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Unital Design Based Sink Location Service for Wireless Sensor Networks

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ABSTRACT In wireless sensor networks (WSNs), providing source node with sink position is an essential principle for geographic routing protocols. Previous works have only focused on the problem of sink localization in a 2-D sensing field while that of 3-D WSNs has received little attention. Providing sink location service with low control overhead and energy consumption is a challenging issue in 3-D WSNs area. In this paper, we propose a unital design based sink location service (UDSL) for WSNs. In this scheme, sink location announcement (SLA) and sink location query (SLQ) packets are forwarded along two paths or blocks. The node located at the intersection of the two paths sends the sink position to the source. In the proposed method, SLA and SLQ messages are constructed using unital design blocks. For this purpose, a mapping from unital design to sink location service has been proposed. However, this basic mapping does not guarantee an intersection of paths,therefore, we propose an enhanced UDSL providing 100% probability of intersection. In order to analyze the proposed scheme's performance, extensive WSNs simulations and experiments have been conducted. The results indicate that UDSL provides reasonable performance in terms of hop counts, path length, and energy consumption for providing sink location service.

INDEX TERMS Wireless sensor networks, sink location service, unital design theory, control overhead, 3-D, geographic routing.

I. INTRODUCTION

Sensing refers to the procedure of gathering information about physical objects or environmental conditions, including the occurrence of events (e.g., changes in a system's state or structural information, such as temperature, volume or pressure). The apparatus unit, performing such sensing task is a sensor [1]. Recent forward leaps of technology made development of low-cost, low power, and multifunctional sensor devices, not only possible but also feasible. These devices are autonomous devices with integrated sensing, processing, and communication capabilities [2]. When many networked sensors cooperatively monitor physical environments, they form a wireless sensor network (WSN) [1]. WSNs are used for various applications such as military, environment, health, and housing [3].

Geographic routing protocol [4] has become an efficient and lightweight solution for information delivery in WSNs, since it requires only local network knowledge and geographic locations to make routing decisions. In geographic routing protocols, a source node forwards its data packet to the one-hop neighbor which is geographically closest to the sink node. This process repeats until the data packet is received by the sink node. Geographic routing requires three fundamental conditions: (a) each node must know its own position, this condition can be fulfilled by Global Positioning System (GPS) [5] or other node localization methods; (b) each node must know the position of its one-hop neighbor nodes, this condition can be fulfilled by sending beacon messages; (c) the source node must know the position information of the sink node. Most of the geographic routing protocols e.g., [6] assume that source node can obtain the sink location by some location service. However, finding the sink position by a source node is a challenging issue in WSN.

A review of the literature relating to the sink localization issue shows that 2D sensor networks have been extensively studied, but when it comes to 3D geospatial and topologies, there is an evident significant gap, which is totally inherited from mainstream technology trend toward 3D sensing and modeling. Since the real-world applications of WSNs are in a 3D environment, and the technological advancements has reached the uptrend of 3D and connectivity, this paper focuses on 3D sink localization. The main challenge in designing a sink localization service is to ensure that two sink location announcement (SLA) and sink location query (SLQ) trajectories have at least one intersection point in a 3D WSN. A combinatorial design theory is concerned with the problem of arranging elements of a finite set into subsets according to rules that are specific to the problem domain. A balanced incomplete block design (BIBD) is one of such designs, which ensures that each pair of lines has exactly one intersection. A unital is another combinatorial design that generates many lines or blocks for specific points. In our proposed scheme, we consider unital design as it can be considered as an extension of the quorum notion (that is used in most of the existing sink localization service methods) and ensures intersection of lines (i.e., SLA and SLQ trajectories in the sink location service). A 3D environment forms a manifold surface, which is quite compatible with unital design. This motivates the use of unital design theory that allows a generation of blocks which provide the possibility to cover a 3D network.

In this paper, to reduce the communication overhead and energy consumption incurred from providing sink location service in 3D WSNs, we propose a novel sink location service based on unital design theory in WSNs. In the proposed method, SLA and SLQ messages are constructed using unital design blocks. For this purpose, a mapping from unital design to sink location service has been proposed. However, this basic mapping does not guarantee an intersection of paths, therefore, we propose an enhanced unital design based sink location service (UDSL) providing 100% probability of intersection.

The performance of the proposed algorithm has been assessed by conducting a series of simulation processes using the NS-2 network simulator [7] and experiments. Simulation and experimental results indicate that our algorithm has reasonable communication overhead (hop counts and path length) and energy consumption. It is worth noting that we only consider the energy consumption imposed by our proposed algorithm, and not the energy consumption induced by interference and other networking issues.

In summary, the contributions of this paper are as follows:

- We review the main existing literature on sink location service for WSNs. We classify the state-of-the-art approaches into two categories: flooding-based and quorum-based approaches.
- We propose a sink localization algorithm based on unital design theory. In particular, we introduce a novel viewpoint of design theory to address sink location discovery problem. Although there are some applications of combinatorial design theory in security [8], [9] and in network design, to the best of our knowledge, this work is the first to apply unital design theory to sink location service.
- We propose an enhanced unital-based sink location service in order to guarantee the SLQ and SLA intersection.
- We propose a 3D sink location service, which, to the best of our knowledge, is not addressed by any of the existing research studies.

This paper is organized as follows: section 2 surveys related works. Section 3 describes the theoretical background of our proposed basic UDSL algorithm. Next, a mapping from unital design theory to sink localization problem is introduced and then, the proposed sink localization algorithm construction and its complexity analysis are explained. The enhanced UDSL algorithm is described in Section 4. Performance evaluation is provided in Section 5. Finally, Section 6 summarizes our results and proposes future research directions.

II. RELATED WORKS

Several studies, for instance [10]–[16] have been performed on location service protocols to solve the sink discovery issue. Location service protocols can be classified into two categories: flooding-based and quorum-based location services, as depicted in Fig. 1.

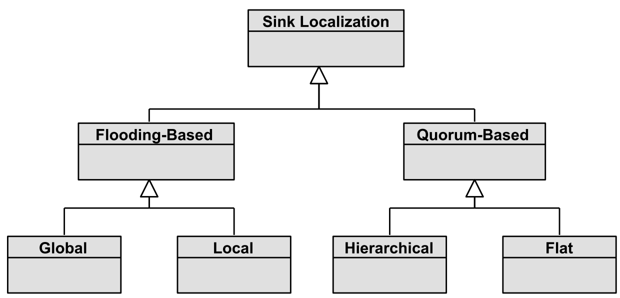


Fig. 1. Taxonomy of sink location services, flooding-based and quorum-based location services.

In flooding-based location service protocols, a sink node periodically floods its own position information throughout the whole network. In quorum-based location service protocols, a sink node disseminates its location announcement message to a set of nodes called location announcement quorum, a source node disseminates a sink query message to a set of nodes called location query quorum. A node which received both messages replies the source with the sink location using sink location reply (SLR) message.

A. FLOODING-BASED ALGORITHMS

Flooding-based location services can be further divided into global and local categories. In global Flooding [10], sink location information is obtained by source nodes through a simple flooding method. In this method, a sink node periodically floods its own position information throughout the whole network; thus, all source nodes in the network can obtain the location of the sink. Each source node maintains a location table that records the most recent positions of sink nodes. A major drawback of global Flooding method is that it consumes a great deal of network resources such as energy and bandwidth where multiple mobile sinks exist in the network. Thus, this method is not suitable for WSNs, as their resources are restricted.

