Self-Organizing Localization for Wireless Sensor Networks Based on Neighbor Topology

Range-free localization with low dependence on anchor node

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***Abstract*—The localization of sensor nodes is one of the key issues for sensor network systems. Therefore, to obtain precise location information, several localization systems have been researched. However, they require an arranged space using a large number of anchor nodes whose locations are well known, or they need advanced information such as radio conditions in the space. Otherwise, the systems cannot be used for a space that cannot be arranged in advance with suitable conditions for these systems operation. Furthermore, some localizations assume the use of advanced distance measurements, such as TOA and TDOA, to achieve high accuracy in estimating locations, but these advanced distance measurement schemes cannot be used for ordinary sensor node systems. To resolve these problems, we propose Self-Organizing Localization for wireless sensor networks. Self-Organizing Localization requires no distance measurement scheme and no advanced information on a space; even then it reproduces a geometry nearly similar to the network's original geometry without anchor nodes, and it reproduces a geometry with two anchor nodes that is nearly congruent with the original. Furthermore, using just three anchor nodes, it estimates node absolute localization with high accuracy. Therefore, it can be applied to any space and any sensor node. In this paper, the algorithm of Self-Organizing Localization is described, and its accuracy based on simulation evaluation is shown.**

Keywords-localization; wireless sensor networks; self-organizing maps;

I. INTRODUCTION

To achieve advanced sensing services, technology that senses the environment with precise location information is indispensable. Therefore, several localization systems that obtain accurate location information have been researched. They are classified into range-based localization [1-6] and range-free localization [8-10]. Range-based localizations assume the use of advanced distance measurement schemes between sensor nodes, such as Time Difference Of Arrival (TDOA) schemes and Time Of Arrival (TOA) schemes. However, such distance measurement schemes are not used in ordinary sensor node systems because they are not suitable for sensor nodes whose functions should be minimized. Some localizations use a Received Signal Strength Indicator (RSSI), which can be used in ordinary sensor node systems; however, these systems require advanced information, and they must have radio condition information sets in the space so they can estimate location with high accuracy. On the other hand, range-free localizations do not need distance measurement schemes; however, to estimate location with high accuracy, they require an arranged space where a large number of anchor nodes are deployed. Some range-free localizations do not need anchor nodes, but they need advanced information on the probable network topology of the space. Therefore, range-free localization cannot be used for a space that cannot be sufficiently arranged in advance.

To resolve these problems, we propose Self-Organizing Localization (SOL) for wireless sensor networks. SOL needs no distance measurement schemes, no advanced information on the space, and its dependence on anchor nodes is very low. SOL achieves the following results by using Self-Organizing Maps (SOM) [14, 15]:

- Without anchor nodes, it reproduces a geometry nearly similar to the network's original geometry.
- With two anchor nodes, it reproduces a geometry nearly congruent with the original, that is, it derives relative node locations on the network.
- With just three anchor nodes, it derives absolute node locations with high accuracy.

According to the above properties, SOL can be applied to any space and any sensor node.

SOL is based on our original localization [13], which assumed an ad hoc network that consisted of many nodes whose locations were unknown and a few anchor nodes whose locations were well known. The localization also assumed a distance measurement scheme that uses an RSSI. SOL eliminates distance measurement schemes because of its application to any sensor node. Then, SOL controls SOM localization based on neighbor topology, which is expressed by hop count between nodes.

In this paper, the algorithm on SOL using SOM is described, and its accuracy based on simulation evaluation is shown. In the rest of the paper, Section 2 describes related work, and Section 3 presents the algorithm of SOL based on our original localization. Then, Section 4 presents the algorithm of SOL based on neighbor topology. Furthermore, Section 5 shows evaluation results for the SOL and discusses its characteristics regarding accuracy of the estimated location.

