# HCRL: A Hop-Count-Ratio based Localization in Wireless Sensor Networks

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*Abstract*—**Determining the positions of nodes is essential in many applications and geographic routing protocols of Wireless Sensor Networks. Since localization is a fundamental component of sensor networks, the cost for localization itself should be minimized. In this paper, we focus on developing a localization algorithm which provides both low-cost and accuracy. Considering these requirements, we propose a novel range-free localization technique, called HCRL, which uses only the ratios of anchor-to-node hop-counts. HCRL satisfies low-cost with a single flooding from a small number of anchor nodes, and subdivides one-hop into several sub-hops by transmission power control to improve localization accuracy. Unlike previous work, we have conducted real experiments, which were made possible by using an external antenna with an omni-directional radiation pattern. The experimental results show that the performance of HCRL is superior to the conventional DV-Hop scheme with a small transmission overhead.**

*Index Terms*— **Wireless Sensor Networks, Localization, Hop-count**

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) have actively been developed for various applications, including habitat/environment monitoring, infrastructure diagnostics, military surveillance, and target tracking. For the successful implementation of these applications, the sensor nodes should be aware of their location. Localization in WSN has been widely studied, and still remains a challenging issue. The localization algorithms in WSNs are divided in two broad categories: range-based and range-free techniques. Range-based techniques estimate the actual distance between an unknown node and anchor nodes whose positions are known. In contrast with range-based localization techniques, range-free methods require no measurement of actual distance between unknown nodes and anchor nodes. These localization techniques are well summarized in [1, 2, 3].

Although localization forms an essential part of the WSN, it is not an application but a fundamental requisite which supports high level applications. Therefore, the localization cost should be minimized. The primary cost factor is that some nodes, called anchors, should be aware of their position. To obtain position information, an anchor node uses a special device such as a GPS module, which leads to high unit price and high energy consumption. A small number of anchor nodes is required to reduce additional expenses caused by localization.

A localization technique which uses hop-count information can minimize the number of anchor nodes because the position of the anchor node can be propagated by packet forwarding. Several hop-count based localization schemes have been proposed to meet the conditions of sparse anchor nodes [4, 5, 6, 7]. This previous work, however, is inefficient to be applied to the real sensor network system in terms of overhead, accuracy, and simplicity.

In this paper, we propose a novel range-free localization technique, called Hop-Count-Ratio based Localization (HCRL), using only hop-count-ratios from anchor nodes to an unknown node, and not using the physical distance information derived from average one-hop distance estimation. HCRL performs localization with only single flooding from anchor nodes to unknown nodes; hence, compared to conventional schemes, it works with a small number of communications between nodes. HCRL achieves low communication overhead by reducing the number of flooding messages by half. In terms of accuracy, HCRL uses the transmission power control to subdivide one-hop into several sub-hops. More accurate localization is possible with accurate hop-ratio information which is obtained from a subdivision of one-hop.

We have implemented the HCRL algorithm on real sensor motes, and have conducted experiments. We used an antenna which guarantees a horizontally omni-directional radiation pattern. The experimental results show that the HCRL scheme presents better localization performance than DV-Hop [4] while consuming less energy. Through the experiments, it is also demonstrated that the localization performance can be improved by the hop-subdivision through transmission power level control.

The rest of the paper is organized as follows: in Section II, we review the existing hop-count based localization schemes. Section III presents the basic mechanism of HCRL. In Section IV, we describe the improvements on the HCRL algorithm. The experimental results are provided in Section V. We conclude the paper in Section VI.

## II. RELATED WORK

Several localization algorithms using hop-counts have been proposed. We classify them into two categories: hop-distance-unaware and hop-distance-aware mechanisms.

A hop-distance-unaware localization scheme calculates the average one-hop distance from the number of anchor-to-anchor hops. In the DV-Hop [4] algorithm, each node exchanges information containing the location of, and the hop-counts to, the anchor nodes. After the information exchanges between anchor nodes are complete, an average distance per hop is calculated. This distance is finally used to estimate the positions of nodes through the "lateration" method. [5] estimates the average one-hop distance by the Hop-TERRAIN method, which is similar to DV-Hop in the first phase, and refines the location of each node in the second phase. In Hop-TERRAIN, an intermediate node sends a new broadcast message to a particular anchor node only if the hop-count information in the message is less than the previous one. In the refinement phase, each node iterates lateration using the estimated positions and ranges of neighbor nodes.