To avoid the overhead of global flooding, a local scheme, named TTDD [11] was proposed. In this scheme, a source node generates a grid structure to send its location's information to the entire network while a sink node floods its location's information within a grid cell size. Therefore, the points of intersection are created between the grid structure and local flooding. However, the grid construction of TTDD for multiple source nodes generates additional overhead and can be energy-intensive.

B. QUORUM-BASED ALGORITHMS

To reduce or avoid the overhead of flooding schemes, quorum-based sink location services [12]–[16] have been proposed. In quorum-based systems, the set of nodes is divided into mutually disjoint subsets where information about each node is replicated within its own subset. These subsets are designed in such a way that their intersection is non-empty. Quorum-based location services can be divided into two categories based on the structure of the quorums: hierarchical and flat. In [12], Yan *et al.* proposed a hierarchical quorum-based location service, in which, the network is divided into a number of small square grids where one node from the grid is selected as a location server (server for short). These servers are referred to as an order-1 server. Some of these order-1 servers are selected as order-2 servers that manage several order-1 servers. This iterative process continues until some order-n servers are selected. In sink discovery phase, first, a node queries the nearest order-1 server, if the node does not find the sink location, it continues to query the nearest order-2 and other servers until it finds the sink location. It is not well-suited for WSNs because of the following reasons: (a) a higher-order server needs a vast amount of memory and computation resources; (b) the failure of any higher-order server will lead to the failure of the service in the wide sensing area; (c) this protocol will generate high overhead due to the update of sink location to several servers; (d) it assumes that the shape of the network is regular so that it can be divided into grids, while in practice, the shape of a network might be irregular shape.

In [13], Stojmenovic *et al.* studied Column-Row Location Service (XYLS), in which the main idea is that sink node disseminates its location along a 'column' or south-north direction to form an update quorum or SLA message. Source node makes a query along a 'row' or east-west direction to form a search quorum or SLQ message. The sink location is detected at the intersection between the update and search quorums.

In XYLS to guarantee the intersection in an irregular WSN, when the SLA and SLQ messages reach the network boundary, they are sent along the boundary of the whole network and will intersect at one of the boundary nodes. The drawback is that if frequent SLA and SLQ messages are required, the network boundary nodes have heavy traffic loads because of delivery of messages along the boundary of the network. In addition, in this protocol the node that informs the source about the sink location was not presented explicitly as part of the protocol.

In [14], a Quorum based Sink Location Service (QSLS) for WSNs was proposed. In this scheme, SLA and SLQ packets are forwarded along two paths by geographic routing protocol. The node located at the intersection of the two paths sends sink position to the source. QSLS chooses four nodes on the boundary of the network (westernmost node, northernmost node, easternmost node, and southernmost node) in the sensing area as anchor nodes. The westernmost and easternmost nodes are used for SLQ messages while the northernmost and southernmost nodes are used for SLA messages. It is presented in Fig. 2. The main limitation of QSLS is that for guaranteeing the intersection of SLA and SLQ trajectories all the sensor nodes must be deployed in 2D plane. Thus, it does not support 3D networks. QSLS cannot support intersection between SLA and SLQ paths in 3D networks. The authors considered a line, though it should be a plane in 3D network.

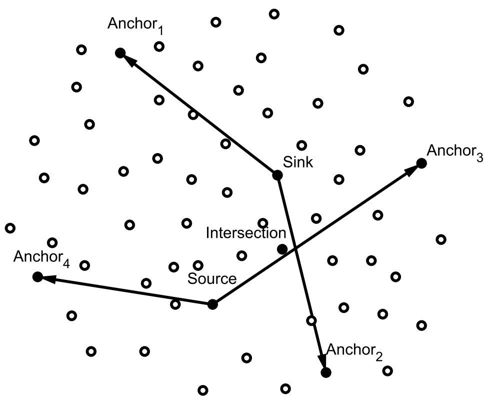


Fig. 2. Proposed sink localization algorithm in [14].

In [15], Sarkar *et al.* studied a double rulings algorithm. In this algorithm, SLA and SLQ quorums form two circle curves. The intersections of two circles are guaranteed by a hash function. The drawbacks are the complexity of the algorithm because of the hash function and the fact that it cannot be used in 3D environments. To use this algorithm in 3D networks, the circles should be transformed into spheres.

In [16], a sink location service based on Circle and Line Paths (CLP) in WSNs was proposed. In this scheme, a source node sends two SLQ messages, one to the center of the network and the other to a node on the edge of the sensor network, thereby generating a SLQ trajectory. A sink node sends SLA message along a circle path, the center of which is the center of the network. In this way, the SLQ and SLA trajectories have one crossing point. It is depicted in Fig. 3. The main limitation of CLP is the same as QSLS.

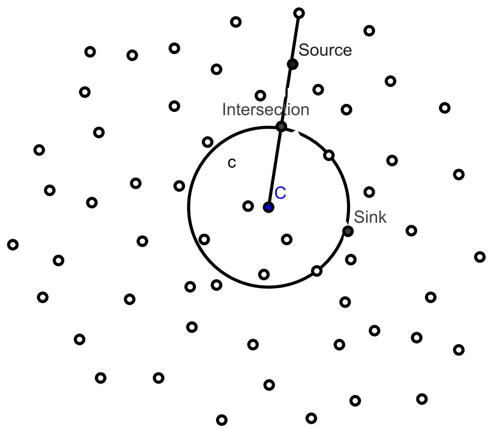


Fig. 3. Proposed sink localization algorithm in [16].

In essence, quorum-based algorithm can be applied to 3D networks, however the previously proposed quorum-based approaches in the literature have not considered it for 3D networks. The existing state-of-the-art solutions have been proposed for 2D WSNs and they cannot support intersection between SLA and SLQ paths in 3D networks.

In this paper, in order to address this gap, we propose a scheme for sink location service to be used in 3D WSNs. Our proposal has a reasonable communication overhead and low energy consumption while provides high success ratio in sink discovery. For this purpose, we make use of the unital design theory in order to provide sink location service. We propose, in what follows, a mapping from unital design to sink location service, as well as an enhanced unital based scheme which achieves 100% success ratio.

III. UNITAL DESIGN FOR SINK LOCATION SERVICE IN WSNs

In this section, first, we present the definition and the example of unital design theory. We then explain a mapping from unital design to sink location service and the proposed UDSL algorithm. Finally, we evaluate the success ratio of the proposed algorithm.

A. MATHEMATICAL BACKGROUNDS: UNITAL DESIGN

To make this paper self-contained, we introduce the basic mathematical background necessary to develop the UDSL algorithm. The proposed sink localization algorithm is based on the points and lines of unital design theory. Let A be a finite set, combinatorial design theory is concerned with the problem of arranging elements of set A into subsets according to rules that are specific to the problem domain. A t-(v,k,λ) design is one of such designs. A t-(v,k,λ) design is a pair $D = \{X, B\}$ where X is a v-set of points and B is a collection of k-subsets of X (blocks) with the property that every t points of X is contained in exactly λ blocks [17].