 ISBN: 978-1-61208-289-9

II. RELATED WORK

Node localizations are classified into range-based and range-free localizations. The typical range-based localizations are shown as follows. RADAR [1], Active Badge [2], and SpotON [3] have been proposed as location estimation methods that use an RSSI. RADAR requires space where radio wave propagation has been measured in advance. Since Active Badge and SpotON use an RSSI for sensing proximity to anchor nodes, these estimated locations have low resolution. Active Bat [4] and Cricket [7] have been proposed as location estimation methods using TDOA. Both estimate locations with high precision based on triangulation; however, they need a space arranged with a large number of TDOA devices. Iterative Multilateration [5] has been proposed as a location estimation method with a small number of anchor nodes; Dolphin [6] is a system that uses Iterative Multilateration. This method and system use triangulation to estimate location and propagate the estimated location to neighbor nodes. The method and system require highly precise distance measurements such as TDOA and suffer from location error that increases as estimated location propagation progresses.

On the other hand, typical range-free localizations are shown as follows. Centroid [8] estimates node location based on the centroid on three anchor nodes that the target node can communicate with directly. The centroid needs an arranged space in which a large number of anchor nodes are deployed. DV-Hop [9] proposed for location estimation using network topology, calculates average distance in 1 hop using communication between anchor nodes, and it estimates node location with the calculated average distance and the number of hops from the anchor node. It also requires a minimum of three anchor nodes. APIT [10] estimates node location based on the geometrical condition that a node can be inside or outside for multiple triangulation. The construction of APIT is based on a three-anchor-node unit, and thus it needs a large number of anchor nodes. These studies [11, 12] apply SOM to wireless localization and provide relative location without anchor nodes. However, they need a training set that leads SOMs to the proper map, and the training set is prepared with information on the space in advance. The accuracy of range-free localizations is very inferior to that of range-based localizations and is insufficient for many sensing services.

III. OUR ORIGINAL LOCALIZATION

Our original localization [13] reproduces network geometry using SOM. In SOM, the number and range of neighbor nodes are important metrics, and SOM converges when the number and range of neighbor nodes are reduced in accordance with a convex decreasing function [14]. In accordance with the above characteristics of SOMs, our original localization has the following two strategies to effectively use the measured distances between nodes.

- In the early phase, the algorithm uses the locations and distances of both 1- and 2-hop nodes and reproduces an inaccurate but characteristic network geometry by emphasizing the distance relation between nodes.
- In the next phase, the algorithm uses the locations and distances of 1-hop nodes and shapes the geometry to minimize distance errors between neighbor nodes.

Therefore, the number and range of neighbor nodes correspond to the hop count, and, in the early phase, the algorithm actively and widely accepts the neighbor location. Then, in the next phase, the algorithm selectively accepts the neighbor location. Furthermore, in order to need no advanced information on the space, the original applies SOM in the following way:

- The SOM input vector is dynamically generated by the location and distance of neighbor nodes.
- The SOM winner is the node that receives the input vector from a neighbor node.

The following explains the algorithm based on the above SOM strategies and applications.

[step 1] Each node generates a random location as its estimated location $w_i(t)$ and then broadcasts its location $w_i(t)$ to neighbor nodes, where t is the number of estimation steps.

[step 2] The node i receives the estimated location information from a neighbor node j; that is, node i, which is the SOM winner, modifies its estimated location $w_i(t)$ to draw near the input vector $m_i(t)$, which is the location estimated from location $w_j(t)$ of node j. The distance $d_{ij}(t)$ between nodes i and j is provided by the node distance measurement function. Therefore, a modified vector $V_i^{\{1\}}(t)$ that reduces $|m_i(t)-w_i(t)|$ is generated (see Fig.1(a)):

$$V_i^{\{1\}}(t) = \frac{d_{ij}(t) - |w_i(t) - w_j(t)|}{|w_i(t) - w_j(t)|}(w_i(t) - w_j(t)) \tag{1}$$

Furthermore, when the estimation is in the early phase, the input vector $m'_i(t)$ is generated using location estimates $w_k(t)$ from a 2-hop node k in a set of 1-hop nodes from neighbor nodes j and the sum of distances $d_{ij}(t)$ and $d_{jk}(t)$. Therefore, a modified vector $V_i^{\{2\}}(t)$ is generated in which the relation of the 2-hop node k is the following (see Fig.1(b)):

$$V_i^{\{2\}}(t) = \frac{d_{ij}(t) + d_{jk}(t) - |w_i(t) - w_k(t)|}{|w_i(t) - w_k(t)|}(w_i(t) - w_k(t)) \tag{2}$$

