行政院國家科學委員會專題研究計畫 成果報告

在無線感測網路中設計並實作一個方向為主的定位系統
研究成果報告(精簡版)

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行政院國家科學委員會補助專題研究計畫 ■ 成 果 報 告
□期中進度報告

在無線感測網路中設計並實作一個方向為主的定位系統

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成果報告類型(依經費核定清單規定繳交)：■精簡報告　□完整報告

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執行單位：致理技術學院 資訊網路技術系

中　華　民　國　96　年　9　月　25　日

中文摘要：

近幾年來，無線感測網路已廣泛應用在許多領域，大部分的應用必須靠感測器的精確位置資訊標示特定地點或區域，然而，受限於電量與計算能力，感測器的精確位置並不容易求得，再者，一些應用場景並不需要精確的位置資訊，因此本計畫提出一個以方向為主的定位方法（稱為 DLS），感測器可以 DLS 方法得到相對於匯集點（Sink）的相對方向。基本上，DLS 是以空間區域性（Spatial Locality Property）基礎，並透過我們設計的錨點佈設策略（Anchor Deployment Strategy）提高錨點附近感測器的定位正確性，藉此感測器可以根據接收到的封包以決定自己的方向。再者，我們還設計虛擬雙方向座標系統（Virtual Dual Direction Coordinate System, VDDC System）以改善靠近兩相鄰方向邊界附近的感測器之定址正確率。本計畫的實驗主要探討感測器個數及通訊半徑在不同方向數的網路之定位正確率。結果顯示當方向數為 4、8 及 16 時，DLS 的平均定位正確率可達 95%、86%及 81%。此外，若 Sink 的位置改變，使用 DLS 仍達到不錯的定位正確率。

關鍵詞： 無線感測網路、定位、接收訊號強度指示、方向為主定位機制

英文摘要：

Recently, the wireless sensor network (WSN) has been widely used in a variety of applications. The majority of such applications rely on the precise location information to indicate the specific location or area. However, precise location information may be unavailable due to the constraints in energy, computation, or terrain. Additionally, numerous applications can tolerate the diverse level of accuracy in such geographic information. Thus, this project designs a direction-based localization scheme, called DLS, whose main goal is for each sensor to determine its direction rather than its absolute position. The direction we are concerned with is the one relative to the sink. Basically, DLS is based on a novel spatial locality property. The effective anchor deployment strategy is also proposed for the improvement of the estimated correctness in direction of the sensor within the communication range of the sink. Additionally, we devise a direction coordinate system, termed virtual dual direction coordinate (VDDC) system. With the aid of the VDDC system, DLS is able to efficiently and precisely position sensors around the axes. We evaluate DLS via simulations in terms of various numbers of sensors and communication ranges for the networks with different numbers of directions. The average correct rates in DLS reach approximately 95%, 86%, and 81% for the networks with 4, 8, and 16 directions, respectively. In addition, DLS also works well regardless of the sink placement as well.

關鍵詞：Wireless sensor networks (WSNs), localization, received signal strength indicator (RSSI), direction-based localization scheme (DLS).

報告內容：

本計畫主要執行成果已發表在2007年三月，第3卷，第6期，*Computer Communications*國際期刊。以下為英文版的成果報告內容（包含前言、研究目的、相關文獻探討、研究方法、模擬結果、分析與討論、結論及參考文獻）。

I. Introduction

The wireless sensor network (WSN) is now in widespread use for a variety of applications, including object detection, target tracking, security surveillance, and environmental monitoring [2], [3], [4], [5]. Essentially, sensors are always arbitrarily scattered in the sensor field without geographic information known in advance. However, numerous applications rely on the geographic information (e.g., location) of the sensor to identify the position of the tracking object [4], [6], to assist in delivering packets to the fields of interests [7], [8], to reduce the number of packets flooding the network for route discovery [9], [10], and to provide sensor deployment for mitigating coverage overlap [11], [12].

Localization, for a sensor to determine its location information has become an attractive research issue in WSNs. Much previous research has proposed numerous localization schemes, which are generally classified into *range-based* and *range-free* localization schemes, depending on the use of distance (range) or angle estimate [13], [14], [15], [16]. GPS is a wide-area system for sensor localization, but extremely expensive and energy-consuming properties make it impractical to be installed in a sensor [17]. Other range-based schemes, including RSSI, AoA, ToA/TDoA, and several protocols based on these representative mechanisms, are proposed in the literature [18], [19], [20], [21]. These approaches achieve sensor positioning, but have constraints in hardware cost (e.g., GPS receiver or smart/directional antenna) and time synchronization. Unlike the range-based technique, the range-free scheme enables sensors to learn their location information without the aid of range estimates [13], [14], [22]. Such techniques, like APIT [14], and MDS [15], DV-hop [23] generally require numerous location-aware nodes, by which location-unknown sensors are able to determine their locations.

The majority of existing localization schemes focus on sensor coordinate estimation. However, the precise position of the sensor is probably difficult to obtain owing to the constraint in energy, computation, or terrain. In WSNs, several applications can tolerate diverse levels of inaccuracy in location, depending on their requirements [25]. Thus, this project develops a fully distributed localization scheme, DLS, which enables a sensor to estimate its direction without GPS-support. Sensor direction means the relative one to the sink. The direction is represented in the form of the *Gray code*, by which a sensor effortlessly enables to recognize whether a packet comes from one of its adjacent directions or not. The main idea of DLS is the *spatial locality property*, by which all sensors are able to determine their directions according to the packets received. Additionally, three novel mechanisms, *anchor deployment strategy*, *multi-message decision scheme*, and *virtual dual direction coordinate system*, are introduced in DLS to assist the sensor in improving the estimated correctness. To our best knowledge, this study is the first investigation to concentrate on direction estimation of the sensor.

