NELS, XYLS, and the proposed scheme. Both NELS and the proposed scheme make crossing points locate inside the network. On the other hand, if XYLS does not have a crossing point between SLA column and SLQ low quorums, it makes crossing points locate in the network boundary. When we recognize the fact that almost source nodes locate inside the network, NELS and the proposed scheme make distances between sources and crossing points shorter than XYLS. Then, NELS and the proposed scheme can provide sink location service faster than XYLS. Thus, location of crossing points may be related with sink location service delay.

7 Conclusion

In this paper, we designed and evaluated novel quorum-based sink location service scheme based on circle and line paths for geographic routing in wireless sensor networks. The proposed scheme only requests each node to use the location information of network center and its *Height* value from the network center during the network initialization phase to guarantee at least crossing point between the SLA and SLQ messages. In the proposed scheme, a sink constructs a SLA circle quorum by sending a SLA message along a circle path with the same *Height*, the center of the circle is the network center. On the other hand, a source node constructs a SLQ line quorum by sending a SLQ message to the network center and a copy of the SLQ message to an edge node in the network boundary. By this way, the proposed scheme can guarantee that the SLA circle and SLQ line quorums have at least one crossing point. Then, the sensor node located on the crossing point sends a SLR message with the location information of the sink to the source node. Thus, the proposed scheme does not need to collect the network boundary information and flood the information to the whole network or to forward SLA and SLQ messages along the network boundary. Our numerical analysis and simulation results verified that the proposed scheme outperforms NELS in the network boundary information-based approach and XYLS in the network boundary forwarding-based approach in terms of the delivery distance, the delivery hop count, and the energy consumption.

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