In contrast with the hop-distance-unaware mechanism, a hop-distance-aware localization scheme assumes that a node is aware of the one-hop distance between its neighbors. In N-Hop Multilateration [6], the distance from an anchor node to an unknown node is determined by adding the physically measured distance. The unknown node maintains the shortest distance to the anchor nodes, and constructs a bounding box for each anchor node. The position of the unknown node is estimated to the center of the intersection of bounding boxes. This is simple and robust to the anisotropic positions of anchor nodes. However, the hop range should be measured a priori, and the range error increases cumulatively as the hop counts increase. The DHL [7] has been proposed to reduce the error of the accumulated range. DHL adjusts the hop distance according to the density of neighbor nodes, and employs the lateration method. The mechanism also should be aware of the hop distance, and the hop distance is inaccurately adjusted when the density of neighbor nodes is extremely low or the neighbor nodes are deployed in an anisotropic manner. The comparison of the three hop-count based localization techniques, DV-Hop, Hop-TERRAIN, and N-Hop Multilateration, is summarized in [8].

## III. BASIC HCRL MECHANISM

In the hop-distance-aware localization scheme, a node should know its communication range or the hop-distance between nodes. The fixed hop-range is hardly applicable to real sensor network applications because the hop-range varies depending on environmental variations of the sensor field (e.g. weather or time variations) [9]. A scheme that measures hop-distance with a measuring device such as an ultrasonic generator/detector is not practical due to its high cost and limited deployment distance. This section describes the basic mechanism of the proposed HCRL scheme from the viewpoint of low-cost, and especially of low communication overhead.

### A. *Localization Information from Single Flooding*

DV-Hop and Hop-TERRAIN calculate the average one-hop distance through communications between anchor nodes. This mechanism's drawback is that each flooding message which originates from an anchor node should reach other anchor nodes, and the anchor node is required to send the average one-hop distance to the unknown nodes by generating another flooding message. Since this double flooding can cause severe energy consumption in a dense network topology, we aim to develop a localization scheme which requires less packet exchanging. Previous schemes perform packet flooding twice in order to derive hop-distance information from the position of anchor nodes and the hop-counts between them. The only information we obtain from single

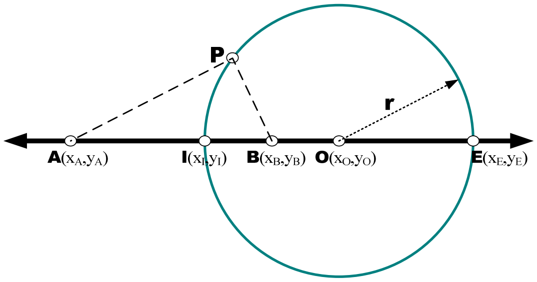


Fig. 1. Apollonius Circle

flooding is the hop-count. With the hop-count information from each anchor node, the hop-count ratio information from arbitrary pairs of anchor nodes is obtained. Our concept is to utilize the hop-count ratio information for localization.

### B. *Apollonius Circle*

To apply the hop-count ratio information to position estimation, the ratio information should be converted into a different form of information. The Apollonius Circle [10], also called the Apollonian Circle, is defined as the set of all points whose distance from two fixed points is in a constant ratio. Figure 1 illustrates the Apollonius Circle. Let *A* and *B* be the fixed points; the locus of a point *P* is a circle where the distance from point *A* and *B* is in a constant ratio, $m:n(m \neq n)$. In case the length of segment $\overline{AP}$ equals to the length of segment $\overline{PB}$ $(m = n)$, the locus of a point *P* is the perpendicular bisector of the segment $\overline{AB}$.

The Apollonius Circle is a circle with a diameter whose length is $\overline{IE}$ where *I* is the internal division point and *E* is the external division point of $\overline{AB}$ in ratio $\overline{AP}:\overline{PB}$. The coordinates of point *I* and *E* are computed as follows:

$$x_I = \frac{mx_B + nx_A}{m+n}, \quad y_I = \frac{my_B + ny_A}{m+n} \tag{1}$$

$$x_E = \frac{mx_B - nx_A}{m-n}, \quad y_E = \frac{my_B - ny_A}{m-n} \tag{2}$$

where $m:n = \overline{AP}:\overline{PB}$. The coordinates of point *O* and radius *r* are obtained with simple computations.

In a sensor field, the fixed points *A* and *B* can be represented as anchor nodes, and the point *P* can be represented as an unknown node. The distance ratio of $\overline{AP}$ and $\overline{PB}$ is obtained by counting hops from the anchor nodes *A* and *B* to an unknown node *P*. Since the position of, and the distance ratios to, two anchor nodes are known by multi-hopping from anchor nodes, the Apollonius Circle ($\frac{\overline{AP}}{\overline{PB}} \neq 1$) or line ($\frac{\overline{AP}}{\overline{PB}} = 1$) is obtained. The final position of the unknown node can be calculated by finding the intersection point of several Apollonius Circles or lines.

