IPSJ SIG Technical Report
Vol.2010-SLDM-144 No.13
Vol.2010-EMB-16 No.13
Vol.2010-MBL-53 No.13
Vol.2010-UBI-25 No.13
2010/3/26

A Study on Localization Performance for Heterogeneous TOA/RSS Networks

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Wireless sensor networks are emerging products for supporting various ubiquitous applications such as automatic monitoring and energy saving control. In such sensor networks, localization technique is important technique to estimate a number of sensors' locations automatically. Most localization techniques assumed to use single ranging method. In this paper, we present a localization technique using time-of-arrival (TOA) and received signal strength (RSS) methods in wireless sensor networks.

1. Introduction

Due to the recent advance in micro electro mechanical systems (MEMS) technique, wireless sensor networks makes a reality and currently receives much attention. In sensor networks, the position of each sensor nodes is important for knowing the location of sensing event or applications such as environment monitoring and navigation. Global positioning system (GPS) is a simple solution to know the node location. However, GPS is not available when the sight to GPS satellite is obstructed such as inside buildings and when the cost of each node is limited. In such cases, localization technique will be important technique to estimates node positions autonomously. Much research on the localization to estimate node positions for multi-hop networks has been conducted.

Localization technique consists of distance measurement (ranging) and position estimation. For distance measurement, time-of-arrival (TOA), angle-of-arrival (AOA), and the received signal strength (RSS) can be employed. TOA measurement enables to estimate distance by detecting the delay of the first arrival signal transmitted from a node. For the TOA measurement, an ultra-sound, wideband pulse transmission and ultra-wide band (UWB) ranging technique which recently standardized in the documentation of IEEE 802.15.4a [1] can be used.

In this paper, we develop localization algorithms for heterogeneous TOA/RSS networks. In the heterogeneous TOA/RSS networks, nodes equipped with TOA and RSS ranging capabilities (TOA/RSS nodes) and nodes equipped with RSS ranging capabilities (RSS nodes) are assumed. The heterogeneous TOA/RSS network enables to design flexible node deployments of TOA and RSS nodes according to localization costs and accuracy requirements. In the heterogeneous TOA/RSS networks, we propose two localization methods of iterative scaling by majorizing a complicated function (I-SMACOF) and hierarchical iterative SMACOF (HI-SMACOF). The performances were validated by using a simulation. The simulation results demonstrated that the proposed HI-SMACOF achieves superior performances compared with other conventional localization methods.

This paper is organized as follows. Related work is presented in Section 2. The proposed localization methods are described in Section 3. The performance evaluation is presented in Section 4. Section 5 concludes the paper and mentions future work.

2. Related Work

The motivation of developing localization technique is to know a number of node positions autonomously with a small number of anchor nodes which positions are known in advance. Much research on the multi-hop localization technique has been discussed in the literature. In [2,5,7], localizations without ranging devices have been proposed. For a precise localization, we focus on a localization using ranging devices. In [3], estimating large number of node positions is conducted by using a multilateration iteratively. In [11], robust trilateration using a rigidity of graph theory for a flipping avoidance has been proposed. In Sweep [8], to estimate the node positions without a flipping as possible for sparse node networks, algorithms to identify a global rigid was employed.

Some of the research applied a multidimensional scaling (MDS) to a multi-hop localization technique. The MDS is a statistical technique used to analyze the

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proximity data in multidimensional space. The proximity matrix constructed by using node distances can be transformed to the coordinate system by using MDS. In [6], MDS-based localization was presented. In dwMDS [9], the weighted version of MDS and the weight assignment corresponding to the properties of measurement noise were proposed.

For heterogeneous sensor networks with TOA and RSS nodes, localization technique using TOA and RSS ranging information has been proposed [10]. Since the localization starts with TOA nodes, sufficient number of TOA nodes is required.

3. Localization for Heterogeneous TOA/RSS Networks

3.1 System overview

In heterogeneous TOA/RSS networks, two types of nodes are co-existed. One node is the RSS node that equip with RSS ranging capability. The other node is the TOA/RSS node that equip with TOA and RSS ranging capabilities. TOA/RSS node can communicate both TOA/RSS node and RSS node.

