Optimized Link State Routing-based Localization for Dense Irregular Sensor Networks

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ABSTRACT

Sensor localization obtained by estimating node positions is an essential technique for wireless sensor networks. Anchor-free localization (AFL) can estimate node positions without anchor nodes. However AFL does not work in an irregular networks. In this paper, we present an optimized link state routing (OLSR) -based localization (ROULA) that achieves desirable performance in dense irregular sensor networks. ROULA is compatible with OLSR protocol and is suitable for dense sensor networks. In addition, ROULA requires less computational complexity except for a sink node merging local coordinates. We present characteristics of the multipoint relay (MPR) selection and the farthest 2-hop node selection used in ROULA and describe how these node selections contribute to reducing the distance error for the localization scheme without ranging devices. Using a simulation, we evaluated the performance of ROULA and found that it was effective in dense irregular sensor networks.

Keywords: Anchor-free, dense irregular sensor networks, localization, MPR selection

1 Introduction

The recent progress in MEMS (Micro Electro Mechanical Systems), embedded systems, and low power wireless communication technology could make sensor nodes a reality. A number of sensor nodes could form a sensor network autonomously by communicating with other sensor nodes. In sensor networks, sensor nodes, shortly nodes, could report various data to observers, such as temperature, light intensity, and infrared signals, relieving human beings of these tasks. For example, sensor networks could be applied to disaster relief, tracking objects, security, and environmental monitoring. In these sensor network applications, the positions of sensor nodes are important because their positions direct where sensing data is collected.

Recently, research is being conducted on how to obtain node positions[1]–[4]. Most localization schemes assume anchor nodes with known positions or that nodes are equipped with ranging devices, such as angle sensing or ultra-sound ranging devices. An anchor node requires GPS (Global Positioning System) or manual positioning, and nodes equipped with ranging devices forces extra cost for sensor networks. Hence, using anchor nodes or installing ranging devices is not appropriate for dense sensor networks.

In this paper, we consider an anchor-free localization scheme that does not require anchor nodes and extra ranging devices. Anchor-free localization (AFL) [5], [6] does not require anchor nodes, and can obtain node positions without ranging devices. However, AFL has an issue in that it cannot work in irregular networks.

Here, we present an optimized link state routing (OLSR) -based localization (ROULA) that achieves desirable performance in dense irregular sensor networks. This paper has the following contributions. First, we present ROULA that is compatible with OLSR protocol and is suitable for dense sensor networks. Each node in ROULA requires less computational complexity than that $O(n^3)$ of MDS-MAP(P) [9] except for a sink node merging local coordinates. Second, we analyze the multipoint relay (MPR) selection and the farthest 2-hop node selection used in ROULA, and expose the relationship between connectivity, which shows how many nodes connect to other nodes in 1-hop on average, and its node distance. The analysis reveals the characteristics of the MPR selection and the farthest 2-hop node selection that contribute to reducing the distance error for the localization scheme without ranging devices.

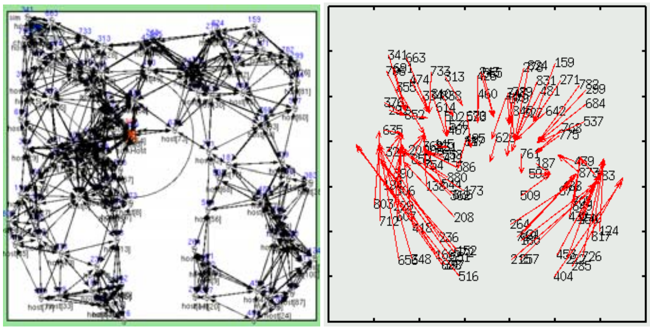
This paper is organized as follows. Related work is reviewed in Section 2. ROULA is described in Section 3. Section 4 presents characteristics analysis of the MPR selection and the farthest 2-hop node selection. Our performance evaluation of ROULA is described in Section 5. Section 6 summarizes the paper and mentions future work.

