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A Multi-hop Topology Control Based on Inter-node Range Measurement for Wireless Sensor Networks Node Localization

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Abstract: In centralized range-based localization techniques, sufficiency of inter-node range information received by the base station strongly affects node position estimation results. Successful data aggregation is influenced by link stability of each connection of routes, especially in a multi-hop topology model. In general, measuring the inter-node range is only performed for position determination purposes. This research introduces the use of inter-node range measurement information for link selection in a multi-hop route composition in order to increase the rate of data aggregation. Due to irregularity problems of wireless media, two areas of node communication have been considered. The regular communication area is the area in which other nodes are able to perform symmetrical communication to the node without failure. The irregular area is the area in which other nodes are seldom able to communicate. Due to its instability, some existing methods tried to avoid the irregular area completely. The proposed method, named Virtual Boundaries (VBs) prioritizes these areas. The regular communication area's nodes have high priority to be selected as link vertices; however, when there is no link candidate inside this area, nodes within the irregular area will be selected with respect to their range to the parent node. This technique resulted in a more robust multi-hop topology that can reduce isolated node numbers and increase the percentage of data collected by the base station accordingly. *Copyright © 2011 IFSA.*

Keywords: Wireless sensor networks; Range-based localization; Multi-hop communication.

1. Introduction

Wireless Sensor Networks (WSNs) are an emerging technology that is being studied by researchers worldwide, which have the potential to be deployed in areas such as environmental, health, home, and other commercial applications [1]. In many applications, measured data are distributed and need to be gathered. Some networks have solid known information on the location of all their nodes, so it is easy to plot the information. On the other hand, in many other cases in which nodes have to be flooded without knowing their land position, or in more extreme cases in which nodes are moving around, a localization process is required.

There have been many studies on localization methods in WSNs [2-4]. In range-based localization, to achieve correct and accurate positions of nodes, it is important to obtain adequate and accurate data on inter-node distances. Due to this, several localization procedures have to be completed successfully, i.e., inter-node range measurements, range data collection from each node to the base station as the data processing unit, and a robust position calculation program. Unfortunately, there is a common problem that usually occurs in real WSN systems: irregularity of wireless radiation [12-16].

The impact of irregularity exists in many layers of communication. The greatest impact is recognized in the routing layer. Moreover, routing protocols that are based on a neighbor discovery technique and multi-round routing rediscovery techniques are severely affected by this irregularity [3]. Unfortunately, most WSN simulators for protocol test purpose, such as in [27], disregard this fact by assuming spherical radio patterns. This leads to inaccurate estimations of application performance.

Some alternative solutions to the irregularity have been introduced, for instance [Zhou et al] proposed the Symmetric Geographic Forwarding (SGF) and Boundary Distance Forwarding (BDF) methods. Those methods emphasized the restriction of forwarding messages using only symmetrical connections and avoid the non-symmetrical connections by means of relative distances. However, these methods in fact will restrict the connection area of a node and cause some far nodes to become isolated, which in turn decrease the network connectivity.

To overcome those disadvantages, we introduce a new concept of node communication boundaries, called Virtual Boundaries (VBs). Assume two virtual layers of circle boundaries exist for every node. Any neighbor node lying inside the inner circle boundary, which we will call the regular communication area, is considered to have stable symmetrical communication with the parent node; therefore it has a higher priority to be selected as a route vertex. If the parent node cannot find any neighbor in the regular communication area, then any node located between the inner and outer virtual boundary, which we will call the irregular communication area, should be used instead to give the parent node opportunity to send its information.

To prove this concept, first we used simulation. Network density is change incrementally. The nodes connectivity to the base station and the multi-hop successful connection rate are observed. Three different topology control methods are introduced; free routing (no boundary), single boundary and the Virtual Boundaries (VBs) method. Irregular communication parameters have been included to make simulation conditions as real as possible. As the result, the number of isolated nodes decreased significantly using the proposed method.

A new experiment system has been built based on our previous research system [5] to confirm the simulation result. Nine experimental nodes were fabricated and tested. Inter-node range was obtained using TDOA of infrared and ultrasonic waves. For more than nine nodes, simulation was used. Some improvement on the hardware side has made to overcome the limitation of infrared communication angle in order to support arbitrarily placement of sensor nodes.

2. The Virtual Boundaries

2.1. Physical Meaning of Virtual Boundaries

In Virtual Boundaries, the node radiation area is divided into three parts as shown by Fig. 1. The first area is the “regular communication area” of a transmitter node, illustrated by node A. It is a circle with radius r_b with node A at the center, whose boundary we call the inner virtual boundary. Within this area, any node that exists is guaranteed unfailing communication with node A. Node B, for instance, can definitely receive the beacon of node A.