Example 1: Consider $X = \{1, 2, 3, 4, 5, 6\}$ and $B = \{124, 126, 134, 135, 156, 235, 236, 245, 346, 456\}$. Then (X, B) is a $2 - (6, 3, 2)$ design. There are $v = 6$ objects and $b = 10$ blocks. Each block contains $k = 3$ objects. Every pair of distinct objects occurs in $\lambda = 2$ blocks.

Definition 1 (Unital Design): Let m be an integer, $m \geq 2$. A unital is a design with parameters of the form $v = m^3 + 1$, $k = m + 1$, $b = m^2(m^2 - m + 1)$, $r = m^2$ and $\lambda = 1$ [18]. We focus on classical $(m^3 + 1, m + 1, 1)$-design or Hermitian unital.

Example 2: Consider $(v,k,\lambda) = (9,3,1)$ unital. There are $v = 9$ objects and $b = 12$ blocks. Each block contains $k = 3$ objects. Every object occurs in $r = 4$ blocks. Every pair of distinct objects occurs in $\lambda = 1$ block. The blocks are: (1,4,8),(7,8,9),(3,6,7),(3,4,9),(4,5,7),(1,2,7),(1,3,5),(2,3,8), (2,4,6),(2,5,9),(1,6,9),(5,6,8).

TABLE 1. Mapping between sink localization and unital design.

Sink Localization Problem	Unital Design
Sensors	v/Point set
SLA/SLQ Trajectories	b/Blocks/Lines
# SLA/SLQ Hops	Size of a block (m+1) minus one
$m^3 + 1$	Size of the point set
$m^2(m^2 - m + 1)$	Size of the block set
1	λ

B. A BASIC MAPPING FROM UNITAL DESIGN THEORY TO SINK LOCATION SERVICE

Sink localization problem can be outlined in terms of unital design. We consider unital design in our proposal due to the fact that subsets of lines or blocks have an intersection point. We propose a basic mapping between a sink localization problem and unital design. According to Table 1, sensor nodes are considered as points and SLA or SLQ trajectories as the lines or blocks. The size of a block minus one is equal to SLA or SLQ hop counts. Since there are m+1 points in each block, hop counts is equal to m. In addition, the size of the point set and block set are equal to m^3+1 and $m^2(m^2-m+1)$, respectively. Finally, according to unital design definition, λ is considered as equal to one.

For example, consider a network with 9 sensor nodes $S = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$, $|S| = |V| = 9$. The size of the point set of unital is determined by the value of m, which should satisfy $S \leq m^3 + 1$ when m is the minimum amount, thus $m = 2$. According to Table 1, size of the point set is $m^3 + 1$, therefore, the unital design has 9 points. The number of blocks $(m^2(m^2-m+1))$ is equal to 12 (refer to Example 2). Blocks are considered as SLA and SLQ paths. We choose two blocks (1,4,8) and (3,4,9) in this example (It is illustrated in Fig. 4). As shown in Fig. 4, hop counts is equal to 2, since there are $m + 1$ points in each block.

C. SYSTEM ENVIRONMENTS AND ASSUMPTIONS

The proposed approach is semi-distributed. In our network model, we consider three kinds of nodes: static sensor nodes, mobile sinks, and a static manager (central) node. Some steps are done by cooperation of all sensor nodes and some by

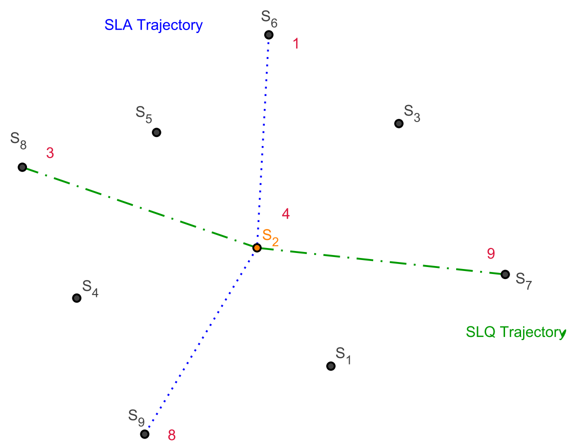


Fig. 4. The mapping example between unital design and sink localization, considering $v = 9$, $m = 2$, $SLA = (1, 4, 8)$, and $SLQ = (3, 4, 9)$.

a manager node. The sensor nodes are distributed randomly (uniformly) in the sensing field and each one has two lists: one for sources and one for sinks. We also assume that each node can obtain its own geographic position using GPS or other location services. An individual node can obtain list of its one-hop neighboring blocks by exchanging beacon message. Moreover, each node can recognize whether it is on the block (SLA or SLQ paths) or not.

D. PROPOSED UDSL SCHEME

In our proposed scheme, first, we generate a unital design and then, we assign blocks to sensor nodes. The source and sink nodes send SLA and SLQ messages to blocks (paths). The node on the crossing point sends sink location to source node.

The proposed scheme consists of two phases:

- Preliminary phase
- Constructing SLQ/SLA blocks

1) PRELIMINARY PHASE

Before network deployment, we generate unital design blocks for allocating to sensor nodes. Consider a wireless sensor network of N sensor nodes. In this phase, a unital design is constructed with parameters $(n^3 + 1, n + 1, 1)$ in which $N \leq n^3 + 1$, while n is the smallest prime power that satisfies this condition. We choose blocks from the existing block repositories of unital design, thus, the order of this phase is $O(1)$, which is handled by the manager node. In the next step, we store the position of the manager node in sensor nodes. After network deployment, each sensor node sends its position to the manager node by geographical routing. The control overhead of geographical routing is typically O(1).

2) CONSTRUCTING SLQ/SLA BLOCKS

In this phase, the paths, which are a subset of the unital using sensor nodes, are constructed as follows: the proposed algorithm needs to select some sensor nodes in the network boundary as anchor nodes. In this phase, first, the boundary of network is determined using boundary detection algorithm [19], [20]. This step has a computational complexity of $O(N)$, where N is the total number of sensor nodes. Subsequently, a number of nodes are selected as anchor nodes and their position is sent to the manager node by geographical routing with communication complexity of $O(1)$. Anchor nodes are a set of selected network boundary nodes and are used as the endpoint of the blocks. In general, the lines are coincident on anchor nodes on the boundary of the network. Four anchors A_0, A_1, A_2, and A_3 are selected according to four extreme nodes. It is supposed that they are the westernmost, northernmost, easternmost, and the southernmost points of a wireless sensor network, as illustrated in Fig. 5. The sensor nodes A_0, A_1, A_2, and A_3 are located at positions $(x_{A_0}, y_{A_0}, z_{A_0})$, $(x_{A_1}, y_{A_1}, z_{A_1})$, $(x_{A_2}, y_{A_2}, z_{A_2})$, and $(x_{A_3}, y_{A_3}, z_{A_3})$, respectively. For simplicity, we show the network model in 2D plane (refer to Fig. 6).