The rest of this report is organized as follows. Section II formulates our network model. Section III then mentions a significant property, spatial locality property. Next, a novel localization scheme based on sensor direction, DLS, is proposed in Section IV. Meanwhile, the simulation results are shown in Section V. Finally, Section VI presents concludes and future research directions.

II. Network Model

The network considered is a square area. Without loss of generality, the sink is placed at the center. We are given N_s stationary sensors, s_i, $i = 1, 2, ..., N_s$, with unknown directions and positions. The sensor is termed *unknown sensor*. All unknown sensors are uniformly scattered in the network. The communication range of a sensor, denoted as r, is a circle centered in the sensor. Each sensor has the communication capability, so as to exchange messages. Currently, we consider an obstacle-free environment, in which each sensor is able to communicate with all of its neighbors. We also consider a connected network, within which each sensor has at least one neighbor.

Let $N_{dir} = 2^n$ be the number of directions, where n is a positive integer, which is determined in advance. Given $N_{dir} = 2^n$ directions, the network is virtually partitioned into $2 \cdot N_{dir}$ distinct regions, comprising N_{dir} *directional regions* and N_{dir} *axis regions*. Each axis region is divided into two sub-regions of equal size with a common virtual borderline called an *axis*. Figure 1 shows an example of our network model. Apparently, a sensor within an axis region is able to receive the packets from sensors at both the same and the neighboring directions.

Two virtual direction coordinate systems, *Virtual Primary Direction Coordinate* (VPDC) system and *Virtual Auxiliary Direction Coordinate* (VADC) system, are created to represent the direction of each sensor and to correct the position of the sensor near the axis, respectively. The VPDC system is expressed by the *primary direction code*, while the VADC system is represented by the *auxiliary direction code*. The primary and auxiliary direction codes of sensor s_i are respectively denoted by $c_{pri}(s_i)$ and $c_{aux}(s_i)$. Sensor direction in the paper means the one in the VPDC system (i.e., primary direction code), so DLS focuses on the estimation of such code of each sensor. Both direction codes are represented in the form of the *Gray code*, arranged counterclockwise and numbered in order. The *Gray code* is a method of encoding binary numbers which has the property that two consecutive numbers differ only in one bit. Based on the *Gray code* representation, each sensor can effortlessly realize whether a packet comes from one of its adjacent directions or not.

Most previous works mentioned the benefit of location-known sensors placement in localization [13], [14]. DLS, thus, deploys a small fraction of direction-aware sensors, called *anchors*, via either digital compasses or manual presetting. That is, each anchor is aware of its direction. The numbers of anchors required in DLS is the same as the number of directions (namely, N_{dir}). All anchors are evenly placed at the range r from the sink on each axis (i.e., there exists only one anchor on each axis).

The communication ranges of the sink, anchors, and unknown sensors are assumed to be identical. DLS exploits the radio propagation model in [30], by which the receiver is able to measure the signal strength in spite of attenuation of radio signal. The perfect spherical radio propagation is also assumed.

Definition 1: Given two sensors s_i and s_j, s_j is said to be the neighbor of s_i if s_j is within s_i's communication range, and vice versa. □

Recall that we use the *Gray code* representation to stand for the direction code. The code assignment of the anchor follows the counterclockwise manner, by which anchor a_{i+1} is regarded as in the counterclockwise direction of anchor a_i. In Figure 1, four anchors (namely, a_1, a_2, a_3, and a_4), whose primary direction codes $c_{pri}(a_1)$, $c_{pri}(a_2)$, $c_{pri}(a_3)$, and $c_{pri}(a_4)$ are respectively indexed by 00, 01, 11, and 10, are placed on each axis. The anchors associated with axes virtually partition the network into 8 regions, termed R_i and A_i, for $i = 1, 2, ..., 4$. The sub-regions of axis region A_i are denoted as $A_i^{(1)}$ and $A_i^{(2)}$. Actually, the primary direction code of each directional region is assigned by the sink. Suppose the direction code of R_i and A_i are respectively denoted by $c_{pri}(R_i)$ and $c_{pri}(A_i)$. As Figure 1 shows, the primary direction codes of four directional regions, $c_{pri}(R_1)$, $c_{pri}(R_2)$, $c_{pri}(R_3)$, and $c_{pri}(R_4)$, are regarded as 00, 01, 11, and 10, respectively. The direction codes of axis regions A_1, A_2, A_3, and A_4 are regarded as 00, 01, 11, and 10, respectively. All sensors in a certain directional or axis region have the same primary direction code. For example, all sensors within R_1, $A_1^{(1)}$, and $A_1^{(2)}$ share direction code 00.

III. Spatial Locality Property

As mentioned before, packet dissemination enables a sensor to determine its direction by means of the information in the received LREQ packet(s). Namely, the estimate for a sensor is obviously associated with

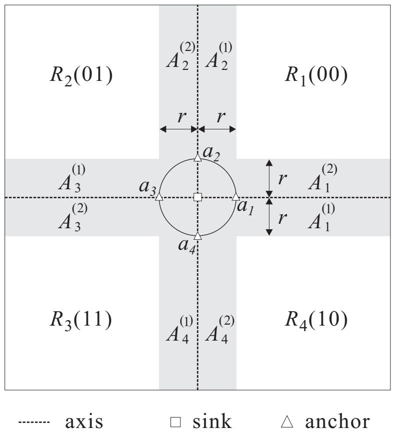


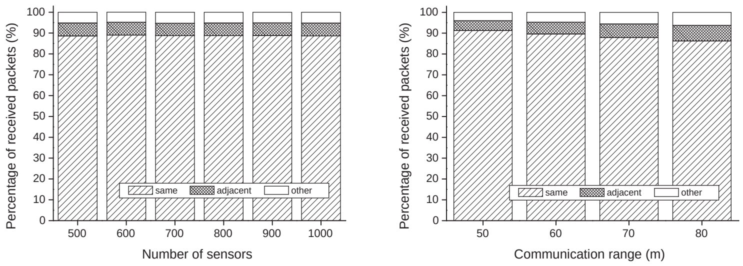
Fig. 1. Example of the network model with $N_{dir} = 4$. Without loss of generality, the sink is placed at the center. Four anchors (i.e., a_1, a_2, a_3, and a_4) are deployed at the range r to the sink on each axis. The network is virtually partitioned into 8 regions: 4 directional regions (i.e., R_1, R_2, R_3, and R_4) and 4 axis regions (i.e., A_1, A_2, A_3, and A_4). Each axis region is divided into two sub-regions. Namely, axis region A_i includes sub-regions $A_i^{(1)}$ and $A_i^{(2)}$.