2 Related work

2.1 Anchor-free localization scheme

N. Priyantha, *et al.* first proposed an anchor-free localization scheme [5] that does not require anchor nodes. AFL has two phases: The first phase estimates node positions roughly without ranging devices, and the second obtains more accurate node positions with ranging technique. In the first phase, AFL selects five nodes that represent x, y axes and the center of the network. Using these five nodes as reference nodes, AFL estimates all other node positions and assigns them relative coordinates with the formula specified in [6].

Several authors [7], [8] have proposed using multidimensional scaling (MDS) to estimate node position. MDS can



(a) Topology (b) Result

Figure 1: Example of irregular network and node positions without ranging information in AFL

also obtain node positions without anchor nodes. Moreover, MDS-MAP(P)[9] localizes nodes in C-shaped networks by having all nodes apply MDS to some small-sized hops. The research motivation and background of MDS-MAP(P) is similar to those of our work. However, all nodes in MDS-MAP(P) are forced to have the computational complexity of $O(n^3)$ except for merging local coordinates, where n is the number of nodes to which MDS is applied. This constraint is such that nodes in dense sensor networks are forced to have much computational complexity and to consume much energy.

2.2 Issue in AFL

As described in the previous section, AFL does estimate node positions correctly in a regular network. However, when the first phase of AFL is applied to an irregular network, the node positions AFL obtains do not correspond to the actual network topology. Here, we define a regular network as one in which the maximum shortest hop distance is a geographically straight path, and an irregular network as one in which the maximum shortest hop distance is not a geographically straight path. Figure 1(a) presents an actual network topology of an irregular network showing an obstruction exists in the middle of the field. Figure 1(b) gives the result of node positions without ranging information in AFL. The positions of the numbers denote the actual node positions, and the arrows indicate the length of the errors from actual node positions to the estimated positions. This incorrect result occurs because the shortest hop-count path between nodes is always configured as a straight path regardless of its actual geographical form even if the path is not straight.

3 OLSR-based localization (RouLa) for dense irregular sensor networks

3.1 Overview

As a solution to the issue stated in Section 2.2, we present ROULA for dense irregular sensor networks. Figure 2 is a conceptual representation of ROULA in irregular sensor networks. An irregular network appears irregular if the network is seen from a global point of view. However, if the network viewed locally, each small-hop network appears regular. In

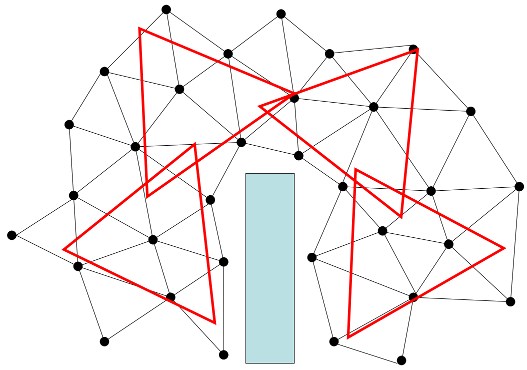


Figure 2: Conceptual representation of ROULA in irregular sensor networks

other words, an irregular network is composed of locally regular networks.

Nodes in ROULA find the combinations of regular triangles that make up an exactly regular network, then they obtain correct coordinates even in irregular networks by merging these regular triangles. With the aim of finding regular triangles in ROULA, first each node selects the farthest 2-hop nodes from itself. Second, nodes flood packets to the farthest 2-hop nodes. Third, nodes match 2-hop sized regular triangles. Finally, a sink node collects local coordinates in the network, and merges all local coordinates into global coordinates.

Here, we note the following distinct aspects of ROULA.

- **Suitability for dense sensor networks:** ROULA employs MPR nodes optimized by the MPR selection in OLSR protocol. OLSR is effective for reducing energy consumption, especially in dense node networks. In addition, MPR selection has the inherent characteristics of reducing distance error in localization for sensor networks, and it is effective in dense node networks as revealed in this paper. These characteristics make ensure ROULA suitable in dense sensor networks.

- **Compatibility with OLSR protocol:** Nodes in ROULA assume to have OLSR protocol in the network layer, and they select MPR nodes to localize their 1-hop nodes without any modification in MPR selection. Therefore, flooding Hello packets and computational complexity of the MPR selection can be saved by using underlying network layer process.