If the modified location $w_i(t)$ of node i by (1) and (2) is the location nearer to the 2-hop node k than to the 1-hop node j, that is, if $|w_i(t) - w_j(t)| > |w_i(t) - w_k(t)|$, then the input vector $m'_i(t)$ is the relocation estimated with locations $w_k(t)$ and $w_j(t)$. $d_{jk}(t)$, which is the distance between node i and node k, becomes larger than $d_{ij}(t)$ when node i is on the broken circular line in Fig.1(c), and the modified vector derived as node i is relocated to the center of the range on the broken circular line. Therefore, the modified vector $V_i^{\{2\}}(t)$ is the following (see Fig.1(d)):

$$V_i^{\{2\}}(t) = w_j(t) - w_i(t) + \frac{d_{ij}(t)}{d_{jk}(t)}(w_j(t) - w_k(t)) \tag{3}$$

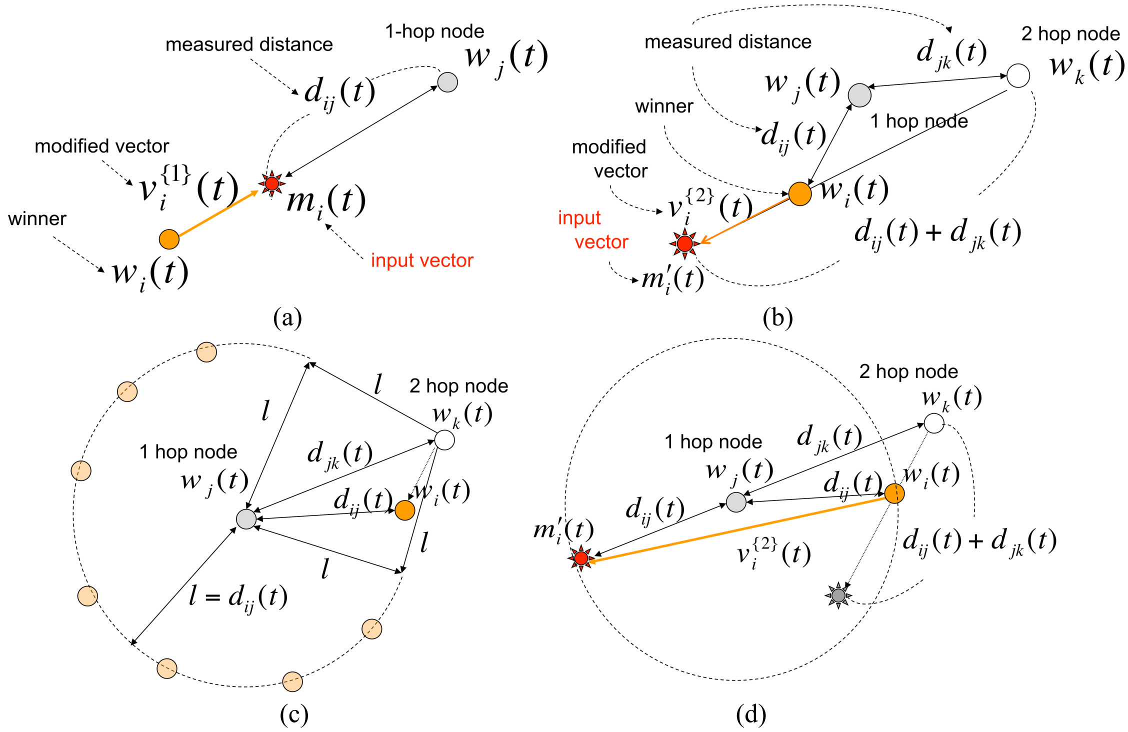

Figure 1. (a) Input vector, winner, and modified vector by 1-hop. (b), (c) and (d) Input and modified vectors by 2-hop.