the direction of its neighbors. Thus, we made numerous prior investigations to observe the impacts of the packets received at a sensor. Figure 2 shows the result in terms of different numbers of sensors and communication ranges. For ease of explanation, the directions where LREQ packets come from are categorized as the *same*, *adjacent*, and *other*, which are listed as below.

- Same: Given a sensor s_i with direction code $c_{pri}(s_i)$, if a sensor s_j is s_i's neighbor and $c_{pri}(s_i) = c_{pri}(s_j)$, then for sensor s_i the packet sent from s_j is indicated by the same.
- Adjacent: Given a sensor s_i with direction code $c_{pri}(s_i)$, if a sensor s_j is s_i's neighbor, and the difference between $c_{pri}(s_i)$ and $c_{pri}(s_j)$ is only in one bit, then for sensor s_i the packet from s_j is indicated by the adjacent.
- Other: For a sensor s_i, the packet from neither the same nor the adjacent is denoted by the other.

Consider a network with $N_{dir} = 4$, for a sensor with direction code 00, a packet from direction 00 is indicated by the same, while a packet from either direction 01 or 10 is viewed as the adjacent. A packet originated from the direction other than 00, 01, and 10 is represented by the other. The observation in Figure 2 reveals that for a sensor, approximately 88.8% packets received come from the sensor(s) in the same direction. The percentages of packets from either the adjacent or other region reach about 5.1% or 6.1%, respectively.

In general, a sensor close to the axis most probably receives packets from the sensors in the same or the adjacent direction. Besides, a sensor within the



(a)

(b)

Fig. 2. Spatial locality property. The network is a $500m \times 500m$ square region with $N_{dir} = 4$. The sink is at the center of the network. (a) percentages of received packets from different directions for a sensor vs. number of sensors. (b) percentages of received packets from different directions for a sensor vs. communication range.

communication range of the sink may receive more packets from the sensors in the other directions than the one near the axis. On the other hand, a sensor will not receive any packet from the adjacent and the other directions if it is far from the axis. Significantly, the increase of the number of sensors will result in more sensors which only receive the packets from the same direction. However, the number of sensors either close to the axis or within the communication range of the sink increases as well. Thus, in Figure 2(a), the average percentage of received packets from either the same, the adjacent, or the other direction approximately remains identical even if the number of sensors increases. Based on the above result, we conclude that a sensor most probably receives the packet(s) from other one(s) located in the same direction with regardless the number of sensors in the network as well as the communication range, and formulate the following spatial locality property.

Property 1: Spatial locality is that most of the packets received at a sensor are likely to be delivered from its neighbors located in the same direction. □

According to the spatial locality property, a sensor and its neighbors are most likely to have the same direction code. Recall that DLS uses the direction information to determine a sensor's direction. An unknown sensor s_i, thus, requires maintaining the information in its neighboring table, each of which is a four-tuple with the format $(id(s_j), c_{pri}(s_j), c_{aux}(s_j), hop(s_j))$, where s_j is one of s_i's neighbors, $id(s_j)$ stands for the identifier of s_j, $c_{pri}(s_j)$ and $c_{aux}(s_j)$ denote s_j's primary and auxiliary direction codes, respectively, and $hop(s_j)$ is the minimum hop distance from s_j to the sink.

IV. Direction-based Localization Scheme (DLS)

In this section, we propose a fully distributed direction-based localization scheme (DLS), for an unknown sensor to determine its direction. DLS comprises two major components, anchor deployment strategy and multi-message decision scheme, to increase the estimated correctness in direction of the unknown sensor. In addition, a hybrid direction coordinate system, involving the VPDC and VADC systems is introduced to resolve the location ambiguity problem.

A. Anchor Deployment Strategy

Numerous existing localization protocols exploit some location-aware anchors to benefit sensor positioning. DLS requires a small percentage of direction-aware anchors as well. With the inherence of the manual placement, the anchor is able to be reasonably set at the designated position. Since packet dissemination starts from the sink, the idea that enhancing the accuracy in direction of the sensor closed to the sink inspires the investigation to design a refined scheme for direction estimating.

Here, we define the *critical region* as below. The sensor within the critical region is called the *critical sensor*.

Definition 2: Given a sink, the critical region, CR, is the area within which all sensors are able to directly communicate with the sink. □

Figure 3 shows a network with $N_{dir} = 8$. The direction code used in the VPDC system obviously requires 3 bits. Consider all anchors are evenly placed at the communication ranges from the sink on each axis. For ease of explanation, we, here, focus on region R_1, with $c_{pri}(R_1) = 000$. Suppose CR in R_1 is divided into CR_1 and CR_2. A sensor within either CR_1 or CR_2 is obviously able to receive the LREQ packet from at least two anchors. Namely, all sensors in CR_2 are within the communication ranges of anchors a_1, a_2, and a_3, while a sensor within CR_1 is able to receive the packet issued from anchors a_1 or a_2 but not from anchor a_3. Note that, some sensors within either CR_1 or CR_2 are within the communication

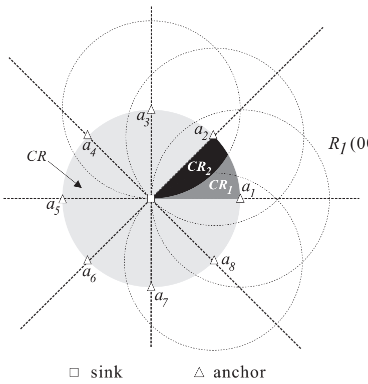


Fig. 3. Anchor deployment strategy. The shaded region in the network is the critical region.

range of anchor a_8. Significantly, a_1 and a_2 are the two closest anchors to the sensor. We consequently give Rule 1 for code assignment of the critical sensor.

