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A RSS-Inconsistency Detection Method for Sequence-Based Localization Algorithms

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***Abstract*—Sequence-based schemes determine beacon sequence to help sensor node localization. Due to the ambiguity of RSS over distance, sequence-based scheme may have RSS-inconsistency problem, i.e., no location in the localization space could match the beacon sequence. Besides, determining the matched location is costly. In this paper, we introduce a RSS-inconsistency avoidance localization scheme, which takes linear-time. Our scheme is applicable to real sensors. Our localization error in real sensors is less than 0.34×communication radius. According to the simulation results in NS-2, our scheme is more accurate and reliable than existing schemes.**

Keywords—localization; mobile anchor; range-free; wireless sensor network

I. INTRODUCTION

Localization is important in wireless sensor networks. Localization schemes in wireless sensor networks can be separated into two categories: range-based scheme and range-free scheme. In range-based schemes, accurate measurement schemes/equipment for determining distances between sensors are necessary, such as received signal strength (RSS) [1], time of arrival (ToA), time difference of arrival (TDoA) [2] and angle of arrival (AoA) [3, 4]. Unlike range based schemes, range-free schemes are based on sensor connectivity [5-9].

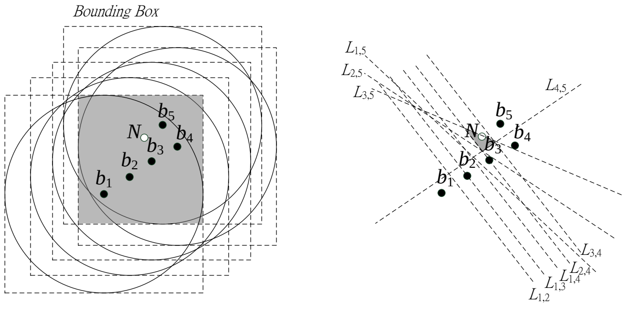
Most of the range-free schemes suffer from irregular communication ranges. To address this problem, irregular communication ranges are simplified as upper bounds of original communication ranges, e.g. bounding box [7]. However, range-free schemes are still lack of efficiency since the set of possible locations of normal nodes could not be reduced efficiently (see Fig. 1(a)), especially in low-beacon-density environments. Ref. [5] presented a sequence-based scheme that uses RSS (received signal strength) to improve accuracy and efficiency (see Fig. 1(b)). For each pair of beacon packets heard by the normal node (i.e., not anchor node), the normal node is regarded to be more near the one with stronger-RSS (called winner). Their main idea is that a location which is closer to all winners and farther apart from all losers is a possible location of the normal node. However, the existence of such a location is not guaranteed, called RSS-inconsistency problem. Besides, determining the intersection of all winner regions is costly.

In this paper, we introduce a RSS-inconsistency avoidance localization scheme in mobile-anchor environments. Our scheme is applicable to real sensors. Our localization error in real sensors, i.e., Octopus X [10], is less than 0.34×communication radius. Besides, our algorithm is low cost and efficient in real wireless sensor networks. According to the simulation results in NS-2, our scheme has better performance than existing range-free localization schemes.

II. RELATED WORKS

Most of range-free schemes are for static-anchor-node environments. In reference [8], the Point-In-Triangulation Test is used to determine the possible region that the sensor node is located in. In reference [9], based on the number of hops between sensor and anchors, the distance between sensor nodes could be estimated to help localizing sensors.

For reducing the cost of anchor nodes, more and more range-free studies consider mobile-anchor-node environments. In reference [6], the LMAP scheme investigated the scenario that mobile anchors broadcast their locations (i.e., beacon packets) periodically. For a sequence of beacon packets which are heard by a sensor node, it is assumed that the first beacon packet and the last beacon packet in the sequence are on the boundary of the sensor node’s communication range. Since the communication range is assumed to be an ideal unit of disk, the perpendicular bisector of the first beacon and the last beacon should pass through the center of the disk (i.e., the location of the sensor node). Hence, a sensor node’s location could be determined if the sensor node heard two sequences of beacons. Besides, a concentric-circle-based method is introduced to improve the performance of LMAP scheme. However, irregular communication range causes huge location error of LMAP. For reducing the effect of irregular communication ranges, in reference [7], sensor nodes’ communication ranges are simplified to be bounding boxes. The intersection of theses bounding boxes is the set of possible sensor node’s locations. Besides, virtual force is used to refine the location of the sensor. Bounding box method could tolerate the unreliability of RSS. The main drawback of bounding box method is lack of efficiency (since the set of possible locations of normal nodes could not be reduced efficiently), especially in low-beacon-density and collinear-beacon environments. In the scenario of mobile anchors, a normal node usually hears fewer and collinear beacons which are broadcasted by the same anchor. In Fig. 1(a), the normal node received four beacons b_1, b_2, b_3, b_4,