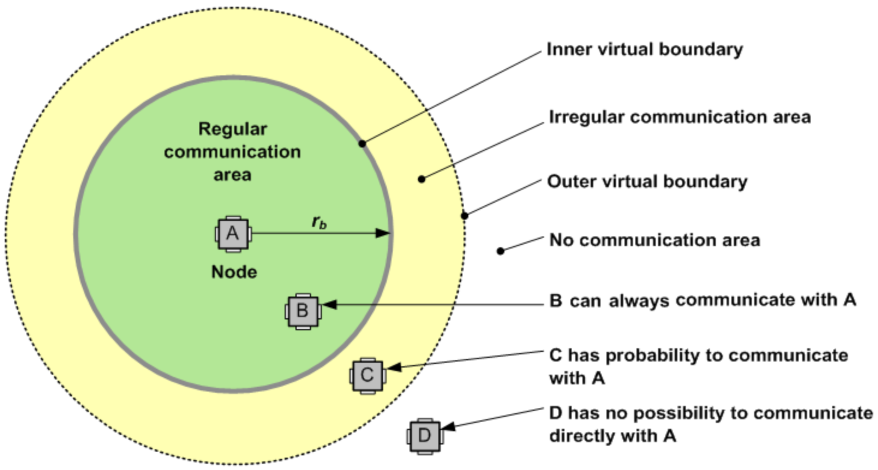

Fig. 1. The Virtual Boundaries and communication areas of a node.

The second area is the “irregular communication area.” This area lies between the virtual boundary and the maximum communication boundary. Within this area, any node can occasionally receive packets from the transmitter. When the signal becomes strong, the receiver, for example node C, will be able to acquire the information. Therefore, this area can still be used for communication, but may require several repetitions.

The third area is the “no communication area,” which is the upper area from the maximum communication boundary. There is no, or a very weak beacon signal remaining in this area so that the communication signal could never be recognized in its complete form. Therefore, no packet sent by the parent node can be received by any node within this area. Node D is an example.

2.2. Theory of Virtual Boundaries

Fig. 2 shows the Virtual Boundaries (VBs) expression. Let transmitter node α have a set of virtual boundaries that are circles with radii r_b and r_m, which correspond to the maximum regular communication range and the maximum irregular communication range.

There are three possibilities of neighbor candidate position (denote by β, $\beta'$and β''). Consider R_i is a set of neighbor i-th hop nodes. Each possibility can be expressed by Eq. (1), Eq. (2) and Eq. (3) as following.

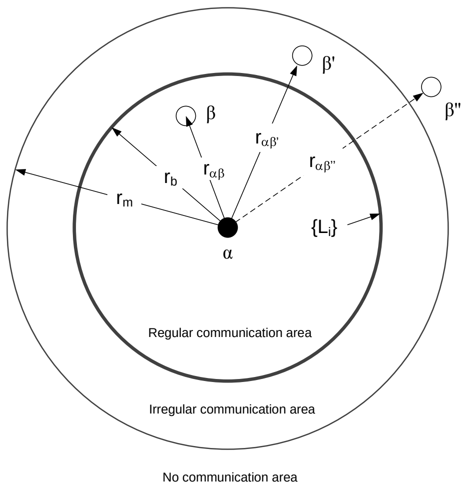

Fig. 2. The Virtual Boundaries expression.

$$\beta \in \{L_i\},\ \beta \in \{R_i\} \rightarrow r_{\alpha\beta} \leq r_b \tag{1}$$

$$\beta' \notin \{L_i\},\ \beta' \in \{R_i\} \rightarrow r_b < r_{\alpha\beta} \leq r_m \tag{2}$$

$$\beta'' \notin \{L_i\},\ \beta'' \notin \{R_i\} \rightarrow r_{\alpha\beta} > r_m \tag{3}$$

A node located inside the inner virtual boundary, associated by r_b, will be considered as an i-th hop node. A node lying between the inner and outer virtual boundary, associated by r_b and r_m respectively, will not be considered as an i-th hop node.

To each area a particular routing protocol will be applied. We introduce the level of confidence or weight value from zero to unity for each neighbor node to represent the percentage of successful symmetrical connections.

Any node inside the regular communication area will have the same highest priority, which is 1.0. The probability to establish a connection is also 1 as shown by Eq. (4). All neighbors can become vertices candidates, and the selection is made only with regard to minimum number of hops to the destination.

$$w_{\alpha\beta} = 1,\ P_{\alpha\beta} = 1 \rightarrow r_{\alpha\beta} \leq r_b \tag{4}$$

The irregular communication area has a variable link level of confidence from 0 to 1, which depends on the receiver's distance from the inner virtual boundary. The closer a receiver to the inner virtual boundary, the higher link level of confidence it has. However, from many wireless communication experiment results, the degradation of communication performance is not linear to the extension of range. Empirical studies, including our experiment, show a nearly cosine value according to the range. Therefore, we propose a cosine approximation as shown by Eq. (5):

$$w_{\alpha\beta} = cos\left(0.5 \cdot \pi \cdot \left(\frac{r_{\alpha\beta} - r_b}{r_m - r_b}\right)\right) \rightarrow r_b < r_{\alpha\beta} \leq r_m \tag{5}$$

Furthermore, this confidence value will be used by the transmitter when there is more than one node having the same chance to be a vertex, both lying in the irregular communication area. The nodes with the highest confidence values will be selected as vertices.