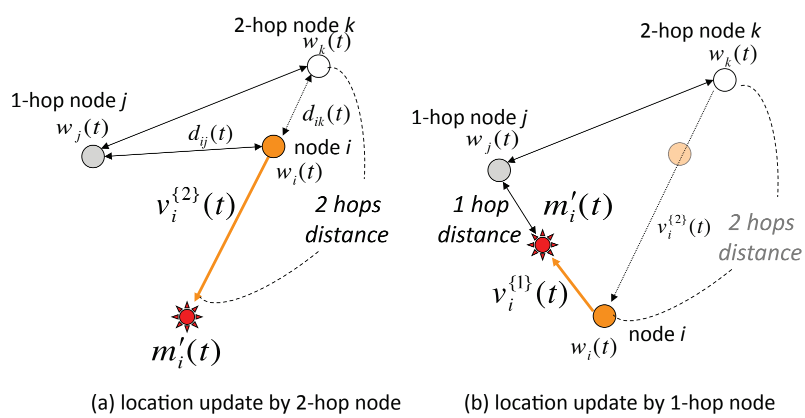

Figure 2. Input and modified vectors by 1-hop and 2-hop node on SOL.

Consequently, using $V_i^{\{1\}}(t)$ and $V_i^{\{2\}}(t)$, each node modifies and updates its estimated location as the following:

$$w_i(t+1) = \begin{cases} w_i(t) + \alpha_i \cdot (V_i^{\{1\}}(t) + V_i^{\{2\}}(t)) & t \le \tau \\ w_i(t) + \alpha_i \cdot V_i^{\{1\}}(t) & t > \tau \end{cases} \tag{4}$$

where τ is a phase threshold and $\alpha_i(t)$ is the learning rate of node *i* at step *t*. $\alpha_i(t)$ is defined as follows:

$$\alpha_i(t) = \eta \cdot \alpha_i(t-1) \quad (0 < \eta < 1) \tag{5}$$

where η is a positive constant of attenuation.

[step 3] The current estimated location is periodically broadcast to neighbor nodes in a period. The node that received the estimated location executes [step 2].

As above, each node repeatedly executes [step 2] and [step 3], and as a result, the network's original geometry is reproduced.

IV. SELF-ORGANIZING LOCALIZATION BASED ON NEIGHBOR TOPOLOGY

The algorithm of SOL works on each node autonomously and is composed as follows.

- Node location estimation function: this function reproduces the similarity to the network's original geometry based on SOMs without anchor nodes.

- Node location adjustment function: this function adjusts the reproduced geometry to the congruence with the network's original geometry with two anchor nodes and adjusts it to node absolute location with three anchor nodes.

In this section, each function as the algorithm of SOL is described.

A. Node location estimation based on neighbor topology

As described in section III, based on Euclidean distance between nodes, the original localization emphasizes graphical features of the topology by 2-hop nodes and aims to reproduce the topology. After that, it minimizes the difference of Euclidean distance between 1-hop nodes. That is, assuming that the Euclidean distance between nodes is accurate, the strategy of the original localization inputs a large amount of displacement by 2-hop nodes and the accurate distance by 1-hop nodes to SOM, and dynamically operates SOM. On the other hand, the SOL cannot use Euclidean distance as a relation between nodes because of the elimination of the distance measurement scheme from the original localization. Therefore, the SOL uses hop count as the relation between nodes, and its strategy is based on the neighbor topology, whose 1-hop neighbor node is nearer than the 2-hop neighbor node, and aims to reproduce the geometry that meets the neighbor topology between nodes. The neighbor topology is much rougher than the Euclidean distance provided by the distance measurement scheme; therefore, the SOL cannot dynamically operate SOM, and must operate SOM gradually. Accordingly, to eliminate the inconsistency with the neighbor topology from the reproduced geometry, the SOL carefully controls the location estimation by the 1-hop and 2-hop neighbor node as follows.