(a) (b)

Figure 1. Gray areas denote possible locations of the normal node which receives beacons b_1, b_2, b_3, b_4, and b_5. (a) Bounding box method. (b) The sequence-based scheme.

and b_5. But the set of possible locations of the normal node, i.e., the gray area, is still large. In reference [5], a sequence-based scheme uses RSS (received signal strength) to improve accuracy and efficiency. The main idea comes from the observation that a normal node is usually closer to the beacon with stronger RSS. For every two beacons, they use the perpendicular bisector to partition the whole space into two regions. The normal node is in the region which is closer to the beacon with stronger RSS. For ease of the following discussion, this region is called a *winner region*. So, the normal node should be in the intersection of all winner regions. In Fig. 1(b), L_{ij} is the perpendicular bisectors for beacons b_i and b_j. RSSs of theses beacons follow $b_1<b_2<b_4<b_5<b_3$, which implies that the intersection of all winner regions are the gray region. Here L_{23} is omitted because L_{23} is overlapping with L_{14}. The main drawback of sequence-based method is its high computation cost. Determining the intersection of all winner regions takes high computation cost, $O(n^4)$, where n is the number of beacons. On the other hand, unreliable RSS results in RSS-inconsistency.

Refer to Fig. 2. It results in the RSS-inconsistency problem that RSS relationship is $b_1>b_2$ and $b_3>b_2$. It means that the normal node N is at $half\_plane_{1,2}$ and $half\_plane_{2,3}$ at the same time. There is incorrect RSS information that $b_3>b_2$.

Definition1. RSS-inconsistency problem: Given a normal node N which receives b_i, b_j, b_k, b_l; if $half\ plane_{i,j} \cap halfplane_{k,l} = \varnothing$, then N is called to have RSS-inconsistent problem. ($half\_plane_{i,j}$ means the half-plane that closer the normal node N, for example, $half\_plane_{1,2}$ is gray region, i.e., left side of L_1.)

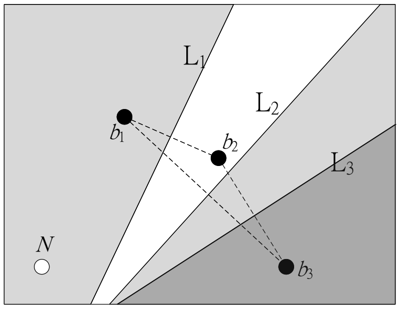


Figure 2. RSS-inconsistency problem. RSSs of theses beacons follow $b_1>b_2$, $b_3>b_2$.

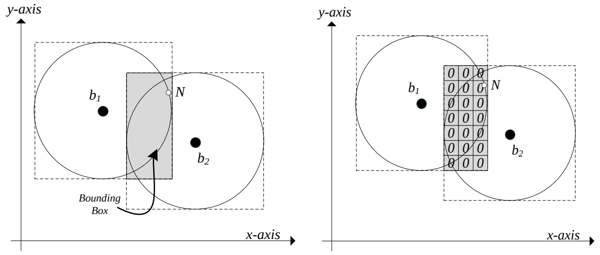


Figure 3. An example of bounding box method. (a) A bounding box determined by beacons b_1 and b_2. (b) The bounding box is further divided into fix-sized grids.

In this paper, we introduce a RSS-inconsistency-avoidance sequence-based scheme. We consider the sensor networks with static normal nodes and mobile anchor nodes. Mobile anchor nodes broadcast their positions (i.e., beacons) periodically. We aim to reduce localization error and computation cost.

III. LOCALIZATION SCHEME

Our scheme includes two phases: the accuracy maintenance phase and the fast convergence phase. The accuracy maintenance phase aims to maintain the localization accuracy, and to reduce the cost of fast convergence. The fast convergence phase aims to improve efficiency and avoid the RSS-inconsistency problem.