The objective of constructing heterogeneous TOA/RSS networks is to use TOA and RSS nodes for a localization. In the most existing localization architectures, localization methods that use only single ranging methods such as TOA and RSS were developed. Although localization using only TOA nodes achieves precise positioning accuracy, it requires a cost hardware for each node. The localization accuracy using RSS nodes is typically not accurate. The localization method using RSS nodes only requires a radio communication capability, hence it is a low cost solution.

The heterogeneous TOA/RSS network enables to use both TOA and RSS nodes. Hence, the network provides a flexible selection of using TOA and RSS nodes according to localization costs and accuracy requirements.

3.2 Iterative SMACOF (I-SMACOF)

To investigate the impact of localization accuracy in a heterogeneous TOA/RSS network, we first propose a iterative SMACOF (I-SMACOF) method. SMACOF is a majorization method for minimizing the stress function $S = s(X)$ for the weighted metric of MDS [13]. A network is considered as a graph, $G = (V, E)$, where V is a set of nodes, and E is a set of wireless links between $\{i, j\}$, and where $i, j \in V$. The stress function is written as

$$s(X) = \sum_{i<j} w_{ij}(d_{ij}(X) - \delta_{ij})^2. \tag{1}$$

The inequality $i < j$ in the equation (1) means that we assume that the ranging information are asymmetric. δ_{ij} is observed ranging information. $d_{ij}(X)$ is estimated distance information from estimated position matrix X. w_{ij} is the weight parameter for representing the predicted accuracy of the ranging information. The position matrix of X can be obtained by minimizing the S. To cope with the localization in a multi-hop network by using SMACOF, following procedures were developed.

(1) **Collecting TOA and RSS ranging information:** Each node measures the distance to other nodes within its communication range and collects TOA and RSS ranging information.

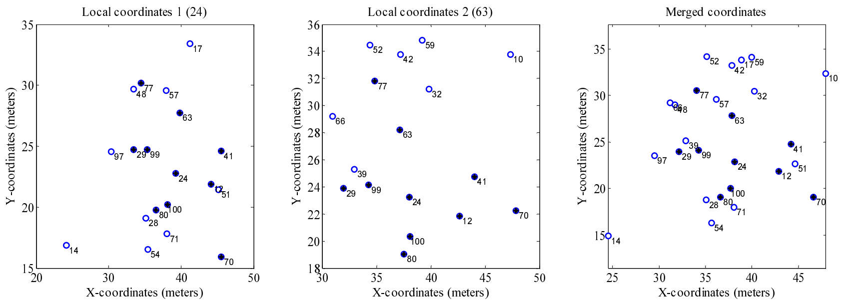
(2) **Applying SMACOF with TOA and RSS ranging information:** Each node applies SMACOF to generate local coordinates within one-hop neighbor nodes by using both TOA and RSS ranging information.

(3) **Iterative merges of local coordinates:** Each local coordinates are collected and iteratively merged based on the shared nodes into one set of coordinates.

In the step (1), nodes conduct distance estimation. Each node connects to the nodes within its communication range. The node conducts ranging between nodes and obtains the distance information. In the step (2), nodes apply SMACOF to estimate node positions within one-hop neighbor nodes. In the SMACOF algorithm, distance information from all nodes is required. The all pairs of node distances are calculated by using shortest path distance. In the equation (1), the weight parameter according to accuracy of distance information can be provided. We give the weight parameter w_{ij} as follows.

$$w_{ij} = \begin{cases} 1/(\delta_{ij} h_{ij}), & \text{if } \delta_{ij} \text{ is RSS} \\ 1/h_{ij}, & \text{if } \delta_{ij} \text{ is TOA} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

In the equation (2), h_{ij} represents the number of hop between nodes. The multi-hop node distance of shortest path distance is not accurate. Hence, the



(a) (b) (c)

Fig. 1 Merging process between two local coordinates. Estimated node positions are represented by circles. The shared nodes are represented by asterisks. (a) and (b) show estimated local coordinates for nodes "24" and "63" generated by using SMACOF. (c) shows merged coordinates based on the shared nodes.