In a no communication area, all nodes will be unable to receive any packets from the transmitter directly, hence, the confidence value should be zero (w $=0$) and the probability of connection establishment will also be zero (P=0).

We also propose a simple formula to calculate the probability of establishing a bi-directional link in the irregular area, which depends on the product of link level of confidence (w) and the random phenomena of irregularity given as product of irregularity factors of transmitter and receiver side node, as expressed in Eq. (6).

$$P_{\alpha\beta} = w_{\alpha\beta} \cdot irreg_{\alpha} \cdot irreg_{\beta} \tag{6}$$

The irregularity factor is an unpredictable attenuation given by the environment and has value vary from zero (no attenuation) to a value determined by random value and the constant of irregularity as expressed by Eq. (7).

$$irreg_{\alpha} = 1 - rand_{\alpha} \cdot irreg_{const} \tag{7}$$

Further, when multi-hop routes are created, for each route consists of N number of link (or hop) from a node to the base station, the route connection probability will be the products of each link probability determined by Eq. (6), as expressed in Eq. (8).

$$P_r = P_1 \cdot P_2 \cdots P_{N-1} \cdot P_N \tag{8}$$

Each node will have to deliver its information to the base station. This means if there are M total nodes there will be M-1 routes from each node to the base station. The total probability of a successful connection and information delivery for the network will be the average probability of all routes determined by Eq. (8). Then the network successful connection probability can be determined using Eq. (9).

$$P_{net} = \sum_{r=1}^{M-1} \frac{P_r}{M-1} \tag{9}$$

2.3. Multi-hop Topology Control Using Virtual Boundaries

Fig. 3 describes a comparison of simple multi-hop topology control methods. Two common methods used in a multi-hop topology control are free routing and single boundary as shown in Fig. 3 left and middle. The chart on the right of Fig. 3 is our proposed VBs method.

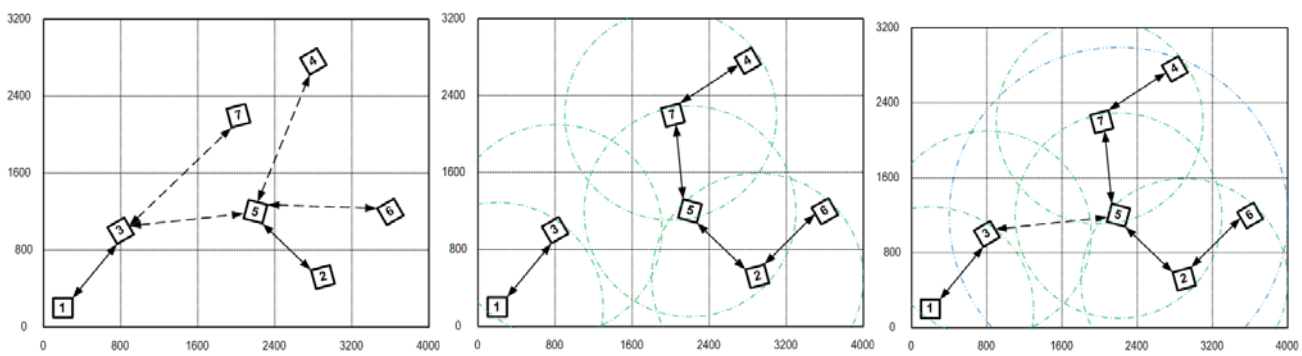

Fig. 3. Illustration of topology control using no boundary (left), single boundary (middle) and VBs.

The free routing has a benefit in providing many route alternatives of link composition. However, the method disregards the quality of links used. Routes will contain many unstable links that have high probability to result in a broken link according to the length. A longer link has a higher probability of breaking.

The restriction of route selection to a certain communication range (Fig. 3 middle) is effective to eliminate the use of an unstable link. However, when the nodes are not distributed uniformly, a partitioned network is more likely to occur. For example, nodes 2, 4, 5, 6, and 7 are partitioned and will not be able to send their data to node 1 and the base station.

The proposed VBs method (Fig. 3 right), introduces the use of unstable links when there is no connection to the base station. As an example, node 5 is applying an upper boundary to get connected with 3. Though using the unstable connection will decrease the stability of the route, it gives a way for data to be sent to the base station. If more than one unstable connection is available, the method will consider the nearest distance node as the best link vertex to use.

3. Evaluation Parameters

Following evaluation parameters are used in the experiments and simulations.

3.1. Packet Reception Rate

Packet Reception Rate (PRR) is one of the link quality metrics adapted from [13] defined as the average of the ratio of the number of successfully received packets to the number of transmitted packets, and it can be computed at the base station. The number of lost packets is determined using the sequence number.

$$Packet\ Reception\ Rate = \frac{number\ of\ succesfully\ received\ packets}{total\ number\ of\ sequentially\ transmitted\ packets}$$

This parameter is used in node to node connection tests to determine the radius of inner virtual boundary (r_b) and outer virtual boundary (r_m).