A. Localization Scheme Overview

1) *Accuracy maintenance:* Since bounding box has low cost and can tolerate the unreliability of RSS, in this phase, we also simplify the communication range to be the bounding box (see Fig. 3(a)). For improving efficiency, this phase is executed only in two cases: initialization and the occurrence of RSS-inconsistency problem (which occurs in the next phase), to maintain the localization accuracy.

2) *Fast convergence:* To improve efficiency, the bounding box determined in the accuracy maintenance phase and the perpendicular bisectors plotted in this phase, the set of possible locations of the normal node is reduced. Fast convergence phase is executed when a new beacon is heard and RSS-inconsistency problem does not occur. When RSS-inconsistency occurs, the fast convergence terminated and the accuracy maintenance phase is executed to improve accuracy. The detail is described in Section III.C.

B. Detail of Accuracy Maintenance Phase

1) *Initialization:* In the initialization, we use the first two beacons the normal node hears to determine the bounding box. Then, the accuracy maintenance phase is not executed until RSS-inconsistency problem occurs. The occurrence of RSS-inconsistency problem implies that the localization result is unreliable. In this scenario, the bounding box is reduced by the new-arriving beacon and hence to improve the localization accuracy.

2) *Cost reduction*: For reducing the computation cost of determining the intersection of winner regions, the bounding box is divided into uniform sized grids (i.e., square regions). Each grid is marked as “0” (see Fig. 3(b)). The number marked

in each grid denotes the weight of the grid. A grid with larger weight means the possibility that the normal node is located in the grid is higher. When a winner region intersects a grid in the bounding box, the grid's weight is added 1.

3) *Localization accuracy maintenance*: Accuracy maintenance phase is also executed when the null-intersection problem occurs. The bounding box is narrowed down by the aid of the original bounding box and a new-arriving beacon. Obviously, the occurrence of RSS-inconsistency problem means unreliable weights of grids. So, we reset the weight of the remaining grids (i.e., grids also in the new bounding box). Weight resetting is for keeping the most possible candidate grids (i.e., the most possible locations of the normal node) which we obtained from steps before the occurrence of RSS-inconsistency problem, and removing the effect of unreliable RSS. In our algorithm, a remaining grid's weight is reset to 1 if its weight is the highest among all remaining grids' weight and 0 otherwise.

C. *Detail of Fast Convergence Phase*

1) *RSS-inconsistency avoidance:* In reference [11], it is shown that ambiguity of strong RSS over distance is lower than ambiguity of weak RSS over distance. Besides, the overlap of ambiguities of two beacons (over distance) is shown to be small when the difference of these two beacons' RSSs is large. For a beacon pair (b_i, b_j) with RSS of b_i> RSS b_j, the possibility that the normal node is closer to b_i is highest if the difference of RSS of b_i and RSS of b_j is largest. Suppose that b^* is the beacon with the strongest RSS so far. For each beacon b_j, the result that the normal node is closer to b^* than b_j and b^* is more reliable than the result that the normal node is closer to b_i than b_j, where $b_i \neq b^*$. For reducing the effect of ambiguity, we always determine the perpendicular bisectors of b^* and a new-arriving beacon. For ease of the following discussion, the union of grids closer to b^* is a *winner region*. In order to represent the fact, the weight of a grid in a winner region is added 1. In Fig. 4, normal node *N* hears a sequence of beacons b_1, b_2, …, b_9. And the RSSs of theses beacons have $b_1<b_2<b_3<b_4<b_5$ and $b_7<b_6<b_8<b_9$. Recall that *N* determines the bounding box by b_1 and b_2 in accuracy maintenance phase. Since b_2 has stronger RSS than b_1, *N* determines the perpendicular bisector of beacon pair (b_2, b_3) when *N* hears b_3. And the weights of grids close to b_3 is added 1 (see Fig. 4(a)). Similarly, *N* determines the perpendicular bisectors of beacon pairs (b_3, b_4) and (b_4, b_5), respectively, when *N* hears b_4 and b_5, respectively (see Fig. 4(b) and Fig. 4(c)).

2) *RSS-inconsistency identification:* After determining the winner region of (b_4, b_5), null- intersection problem occurs (see Fig. 4(c)). Since the intersection of winner regions is null, the highest weight should be smaller than the number of determined perpendicular bisectors. In the case of Fig. 4(c), there are three determined perpendicular bisectors, but the highest weight is 2.