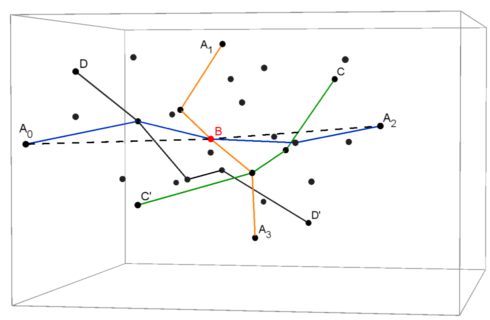


Fig. 5. The proposed algorithm in a 3D network model.

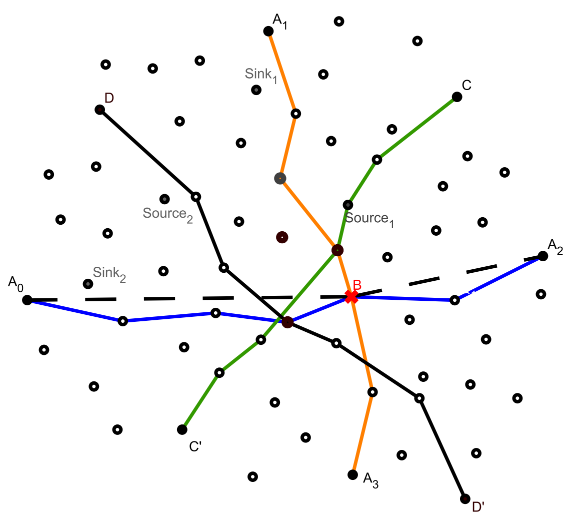


Fig. 6. The proposed algorithm in 2D plane.

The rest of the algorithm is done by the manager node. The manager node has the position of all anchor nodes. In the next step, the first block is assigned so it contains A_1 and A_3. In order to do this, A_1 is connected to A_3 through Euclidean line. According to Table 1, a block has $q = m+1$ sensors and now, we have two sensors. For other *q-2* remained sensors of block $\overline{A_1 A_3}$, the least squares method is used for selecting *q-2* points. In this method, *q-2* sensors that are near $\overline{A_1 A_3}$

are selected. In other words, *q-2* points are chosen so that anchor line $\overline{A_1 A_3}$ would be the best fitting curve for it. The order of this step is $O(q) = O(n) = O(\sqrt[3]{N})$. The manager node chooses one block from unital repository and sends the block_id to sensors by geographical routing and the sensors save it to theirs block_id field. Now, the first block of unital is assigned to q selected sensors.

Once the first block has been constructed, a second block can be assigned that contains A_0 and A_2. Similar to the first step, we construct Euclidean line between A_0 and A_2. The nearest node to $\overline{A_0 A_2}$ is found from the block $\overline{A_1 A_3}$ and is called B. Now, there are three points of block and for choosing the remaining *q-3* points for completing block $\overline{A_0 A_2}$, we consider two Euclidean lines $\overline{A_0 B}$ and $\overline{BA_2}$ and again use the least squares method for *q-3* points. After selecting q sensor nodes, a block from the unital blocks is selected which has a node in common with the first block and which is assigned to sensors.

The construction of blocks at most $n^2(n^2 - n + 1)$ lines is continued, while we can assign unital blocks to sensors. For this reason, for other boundary nodes, the block similar to previous step is constructed. For example, for boundary node C, the farthest node from the other side of the network is selected and called C'. After constructing Euclidean line $\overline{CC'}$, we obtain the remaining *q-2* points like previous step through least squares method. When these steps have been completed, the network is ready.

The construction algorithm is summarized in Algorithm I.

Algorithm 1 Sink Localization Algorithm

Require: N {total number of nodes}

Find minimum prime power n such that $N \leq n^3 + 1$ (manager node)
Generate the unital design with parameters $(n^3 + 1, n + 1, 1)$ (unital of order n)
Determine the boundary of the network using boundary detection algorithm
Select a number of nodes as anchor nodes and send the position of the anchors to the manager node
Construct the paths based on unital blocks

E. COMPLEXITY ANALYSIS

The proposed algorithm has a linear time complexity with respect to the size of the network. More specifically, unital design block selection has a computational complexity of $O(1)$, because we choose blocks from a repository of blocks. Sending positions of the sensors to the manager node has a communication complexity of $O(1)$. Determining the boundary of the network has a complexity of $O(N)$, where N is the total number of sensor nodes. The least square method for constructing SLA and SLQ blocks has a complexity of $O(\sqrt[3]{N})$. Furthermore, the proposed algorithm has a computational complexity of $O(1 + N + \sqrt[3]{N}) = O(N)$ and a communication complexity of $O(1)$. These steps will be executed only once during network initialization phase.

F. SINK LOCATION SERVICE

Upon detecting an event, a sensor node becomes a source node, e.g., node $Source_1$ in Fig. 6. The source node is on the block or near the block. If it is on the block, it sends a SLQ message, which contains the source node location and the detected event type, to another node on the block, thus generating a SLQ trajectory. If it is not on the block, it forwards a SLQ packet to the nearest block. The set of sensor nodes, which have overheard the SLQ packet along the location query block, saves the location of source node in its source list table.

When a sink joins the sensor network, it gets a block id by querying neighbor sensor nodes. Then it creates a SLA packet, that contains the following field: sink_location and block_id. The sink_location field is set to the location of the sink and the block_id is set to the value gotten from neighbor node, and then the sink node sends the SLA packet to the nearest node on the block which has the same block id. The set of nodes, which have overheard the SLA packet along the location announcement block, saves the sink location in its sink list table and then forwards the SLA packet to another node on the block. Thus the SLA path is constructed. E.g., node $Sink_1$ in Fig. 6 is the sink node. The node located at the intersection of the two blocks sends sink position to the source.

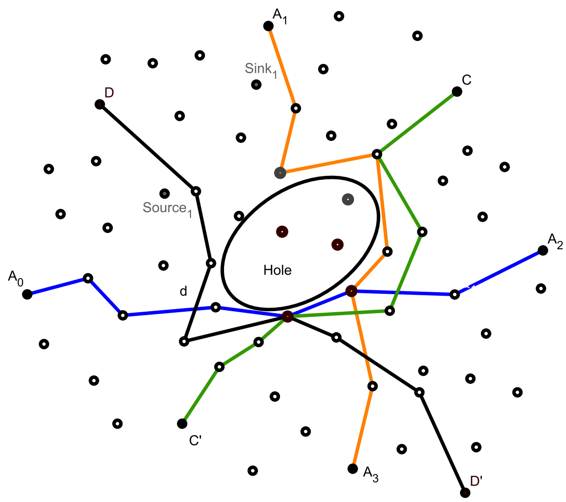


Fig. 7. An example of irregular sensor network and possible SLA and SLQ trajectories.

G. THEORETICAL ANALYSIS

1) SUPPORTING IRREGULAR SENSOR NETWORK TOPOLOGIES

Sensor networks mostly have irregular shapes. The USDL can work perfectly in irregular sensor networks. Fig. 7 shows an irregular sensor network with a hole region in the center. In the second phase of UDSL algorithm, after Euclidean line construction, we choose q sensors that are close to Euclidean line but are not placed in the hole region. Since there is no sensor node located on the near the line, the block is constructed around the hole region. According to Fig. 7, we can see that in the irregular sensor network, the blocks of proposed algorithm can be constructed, thus the intersection of SLA and SLQ paths can be guaranteed.