$1/h_{ij}$ is multiplied in the weight. An accuracy of RSS ranging goes wrong when a node distance is farther [12]. The $1/\delta_{ij}$ is multiplied in the RSS weight.

The SMACOF algorithm gives the local coordinate that represents a relative node positions within one-hop nodes. Each set of local coordinates are iteratively merged into one set of coordinates based on the shared nodes. The merging process is as follows. The orientation of each local coordinates generated by SMACOF is arbitrary determined. The orientation is determined based on shared nodes that share same coordinates between two local coordinates. We used a Procrustes analysis [13] to get the orientation. Fig. 3.2 shows a snapshot of a merging process between two local coordinates. Figs 3.2(a)(b) show the local coordinates generated by using SMACOF. Two sets of local coordinates are merged based on shared nodes. The coordinates that are not shared in the two coordinates are added and the coordinates of shared nodes are averaged. The merging process is iteratively conducted until the all nodes in a network are included.

3.3 Hierarchical Iterative SMACOF (HI-SMACOF)

We next developed a hierarchical iterative SMACOF (HI-SMACOF). HI-SMACOF is a hierarchical version of I-SMACOF. The drawback of I-SMACOF is that TOA ranging information is only once utilized to estimate node positions with the RSS ranging information. In HI-SMACOF, the TOA ranging information is further utilized to refine the node positions. HI-SMACOF is operated as follows.

(1) **Collecting TOA and RSS ranging information:** Each node measures the distance to other nodes within its communication range and collects TOA and RSS ranging information.

(2) **Applying SMACOF with TOA and RSS ranging information:** Each node applies SMACOF to generate local coordinates within two-hop neighbor nodes by using both TOA and RSS ranging information.

(3) **Applying SMACOF with TOA ranging information:** Each node applies SMACOF to generate local coordinates within one-hop neighbor nodes by using TOA ranging information.

(4) **Iterative merges of local coordinates:** Each local coordinates are collected and iteratively merged based on the shared nodes into one set of coordinates.

(5) **Scaling coordinates from anchor nodes:** When anchor nodes are existed in a network, overall coordinates is scaled based on the positions of anchor nodes.

In the step (2), the local coordinates are generated by using SMACOF with TOA and RSS ranging information within two-hop. Next in the step (3), each node generates the local coordinates by using SMACOF with only TOA ranging information within one-hop. Each set of local coordinates generated in the step (2) is merged with the local coordinates with TOA ranging information. This merging process is conducted for all two-hop TOA nodes. In the step (4), the local coordinates are iteratively merged into one set of coordinates in the network as well as I-SMACOF. In the step (5), one set of coordinates can be scaled based on the positions of anchor nodes.

4. Performance Evaluation

4.1 Simulation assumptions

The developed localization algorithms for heterogeneous TOA/RSS networks were evaluated by using a simulation. The RSS measurement is modeled as [12]

$$P_r = P_t - 10n_p \log_{10}(d/d_0) + X_\sigma. \qquad (3)$$

P_t (dBm) is the received signal strength at reference distance d_0. d is the actual

Table 1 Simulation parameters.

Parameter	Value
n_p	3.0
P_t	-63.0 – -51 (dBm)
σ_{dB}	6.0 (dB)
Receiver sensitivity	-85.0 (dBm)
σ_v	0.25 (m)

distance. X_σ is zero-mean Gaussian distribution with variance σ_{dB}, and n_p is path loss exponent determined in the measurement environment [12]. The TOA measurement for line-of-sight is modeled as

$$\hat{r} = d + n, \tag{4}$$

where $n \sim \mathcal{N}(0, \sigma_v)$. The noise in TOA measurement is modeled as zero-mean Gaussian distribution $\mathcal{N}(0, \sigma_v)$ with variance σ_v. Table 1 shows the simulation parameters used in the simulation experiments.