3) *Removing the effect of RSS-inconsistency:* When RSS-inconsistency problem occurs, it means the weights of grids are not reliable. For improving accuracy, accuracy maintenance phase is executed again. In fact, the weight of highest-weight grids are more reliable than the weight of lower-weight grids (detail could be found in Section III(b)). So, in accuracy maintenance phase, weights of highest-weight grids are reset to 1 and the weight of the remaining grids are reset to 0. Besides, the bounding box is determined again in the accuracy maintenance phase. The new bounding box is the intersection of the bounding box of the new-arriving beacon, i.e., b_6, and the original bounding box (see Fig. 4(d)). After the new bounding box is determined, the fast convergence phase is executed again.

4) *Back to fast convergence phase:* Since b_6 is the only beacon that normal node *N* has heard after the occurrence of RSS-inconsistency problem, b_6 is regarded as the beacon with the strongest RSS. Similarly, *N* determines the perpendicular bisectors of beacon pairs (b_6, b_7), (b_6, b_8), and (b_8, b_9), respectively, when *N* hears b_7, b_8, and b_9, respectively (see Fig. 4(f), Fig. 4(g) and Fig. 4(h)). Then, the possible location of *N* is the union of highest-weight grids. In Fig. 4(h), the grid with weight 4 is the possible location of *N*.

IV. ANALYSIS AND DISCUSSION

A. *Cost and performance*

Our scheme has significant improvement. First, our scheme takes linear time $O(gn)=O(n)$ and works in a distributed manner, where *g* denotes the number of grids in the bounding box and is a constant in our scheme. The sequence-based scheme takes $O(n^4)$ and works in a centralized manner. Second, our scheme is efficient in low-beacon-density environments. We use the strongest-RSS beacon and new-arriving beacon to determine reliable winner regions and to reduce the occurrence of RSS-inconsistency problem. Third, we provide an acceptable solution to the RSS-inconsistency problem. When null-intersection problem occurs, the results obtained from beacons before the occurrence of RSS-inconsistency is kept and the effect of RSS-inconsistency is removed (by resetting grid weight). Besides, the bounding box is used to maintain the localization accuracy.

B. *Accuracy Limitation*

It is proved that determining the intersection of winner regions is costly, $O(n^4)$. Grid-scan and sampling method are well-known solutions for cost reduction. Grid-scan divides the

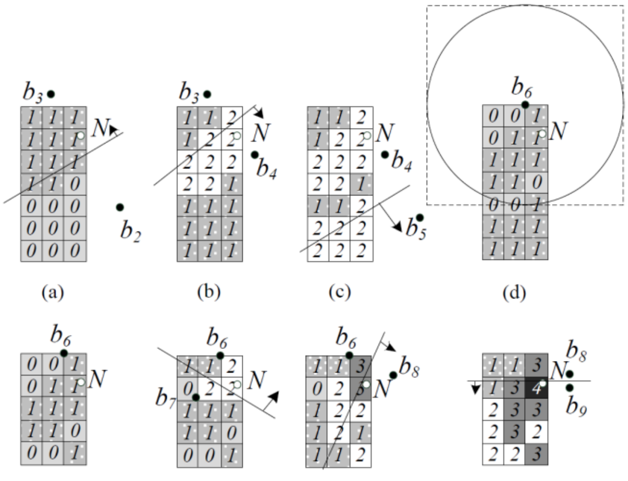
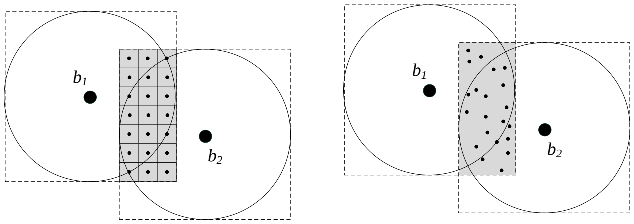


Figure 4.An illustrative example of our scheme



(a) (b)

Figure 5. (a) Grid-Scan based method. (b) Sample based method.

whole region into uniform-sized grids and winner region are represented by grids (see Fig. 5(a) [8]. In sampling method, winner region are represented by samples (see Fig. 5(b)). Clearly, a large number of samples result in high cost. However, a small number of samples in the winner region usually results in that no samples fall in the intersection of winner regions. So, we adopt grid-scan in our scheme.