2) SUCCESS RATIO

For success ratio, we focus on the probability of intersection of SLA and SLQ trajectories (blocks). The probability of intersection of two blocks is the probability of intersection of each sensor of block A in other blocks. Each block has $q+1$ sensors and each sensor occurs in q^2 blocks of all $q^2(q^2-q+1)$ blocks. Thus, the probability P of intersection of two paths can be calculated as follows:

$$P = \frac{(q^2-1)(q+1)}{q^2(q^2-q+1)-1} = \frac{(q+1)^2}{q^3+q+1} \quad (1)$$

According to Eq. (1), the basic mapping from unital design to sink localization does not give 100% intersection and the probability tends to $O(\frac{1}{k})$. In order to improve the intersection probability, we propose in the next section an enhanced unital-based sink localization for WSNs.

IV. AN ENHANCED UNITAL DESIGN BASED SINK LOCATION SERVICE IN WSNS

In this section, we present an enhanced unital-based sink location service for WSNs. The SLA and SLQ trajectories must be carefully constructed to increase the probability that two paths have at least one intersection point. According to unital design properties, we cannot guarantee that two paths have one crossing point. To address this issue, we make use of Blocking Set (BS) concept in unital.

Definition 2: Blocking Set. A blocking set in a projective plane P is a subset of points in P that meets every line of P but contains no line of P [18].

For example, the generalized quadrangle has 15 points and 15 blocks (lines). The blocks are: (1,2,3), (3,4,5), (5,6,7), (7,8,9), (9,10,1), (2,14,7), (3,15,8), (4,11,9), (5,12,10), (6,13,1), (13,8,12), (12,2,11), (11,6,15), (13,4,14), (14,10,15). The blocking set of the generalized quadrangle is {2, 4, 6, 8, 10, 12, 14}.

We use Definition 2 in the context of proposed approach as a set of sensors intersecting every block, but not containing any block completely. E.g., sensor nodes BS_1, BS_2, and BS_3 in Fig. 8 are in the blocking set.

Definition 3: Blocking Set Trajectory. A trajectory that is constructed using blocking set points.

In the enhanced algorithm, the SLA packet is forwarded to blocking set path in addition to its block. E.g., $\overline{BS_2\, BS_1\, BS_3}$ in Fig. 8 is the blocking set path. This enhanced algorithm is based on the fact that the blocking set path intersects with any blocks. Therefore, SLA trajectory intersects with SLQ trajectory.

Proposition 1: The maximum hop number of blocking set path is $m^2-m-1+\frac{m^2-1}{2}$.

Proof: According to [21, Th. 2.1], a blocking set (S) of a hermitian unital U is defined as $|S| \geq \frac{3m^2-2m-1}{2}$. The blocking set trajectory is constructed using blocking set points, and the path is one less than the size of the blocking set. Thus, the maximum hop number forms $m^2-m-1+\frac{m^2-1}{2}$. □

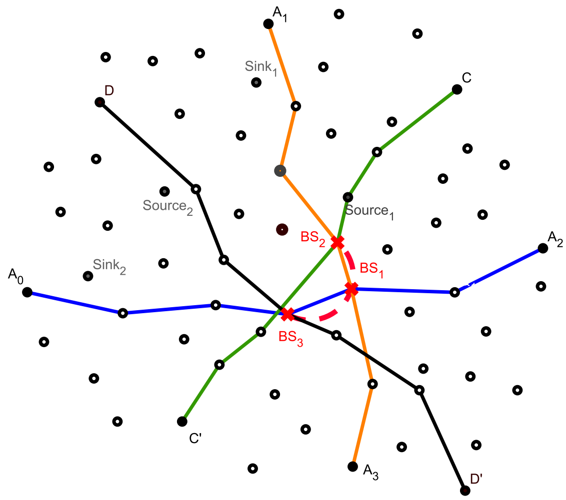


Fig. 8. An example of the enhanced proposed algorithm, sensor nodes BS_1, BS_2, and BS_3 are in the blocking set.

In enhanced algorithm, after generating blocks of unital, in the second phase of proposed algorithm "Constructing SLQ/SLA blocks", after finding the sensor node that is located in the intersection of Euclidean line between boundary nodes and other constructed block, we set this sensor as a blocking set sensor. It is assumed that each sensor has a BS field (initially false). In fact, the sensors in intersection points of paths form the blocking set. The number of blocking set sensors is less than $\frac{3m^2-2m-1}{2}$. In order to guarantee the intersection of SLA and SLQ trajectories, when the sink node sends SLA packet, it sends to SLA blocks and blocking set path. For sending SLA packet to blocking set path, the blocking set sensor sends SLA packet to the neighbor blocking set sensor and this process repeats until there is no neighbor sensor with blocking set specification. According to the property of blocking set, two paths have intersection point. This way, it is guaranteed that the SLQ and SLA paths have one crossing point in sensor networks. The enhanced algorithm is summarized in Algorithm II. Note that we augment the algorithm using blocking set concept and change one step of the algorithm with complexity of $O(1)$, and thus the complexity does not change.

A. THEORETICAL ANALYSIS

1) SUCCESS RATIO

In UDSL, both SLA and SLQ packets are transmitted along the blocks of the unital of the network. In addition, SLA packet is transmitted along the blocking set trajectory. According to Definition 2, blocking set has intersection with all the blocks of unital. So the intersection probability of UDSL is 100%.

2) MULTIPLE SOURCE NODES AND SINKS

It might happen that multiple sources and sinks exist in WSNs. Consider a scenario of the UDSL scheme with

Algorithm 2 Enhanced Sink Localization Algorithm

Require: N {total number of nodes}

1: Find minimum prime power n such that $N \leq n^3 + 1$ (manager node)
2: Generate the unital design with parameters $(n^3 + 1, n + 1, 1)$ (unital of order n)
3: Determine the boundary of the network using boundary detection algorithm
4: Select a number of nodes as anchor nodes and send the position of the anchors to the manager node
5: Construct the paths based on unital blocks that every two lines have a common point in blocking set

multiple source and sink nodes. In this scenario, the SLA trajectory of any sink and the SLQ trajectory of any source have exactly one intersection. Once a sink sends an SLA message to the nearest block, all sources can obtain the location of the sink from an overhearing sensor node on intersection of blocking set trajectory and SLQ path; once a source sends a SLQ message to the nearest block, it can obtain the location information of all sinks from an overhearing sensor node on the intersection. In other words, since every two lines are intersected in one point, we can have multiple sources and sinks in WSNs.

As depicted in Fig. 8, once a sink node $Sink_1$ forwards a SLA message, all source nodes $Source_1$ and $Source_2$ can get the position of the sink from the node located on corresponding blocking set sensor; once a source node $Source_1$ sends a SLQ message, it can get the position of all sinks ($Sink_1$ and $Sink_2$) from the node located on the corresponding blocking set sensor.

3) INTERSECTION OF EVERY TWO TRAJECTORIES

Theorem 1: Every two SLA and SLQ trajectories intersect in one point.

Proof: In a unital, every two blocks have no intersection point but in enhanced UDSL, we use blocking set sensors concept. According to Definition 2, blocking set sensors are a subset of sensors in network that meet every block of unital. SLA and SLQ trajectories are equivalent to blocks of the unital. In addition, SLA path contains blocking set sensors. Thus the intersection of SLA and SLQ is guaranteed. □

V. PERFORMANCE EVALUATION

In this section, we evaluate our proposed algorithm by simulation and experimental setup.