- **Less computational complexity:** Each node in ROULA requires computational complexity of $O(M_2 M_1^2)$ except for merging local coordinates, where M_n denotes the number of shortest n-hop nodes. Thus, ROULA requires less computational complexity in comparison with the $O(N_2^3)$ in which MDS is limited to 2-hop nodes, where N_n is the number of n-hop nodes.

We discuss the remarkable perspectives of ROULA. Nodes in ROULA employ OLSR developed for adhoc networks in the network layer. While OLSR is one of the standardized routing technique exactly in adhoc networks, nodes are expected to have the following benefits for using OLSR in sensor networks. Nodes in OLSR always hold 2-hop node information in the proactive action, and they update 2-hop node information automatically. Hence, nodes are easy to synchronize connectivity information to node localization even if network topology dynamically changes. Add that, since nodes hold the 2-hop nodes information in the network layer, they need not to have extra scheme to obtain 2-hop node information. This is an essential scheme for resource constrained node networks.

In this work, we have the following three assumptions. First, a sufficient number of 2-hop paths are in the network to make 2-hop sized regular triangles. Second, nodes are equipped with OLSR protocol in the network layer. Third, nodes know their length of the communication range.

3.2 Algorithm

ROULA is organized as described below.

1. **MPR selection:** Nodes flood Hello packets including own 1-hop nodes list to their 1-hop nodes. Once a node has 2-hop nodes list, it selects MPR nodes. The flooding complexity of Hello packets is $O(M_1)$. The computational complexity of the MPR selection is $O(M_2 M_1^2)$.

2. **Farthest 2-hop node selection:** Each Node selects the farthest 2-hop nodes for each MPR nodes from itself. The computational complexity of the farthest 2-hop node selection is $O(M_2 M_1)$.

3. **Making regular triangle:** Nodes flood TRI_NOTICE packets to their farthest 2-hop nodes with their farthest 2-hop nodes list. Then, nodes received TRI_NOTICE packets match regular triangles using received the farthest 2-hop nodes lists. Next, nodes get local coordinates by merging regular triangles if there are common nodes in regular triangles. The flooding complexity of TRI_NOTICE packets is $O(M_1)$ because the number of the farthest 2-hop nodes is approximately M_1 as described in Section 4.2. The computational complexity of matching regular triangles is $O(l \log_2 l)$, where l is the size of received farthest 2-hop node lists. The computational complexity of merging regular triangles is not higher than $O(N_2^3)$ since the number of regular triangles each node matches is not so many.

4. **Merging local coordinates:** A sink node floods MAP_REQ packets to all nodes in the network. Receiving nodes send back MAP_REP packets with their local coordinates. Once a sink node receives all local coordinates in the network, it merges them into global coordinates. Merging local coordinates in a sink node requires high computational complexity. However, we do not give a detailed description of merging local coordinates in this paper. We will describe them in a future report.

5. **Converting to absolute coordinates:** If at least three anchor nodes are in the network, relative coordinates can be converted into absolute coordinates that have correct network orientation. This phase is optional.

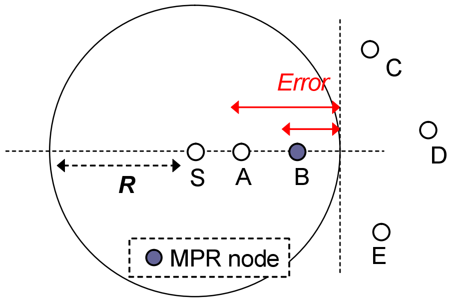


Figure 3: Distances of 1-hop nodes

Next, we give below the detailed motivation of employing MPR nodes and how nodes make regular triangles.