3.2. Network Connectivity

In general, connectivity is expressed as the percentage of node pair connections that can be drawn graphically over the total node pair combination inside the network. In cases of multi-hop data aggregation, each route composed from nodes to base station is comprise from several node pair. Any node with complete route to the bases station should be considered as “connected” and has unity connectivity, otherwise node with incomplete route will be consider as “isolated” and the connectivity should be zero. Thus, the network connectivity can be defined as the number of complete routes over the total number of nodes.

$$netwotk\ conectivity = \frac{number\ of\ connected\ nodes}{total\ number\ of\ nodes}$$

The connection mentioned here means only symmetrical or bi-directional connection.

3.3. Successful Connection Rate

Due to instability of connections within the irregular area, vertices persist in these area will degrade the successful route probability. Successful Connection Rate parameter is proposed to assess the overall probability of successful routes established over the network

$$\text{Successful Connection Rate} = \frac{\text{Sum of connection probability}}{\text{total number of connections}}$$

3.4. Data Aggregation Rate

This metric is proposed to evaluate the percentage of data points that can be aggregated by the base station from nodes all over the network. The base station will calculate the position of the nodes; whether or not a sufficient amount of data has been collected will be directly affected by the error in that calculation.

$$\text{Data Aggregation Rate} = \frac{\text{Number of collected data}}{\text{total number of nodes}}$$

3.5. Average Localization Error

This metrics is adapted from [14] to evaluate the accuracy of localization result performed using the collected data. The average distance between estimated location and the actual location of all sensor nodes will be resumed using following formula.

$$\text{Average Localization Error} = \frac{\text{Sum of node location errors}}{\text{total number of nodes}}$$

4. Simulations and Experiments

4.1. Simulations

Simulations had performed in order to have comparative routing result for not using boundary (free route) condition, using single boundary and using virtual boundaries (VBs) condition. Parameters applied in our simulations are as follow; Network deployment area is 10 x 10 meters square. Number of node is 100 including 3 anchor points. Inner virtual boundary radius is 1450 millimeters. Upper virtual boundary radius is 2450 millimeters. Range measurements error confident is 1 % from the value of inner virtual boundary, or 0.015 meter. Irregularity constant used is 0.2. All nodes are spread in random position using a random function. Except for the anchor nodes positions are fixed at (500, 500), (500, 9500) and (9500, 9500) millimeters respectively. The node also has ability to retrieve a broken link three times before omitting a connection. Fig. 4 shows an example of routing simulation results.

Evaluation parameters used in simulation are connectivity and connection successful rate. As shown in Fig. 5, during experiments, node density is change from 0.1 (10 nodes) to 2.0 (150 nodes) with 10 node incremental in each measurement. No boundary and VBs method has a high connectivity, that means almost all the node will be able communicate with the base station, on the other hand, the single boundary rule prevents a node to contact another node lying in irregular area had caused partitioned network and some isolated nodes, which in turn decrease the connectivity. However, in case of multi-hop successful communication rate, the increase of node density allow the single boundary and the VBs to create as many as possible stable links while the no boundary method will still deploys irregular connection, which in turn, lock the multi-hop connection successful rate low.

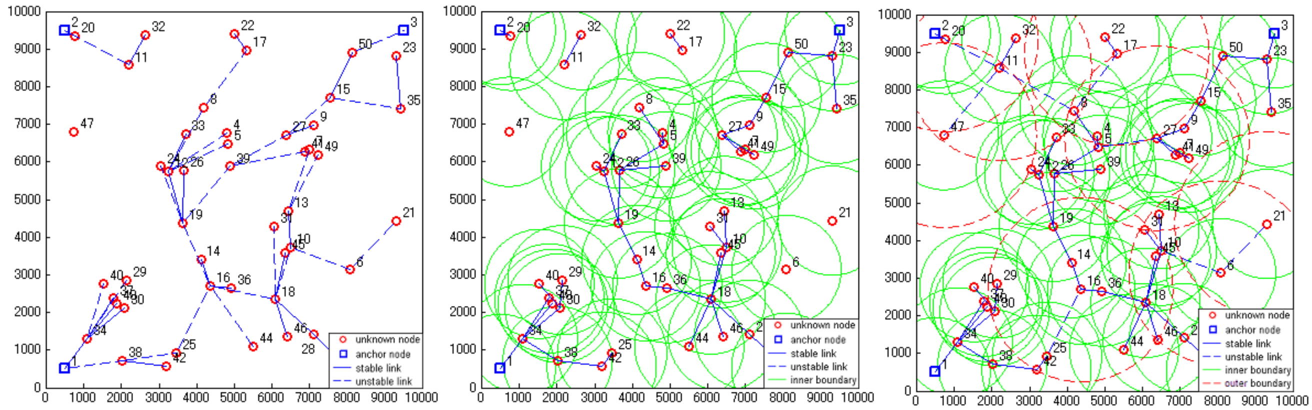

Fig. 4. Routing result density for no boundary, single boundary and the VBs respectively from left.