It is well-known that in grid-scan method, the localization accuracy depends on grid size. Small grids (i.e., a large number of grids) lead to high localization accuracy but also lead to high computation cost. In our scheme, the accuracy could not be improved when there is only one grid in the intersection of winner regions (i.e., there is only one highest-weight grid). For applications requiring high accuracy, the highest-weight grid could be further divided into several equal grids if there is only one highest-weight grid.

V. EXPERIMENTAL RESULT

Our experiments include two parts: implementation in real sensors and simulation in NS-2.

A. Implementation in real sensor nodes

We implement our scheme on real sensor nodes, Octopus X [10], which uses 8051MCU. The Mac protocol is IEEE 802.15.4. The channel is 2.4 GHz. The sensor network has size 50m×50m, 15 static normal nodes, and one mobile anchor. For every time slot, the mobile anchor moves 10 m and broadcasts its location. The mobile anchor is equipped with the GPS receiver BU-353 to offer real location information. The error of localization of GPS is within 10m. Sensor communication radius (i.e., R) is 25m. Fig. 6(a) shows the environmental effect on the communication of Octopus X. The successful transmission rate decreases as the distances from transmitter to receiver increases. When the distance is the communication radius, the successful transmission rate is only 10%. In the scenario shown in Fig. 6(a), our localization error in Octopus X is shown in Fig. 6(b). In Fig. 6(b), our localization error is larger than R in the first time slot. This is because some normal nodes do not receive any beacon in the first time slot.

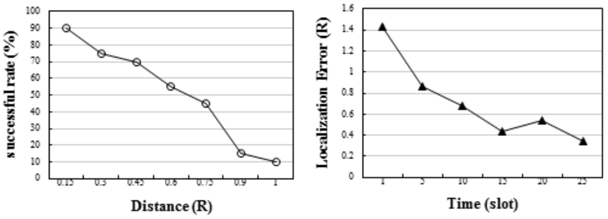


Figure 6. Localization error of our scheme on real sensors. (a) Distance between sensors vs. successful transmission rate. (b) Localization error vs. time slots.

After all normal nodes have received sufficient beacons (e.g., time slot 25), our localization error is lower than 0.34R. It also shows that our scheme could tolerate ambiguity of RSS over distance. This is because our scheme uses highest RSS beacon to guarantee higher reliability. Due to the GPS error, the localization error of time slot 20 is greater than that of time slot 15.

B. Simulation in NS-2

Here we use NS 2.34 to illustrate the accuracies of localization schemes in the regular communication range environments and irregular communication range environments.

1) *Localization error in mobile-anchor environments:* In this simulation, the network has size 500m×500m, 100 normal nodes, and 5 mobile anchor nodes. The anchor nodes are randomly work. Sensor communication range is 100m. Anchor nodes broadcast their locations per 250m move. We compare the accuracy of our scheme, LMAP scheme and LMAP-enhance scheme [6], and DRLS scheme [7]. The localization error is represented as the ratio of the distance between the physical location and estimated location to the communication range.

1-a) *Irregular communication range:* DOI is used to represent the degree of irregularity of communication range. There are the upper bound and lower bound on the communication radius. The lower bound denotes the distance from transmitter to receiver which has 100% successful transmission rate, while the upper bound denotes the ideal communication range (i.e., the distance with greater than 0 successful transmission rate). If a normal node is outside the upper bound of communication range of the anchor node, the normal node is unable to receive beacons from the anchor node. If a normal node is inside the lower bound of communication range of the anchor node, the normal node always receives beacons from the anchor node. DOI is (1−lower bound)/upper bound. In this simulation, DOI varies from 0.1 to 0.9. Fig. 7 shows that the localization error increases as the DOI increases. When DOI is greater than 0.5, the localization error increases rapidly. Besides, Fig. 7 shows that our scheme has better performance than other schemes. Since the radio range in any direction varies randomly between the upper bound and the lower bound, the localization error of DRLS for DOI=0.7 and DOI=0.8 is fewer than that for DOI=0.6.

1-b) *Regular communication range:* Fig. 8 shows that when the communication range is an ideal disk (i.e., DOI=0), our scheme has higher localization accuracy than the other schemes. Notice that our scheme is efficient. Our scheme is accurate even when sensor nodes receive few beacons.