A. SIMULATION

A series of simulations has been conducted using the NS-2 network simulator [7] for evaluating the performance of the proposed sink localization algorithm. The NS-2 does not support 3D environment. Therefore, authors have added 3D capability to it. In order to achieve this, some modifications were required. They are as follows:

- Extension of WSN's environment to support 3D topology, by adding Z dimension to "Topography" class.
- Extension of sensor node position to 3D by implementing Z dimension to "mobilenode" class.
- Extension of sensor node mobility to 3D by adding Z dimension to "setdest" class (Defining new "set_destination3d" method in "mobilenode" header, which takes X, Y, Z destination positions of a sensor node along with mobility speed).

The size of the sensor network is set to 100m × 100m × 100m where 200 sensor nodes are randomly deployed. IEEE 802.15.4 is utilized as the MAC protocol. The radio range of nodes is 250m. The radio-propagation model and antenna type are set to two-ray ground model and omni antenna, respectively. We set the level of energy of the node at the beginning of the simulation. Each sensor node has an initial energy of 100J. The energy consumption rates for transmitting and receiving a single packet are 31mW and 35mW, respectively. To ensure the reliability of the assessment results, 30 simulation analysis process runs were performed. In each run, different sink and source nodes were used. Simulation time is 1000s.

B. EVALUATION CRITERIA

We evaluate the performance of the proposed sink localization algorithm using two criteria:

1) TOTAL TRANSMISSION

Total transmission is the total delivery distance of SLA, SLQ, and SLR in one location service discovery. Total transmission was calculated as a total number of hops and total path length (total distance).

2) ENERGY CONSUMPTION

Energy consumption of sensors is proportional to the number of hops [16]. We calculate the energy consumption as the aggregation of the energy cost of transmitting and receiving messages. We adapt the energy consumption model proposed in [16], which calculates the energy consumption through multiplying the total hop count by the sum of transmitting (E_t) and receiving rates (E_r) in one-hop packet transmission of sensors. The total energy consumption of UDSL defined as follows:

$$E_{UDSL} = (E_t + E_r) * \text{hop counts} \tag{2}$$

This energy model is also adapted by several data communication protocols in WSNs [22], [23].

Three case studies are explored in following subsections; in the first case study, one source and sink are considered. In the second case study, the impact of number of sinks on the total transmission and energy consumption is studied. Finally, the effect of changing the number of the sources on the total transmission and energy consumption is investigated.

C. SIMULATION RESULTS

The simulation results are shown in Figs. 9 to 17, where each point is the average result of 30 independent simulations with a confidence interval of 95%.

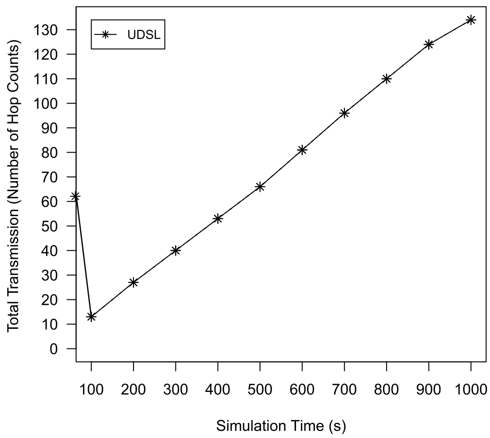


Fig. 9. **Total transmission in the case of single sink and source (Number of Hop Counts), simulation time is 1000s.**

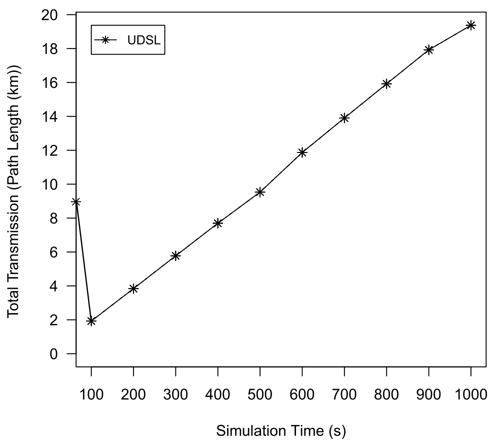


Fig. 10. **Total transmission in the case of single sink and source (Path Length), simulation time is 1000s.**

1) RESULTS FOR SINGLE SOURCE AND SINK

Fig. 9 shows the total transmission of proposed sink location discovery in the case of single sink and single source for different simulation times in the network. In our scheme, not all nodes in the network need to participate in SLA and SLQ packets delivery. Sink sends the SLA along the block until it reaches the blocking set sensor and blocking set trajectory with constant hop number, and source only sends the SLQ message along the block until it reaches the blocking set sensor, thus its hop count slightly increased with the simulation time. As shown in Fig. 9, the total transmission of our scheme is high at the beginning and the reason is the setup costs of our scheme. This overhead occurs only one time before starting the network operation.

In order to guarantee intersection of the SLA and SLQ quorums of CLP [16] in the 3D network, we should consider the SLA circle as a sphere and the SLQ line as a plane. To use QSLS [14] in 3D networks, we consider the SLA and SLQ lines as planes. In our proposed approach, we just take into account two lines (blocks) and thus the total transmission criterion of the proposed approach is smaller than of the sphere and plane.

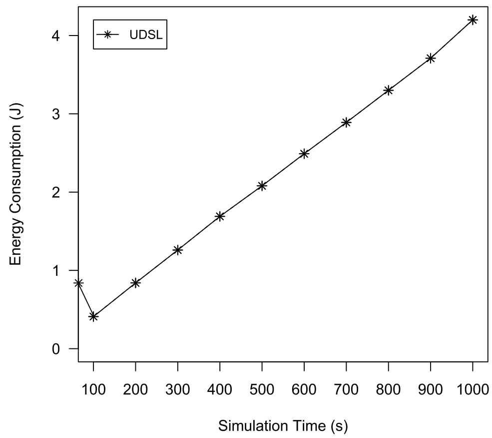


Fig. 11. **Energy consumption in the case of single sink and source, simulation time is 1000s.**

Fig. 10 depicts similar results as in Fig. 9 but for path length criterion. Similar discussion as made for previous results can be made here as well.

Fig. 11 shows the energy consumption of proposed sink location discovery in the case of single sink and single source for different simulation time in the network. As indicated in Fig 11, the obtained results show a similar pattern to that of hop counts, because the energy consumption for sink localization is proportional to the number of hop counts.