- SOL lets $d_{ij}(t)$, which is the distance between 1-hop neighbor nodes, be constantly 1, which is the number of hops.
- SOL estimates the location by 2-hop neighbor nodes only when the relative location to 2-hop neighbor nodes is inconsistent with the neighbor topology as in Fig.1(d) (that is, $d_{ij}(t)>d_{ik}(t)$). Because the number of hops is inaccurate as a distance between nodes, the modified vector $V_i^{\{2\}}(t)$ in Fig.1(d) and (3) is a large amount of displacement, and is very inaccurate. When such a modified vector by 2-hop neighbor node is frequently inputted to SOM, SOM oscillates, becomes unstable, and then converges to a state far from the optimal state. Therefore, SOL sets the modified vector as shown in Fig.2(a) only when the relative location to 2-hop neighbor nodes is inconsistent with the neighbor topology, and lets node keep away from 2-hop neighbor nodes
- Next SOL brings node close to 1-hop nodes as shown in Fig.2(b).

From the above, SOL aims to eliminate the inconsistency with the neighbor topology, and reproduces network topology. Summarizing, on the SOL, each node modifies and updates its estimated location as the following:

$$V_i^{\{1\}}(t) = \frac{1-|w_i(t)-w_j(t)|}{|w_i(t)-w_j(t)|}(w_i(t)-w_j(t)) \tag{6}$$

$$V_i^{\{2\}}(t) = \frac{1+1-|w_i(t)-w_k(t)|}{|w_i(t)-w_k(t)|}(w_i(t)-w_k(t)) \tag{7}$$

$$w_i(t+1) = \begin{cases} w_i(t)+\alpha_i\cdot(V_i^{\{1\}}(t)+V_i^{\{2\}}(t)) \\ \quad |w_i(t)-w_j(t)| > |w_i(t)-w_k(t)| \\ w_i(t)+\alpha_i\cdot V_i^{\{1\}}(t) \quad otherwise \end{cases} \tag{8}$$

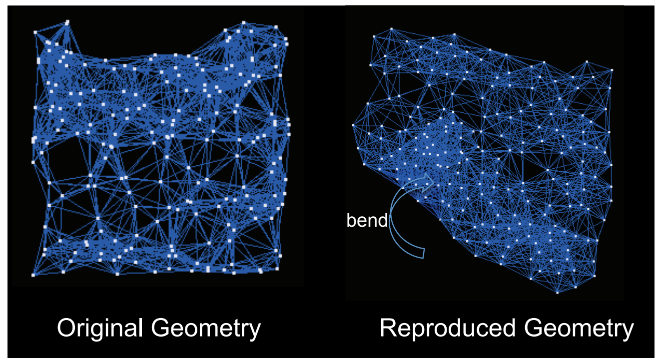

Figure 3. Example of mis-reproduced network geometry.

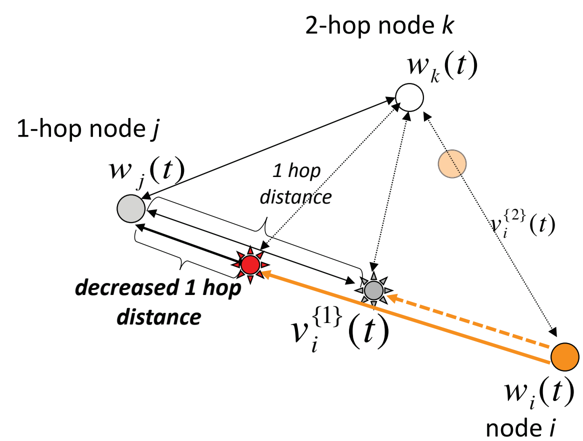

Figure 4. Location update based on decreased 1-hop distance.

In (6), (7) and (8), node j is a 1-hop node from node i, and node k is a 2-hop node from node i.

B. Node location re-estimation

When the number of neighbor nodes selected as input vectors is small, or when the range of neighbor nodes selected as input vectors is narrow, the reproduced geometry is correct locally, but is inconsistent with the entire geometry (mis-reproduction, see Fig.3).

SOL does not dynamically operate SOM, but aims to gradually reproduce network geometry which is narrow, using the 1-hop and 2-hop range nodes. Then, it may suffer from mis-reproducibility. Consequently, in SOL, each node confirms the inconsistency with neighbor topology at the end of iteration to measure mis-reproduced geometry as follows.

$$\frac{I_i^{\{2\}}}{N_i^{\{2\}}} < \theta \tag{9}$$

$I_i^{\{2\}}$ is the number of inconsistent 2-hop neighbor nodes on node i, $N_i^{\{2\}}$ is the number of 2-hop nodes on node i, and θ is the threshold of inconsistency. If (9) is not met, the node aims to dispel the mis-reproduction as follows.