3.3 MPR selection

All nodes in ROULA must choose the candidates of 2-hop nodes out of all 2-hop nodes to make 2-hop regular triangles. However, which nodes should be chosen as 2-hop nodes ? Here, to make this problem simple, we consider the distance between source and 1-hop nodes instead of the 2-hop node distance. Figure 3 shows that node S with its communication range R has 1-hop nodes, nodes A and B. Assume that when a node knows the length of communication range, the node estimates 1-hop nodes without any ranging devices. The node should regard the distance between source and 1-hop nodes as R since it cannot measure the distance. Therefore, if node S in Fig. 3 chooses node B that is closer to the radio boundary rather than node A as a 1-hop node, the distance error would be smaller than that of choosing node A. For the purpose of finding the node that is close to its radio boundary, we introduce the MPR selection [10] used in OLSR.

The MPR selection was developed for optimizing the relaying 1-hop node in OLSR protocol. The MPR selection selects the MPR nodes that are the more covered 2-hop nodes for flooding, and this can reduce the number of redundant retransmission nodes. Consequently, MPR selection can find the nodes that are close to the radio boundary. For example in Fig. 3, $MPR(S)$ is node B, $MPR(u)$ is the set of MPR selected by node u.

Here we introduce some notations. Let denote the wireless network as a bidirectional undirected graph $G(V, E)$. Let $N(u)$ be the 1-hop nodes of node u. Let $N^2(u)$ define the 2-hop nodes of u. For a node $v \in N(u)$, let $d_u^+ u(v)$ be the number of nodes of $N_2(u)$ which are in $N(v)$: $d_u^+(v) = |N_2(u) \cap N(v)|$. For a node $w \in N_2(u)$, let $d_u^-(w)$ be the number of nodes covered by $N(v), v \in N(u)$: $d_u^-(w) = |N(u) \cap N(v)|$.

The algorithm for the MPR selection is described in Algorithm 1. As found in Algorithm 1, OLSR supports MPR redundancy by MPR_COVERAGE that ensures reachability for 2-hop nodes from MPR nodes. MPR_COVERAGE is specified by how many MPR nodes should cover 2-hop nodes. MPR_COVERAGE affects how many nodes can make regular triangles in ROULA because MPR_COVERAGE have the number of MPR nodes increase. In this paper, we do not describe the effectiveness of MPR_COVERAGE. Instead, we

Algorithm 1 MPR selection ($u \in V$)

for all nodes $v \in N_2(u)$ **do**
  if ($d_u^-(v) \leq$ MPR_COVERAGE) **then**
    Select v as $MPR(u)$
    ▷ *Select poorly covered node v as MPR*
    $N(u) \leftarrow N(u) - \{v\}$
    $N_2(u) \leftarrow N_2(u) - N(v) \cap N_2(u)$
while ($N_2(u) \neq \emptyset$) **do**
  for all nodes $v \in N(u)$ **do**
    if ($d_u^+(v) = \max_{w \in N(u)} d_u^+(w)$) **then**
      Select v as $MPR(u)$
      ▷ *Select the node v which covers the maximum number of $N^2(u)$ as MPR*
      $N(u) \leftarrow N(u) - \{v\}$
      $N_2(u) \leftarrow N_2(u) - N(v) \cap N_2(u)$

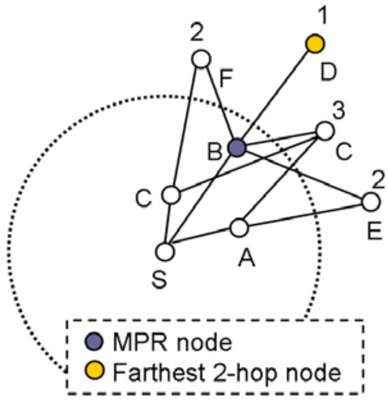


Figure 4: Relationship between source and 2-hop node distance.

preset MPR_COVERAGE as 3.

3.4 Farthest 2-hop node selection

Let $F2(u)$ be the set of farthest 2-hop nodes of node u. $F2(u)$ are the farthest in $N_2(u)$ from u for each $MPR(u)$. For the farthest 2-hop node selection, we use $d_u^-(w)$ determined in MPR selection. Note that nodes need not to have any connectivity information other than MPR selection in the farthest 2-hop node selection. In Fig. 4, each numbers above the nodes shows $d_S^-(w)$ or how many each 2-hop nodes are covered by $N(S)$. As shown in Fig. 4, if the node distance from node S is farther, such as nodes S and D, $d_S^-(w)$ is small. This is because in plane node density connectivity between 2-hop nodes and the source nodes is small when the node distance is farther. Based on this assumption, nodes select the farthest 2-hop nodes as described in Algorithm 2. For example in Fig. 3, $F2(S)$ is node D.