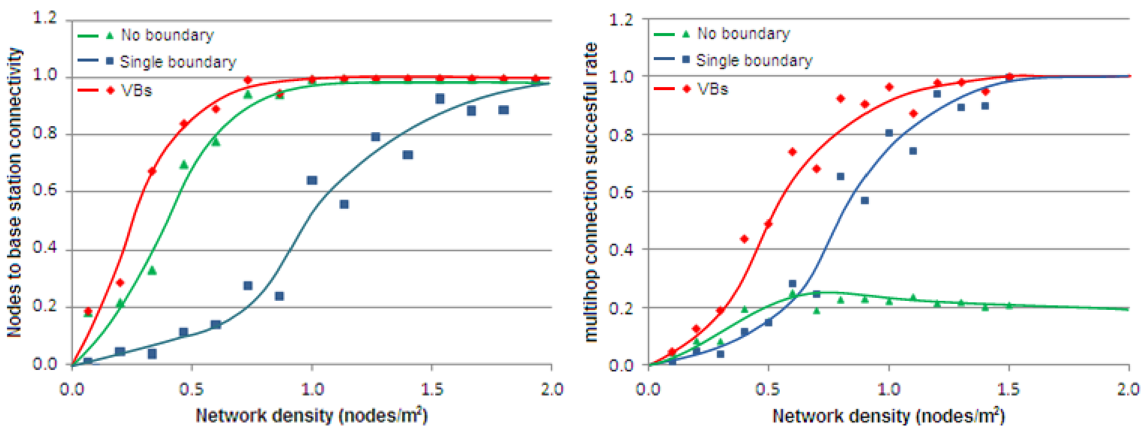

Fig. 5. Simulation result for connectivity (left) and successful connection rate.

4.2. Experiments

4.2.1. Node Design

As mention previously, an experimental system of range base localization was built by [5] utilizes infrared communication and a TDOA of infrared and ultrasonic using m-sequence method. However there was a constrain of infrared devices communication angle which caused the placement of sensor node should be directed in such a way to enable communication. To overcome the limitation, more infrared devices have deployed in circular distributed. As the result, the new system can support a true two dimensional arbitrary nodes position.

Fig. 6 left shows the functional blocks inside the experimental node. The main controller is the H8/3048F running at 16 megahertz. To support range measurement using cross correlation and data storage, an additional 1 M bit external SRAM is used instead of the internal RAM. Fig. 6 middle shows the arrangement of infrared device (IR*n*) and ultrasonic devices (US*n*) for range measurement.

The infrared devices are also used for communication. Fig. 6 right shows a photograph of the real experimental node.

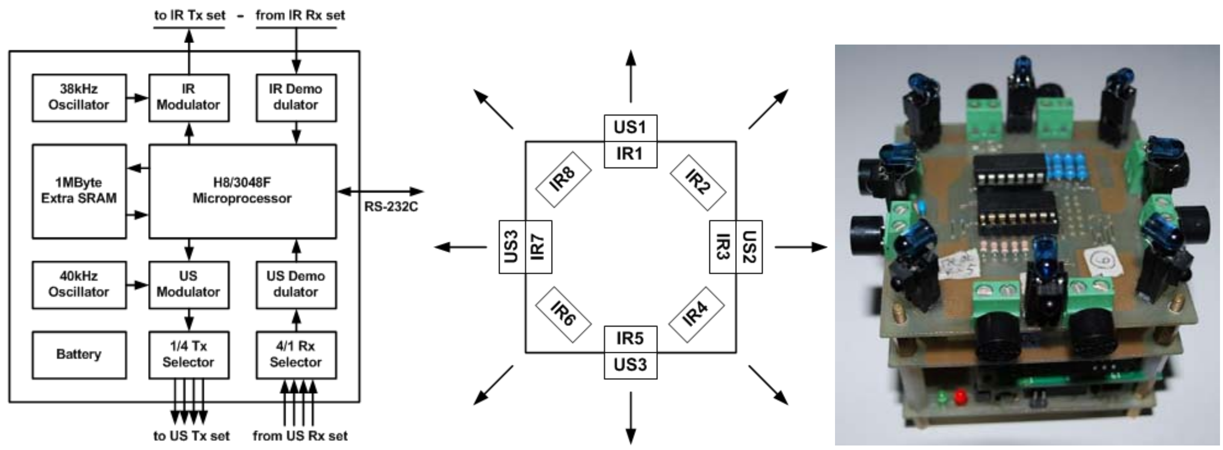

Fig. 6. Experimental node diagram (left), IR and US devices layout (middle) and real node.

4.2.2. Node Communication and Range-measurement Tests

In first experiment, a pair of prototype nodes is used to observe the infrared pattern model. A prototype node emitted a set of test bits in the centre of the test field while another node moved perpendicularly away from the centre, repeated every 15 degree angle step from 0 to 360 degrees. Fig. 7 left shows the experimental result.