For the metric of localization performance, we used the root mean squared error (RMSE) defined as

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2}, \tag{5}$$

where (x_i, y_i) represents the actual position of node i, and $(\hat{x}_i, \hat{y}_i)$ is the estimated position. Field size of a network is 50 × 50 (meters). The communication range is given by the equation (3). TOA ranging coverage is assumed to be identical to RSS ranging coverage. Simulation trials were conducted 40 times with random seeds and these were averaged. The 95% confidence intervals were plotted.

4.2 Impact of number of TOA and RSS nodes

The impact of the number of TOA and RSS nodes for I-SMACOF is evaluated. Fig. 2 shows an example node deployments of heterogeneous TOA/RSS networks when 100 nodes are randomly deployed. Fig. 3 shows a connectivity relationship between TOA connectivity and RSS connectivity. TOA connectivity is the average number of nodes that TOA nodes connect to other TOA nodes within one-hop in a network. RSS connectivity is the average number of nodes that TOA/RSS and RSS nodes connect to other TOA/RSS and RSS nodes within one-hop in a network. The TOA and RSS connectivities are increased by increasing the P_t.

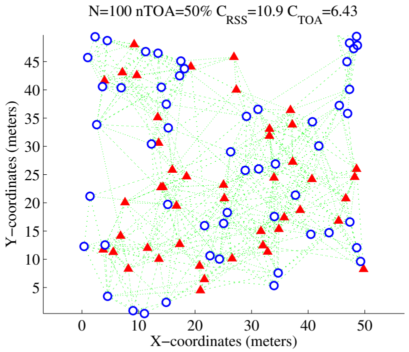


Fig. 2 Example topology of heterogeneous TOA/RSS networks. TOA/RSS nodes are represented by triangles. RSS nodes are represented by circles.

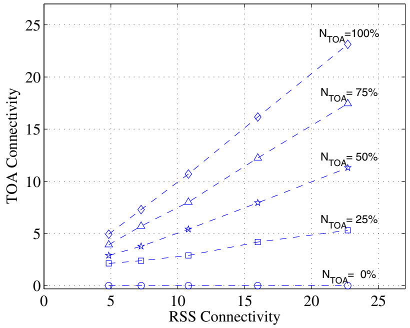


Fig. 3 The connectivity relationship between RSS connectivity and TOA connectivity.

Fig. 4 shows average RMSE of I-SMACOF for varying the number of TOA nodes. The ratio of the number of TOA nodes of all nodes were varied from 0% to 100%. 100 nodes were randomly deployed and 5 anchor nodes were randomly selected. As shown in Fig. 4, I-SMACOF was best performance when the ratio of number of TOA nodes was 100%. When the ratio of TOA nodes was decreased, the RMSE was increased. The result suggests that using only TOA nodes has advantage to obtain an accurate localization. However, there were cases that RMSE of I-SMACOF for 100% TOA nodes was larger when it compares RMSE of I-SMACOF of larger RSS connectivities. For example, when RMSE of I-SMACOF for 100% TOA nodes when TOA (i.e., RSS) connectivity was 5 was larger than the RMSE of I-SMACOF for 0% TOA nodes when RSS connectivity was over 10.

The reason that RMSE of I-SMACOF had poor performance is that I-SMACOF has a flipping of merging local coordinates when the connectivity is small. RMSE of each local coordinates generated by SMACOF for varying the number of TOA nodes was plotted in Fig. 5. The local coordinates of SMACOF for 100% TOA nodes were best performance regardless of the connectivities. Fig. 6 shows an

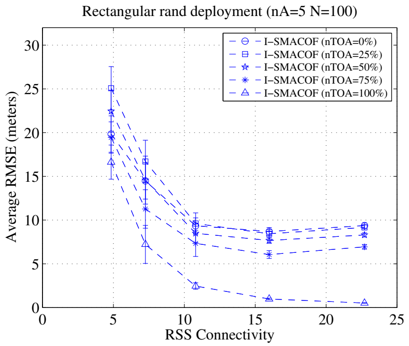


Fig. 4 Average RMSE of I-SMACOF for varying the number of TOA nodes.