- Reset the learning rate $\alpha_i(t)$ to 1, and re-estimate from the current estimated location to correct the inconsistency in 2-hop geometry.
- Broadcast the message of resetting the learning rate based on the number of message forwardings to neighbor nodes.
- The nodes that receive the message reset$\alpha_i(t)$ to *1/(the number-of-message-forwardings)*, and re-estimate from the current estimated location to correct the inconsistency in 2-hop geometry. And they also broadcast the message of resetting the learning rate based on the number of message forwardings to their neighbor nodes.

Thus, nodes reset smaller learning rate according as the number of message forwardings, and the re-estimation works in local range of mis-reproduced node. On the re-estimation, SOL decreases 1-hop distance that is used by the location update based on 1-hop neighbor node, because SOL brings a node closer to 1-hop neighbor node and raises the probability which the inconsistency with neighbor node topology is eliminated (see Fig.4). Furthermore, SOL makes smaller 1-hop distance as the number of re-estimations increases, and more strongly aims to eliminate the inconsistency with neighbor topology.

C. Node location Adjustment Function

It is expected that the reproduced network geometry has the geometric property of the network's original geometry; therefore, we assume that the reproduced geometry is nearly similar to the network's original geometry, and the reproduced network geometry is defined and adjusted as follows.

- Without an anchor node
  The reproduced geometry is a figure similar to the network's original geometry.
- With two anchor nodes
  Leaving the location of the anchor node unknown, the network geometry is reproduced. Then r, which is a similar scale, is derived using the estimated location and true location of two anchor nodes as follows.

$$r = \frac{d_{ab}}{D_{ab}} \tag{10}$$

$$d_{ab} = |w_a - w_b| \tag{11}$$

d_{ab} is an estimated distance between anchor nodes a and b according to (11), D_{ab} is the true distance between anchor nodes a and b, w_a is the estimated location of anchor node a, and w_b is the estimated location of anchor node b. Consequently, the adjustment for the reproduced network geometry from similarity to congruence is shown as follows:

$$w_i^A = \frac{w_i}{r} \quad i \in NW \tag{12}$$

w_i^A is the adjusted location of node i and NW is a set of nodes on the network. That is, each node can derive its relative location on the network using the estimation and the adjustment.

- With three anchor nodes
  As with the case of two anchor nodes, leaving the location of the anchor nodes unknown, the network geometry is reproduced, and then the three anchor nodes flood their true location and estimated location. The true location $W_A=(X_A,Y_A)$ of an anchor node is expressed as follows using its estimated location $w_A=(x_A,y_A)$.

$$\begin{aligned} X_A &= ax_A + by_A + t_x \\ Y_A &= cx_A + dy_A + t_y \end{aligned} \tag{13}$$

On each node, using simultaneous equations composed by (13) of three anchor nodes, these six coefficients (i.e., a, b, t_x, c, d, t_y) are gained. Also, its estimated location $w_i=(x_i,y_i)$ is transformed to the absolute location $w_i^A=(x_i^A,y_i^A)$ as follows by using affine transformation.

$$\begin{pmatrix} x_i^A \\ y_i^A \\ 1 \end{pmatrix} = \begin{pmatrix} a & b & t_x \\ c & d & t_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_i \\ y_i \\ 1 \end{pmatrix} \tag{14}$$

Summarizing, based on the assumption that the reproduced geometry is similar to the network's original geometry, SOL reproduces a similar geometry for the network original geometry without anchor nodes, and it reproduces a congruent geometry for the original geometry with two anchor nodes; that is, it derives relative node location on the network. Using three anchor nodes, the SOL reproduces the network geometry with absolute node location.