Algorithm 2 Farthest 2-hop node selection ($u \in V$)

for all nodes $v \in MPR(u)$ **do**
  if ($d_u^-(z)_{z \in N(v)-N(u)} = \min d_u^-(z)$) **then**
    Select z as $F2(u)$

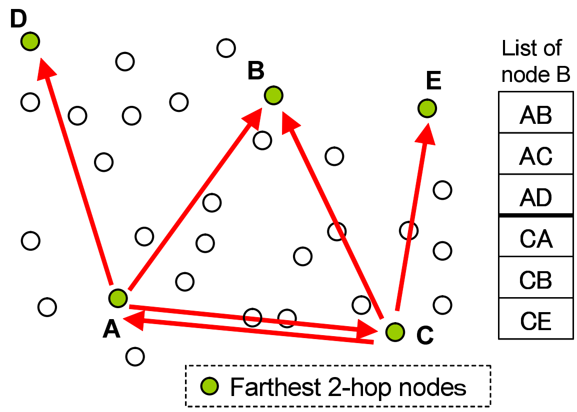


Figure 5: Illustration of matching regular triangles for node B. The list shows the received farthest 2-hop nodes list of node B after receiving TRI_NOTICE packets from node A, C

3.5 Making regular triangles

We illustrate how nodes are arranged into regular triangles in Fig. 5. Now, we focus on matching regular triangle ABC for node B. Each arrow in Fig. 5 shows the direction of farthest 2-hop nodes; for instance, node A has three farthest 2-hop nodes AB, AC, AD. Nodes A, B and C flood TRI_NOTICE packets to their farthest 2-hop nodes including their farthest 2-hop nodes list. The list in Fig. 5 shows the received farthest 2-hop nodes list of node B after exchanging TRI_NOTICE packets. Node B knows nodes A and C are the farthest 2-hop nodes. Next, node B finds two combinations of regular ABC triangles by matching AC and CA in the received farthest 2-hop nodes list. Regular triangles consist of the farthest 2-hop nodes and the MPR nodes. These nodes that comprise the regular triangles are given local coordinates as relative regular triangles; which is to say, the farthest 2-hop nodes are positioned at $Range \times 2$, and MPR nodes are positioned at $Range$, where $Range$ is the length of communication range.

4 Characteristics analysis

4.1 Characteristics of MPR selection

We verified the distance characteristic and the number of its nodes of MPR selection and the farthest 2-hop node selection described in Sections 3.3 and 3.4. We placed nodes randomly in a plane field and set the length of the communication range as 100 $[m]$. Figure 6 presents the numerical result of calculating the average distance of all 1-hop nodes and MPR nodes plotted with dots and its standard deviation plotted with a line. The result is plotted against connectivity.

As shown in Fig. 6, the average distance of MPR nodes is closer to 100 than that of all 1-hop nodes. Furthermore, the standard deviation of MPR nodes is smaller than that of all 1-hop nodes. These results demonstrate the MPR selection can select the nodes close to the radio boundary with small variance. Although the MPR nodes are closer to their radio