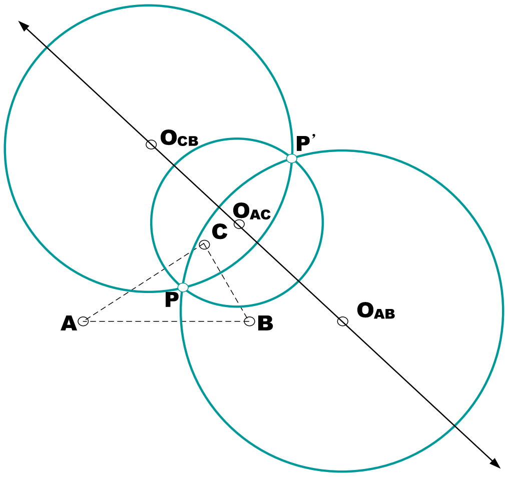


Fig. 2. Three Apollonius Circles of a triangle

### C. *Minimum Number of Anchor Nodes*

To find a unique intersection point, a certain number of circles are required. The lateration method calculates the intersection point from three circles. Although our approach also uses circles, the required number of circles is different from the lateration method due to the characteristics of the Apollonius Circle. We know that one Apollonius Circle can be obtained from a pair of two fixed points. Therefore, $\frac{n(n-1)}{2}$ Apollonius Circles are obtained where *n* is the number of different fixed points. Figure 2 shows a general example of three Apollonius Circles of a triangle. For the given fixed points *A*, *B*, and *C*, we have three segments $\overline{AB}$, $\overline{AC}$, and $\overline{CB}$. The three Apollonius Circles whose center points are $O_{AB}$, $O_{AC}$, and $O_{CB}$ are constructed from a point *P* with $\overline{AB}$, $\overline{AC}$, and $\overline{CB}$ respectively. The three center points of the Apollonius Circles, which are constructed from a triangle $\Delta ABC$, are collinear. Hence we have two intersection points *P* and *P*', which are the isodynamic points of the triangle $\Delta ABC$ [11]. The relation between the two points *P* and *P*' is as follows:

$$\frac{\overline{AP}}{\overline{PB}} : \frac{\overline{AP}}{\overline{PC}} : \frac{\overline{CP}}{\overline{PB}} = \frac{\overline{AP'}}{\overline{P'B}} : \frac{\overline{AP'}}{\overline{P'C}} : \frac{\overline{CP'}}{\overline{P'B}} \tag{3}$$

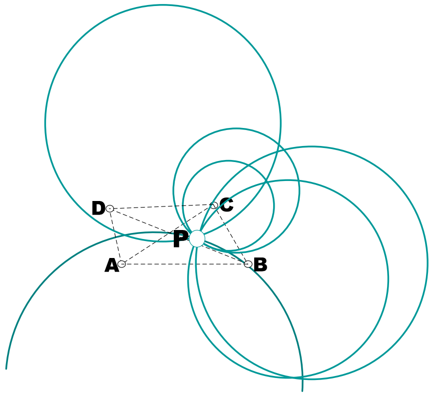


Fig. 3. An example of six Apollonius Circles with four fixed points

Three Apollonius Circles of a triangle have two intersection points, which implies that we can not determine the position of an unknown node from three different anchor nodes. To find one unique intersection point with the Apollonius Circles, at least four fixed points are required. With the four points, six circles or lines indicate an unambiguous intersection point. Figure 3 shows an example that an apparent intersection point *P* can be obtained where another fixed point *D* is added in Figure 2. Consequently, at least four different anchor nodes are required to estimate the position of an unknown node.

The localization mechanism which utilizes hop count ratios requires one additional anchor node compared to conventional trilateration-based techniques. In real world where the estimated distance derived from hop-count is erroneous, even lateration-based techniques necessitate more than three anchor nodes. Therefore, use of one more anchor node can be regarded as trivial

### *D. The Basic HCRL Algorithm*

We now understand that the position of an unknown node can be calculated with the hop-count information, which is obtained by single message flooding, from more than four anchor nodes. Figure 4 describes the basic mechanism of the HCRL scheme.