Rule 1: Suppose a_i and a_j are the two closest anchors to the critical sensor s_i. The direction code of critical sensor s_i is defined as $c_{pri}(a_i)$ if $c_{pri}(a_i)$ is precedent to $c_{pri}(a_j)$ in the Gray code sequence.

Obviously, a sensor within either CR_1 or CR_2 has the accurate direction code 000. All critical sensors in other directions are also aware of the correct direction codes in accordance with Rule 1. Recall that accurate estimation of critical sensors significantly assists unknown sensors in direction estimations because the LREQ packet is initiated from the sink. As a result, DLS exploits an elegant anchor deployment strategy, which locates all anchors evenly at the communication ranges from the sink on each axis, to reduce the propagation errors in the course of packet dissemination.

B. Multi-message Decision Scheme

As mentioned before, one-message decision scheme only relies on one LREQ packet for sensor direction learning. The localization protocol based on such scheme is straightforward and cost-effective, as well as easy to implement. However, the technique obviously incurs erroneous estimates if a sensor only receives one LREQ packet which comes from the other direction. Inspired by the spatial locality property, a novel multi-message decision scheme is utilized in DLS. The main idea of the scheme is taking a reasonable duration into account to consider more LREQ packets for the improvement of the accuracy in direction estimating.

Figure 4 illustrates the transitions among the states. Each sensor maintains the information of the neighbors in its own neighboring table. All sensors are initially in the *Idle* states. A sensor in the *Waiting* and the *Learning* states is to gather more LREQ packets and to determine its direction according to the received LREQ packets, respectively. In the *Sending* state, a sensor

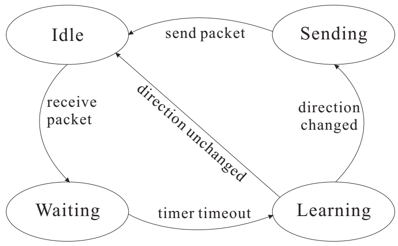


Fig. 4. State transition diagram of DLS at each sensor.

immediately sends an LREQ packet to propagate the current estimate to all of its neighbors, and then enters the *Idle* state.

C. Virtual Dual Direction Coordinate (VDDC) System

The spatial locality property implies that for a sensor most of the received LREQ packets come from its neighbors in the same direction. Although the anchor deployment strategy guarantees accurate estimates for all critical sensors, erroneous estimates are likely to occur during packet dissemination. The circumstance is significantly revealed in the axis region.

As Figure 5 shows, the shaded regions are the axis regions. Each direction has two axis sub-regions. In spite of the utilization of the multi-message decision scheme, a sensor within the axis region may significantly obtain the erroneous estimate. Specially, the direction code of such sensor is probably identical to the one of the adjacent direction. For example, a sensor, s_i, actually locates within $A_1^{(2)}$ (i.e., $c_{pri}(s_i) = 00$), but may be regarded as locating in R_4 (i.e., $c_{pri}(s_i) = 10$) if most of LREQ packets received come from direction 10. Such incorrect estimation obviously incurs less performance in sensor localization. To efficiently improve the DLS of estimated correctness in direction of the sensor within the axis region, DLS considers an auxiliary coordinate system, VADC, associated with the VPDC system. The VADC system is generated by counterclockwise rotating the VPDC system with an angle $\alpha = \frac{\pi}{N_{dir}}$. The approach to code assignment in the VADC system resembles that in the VPDC one.

As shown in Figure 6, a system, involving the VPDC and VADC systems, is named the *Virtual Dual Direction Coordinate* (VDDC) system. The dark and gray broken lines respectively indicate the VPDC and VADC systems. Figures 6(a) and 6(b) show the VADC systems for $N_{dir} = 4$ and 8, respectively. Figure 5 demonstrates an example of the coding system exploited in DLS. For ease of description, each direction is assumed to comprise 4 sub-regions. Two of the sub-regions are directional sub-regions, and the other two ones are axis sub-regions. All sensors hold two direction codes at the end of direction estimation.

The main goal of the VADC system is to enable a

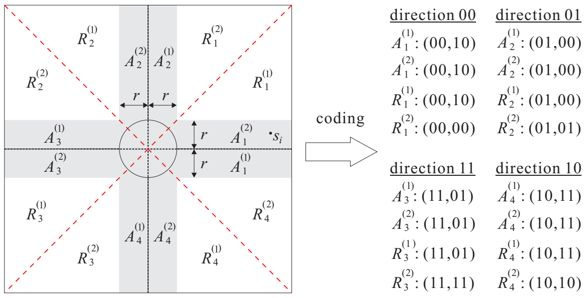


Fig. 5. Coding system with $N_{dir} = 4$ in DLS, where r is the communication range of a sensor. Each directional region R_i comprises many regions, individually represented by $R_i^{(1)}$, $R_i^{(2)}$, $A_i^{(2)}$, $A_{i+1}^{(1)}$, and the critical region in R_i. All unknown sensors are identified as two direction codes, represented in the form (primary direction code, auxiliary direction code).