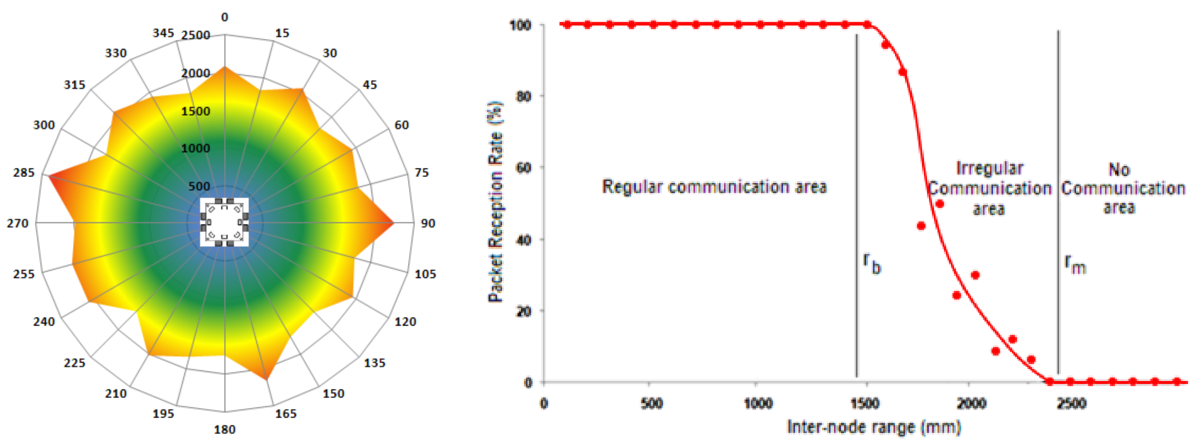

Fig. 7. Experimental node wireless pattern (left) and packet reception rate test result.

To observe the packet reception rate, a node sent a “hello” packet and another node reply an “acknowledge” packet. The inter-node range then increased from 100 mm to 3000 mm by 100 mm step. The communication is repeated 100 times for each step. Fig. 5 right shows the average result (in percent) of successfully packet replied over the total number of 100 request packets. From this figure, the reasonable value for inner and outer virtual boundary, r_b and r_m, are 1450 millimeters and 2450 millimeters respectively.

Inter-node ranges were measured using difference time of arrival (TDOA) of m-sequence modulated infrared and ultrasonic and their cross-correlation function. One node remains in fixed position while another was moved incrementally from 100 millimeter to 1800 millimeter with 100 mm step. During range measurement orientations also changed arbitrarily for 0 and 45. Fig. 8 described the experiment setup and the result. (a) to (d) denote four combination of orientation. Error deviation is around 18 mm.

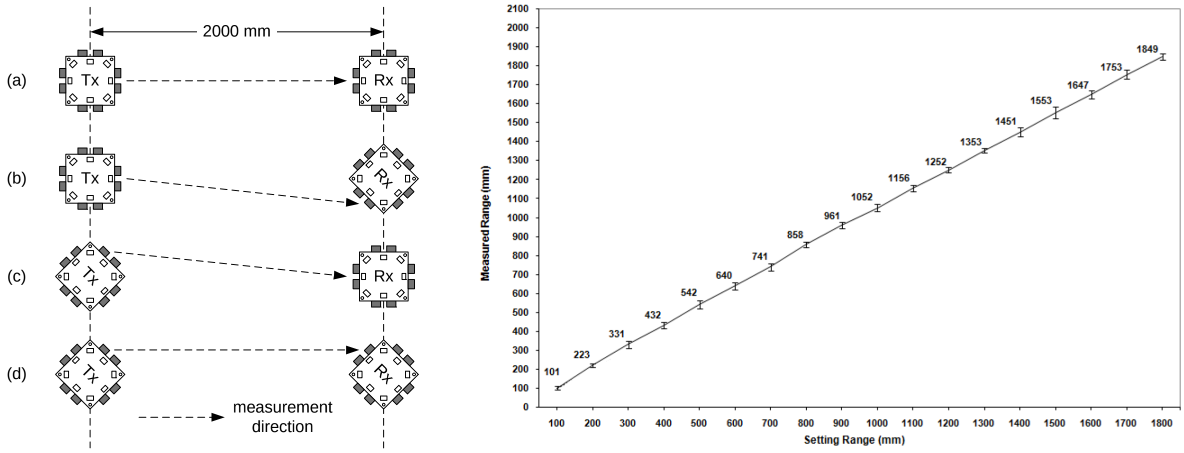

Fig. 8. Inter-node range measurement setup and result for arbitrary orientation of nodes.

4.2.3. Multi-hop Topology Control

Fig. 9 left side shows the experiment setup to demonstrate effect of the VBs to the multi-hop topology. Due to small number of nodes, the experiment sensor field size has reduced to only 4 x 4 meters. With 9 nodes, the network density is around 0.56 nodes/meter squares.

Nodes 1, 2 and 3 were dedicated as anchor (known position) nodes and located on (200, 200), (200, 3800) and (3800, 3800), in millimeter, respectively. Six other nodes were placed arbitrarily in their positions and orientations. The value of $\boldsymbol{r_b}$ and $\boldsymbol{r_m}$ used are 1450 and 2450 millimeters respectively. Fig. 9 right side shows the photograph of real experiment model.