2) *Evaluation in static anchor environments:* In this simulation, our scheme is compared with sequence- based scheme [5]. There are 100 normal nodes and the number of static anchor nodes varies from 3 to 7. Sensor communication

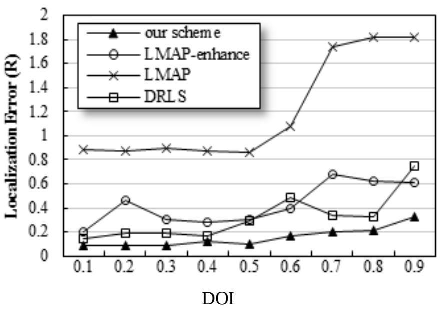


Figure 7. Localization error vs. DOI.

range is 100m. Each anchor broadcast one beacon. Due to sequence-based scheme is not applicable to large sized networks (the localization error and computation cost of sequence-based scheme in large sized networks is huge and unacceptable), network size varies from $R\times R$ to $3R\times 3R$.

2-a)*Regular communication range:* Due to the complex computation of sequence-based scheme, Fig. 9(a) shows that sequence-based scheme has better performance than our scheme when network size is extremely small, i.e., $R\times R$. This is because sequence-based scheme determines the intersection of winner regions corresponding to $O(n^2)$ perpendicular bisectors, while our scheme determines the intersection of winner region corresponding to $O(n)$ perpendicular bisectors. When the network size becomes larger, our scheme has better performance even in small network environment (see Fig. 9(b)). Our strength comes from the bounding box determined in accuracy maintenance phase.

2-b) *Irregular communication range:* Both Fig. 9(c) and Fig. 9(d) verify that using strongest-RSS beacons and removing the effect of RSS-inconsistency could increase the reliability.

VI. CONCLUSION

In this paper, we introduce a RSS-inconsistency avoidance localization scheme in mobile-anchor environments. For null-intersection-avoidance, the strongest-RSS beacon is used to increase the reliability that the normal node is in the winner region. Further, when unavoidable RSS-inconsistency occurs, we reduce the effect of RSS-inconsistency and keep the useful results by grid weight resetting and narrowing down the bounding box. According to the experiment, our scheme is applicable to real sensors and has low localization error (i.e., 0.34×communication radius). According to the simulation results in NS-2, our scheme has better performance than existing range-free localization schemes.

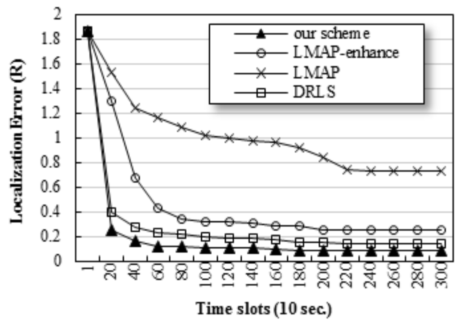
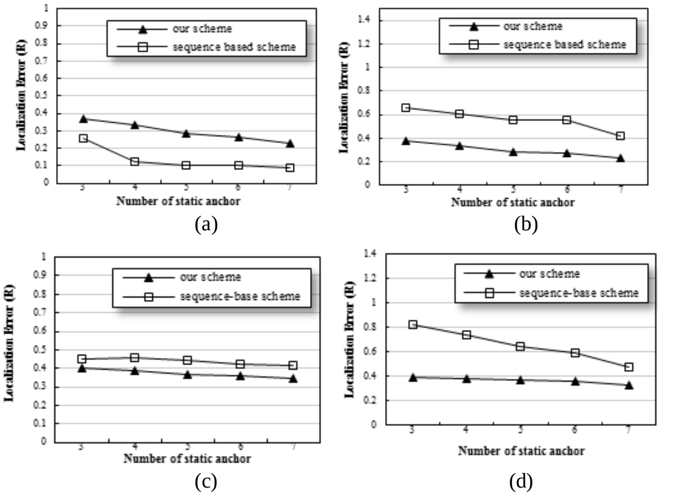


Figure 8. Localization error in regular communication range environments.



(a) (b)

(c) (d)

Figure 9. Localization error in static anchor environments. (a) Network size $R\times R$ and DOI =0. (b) Network size $3R\times 3R$ and DOI =0 (c) Network size $R\times R$ and DOI =0.7. (d) Network size $3R\times 3R$ and DOI =0.7.

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