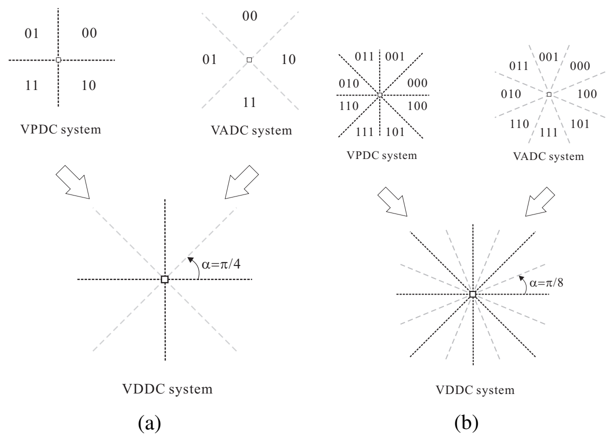


Fig. 6. Example of the virtual dual direction coordinate (VDDC) system. (a) VDDC system for $N_{dir} = 4$. (b) VDDC system for $N_{dir} = 8$.

sensor within the axis region to be aware of the axis to which it is close although obtaining an incorrect primary direction code. Taking the VADC system into account, each sensor in the network will have two direction codes, primary direction code and auxiliary direction code. The effectiveness of the VADC system is mentioned in the following. In Figure 6, suppose most of LREQ packets s_i received come from R_4, $c_{pri}(s_i)$ is determined as 10 according to the multi-message decision scheme. Apparently, the direction code of s_i is incorrect in case of the only usage of the VPDC system. Based on the spatial locality property, s_i is most likely to obtain auxiliary direction code 10 because most LREQ packets come from regions $R_1^{(1)}$, $A_1^{(2)}$, $A_1^{(1)}$, and $R_4^{(2)}$, all of whose auxiliary direction codes are 10. Note that sensor s_i is most unlikely to receive the LREQ packets from direction 11, so the sensor realizes that it is near the axis 00 rather than axis 10 though $c_{pri}(s_i) = 10$. Significantly, the VDDC system efficiently identifies the exact axis to which a sensor close in spite of the incorrect estimate in the primary direction code.

V. Performance Evaluations

In this paper, we experiment DLS on different networks by C++. Most sensor localization protocols mention that the number of sensors and communication range significantly lead to different levels of accuracy. We, thus, conduct numerous simulations to evaluate the influences of these factors on DLS.

Much research on localization addresses that correctness of a sensor in physical position is the most important concerns. Thus, in the paper, we also focus on accuracy in directional information by using a metrics called *estimated correctness* to validate the performance of DLS.

Recall that the network model used in DLS involves multiple directional and axis regions. As shown in Figure 1, the estimate of a sensor locating in R_1 is undoubtedly correct if its estimated primary direction code is 00. Note that the VADC system is devised to improve the estimate of the sensor in the axis region. Therefore, although obtaining an incorrect primary direction code, a sensor in $A_1^{(1)}$ or $A_1^{(2)}$ is also correctly estimated in case its estimated auxiliary direction code is 10. Let P be the set of sensors with the accurate estimates in primary direction code. Let A be the set of sensors within the axis region, which obtain the incorrect primary direction code but accurate auxiliary one, corresponding to the axis regions. The sizes of P and A are respectively termed N_P and N_A. Under the consideration of the VDDC system, the correct rate of DLS, termed C_{dual} is represented as below.

$$C_{dual} = \frac{N_P + N_A}{N_s},$$

where N_s is the number of sensors in the network.

A. Simulation Environment

In the simulation, the network is a square area with the size of $500m \times 500m$. Various numbers of directions, such as 4, 8, and 16 are considered. The sink is situated at the center of the network. All sensors are randomly scattered with a uniform distribution within the square area. A probabilistic bound to achieve connected network is addressed in [31]. Therefore, our simulations differ from the numbers of sensors with 500, 600, 700, 800, 900, and 1000. The sink, anchors, as well as sensors have the same communication ranges, which range from $50m$ to $80m$ with a step of $10m$. Additionally, all simulation results are averaged over 30 simulation runs, respectively.

B. Simulation Results

Extensive simulations are first performed to evaluate the efficiencies of diverse anchor deployment approaches. We, then, show the performances of DLS

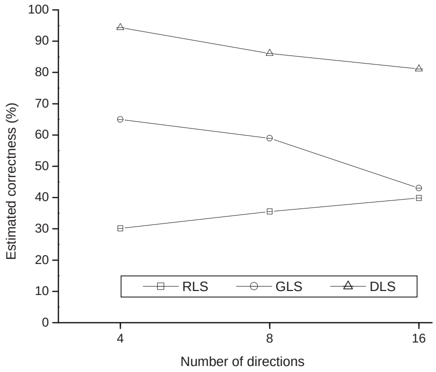


Fig. 7. Estimated correctness for different anchor deployment strategies and the number of directions.

with the random and greedy methods with respect to different numbers of sensors and communication ranges. Besides, the scenario, where the sink is placed at the edge of the network, is also evaluated.

1) Effects of Anchor Deployment Strategy: Here, we devise two methods, random and greedy methods, to evaluate the impacts of different anchor deployments on sensor localization. The numbers of anchors in both approaches are identical and equal to N_{dir}. For ease of representation, the random and greedy methods, here, are respectively indicated by RLS and GLS. In RLS, all anchors are randomly deployed within the whole network, whereas in GLS, whose main idea is to improve the estimated correctness of the critical sensors, anchors are evenly distributed in each direction within the critical regions. Additionally, both of which also use the multi-message decision strategies for direction estimation.

Figure 7 shows the estimated correctness for different anchor deployment strategies. Obviously, GLS outperforms RLS regardless of the number of directions. Due to random deployment of anchors, the average correct rates of RLS to 4, 8, and 16 directions are approximately 30.13%, 35.52%, and 39.82%, respectively. The correct rate actually improves with the increase of N_{dir} because of the existence of more anchors.