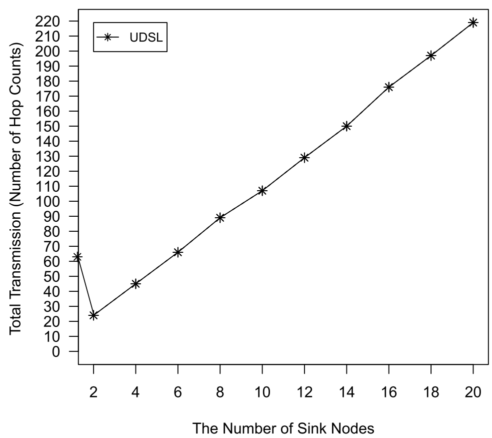


Fig. 12. **Total transmission in the case of single source and multiple sinks (Number of Hop Counts), considering varying number of sinks from 2 to 20.**

2) RESULTS FOR SINGLE SOURCE MULTIPLE SINKS

It is for considering the impact of the number of sinks in the algorithm. It means at one sink location discovery process; one source sends packet to SLQ path. It does not mean the existence of single source in the whole WSN area. Fig. 12 shows the total transmission in case of single source while the number of sinks varies from 2 to 20. If the number of sink nodes increases, total transmission of UDSL increases due to the increase of SLA paths by sinks. As it can be seen in Fig. 12, the total transmission of UDSL scales with the

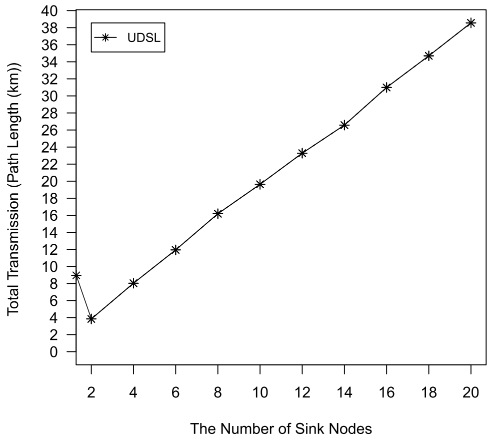


Fig. 13. **Total transmission in the case of single source and multiple sinks (Path Length), considering varying number of sinks from 2 to 20.**

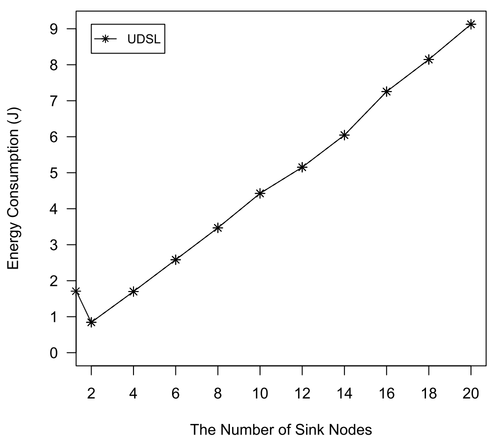


Fig. 14. **Energy consumption in the case of single source and multiple sinks, considering varying number of sinks from 2 to 20.**

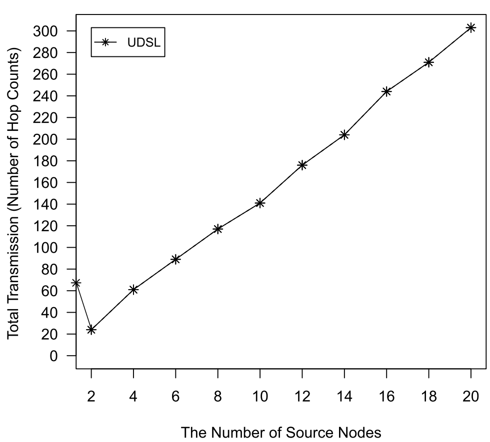


Fig. 15. **Total transmission in the case of single sink and multiple sources (Number of Hop Counts), considering varying number of sources from 2 to 20.**

number of sinks, because each sink sends its own location throughout the SLA block.

Fig. 13 presents similar results as those presented for hop counts, but for path length criterion.

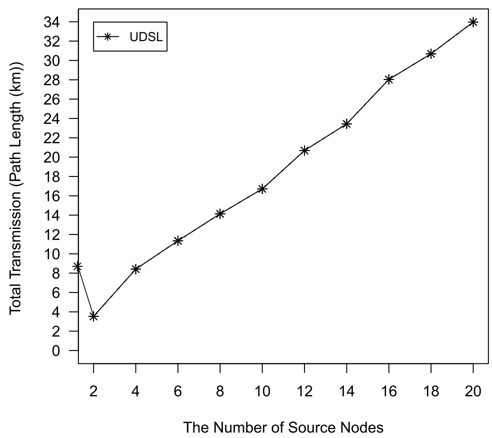


Fig. 16. **Total transmission in the case of single sink and multiple sources (Path Length), considering varying number of sources from 2 to 20.**

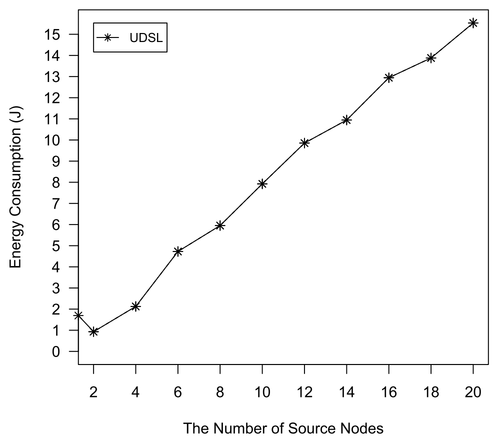


Fig. 17. **Energy consumption in the case of single sink and multiple sources, considering varying number of sources from 2 to 20.**

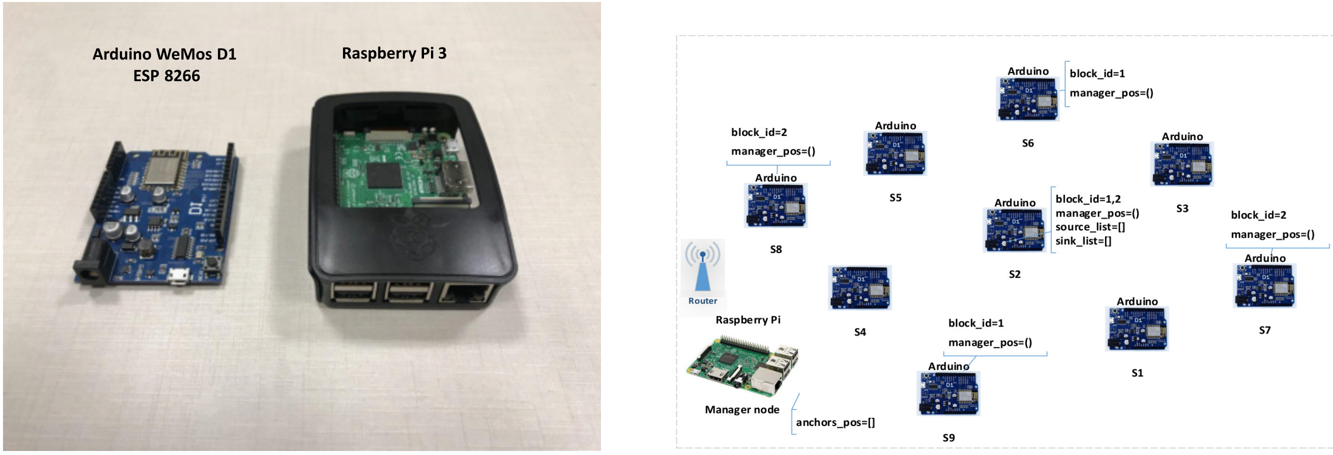
Fig. 14 shows the energy consumption of proposed sink location discovery in the case of single source and multiple sinks for different number of sinks in the network. As shown in Fig. 14, we obtain similar results as in Fig. 12, because the energy consumption in this case is proportional to the number of hop counts of SLA path.