First, each anchor node broadcasts a flooding message *FM* including *Node ID*, *coordinates*, and hop-count *HC*. *HC* is set to 1 at the anchor nodes. During flooding, unknown nodes store the *FM* where the *Node ID* is new, or update the *FM table* provided that the *HC* is less than the information received previously. If an unknown node collects equal or more than four *FM*s, which come from different anchor nodes and include the smallest *HC,* it constructs Apollonius Circles and estimates its position.

```
▶ Initialization:
for each anchor node
    $HC \leftarrow 1$;
    broadcast FM

▶ Checking FM:
if a node receives FM
    if (Node ID is not new) and (HC is larger than before)
        drop FM;
    else
        if Node ID is new
            store FM;
        else if HC is smaller than before
            update FM;
        $HC \leftarrow HC + 1$;
        broadcast FM ;
    if the number of $FM \geq 4$
        construct Apollonius circles;
        estimate intersection of the circles;
```

Fig. 4. Pseudo Code of the basic HCRL algorithm

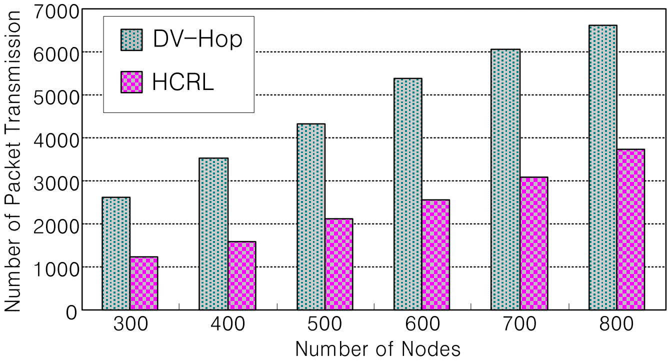


Fig. 5. Comparison of transmission overhead

### *E. Communication Overhead*

Since the Apollonius Circle is constructed with only the hop-count ratios and the positions of anchor nodes, HCRL requires only single anchor-to-node flooding. The previous hop-distance-unaware localization schemes such as DV-Hop require flooding twice to obtain the average one-hop distance. Figure 5 shows the simulation result which compares the transmission overhead between DV-Hop and HCRL, where the nodes are randomly placed in a 500m×500m network field with four anchor nodes, and the transmission range is 60m. From the result, we found that the number of packets required for HCRL maintains only half of the conventional schemes, independent of the number of nodes. This implies that HCRL consumes only the half of energy compared to DV-Hop at the localization stage.

## IV. ENHANCING THE HCRL ALGORITHM

The existing hop-count based localization schemes regard each one-hop as having the same distance value or divide one-hop into several sub-hops based on the density of nodes in the sensor field. An accuracy improvement technique based on probability works well under the condition that nodes are uniformly deployed; however, the localization error dramatically increases where the distances between nodes are not uniform. In this section, we describe how the transmission power control applied to HCRL improves localization performance without cost increase. A method which reduces the number of communications in determining node connectivity is also provided.

### A. Subdivision of One-Hop

To improve localization accuracy, the HCRL algorithm, if necessary, utilizes transmission power control, which is provided by most off-the-shelf sensor motes, to subdivide one-hop into several sub-hops. With the signal propagation model, the relation of a certain transmission power level $P_d$ and its communication distance $d$ is obtained as follows:

$$\frac{P_{\max}}{P_d} = \left(\frac{d_{\max}}{d}\right)^2 \tag{4}$$

where $P_{\max}$ is the maximum transmission power of the sender, and its communication distance is $d_{\max}$ . To shorten the communication range by $n$ times (to divide one-hop to $n$ sub-hops), the transmission power must be reduced by $n^2$ times.