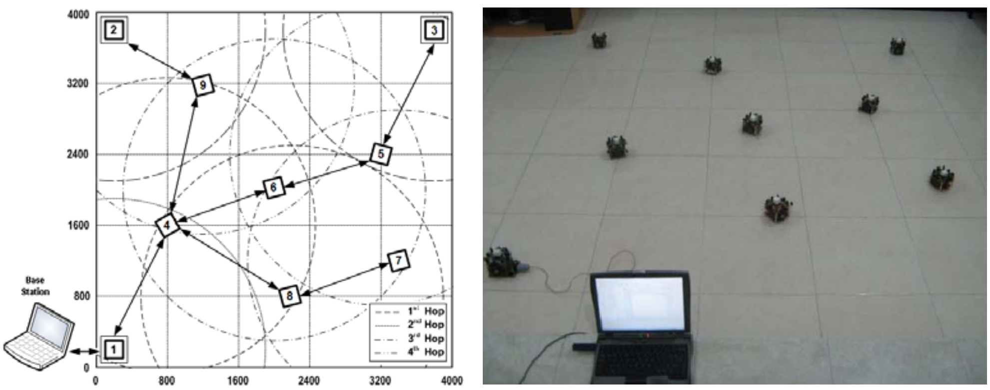

Fig. 9. Scheme (left) and photograph of real experiment model.

Fig. 10 shows topology results comparison. From the three scenario, it can be seen that the free routing (left) and VBs (right) have completed routes from base station (node 1) to all the nodes. The single boundary results some unconnected node and parted network and has only 55.6 % of connectivity. This result similar to the simulation result, as seen in Fig. 11 left side, at 0.56 network density the no boundary and VBs method have high connectivity (around 80 % to 95 %) compared with 100 % in the experiments. On the other hand single boundary has only around 15 % connectivity in simulation, compared to 55.6 % in the experiment. This result shows that at low density networks, the single boundary method is not effective to use compared to the no boundary and VBs.

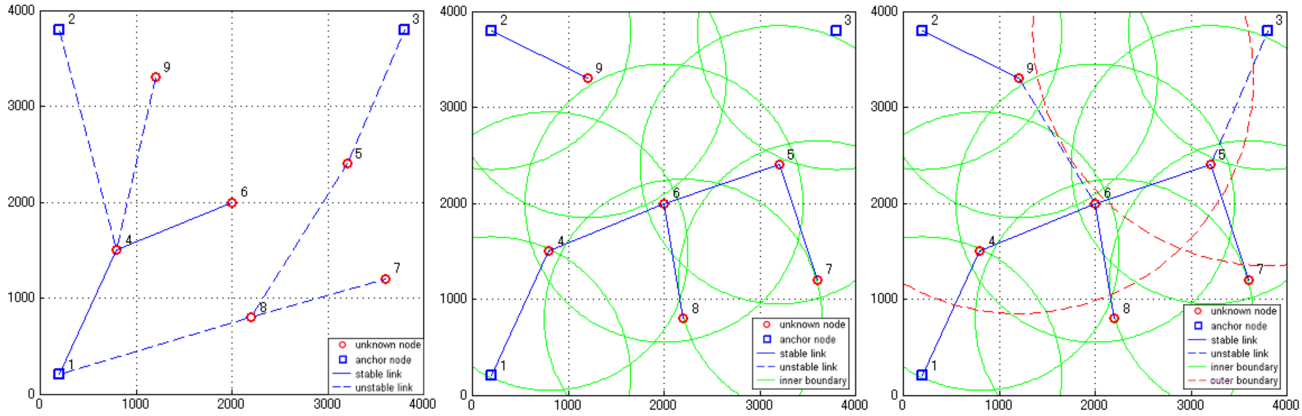

Fig. 10. Topology resulted by the three compared methods in experiment.

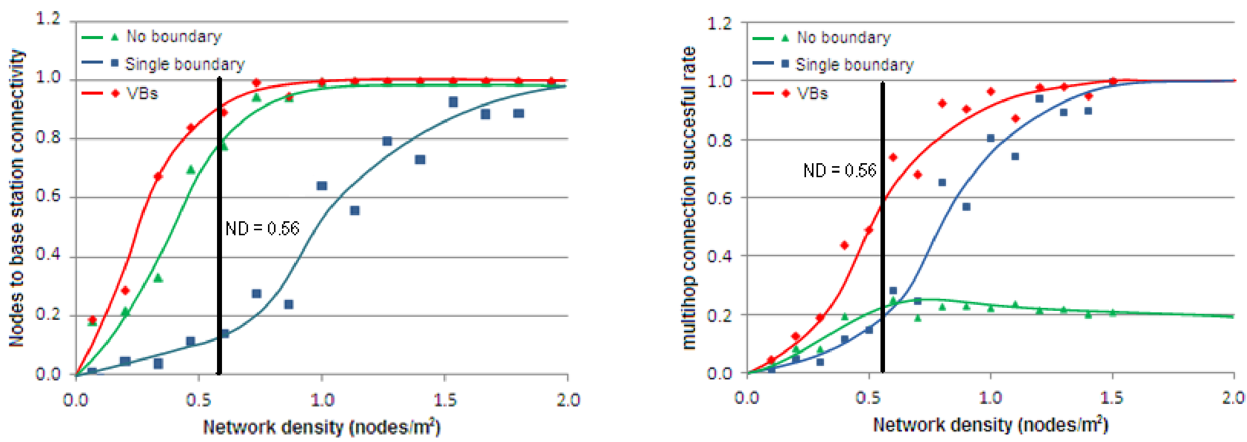

Fig. 11. Comparing network connectivity (left) and successful connection rate.