In GLS, the average estimated correctness in terms of 4, 8, and 16 directions reach 64.96%, 58.93%, and 43.00%, respectively. Since GLS exploits the strategy, which places all anchors within the critical region, in sensor localization, more critical sensors enable to obtain the more accurate estimations. Based on the packet propagation, the unknown sensors will learn the high level of accuracy in direction by means of packet propagation. However, the result shows that more directions in GLS obviously incur the disappointing performance. Because all anchors are randomly placed within the critical region of each direction, a critical sensor within multiple anchors' communication ranges has a high chance to receive the LREQ packets from the anchors with different direction codes. Therefore, a sensor may consequently obtain the erroneous direction.

To consider the tradeoff between the number of anchors and the locations of anchors, DLS places all anchors at the communication range from the sink on each axis. Figure 7 reveals that DLS achieves approximate 94.33%, 86.06%, and 81.09% in correct rates for 4, 8, and 16 directions, respectively. Such anchor deployment technique guarantees a critical sensor not only receives the LREQ packets transmitted from the limited anchors, but also avoids much communication and computation overhead. Therefore, a sensor does not suffer from the interference resulted from the LREQ packets from other directions, and quickly achieves the direction estimation.

2) Comparison of Different Localization Schemes: Figure 8 shows an example result of spatial sensor distribution, in which the circle and cross respectively represent the sensors with the accurate and erroneous estimates. The network with $N_{dir} = 4$ consists of 500 sensors, and the communication range of each sensor is $80m$. In this case, totally 438 sensors are identified the accurate directions. Namely, DLS achieves an estimated correctness of approximately 88%. Significantly, incorrect estimated sensors always appear in the vicinity of the axis region due to the receipt of numerous packets from other directions.

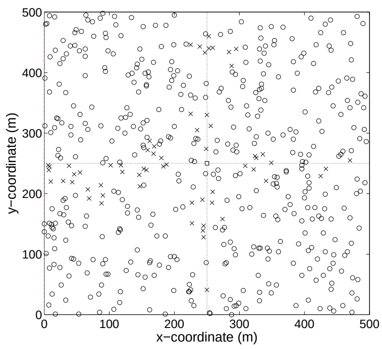


Fig. 8. Example of spatial sensor distribution for 500 sensors scattered in the network with $N_{dir} = 4$. The blue and red sensors respectively represent the sensors with accurate and erroneous estimates.

Figures 9 and 10 respectively show the simulation results of the estimated correctness in terms of different numbers of sensors and communication ranges for RLS, GLS and DLS. Among these localization schemes, the performance of DLS is obviously better than those of both GLS and RLS in case of the

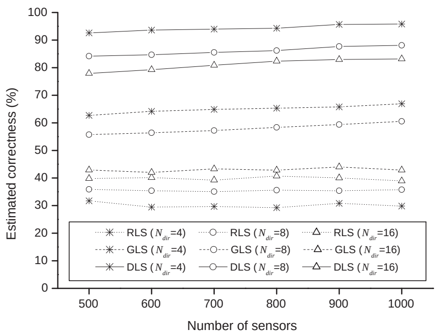


Fig. 9. Estimated correctness vs. number of sensors for different localization schemes. The number of directions in the network is 2^n.

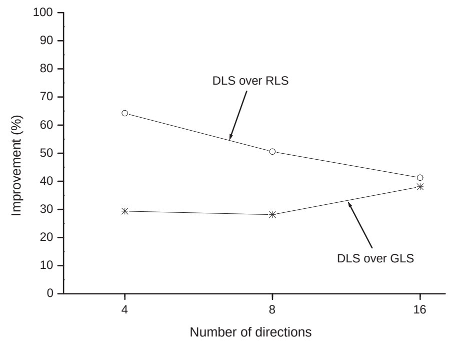


Fig. 11. Improvements of DLS in correct rates compared to RLS and GLS.

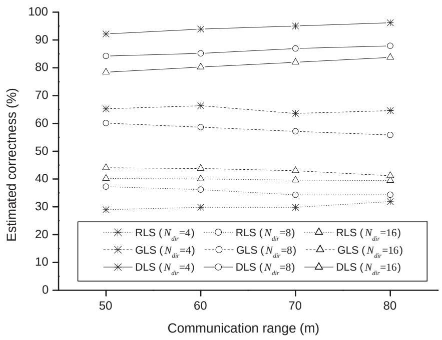


Fig. 10. Estimated correctness vs. communication range for different localization schemes.

corresponding N_{dir}. We conclude that with the aid of our anchor deployment and VDDC strategies, all critical sensors exactly determine their directions, and further enhance the effectiveness of sensor direction learning.

Note that the values of C_{dual} decrease in both DLS and GLS with the increases of N_{dir} because of a significant increase in the size of the axis region. A sensor may receive numerous LREQ packets coming from the sensors placed in the different directions. Such LREQ packets actually enable a sensor to obtain the incorrect estimation although the multi-message decision scheme is exploited. Unlike GLS and DLS, RLS focuses on anchor deployment in the random manner. The numbers of anchors and directions are identical, so the number of anchors increases with the increase of N_{dir}. The result of RLS significantly reveals that more N_{dir} leads to the increase of C_{dual}.

Both RLS and GLS respectively cause the slight variations in estimated correctness, while DLS results in a steady increase in C_{dual} if either the number of sensors or the communication range increases. The value of C_{dual} in RLS is limited between 30% and 40%, and the value of C_{dual} in GLS is limited between 43% and 65%. The phenomenon in RLS or GLS is resulted from the random anchor deployment, by which unknown sensors within the critical region are likely to obtain the incorrect estimates. Unlike the results of RLS and GLS, the estimated correctness of DLS rises gently for N_{dir}=4, 8, and 16 owing to the effectiveness of the proposed anchor deployment strategy.