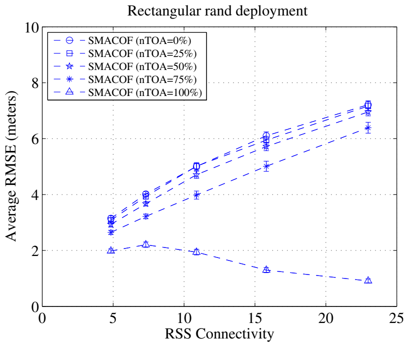
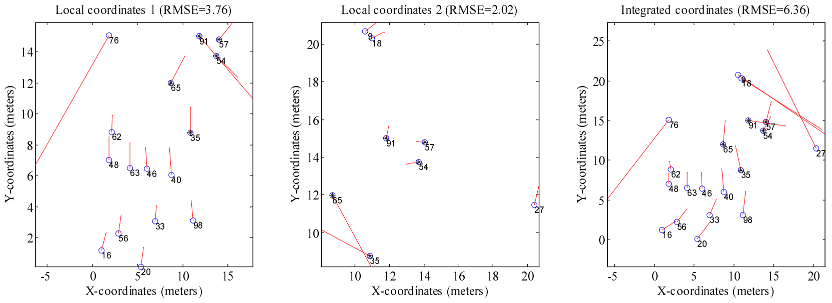


Fig. 5 Average RMSE of local coordinates generated by using SMACOF for varying the number of TOA nodes.



(a) (b) (c)

Fig. 6 Error propagation incurred by a flipping problem. Estimated node positions are represented by circles. The shared nodes are represented by asterisks. The errors are represented by solid lines. (a) and (b) show estimated local coordinates for nodes. (c) shows merged coordinates based on the shared nodes.

example of error propagation incurred by a flipping problem. The estimated positions of nodes “54”, “91” in Fig. 6(a) were wrongly located at the bottom of “65”. When the two sets of coordinates were merged into one set of coordinates based on the flipped shared nodes, the merged coordinates have wrong orientation of the coordinates. Once the flipping is happed, the errors are expanded [11].

A solution to avoid the flipping problem is to increase the number of nodes in local coordinates. When the number of nodes is increased, the number of shared nodes in the step of merging local coordinates is increased. The possibilities of flipping are then reduced.

Using only TOA nodes provides an accurate localization. However, it has possibilities of flippings in a multi-hop localization environment. In heterogeneous TOA/RSS networks, TOA nodes can use RSS nodes to increase the connectivity. In HI-SMACOF, nodes first generate local coordinates by using TOA and RSS nodes in order to avoid the flipping. Nodes then refine local coordinates by using TOA ranging information as described in Section 3.3.

4.3 Performance comparisons

The performance of proposed I-SMACOF and HI-SMACOF are compared with other localization methods. We implemented an iterative trilateration (I-TL) and hierarchical iterative trilateration (HI-TL) [10]. I-TL is the method node conducts a trilateration to unknown node from anchor nodes. Once the node is estimated its positions, it is configured as pseudo-anchor nodes to join a localization. HI-TL is the method that TOA nodes first estimate unknown TOA node positions by using a trilateration. The TOA nodes then estimate remaining RSS node positions in a network.

Fig. 7 shows localization results for I-SMACOF and HI-SMACOF when the number of TOA nodes is 0%. The estimated node distances of I-SMACOF were shorter than actual node distances. This is because the multi-hop node distance is approximated by using shortest path distance. Node distances of coordinates generated by using SMACOF tend to be shorter.

Fig. 8 shows average RMSE for various connectivities when the number of TOA nodes is 0%. The performance of HI-SMACOF outperformed the I-SMACOF. This is because scaling coordinates based on anchor nodes improves the multi-hop localization performance.

Fig. 9 shows average RMSE for various connectivities when the number of TOA nodes is 25%. The RMSE of HI-SMACOF outperformed the other methods regardless of various connectivities. This is because HI-SMACOF utilizes TOA ranging information after determining the local coordinates with RSS and TOA nodes.