### B. The Improved HCRL Algorithm

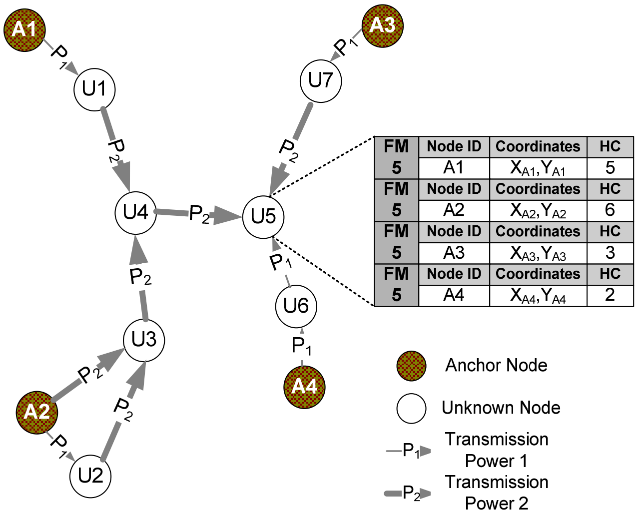
Figure 6 summarizes the algorithm of HCRL where the concept of hop subdivision is applied. First, each anchor node broadcasts *FM*s as described in the basic HCRL mechanism. The difference is that the nodes broadcast as many *FM*s as the number of sub-hops. The *HC* is now set to 0 at the initialization phase and then re-set to 1 to $N$ according to the transmission power $P_k$ ($k$ = 1…N). When a node (either an anchor node or an unknown node) receives a flooding message *FM*, it checks whether the *FM* comes from different anchor node, or whether the *HC* is less than that received previously if the *Node ID* is already stored. Through this verifying step, a node stores only one *FM* which contains the smallest *HC* for each anchor node. If the received *FM* has the smallest *HC* for the anchor *Node ID*, the node adds $k$ to *HC* and forwards *FM* at a transmission power of $P_k$ ($k$ = 1…N). At each transmission, $P_k$ increases from 1 to $N$. Note that a sleep time is required before transmitting a flooding message at the next transmission power. To avoid increasing the number of flooding messages, a node should receive the flooding messages in ascending order of transmission power. If a node receives a flooding message of $P_{k+1}$ before a message of $P_k$, the node may broadcast a redundant message. If an unknown node collects equal or more than four *FM*s from the different anchor nodes, it finally estimates its position by finding the intersection point of constructed Apollonius Circles. The node updates the *FM* and re-estimates its position provided that the new-coming *FM* contains smaller a smaller value for the *HC* than already stored.

```
▶ Initialization:
for each anchor node
    HC ← 0;
    for each transmission power $P_k$ ($k$ ← 1…N)
        HC ← k;
        broadcast FM at transmission power of $P_k$;
        sleep();

▶ Checking FM:
if a node receives FM
    if (Node ID is not new) and (HC is larger than before)
        drop FM;
    else
        if Node ID is new
            store FM;
        else if HC is smaller than before
            update FM;
        for each transmission power $P_k$ ($k$ ← 1…N)
            HC ← HC + k;
            broadcast FM at transmission power of $P_k$;
            sleep();
            if the number of $FM \geq 4$
                construct Apollonius circles;
                estimate intersection of the circles;
```

Fig. 6. Pseudo Code of the improved HCRL algorithm

Figure 7 illustrates a scenario to exemplify the HCRL algorithm. The figure shows how the unknown node *U5* collects the information to estimate its location from four different anchor nodes *A1*, *A2*, *A3*, and *A4*. In this scenario, we assume that the one-hop range is divided into two



| FM | Node ID | Coordinates | HC |
|---|---|---|---|
| 5 | A1 | $X_{A1}, Y_{A1}$ | 5 |
| FM | Node ID | Coordinates | HC |
| 5 | A2 | $X_{A2}, Y_{A2}$ | 6 |
| FM | Node ID | Coordinates | HC |
| 5 | A3 | $X_{A3}, Y_{A3}$ | 3 |
| FM | Node ID | Coordinates | HC |
| 5 | A4 | $X_{A4}, Y_{A4}$ | 2 |

Fig. 7. An example of packet flooding in the HCRL algorithm

sub-ranges. Therefore, each node sends an *FM* including an *HC* added with 1 for transmission at $P_1$ and an *FM* including an *HC* added with *2* for transmission at $P_2$. For the unknown node *U1*, since the *FM* can be received at the transmission power of $P_1$ from *A1*, it stores the *FM* including the *HC* of *1*. *U2* also stores the *FM* including the *HC* of 1 in the same manner as *U1*. On the other hand, *U3* receives *FM*s which have the same *Node ID* as *A2* from both *A2* and *U2*. Through the checking step, *U3* stores only the *FM* including the *HC* of 2, which comes from *A2*. In this method of verifying and maintaining the smallest *HC*, *U5* collects four *FM*s which have the smallest *HC*s for each anchor node.

### *C. Reducing Communication Overhead with RSS Cutoff*

To construct Apollonius Circles, HCRL collects hop-counts based on the connections between nodes. In addition, since HCRL may divide a one-hop range to several sub-ranges through transmission power control, determining the reliability of connectivity is helpful to clarifying the border of sub-ranges and consequently improving the localization accuracy. Reliable connectivity can be identified by simply ascertaining that a node receives more than a certain number of messages during a particular time period. This method, however, is not practical because it induces a heavy communication overhead or requires a lengthy monitoring time. To determine reliable connectivity without increasing communication or delay overhead, HCRL utilizes RSS as the indicator for a reliable connection.