V. EVALUATION OF ACCURACY

A. Evaluation Method

TABLE I. SIMULATION PARAMETERS FOR PROPOSED METHOD

Maximum communication range on wireless media	0.2
Wireless media access control	CSMA/CA
Initial estimated location	random
Constant of attenuation η	0.99
Threshold of Inconsistency θ	0.05
Number of iterations for update	600
Maximum number of re-estimation	2
Decreased 1-hop distance	1/(number-of-estimations)

 ISBN: 978-1-61208-289-9

The space in which nodes are deployed is defined as a 1.0×1.0 plane. Table 1 shows the summary of simulation parameters used in the evaluation.

The similarity and congruence with the network's original geometry is evaluated based on (10) and (11) as follows.

$$r_{ij}^M = Mean[r_{ij}] \quad r_{ij} = \frac{d_{ij}}{D_{ij}} \quad i,j \in NW \tag{15}$$

$$r_{ij}^V = 1 - \frac{(Mean[r_{ij}])^2}{Mean[r_{ij}^2]} \tag{16}$$

Mean[x] is the average of set *x*, and *NW* is the set of nodes on the network. The accuracy of absolute location is evaluated based on (12) as follows.

$$Err_{ave} = \frac{1}{N}\sum_{i=1}^{N}\left|W_i - w_i^A\right| \tag{17}$$

N is the number of nodes, W_i is the true location of node i and w_i^A is the estimated and adjusted location of node i .

B. Evaluation of Similarity and Congruence

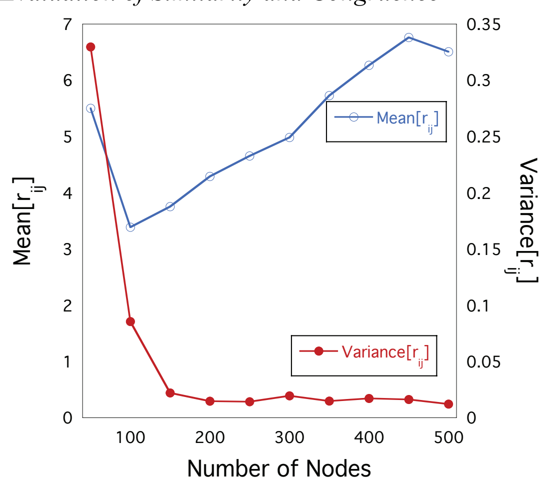

Figure 5. Dependence of r_{ij}^M and r_{ij}^V on number of nodes without anchor node.

Figure 5 shows the dependence of r_{ij}^M (broken line) and r_{ij}^V (solid line) on the number of nodes (50~500 nodes) without an anchor node. The r_{ij}^M and r_{ij}^V shown are averaged over 20 network topologies generated with randomly deployed nodes. When the number of nodes is smaller than 100, r_{ij}^V is a large value. In that case, the original geometry is sparse or fragmented because the density of nodes is low. Therefore, SOL cannot effectively estimate a network geometry in which the density of nodes is low. When the number of nodes exceeds 150, r_{ij}^V becomes small, and the estimated geometry is very near to being similar to the original geometry. When the number of nodes exceeds 250, r_{ij}^V approaches 0.01, and the estimated geometry is very similar to the original geometry. r_{ij}^M is not 1 for any case, regardless of number of nodes. Therefore, the scale of reproduced geometry is different from the original geometry, but is graphically similar to the original geometry.

Figure 6 shows r_{ij}^M and r_{ij}^V on the number of nodes (50~500 nodes) with two anchor nodes. The two anchor nodes are respectively the nearest node to the origin and the farthest node from the origin. When the number of nodes exceeds 150, r_{ij}^M approaches 1 and r_{ij}^V approaches 0.01. Then, the reproduced and adjusted geometry is nearly congruent with the network's original geometry.

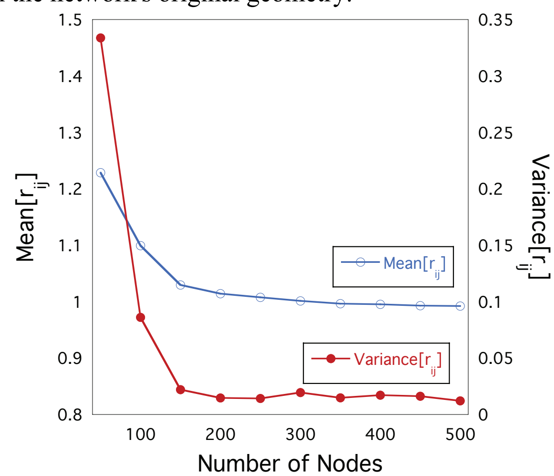

Figure 6. Dependence of r_{ij}^M and $\$\ r_{ij}^V$ on number of nodes with two anchor nodes.