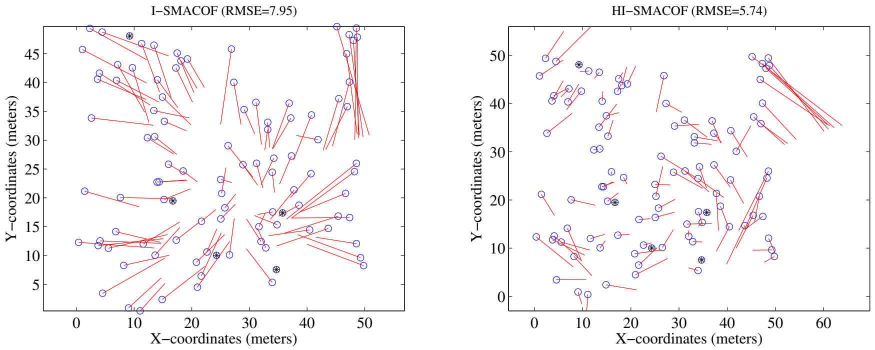


Fig. 7 Localization results for I-SMACOF (left) and HI-SMACOF (right) when the number of TOA nodes is 0%. The actual RSS node positions are represented by circles. The anchor nodes are represented by asterisks. The errors are represented by solid lines.

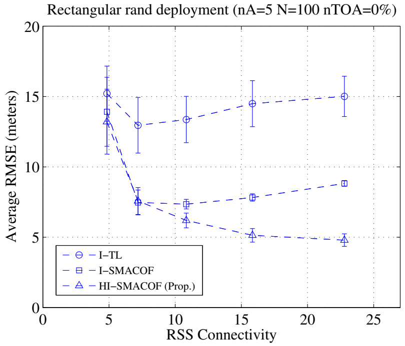


Fig. 8 Average RMSE for various connectivities when the number of TOA nodes is 0%.

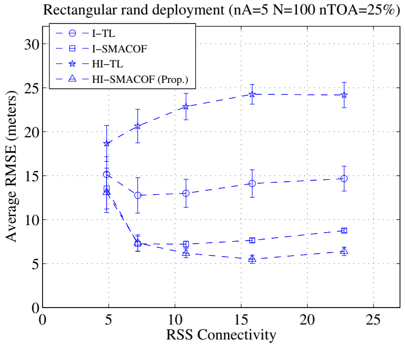


Fig. 9 Average RMSE for various connectivities when the number of TOA nodes is 25%.

Fig. 10 shows localization results for HI-TL and HI-SMACOF when the number of TOA nodes is 50%. Fig. 11 and Fig. 12 show average RMSE for various connectivities when the numbers of TOA nodes are 50% and 75%. The HI-SMACOF was proven to be accurate than other methods.

Fig. 13 shows average RMSE for various connectivities when the numbers of TOA nodes are 100%. RMSE of HI-SMACOF slightly better than I-SMACOF. The result suggests that updating coordinates of TOA ranging information provides a benefit for a localization.

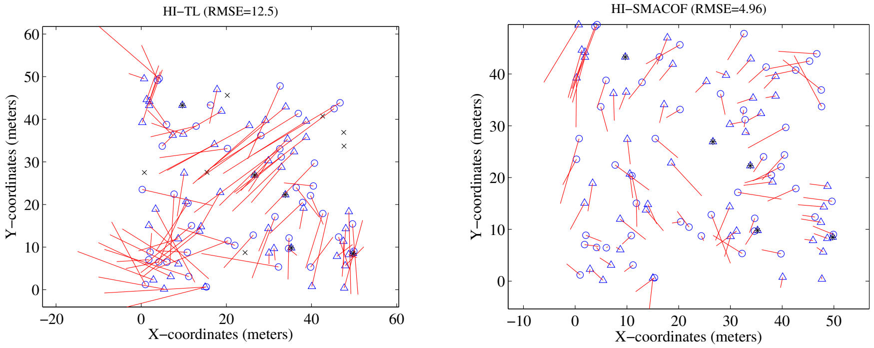


Fig. 10 Localization results for HI-TL (left) and HI-SMACOF (right) when the number of TOA nodes is 50%. The actual RSS and TOA node positions are represented by circles and triangles. Unlocalized node represents cross. The anchor nodes are represented by asterisks. The errors are represented by solid lines.