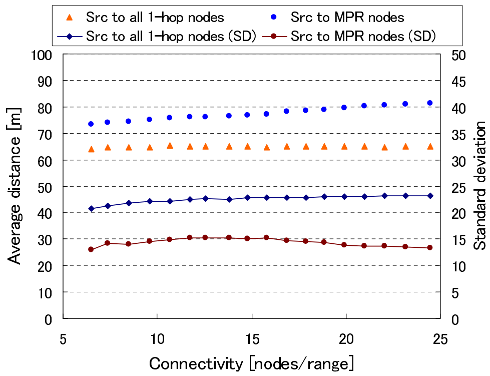


Figure 6: Average distance and standard deviation of 1-hop nodes and MPR nodes

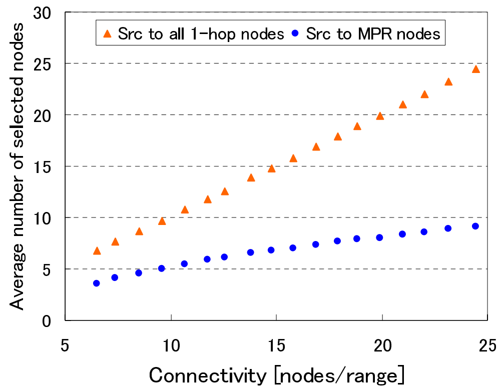


Figure 7: Average number of all 1-hop nodes and MPR nodes

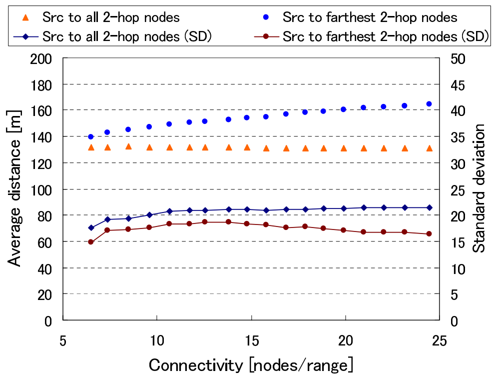


Figure 8: Average distance and standard deviation of all 2-hop nodes and the farthest 2-hop nodes

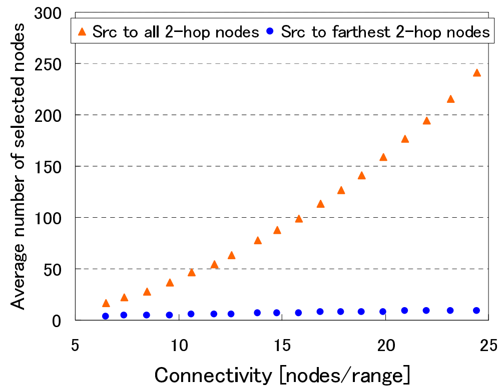


Figure 9: Average number of all 2-hop nodes and the farthest 2-hop nodes

boundary as the number of nodes increases, the average distance of MPR nodes never arrives at 100 even if connectivity is high enough. For this reason, we previously conducted linear approximations of the distances from source nodes to MPR nodes and the farthest 2-hop nodes, and used these distance approximations in making regular triangles.

Figure 7 presents the average number of MPR nodes and all 1-hop nodes per node. The MPR selection can reduce the number of 1-hop nodes significantly. This is a well known characteristic in OLSR, that of reducing redundant retransmission nodes. In ROULA, this characteristic contributes to reducing the number of the farthest 2-hop nodes.

4.2 Characteristics of farthest 2-hop node selection

The numerical result of the average distance of all 2-hop nodes and the farthest 2-hop nodes is given in Fig. 8. The average distance of the farthest 2-hop nodes is closer to 200 than that of all 1-hop nodes. Moreover, the standard deviation of the farthest 2-hop nodes is smaller than that of all 1-hop nodes. These results demonstrate that the farthest 2-hop node selection can select the nodes close to the 2-hop ahead radio boundary with small variance.

Figure 9 shows the average number of the farthest 2-hop nodes and all 2-hop nodes per node. The number of the farthest 2-hop nodes is same as that of MPR nodes. Therefore, the number of farthest 2-hop nodes is approximately M_1. This characteristic contributes to reducing the flooding complexity of TRI_NOTICE packets. Furthermore, the small number of farthest 2-hop nodes guarantees that the received farthest 2-hop node lists are small. For this characteristic, the computational complexity of matching regular triangles is less than the $O(N_2^3)$ of MDS as described in Section 3.2 3).