To explicitly outline the effectiveness of DLS, Figure 11 illustrates the improvements of DLS in correct rate compared to RLS and GLS. Here, the correct rate of each scheme for any number of directions is the average of correct rates generated by all cases with different numbers of sensors and communication ranges. Significantly, DLS outperforms RLS for N_{dir}=4 about 64.20%, for N_{dir}=8 about 50.55%, and for N_{dir}=16 about 41.27% on average. Besides, DLS also outperforms GLS for N_{dir}=4 about 29.37%, for N_{dir}=8 about 28.13%, and for N_{dir}=16 about 38.09% on average.

The observation from Figure 9 shows that DLS performs best among the three localization approaches for the corresponding number of directions. In DLS, the correct rate slightly increases if the number of sensors increases. Generally, more sensors in the network means that a sensor has more neighbors. Thus, the sensor can receive more LREQ packets, which significantly lead to more accurate estimation owing to the multi-message decision scheme. The curves for N_{dir}=4, 8, and 16, in terms of GLS, rise gently with the aid of the multi-message decision mechanism. Although such scheme advantages a sensor to obtain the accurate estimate, some sensors with incorrect direction within the critical region in GLS may incur the poor performance during LREQ packet dissemination. In RLS, all anchors are randomly deployed in the whole network. The estimated correctness has slight variation for different numbers of sensors because of the invalidation of the multi-message decision scheme.

In Figure 10, for DLS, the increase of communication range results in the larger critical region. Thus, the number of critical sensors, whose directions are always accurate also increases. Such critical sensors further lead to the accurate estimate of the unknown sensor within the non-critical region, and, consequently, improve the performance of sensor localization. Additionally, large communication range increases the number of neighbors of a sensor. Therefore, a sensor receives more LREQ packets, and then obtains the accurate direction by means of the multi-message decision scheme. With the characteristic of random anchor deployment, RLS causes slight variation in C_{dual} for distinct communication ranges. In GLS, with the increase of the communication range, the number of unknown sensors within the critical region may increase owing to more LREQ packets coming from different directions. Such LREQ packets eventually degrade the correct rates of unknown sensors within the critical region. Furthermore, the increase of sensors with erroneous directions may result in the disappointing performance of localization because such incorrect direction information will be propagated via LREQ packets.

Figure 12 demonstrates the effectiveness of DLS in diverse high density networks. The results are generated by averaging the estimated correctness for various communication ranges in the corresponding number of sensors. Obviously, DLS reaches approximately 96.51%, 90.27%, and 85.59% in accuracy for N_{dir}=4, 8, and 16, respectively. The correct rates for $N_{dir} = 4$, 8, and 16 all keep rising with large number of sensors because the multi-message decision scheme works significantly. Note that the curves for N_{dir}=4, 8, and 16 rise gently after 1000 sensors. We reason that more sensors within the axis regions are likely to deteriorate the correct rate. Overall, the multi-message decision scheme is able to tolerate the estimated errors in spite of large number of sensors within the axis regions. Consequently, DLS can achieve well level of accuracy, especially for high dense WSNs.

3) Effects of the VADC system: As mentioned before, the VADC system is mainly to improve the estimated correctness of the sensor within the axis region. Numerous non-critical applications, such as environmental monitoring can tolerate the inaccuracy in geographic information. Thus, C_{dual} is obviously unsuitable for such applications to evaluate the estimated correctness. Here, we devise the metrics, C_{pri}, revised from C_{dual} to evaluate the effect of the VADC system in sensor localization. Compared to C_{dual}, C_{pri} does not consider the effect of N_A because N_A is related to the VADC system. The C_{pri} is defined as

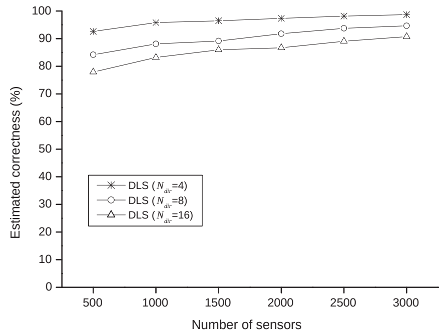


Fig. 12. Performance of scalability of DLS.

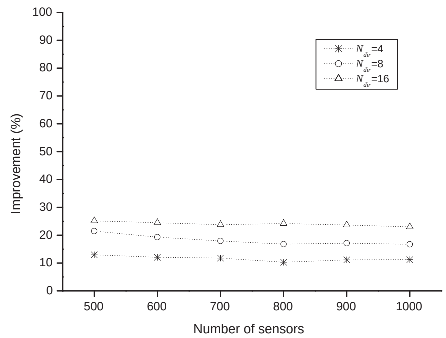


Fig. 13. Improvements of DLS in correct rates compared to DLS-VADC for different numbers of sensors. DLS-VADC means the VADC system is not involved in DLS.

follows.

$$C_{pri} = \frac{N_P}{N_s},$$

where N_s is the number of sensors in the network.

To demonstrate the effectiveness of the VADC system, we make the simulations about the improvement of the VADC system in terms of different numbers of sensors and communication ranges, respectively. In Figures 13 and 14, DLS-VADC means the approach, excluding the VADC system from DLS. Overall, DLS-VADC reaches 82.74%, 67.83%, and 57.05% in the estimated correctness for N_{dir}=4, 8, and 16, respectively. As shown in Figures 13 and 14, the improvement in estimated correctness becomes remarkable with the increase of N_{dir}. The VADC system significantly leads to the improvement in the estimated correctness for $N_{dir} = 4$ about 11.59%, for $N_{dir} = 8$ about 18.23%, and for $N_{dir} = 16$ about 24.04% on average. Intuitively, the increase of N_{dir} implies the increase of the sensors within the axis regions. The VADC system enables to increase the value of N_A, and consequently enhances the performance in sensor localization.