3) RESULTS FOR SINGLE SINK MULTIPLE SOURCES

Fig. 15 shows the total transmission of the proposed algorithm in the case of single sink and varying number of sources from 2 to 20. In Fig. 15, the total transmission of UDSL is changed with the number of sources, due to the fact that all sources need to query the sink location. If the number of source nodes increases, the control overhead of UDSL increases because of the increase of SLQ block trajectory.

As shown in Fig. 16, we obtain similar results as in Fig. 15, but for path length criterion.

Fig. 17 shows the energy consumption of the proposed sink location discovery in the case of single sink and multiple sources for different number of sources in the network.



(a) (b)

Fig. 18. **(a) Experimental setup, considering Raspberry Pi 3 for the manager node and Arduino WeMos D1 ESP8266 for the sensor nodes. (b) Small scale environment with nine sensors, one manager node, and one Wi-Fi router.**

As shown in Fig. 17, we obtain similar results as in Fig. 15, because the energy consumption in this case is proportional to the number of hop counts of SLQ path.

D. EXPERIMENTAL SETUP

In order to demonstrate the applicability of the proposed algorithm in a real-world scenario, we setup a small scale experimental environment having nine sensor nodes, one manager node, and a Wi-Fi router, as illustrated in Fig. 18.

TABLE 2. **Sensor device's characteristics.**

Name	Cost per node US$	Processor	RAM
Raspberry Pi 3	25-35	ARM BCM2837	1GB
Arduino WeMos D1	7	ESP-8266EX	4M

We chose a Raspberry Pi 3 for the manager node and Arduino WeMos D1 ESP8266 for the sensor nodes (please refer to Table 2 for detailed specifications). Each sensor node, which is a DHT11, monitors the environment's temperature. The 5V power supply of the thermal sensor consumes 2.5mA [24]. The Wi-Fi module of the sensor consumes up to 140mA and 60mA during transmission and receiving modes, respectively. The placement of the nodes in the target environment is demonstrated in Fig. 4. We used a Wi-Fi access point to enable the sensors to connect the local network. In this experiment, the Raspberry Pi node (i.e., the manager node) runs Raspbian Linux.

In order to setup the network, in the first step, we generated the unital design blocks (as explained in example 2) using r package [25] in Raspberry node. We set the position of the manager node in each Arduino node. In the next step, we selected the following sensor nodes, S_8, S_6, S_7, and S_9, as anchor nodes. Each anchor node sends its position to the manager node using a geographic routing algorithm (e.g., [26]).

The manager node connects nodes S_6 and S_9 through Euclidean line (the first block). Then, it finds the nearest sensor to Euclidean line by calculating the least square, and selects S_2 as the third sensor for the first block. The manager node selects block $(1, 4, 8)$ from unital and sends block_id 1 to sensors S_6 and S_2, and S_9 using a geographical routing algorithm. Each node after receiving data packet from the manager node stores it in its memory in a variable named 'block_id'. The manager node repeats this step for nodes S_8 and S_7, selects block $(3, 4, 9)$ and sends the block_id 2 to sensors S_8, S_2, and S_7. Node S_2 is a common node between two blocks 1 and 2, which means S_2 is the intersection of two paths. All these steps will be carried out only once by the manager node during the network initialization phase.

We consider node S_8 as a sink node and S_6 as a source node. The source node S_6 measures the temperature and sends its position and the acquired data to its neighbors which have the same block_id. The sensor node can obtain its one-hop neighbors' block_id by beacon messages. When the sensor node S_2 receives the packet, it stores the temperature data and the source_id in its source list. Sink node S_8 sends its position and block_id to its neighbors that have the same block_id. The sensor node S_2 that receives both data packets, sends sink position to the source node using a geographic routing protocol.

Our experiment consists of sending a measurement command by the source node every 100s to each block during 1000s. For our implementation, the setup cost is about 22 hops, and SLA, SLQ, and SLR transmission for one sink location discovery are about 6 hops. The energy consumption during the setup phase is about 2.8J. Total transmission and energy consumption during the experiment slightly increased with time. In Fig. 19 and Fig. 20 we show the results. As expected, the simulation and experimental results have a similar pattern.

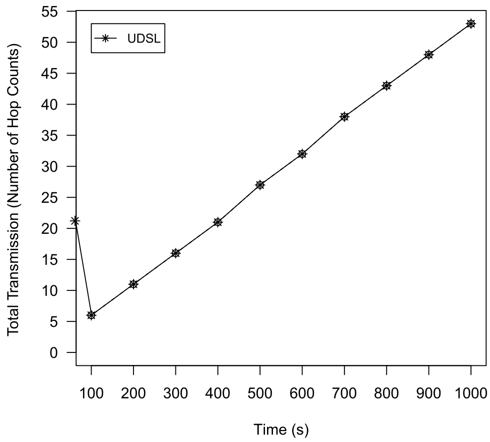


Fig. 19. **Total transmission in the case of single sink and source (Number of Hop Counts), experimental setup with nine sensors.**

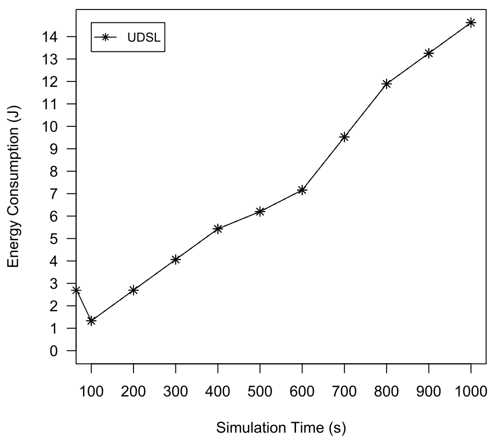


Fig. 20. **Energy consumption in the case of single sink and source (J), experimental setup with nine sensors.**

The communication cost and energy consumption of the algorithm is increased when implemented in a network of large scale. It requires just a one-time computation during the initialization of the network and it does not relate to the network operation time. To reduce communication cost, we use ZigBee instead of Wi-Fi module in large scale networks.

VI. CONCLUSION

In geographic routing, source nodes require to be aware of the location of sinks to send their data. The challenge of this paper is how to guarantee that two SLA and SLQ trajectories to have at least one intersection in 3D arbitrary sensor networks. In this paper, we proposed sink localization based on the unital design theory. In the proposed scheme, the SLA and SLQ packets are sent along unital blocks. It does not guarantee the intersection of any two SLA and SLQ trajectories. Finally we propose an enhanced unital-based scheme using blocking set concept which guarantees the SLA and SLQ intersection. Evaluation of the proposed algorithm was done by the simulation and experimental methods. Through simulation and experimental results, it was revealed that our proposed algorithm offers reasonable performance in terms of total transmission and energy consumption. In the future work, we will focus on sink location service in mobile sensors and mobile sinks environment.

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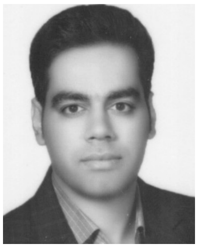

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