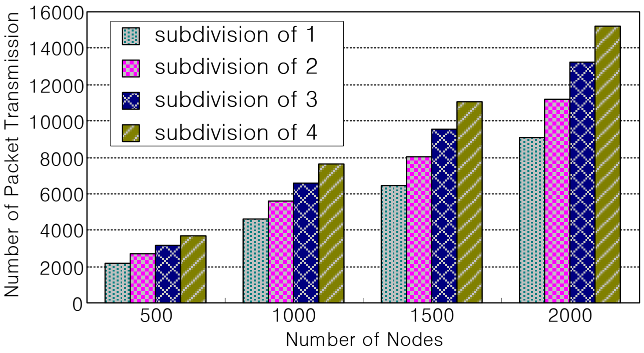


Fig. 8. Transmission overhead increase by one-hop subdivision

Recent studies [13, 14] on the relationship between the Packet Reception Rate (PRR) and RSS using the CC2420 radio module [15] show that the PRR decreases dramatically at less than about -87dBm. This means that a node receiving a message at RSS of less than -87dBm, may not receive a message from the same transmitter next time. In other words, the possibility that a node with less than -87dBm is located near the border of the communication range is high, where no obstacle exists. Therefore, we set -87dBm as the minimum cutoff strength for reliable connectivity. If a node receives the flooding message at less than -87dBm of RSS, the node does not make a connection with a transmitter, which means that the node does not relay the flooding message, including increased hop counts, to other nodes.

### *D. Transmission Overhead Caused by Hop Subdivision*

In cases where HCRL uses the one-hop subdivision technique, the number of transmissions for each node increases by *n* times according to the sub hop-ranges, where the one-hop is divided into *n* sub-hops. The total transmission overhead of whole network field, however, does not increase as much proportionally as the increased number of sub-ranges. This is because a node which already received the flooding message initiated from a certain anchor node will never relay other flooding messages which started from the same anchor node as long as they have fewer hop counts than before. Figure 8 is the simulation result that shows how one-hop subdivision increases the transmission overhead where the nodes are randomly placed in a 500m×500m network field with four anchor nodes and the transmission range is 120m. As the one-hop is divided more finely, the number of transmissions increases. However, the increased overhead for a subdivision of four does not exceed double the overhead of no subdivision.

## V. EXPERIMENTS

In this section, we validate that our algorithm provides a better localization performance than the DV-Hop scheme through real experiments in two different network topologies. We have implemented the HCRL algorithm on "Tmote Sky" [16] sensor motes with an external antenna. The experiments were conducted in a relatively obstacle-free, flat, and sandy plain. Figure 9 shows a picture of the sensor mote which was used in the experiment and the experimental site.

Fig. 9. (a) The sensor node with an external antenna, and (b) experimental site

### A. *Antenna Mounting*

To achieve a reasonable localization result, HCRL, like other hop-count based localization schemes, requires a horizontally omni-directional radiation pattern and a symmetric link between nodes. In the real world, however, the radio signal does not radiate in all directions with the same strength, due to electrical interference caused by devices on the sensor mote and environmental reasons such as multi-path fading, shadowing, and reflection [17, 18]. To reduce the interference by electrical devices on the sensor mote [14], we changed the antenna type from an internal to a $\frac{5}{8}$ wavelength external one, keeping 10cm away from the mote using $50\Omega$ coaxial cable. Note that a $\frac{5}{8}$ wavelength antenna has been chosen to shorten the radio range due to the spatial limitations of the experimental site.

### B. *One-hop Subdivision*

HCRL divides a one-hop range into several sub-ranges by controlling the transmission power level. Since the experiments are conducted only in an obstacle-free environment, we assume that the communication range decreases doubly where the transmission power decreases quadruply. Figure 10 shows the average RSS values versus distance for eight different output power levels in an obstacle-free environment. Since -3dBm indicates half of the output power, we calculated a transmission power of 0dBm for one-hop range, -7dBm for $\frac{1}{2}$ hop range, and -15dBm for a $\frac{1}{4}$ hop range. In other words, 0dBm denotes $P_1$, -7dBm denotes $P_2$, and -15dBm denotes $P_3$ in terms of the HCRL algorithm. Both Figures 10(a) and 10(b) show that our assumption is roughly valid over -87dBm of RSS which is the minimum cutoff strength. In Figure 10(b), a longer communication range is shown as the height of antenna is changed from 20cm to 60cm, but the assumption is still valid.

Due to limited space, our experiments were conducted with two sub-hop ranges. The top of the antenna was at a height of 20cm. Note that, for a more reliable connection, we set the RSS cutoff to -80dBm which corresponds to 80% of the PRR, instead of -87dBm. Therefore, in our experiments, the hop ranges for $P_1$ and $P_2$ are approximately 600~750cm and 1200~1500cm, respectively.