Fig. 14 shows the ratio of localized nodes when the number of TOA nodes is 25%. The ratio of localized nodes was the number that nodes could estimate node positions. HI-TL had low ratio of localized nodes. The RSS nodes may not connect to at least three TOA nodes in heterogeneous TOA/RSS networks. In such case, HI-TL cannot localize RSS nodes. HI-SMACOF had 100% ratio of localized nodes. HI-SMACOF starts with localization by using TOA and RSS nodes. Therefore, HI-SMACOF completed the localization for all nodes in heterogeneous TOA/RSS networks.

5. Summary

We proposed I-SMACOF and HI-SMACOF that achieve localizations in heterogeneous TOA/RSS networks. HI-SMACOF utilizes TOA and RSS nodes to increase the number of nodes in local coordinates. Using RSS nodes to increase the connectivity gives a benefit to avoid the flipping problem in a multi-hop localization environment. HI-SMACOF also take an advantage of accurate TOA ranging information by updating local coordinates with TOA ranging informa-

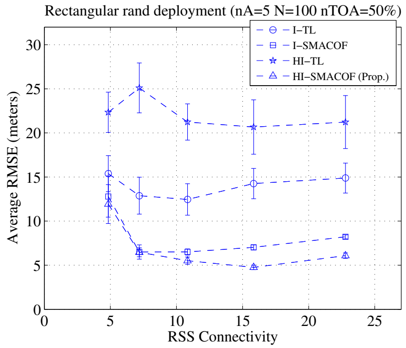


Fig. 11 Average RMSE for various connectivities when the number of TOA nodes is 50%.

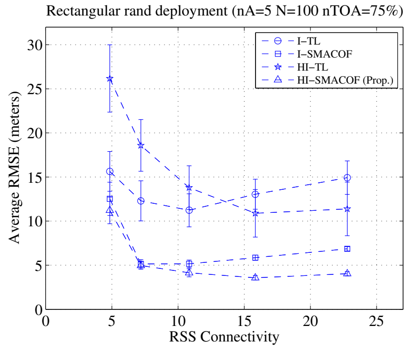


Fig. 12 Average RMSE for various connectivities when the number of TOA nodes is 75%.

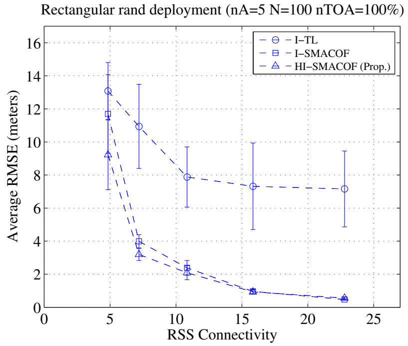


Fig. 13 Average RMSE for various connectivities when the number of TOA nodes is 100%.

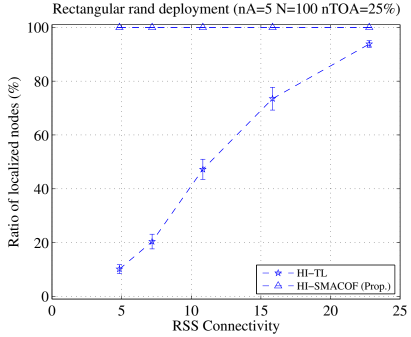


Fig. 14 Ratio of localized nodes for various connectivities when the number of TOA nodes is 25%.

tion.

The performances of proposed I-SMACOF and HI-SMACOF were compared with other localization methods. Simulation results demonstrated that HI-SMACOF outperformed other localization methods.

In this work, performance with node deployments in a non-convex network was not evaluated. The localization performance in non-convex network will be discussed in a future report.

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