5 Evaluation

5.1 Simulation parameters

We evaluated the performance of ROULA in a simulator. Table 1 shows the simulation parameters of our simulation. We defined an obstruction $[height, width]$ in a way that shows its the size. We placed the obstruction $[height, width]$ in the middle of the field, and varied its $height$ to evaluate an irregular network. We fixed the $width$ of the obstruction as 100. We defined the positioning error as the average positioning error of all nodes and normalized this by the communication range. For the purpose of getting an absolute positioning error, we assumed three nodes that have minimum positioning error are anchor nodes. We assumed symmetrical link communication and a fixed communication range with no fluctuation.

Table 1: Simulation parameters

Field	500 $\times$ 500 [m]
Communication range	100 [m] (no fluctuation)
Number of nodes	60–180 (interval=10)
Deployment	Random (int-type distribution)
Obstruction $[height, width]$	$0 \leq height \leq 300$ (interval=100) $width = 100$ [m]

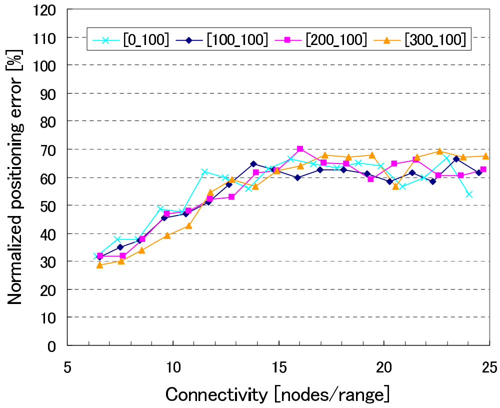


Figure 10: Normalized positioning error for the various obstruction scenarios

5.2 Simulation result

Figure 10 presents the results of normalized positioning error for the various obstruction scenarios. ROULA achieved almost less than 70% positioning error regardless of the obstruction size. The positioning error tended to be higher until the connectivity was 15. This is because the coverage showing the percentage of nodes that could localize became high, as is given in Fig. 11. Once connectivity is over 15, positioning error and coverage converge. We can see that ROULA can localize nodes regardless the obstruction size of an obstruction in a network.

Figure 11 gives the result of coverage for the various obstruction scenarios. The coverage is low when connectivity is low. This is because ROULA cannot find sufficient combinations of regular triangles in low density sensor networks. Thus, the coverage improves with increases in the number of nodes. The number of nodes contributes to increasing the common nodes in the phase of merging local coordinates for ROULA. The coverage achieved was almost 80–90% when connectivity was over 15; nevertheless, ROULA never achieved 100% even if connectivity was high enough. This is because ROULA does not localize all nodes in local coordinates. However, the coverage is expected to be 100% if nodes execute centroid positioning with computational complexity of $O(1)$ after finishing the sink node merging phase.

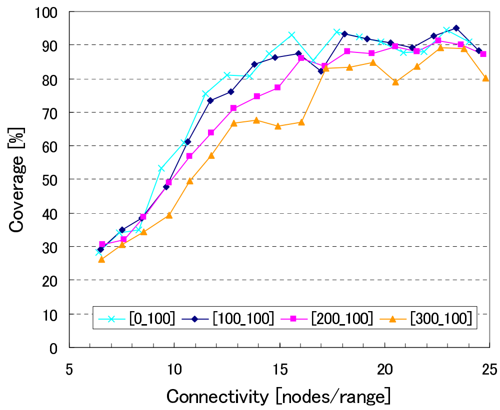


Figure 11: Coverage for the various obstruction scenarios

6 Summary and future work

In this paper, we presented ROULA, a localization technique that achieves desirable performance in dense irregular sensor networks. ROULA is compatible with OLSR protocol and is suitable for dense sensor networks. In addition, ROULA requires less computational complexity except for a sink node merging local coordinates. We revealed that MPR selection and the farthest 2-hop node selection have the characteristics of selecting the node that is closer to the radio boundary. Using a simulation, we evaluated the performance of ROULA and found that it was effective in dense irregular sensor networks. In this paper, we did not consider the computational complexity of a sink node merging local coordinates. This is to appear in a future report.

In future work, we are to release a performance analysis comparing ROULA with other localization techniques in a simulator.

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