C. Evaluation of absolute location

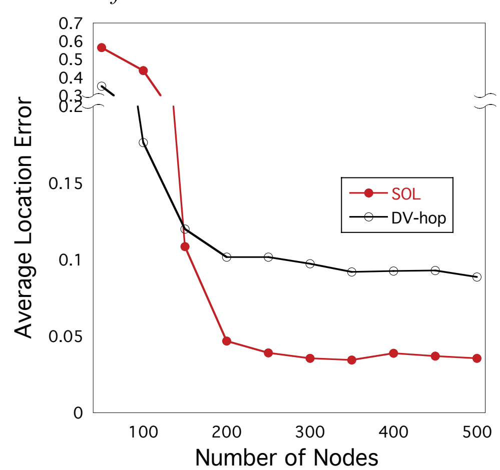

Figure 7. Dependence of average location error on number of nodes with three anchor nodes.

To evaluate accuracy of the absolute node location, compare its accuracy with that of DV-Hop in accordance with (17). DV-Hop can estimate node location with just three anchor nodes and without special distance measurement and previous information on the space in advance. The others do not meet the above restriction. DV-Hop calculates the average distance in 1 hop using the hop count between anchor nodes based on the minimum hop route and the distance between anchor nodes, and it estimates node location with triangulation that uses the location of each anchor node and the calculated distance to each anchor node. Figure 7 shows the comparison of SOL with DV-Hop on average location error in accordance with (17). The three anchor nodes are respectively the nearest node to the origin, the farthest node from the origin, and the farthest node from the above two anchor nodes.

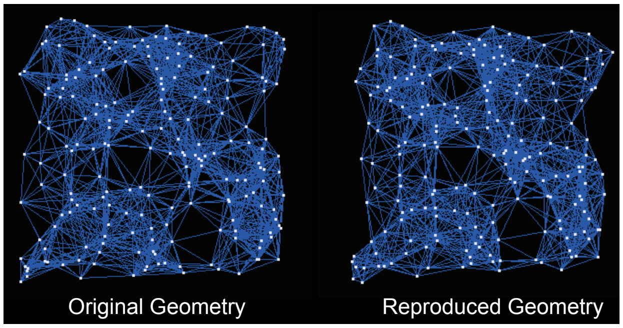

Figure 8. Comparison of reproduced geometry with original geometry on 200 nodes.

When the number of nodes is smaller than 100, SOL location accuracy and DV-Hop location accuracy are low. On a low-density network, SOL cannot effectively reproduce network geometry, and DV-Hop cannot estimate node location. Furthermore, the route based on the minimum hops becomes a zigzag or bent path rather than a straight-line, and, thus, the calculated average distance on 1 hop is inaccurate. Therefore, the accuracy on the estimated node location of DV-Hop becomes low. Any localization that depends on network topology has the problem that accuracy decreases in low-density networks.

When the number of nodes exceeds 200, the average location error of DV-Hop approaches approximately 0.1, and that of SOL approaches approximately 0.04. Therefore, the accuracy of SOL is much superior to that of DV-Hop (see Fig.8).

VI. Conclusion

In this paper, Self-Organizing Localization for wireless sensor networks was proposed. SOL requires no distance measurement schemes and no advanced information on the space, and its dependence on anchor nodes is very low. On the suitable density of nodes, SOL achieves the following results by using SOM.

- Without anchor nodes, it reproduces a geometry very similar to the network's original geometry.
- With two anchor nodes, it reproduces a geometry nearly congruent with the original, that is, it derives relative node locations on the network.
- With just three anchor nodes, it derives absolute node locations with high accuracy

Given the above properties, SOL can be applied to any space and any sensor node.

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 ISBN: 978-1-61208-289-9