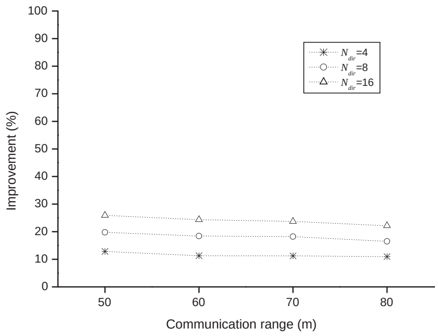


Fig. 14. Improvements of DLS in correct rates compared to DLS-VADC for various communication ranges. DLS-VADC means the VADC system is not involved in DLS.

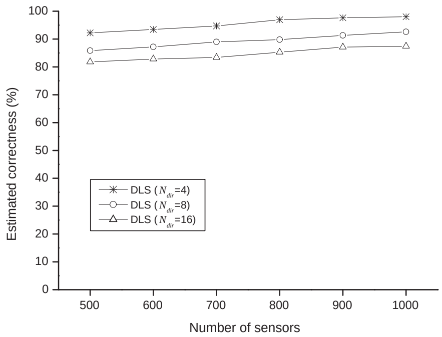


Fig. 15. Estimated correctness vs. number of sensors in DLS, where the sink is placed at the edge.

4) Edge Sink Performance: Figures 15 and 16 illustrate the results of DLS used in the network, in which the sink is assumed to be placed at one edge. We also evaluate the performance of DLS in a network with $500m \times 500m$ size with regard to the number of sensors and communication range for various N_{dir}. Figures 15 and 16 illustrate the results for various number of directions. Overall, either the large number of sensors or the increase of communication range actually advantages sensors to learn the accurate direction.

The increase of the value of N_{dir} dramatically incurs disappointing results due to the enlargement of axis regions. DLS leads to average correct rates for $N_{dir} = 4$ about 95.49%, $N_{dir} = 8$ about 89.29% and for $N_{dir} = 16$ about 84.64%. Actually, placing the sink at the edge of the network causes the network to be partitioned into 2, 4, and 8 distinct regions although N_{dir}=4, 8, and 16, respectively. Here, we focus on the correct rates between the corresponding scenarios in the different sink placement methods. The results for $N_{dir} = 4$ and 8 shown in both Figure 9 and Figure 10

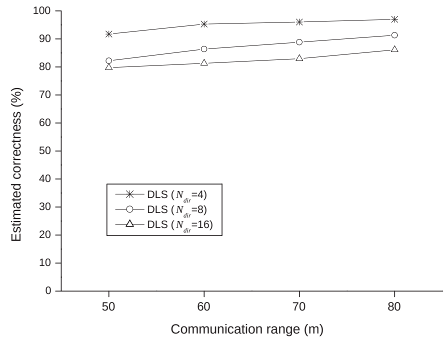


Fig. 16. Estimated correctness vs. communication range in DLS, where the sink is placed at the edge.

outperform the results for $N_{dir} = 8$ and 16 revealed in both Figure 15 and Figure 16, respectively. The reason is that placing the sink at the edge significantly enlarges the axis regions, and further deteriorates the correct rate.

VI. Conclusions

To our best knowledge, the paper is the first investigation to the localization based on sensor direction. We introduce an effortless and cost-effective localization solution, DLS, whose main goal is for each sensor to estimate its direction related to the sink. Spatial locality property motivates DLS for direction estimating according to the packets received at a sensor. DLS not only uses the elegant anchor deployment strategy for the improvement of estimated correctness, but also efficiently exploits the virtual dual direction coordinate system for the identification of the precise location of the sensor around the axis.

Two important factors, number of sensors and communication range, are studied in the simulations. For the scenario, in which the sink is placed at the center, the average correct rates for $N_{dir} = 4$, 8, and 16 are approximately 94%, 86%, and 81%, respectively. In general, DLS outperforms RLS and GLS in direction estimation owing to the use of a well-designed anchor deployment strategy. DLS is well-suited to high dense WSNs as well. With the aid of the VDDC system, DLS enables a sensor to efficiently recognize that it is near the axis although it obtains an incorrect direction code. Additionally, the proposed DLS is also suitable for the scenario in which the sink is not at the center of the network.

For the enhancement of direction determination at each sensor, future studies can investigate techniques, such as the Bayesian inference method, which takes the prior estimates into account, and weight-based approach, which assigns the individual weight to each packet by means of its RSSI value. Furthermore, an efficient routing protocol for WSNs is being designed on the basis of the information of the relative direction and the hop count obtained by DLS.

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計畫成果自評：

本計畫的研究成果與原計畫內容相符，預期之研究目標均已達成。以下列出本研究的主要成果：

(1) Sensor Node之地理資訊應用在定位技術的可行性與適用性。
(2) 以Gray Code表示Sensor Node的方向以簡化定位過程的複雜性。
(3) 探討不同Anchor佈設策略對定位正確率的影響。
(4) 虛擬多方向座標系統可增加定位的正確率。
(5) 本研究定位方法不受Sink佈建位置的影響。

以往的研究中未提出以方向為主的定位機制，為了簡化定位過程的複雜性卻又考量定位正確率及實用性，因此本研究試圖以自行設計的方向碼表示Sensor Node的方向進行定位，該研究可視為Sensor定位之另一選擇方案，因此有一定的學術價值。吾人認為，基於本研究所設計的方向碼不僅適用於Sensor Node的定位，亦可提升封包繞送（Routing）的效能，此部分將可作為後續研究的參考。

本計畫之主要成果已發表於*Computer Communications* (Vol. 30, No.6, pp. 1424-1439)。