The successful connection rates from left to right results are 81.2 %, 62.5 % and 92.9 % respectively. Compared to the simulation result in Fig. 11 right side, similarly at low density as the experiment, the single boundary has the lowest successful connection rate. However, the result for no boundary is a little bit lower than simulation condition. VBs has the highest rate of successful connection.

4.2.4. Node Position Determination

After all possible inter-node range data have gathered by the base station, position determination was performed using the steepest descent method. For each the three methods, data gathered and position determination were repeated 40 times. Fig. 12 shows the plotted of node original positions and their approximation results.

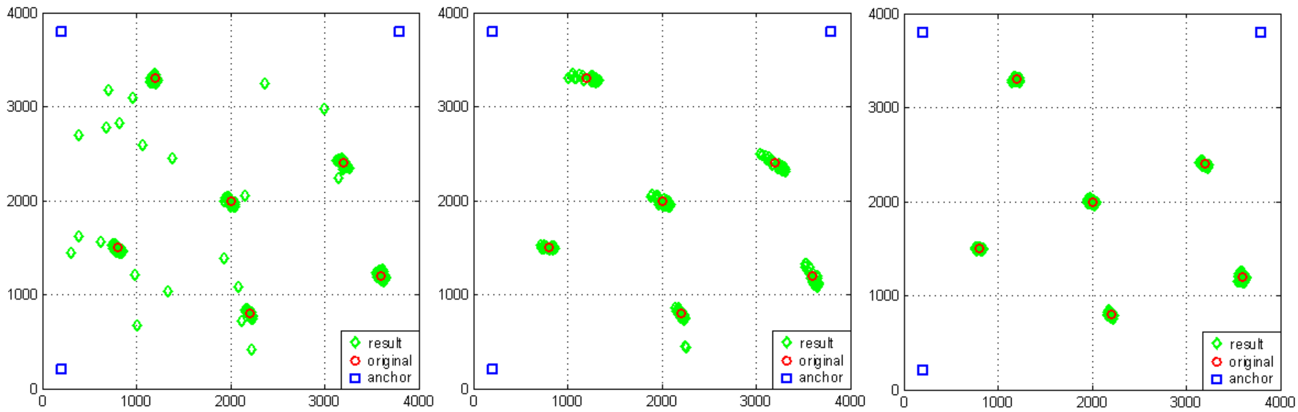

Fig. 12. Localization experiment result for no boundary, single boundary and the VBs respectively from upper.

From total 33 combinations of inter-node range data, the free routing can collects 14 data or only 42.4 %. The single boundary method collects 15 data or 45.5 %. The VBs method collects 16 data or 48.5 %. Fig. 13 shows the localization errors in millimeters for the three methods observed in 40 trials. The average position errors are 639, 176 and 23 millimeters for no boundary, single boundary and VBs respectively.

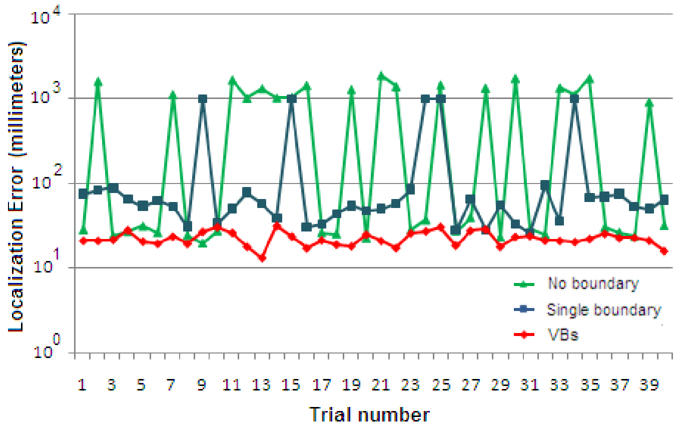

Fig. 13. Localization errors for no boundary, single boundary and the VBs.

5. Conclusions

A new multi-hop topology control method called Virtual Boundaries (VBs) has been introduced. The art of this method is dividing communication areas of a node into three zones separated by two virtual circles defined with the parent node as its center. In each zone, a different protocol will be applied in order to select vertices nodes for composing a multi-hop route. Simulations and experiment were performed to confirm the method.

Simulation results for network connectivity show that VBs method has outperformed the no boundary method and single boundary method at low density networks. However in high density networks, the connectivity of single boundary method increase significantly close to the VBs has, and the no boundary method is also equalize the VBs method connectivity. Simulation results for successful communication rate show that VBs once again outperformed the no boundary and single boundary method. Overall, the VBs can maintain a more robust topology for both low density and high density networks.

Experiment result using nine prototype node with infrared communication and inter-node range measurement function shown the fact that using VBs can gain more range data aggregation from networks to the base station number, which in turn, increase the accuracy of position determination.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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