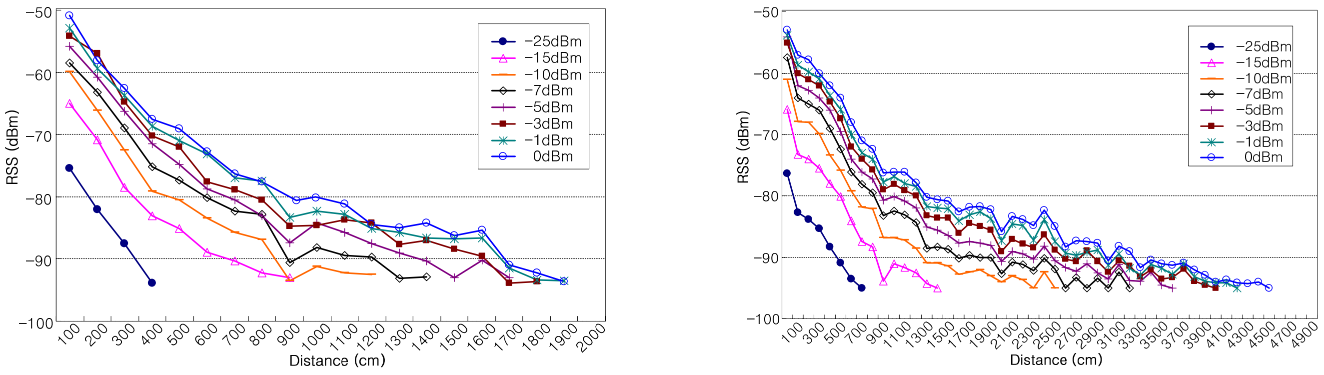
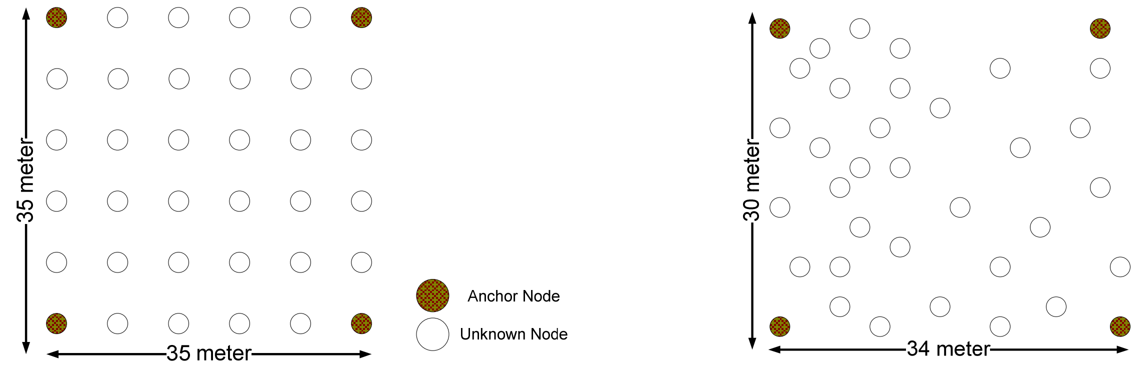


Fig. 10. Average RSS vs. distance in an obstacle-free environment. The top of antenna is at a height of (a) 20cm and (b) 60cm. Experiments were conducted with "Tmote Sky" sensor mote and a $\frac{5}{8}$ wavelength external antenna



(a) (b)

Fig. 11. (a) Grid network topology (b) random network topology

### C. *Evaluation*

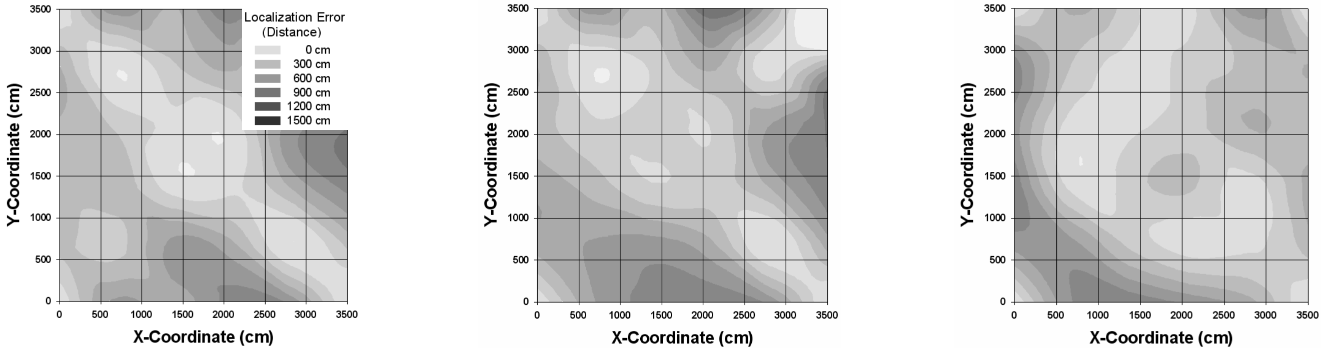
We have conducted experiments in two different network topologies: one was grid shaped, and the other had a random topology, as shown in Figure 11. The topology size was 3500cm×3500cm for the grid, and 3400cm×3000cm for the random topology. For each topology, we examined HCRL without hop subdivision, HCRL with hop subdivision, and the DV-Hop localization scheme. The number of motes was 36; four of these were for anchor nodes and the rest were unknown nodes. Since the positions of anchor nodes may have a great effect on the localization result in both DV-Hop and HCRL, we located the anchor nodes on the verge of experimental field for the fair comparison.

Figure 12(a), 12(b), and 12(c) present the localization error of DV-Hop, HCRL without hop subdivision, and HCRL with 2 hop subdivisions in the grid topology, respectively. In the case of the grid topology, the performance of each scheme was almost same. The average error distance was around 400cm for all the three cases. All three algorithms provide better localization performance at the middle area of the topology than at the edge. Note that the HCRL algorithm which adopts hop subdivision did not present a significant improvement in terms of localization performance of the average error distance in the grid topology. This is caused not only by the type of topology, but also by the distance between nodes. In the grid topology, the distance between neighbor nodes was 700~990cm; therefore, a sub-hop of around 600~750cm might not work properly. Figures 13(a) and 13(b) show the localization error difference between DV-Hop and basic HCRL (no sub-hops applied), and DV-Hop and the improved HCRL with subdivision, respectively. A positive value indicates the area in which HCRL outperforms DV-Hop. A negative value indicates the opposite situation. As shown in Figures 12 and 13, although the average error is almost same in the basic HCRL and the improved version, hop subdivision improved the erroneous localized area.

In the case of random topology, the basic HCRL presents almost the same localization result as DV-Hop, as shown in Figures 14(a) and 14(b). The average error distance was around 450cm for the both cases. The estimation of the position was erroneous at the middle and the edge areas in both algorithms. In contrast with the grid topology, the improved HCRL with hop subdivision outperforms DV-Hop for the overall experimental area as shown in Figure 14(c). The average error distance decreased to about 260cm. Figure 15 shows how much HCRL improves by adopting hop subdivision in the random topology. As Figure 15(b) shows, the HCRL enhanced the localization performance at the areas where DV-Hop presented erroneous results.

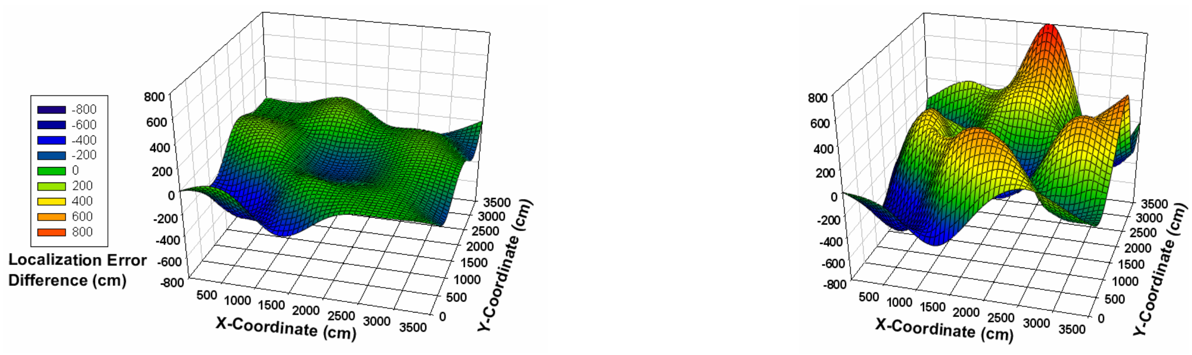
## VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed HCRL, a localization method which aims at low cost in a real sensor network system. For this goal, we focused on finding a localization method which provides relatively accurate performance with the minimum transmission overhead, under the condition that the sensor network has a small number of anchor nodes. HCRL reduces the transmission overhead by half compared to conventional hop-count based localization schemes. This is possible because HCRL estimates the unknown position with anchor-to-node hop-count ratios; this is obtained from only a single flooding.



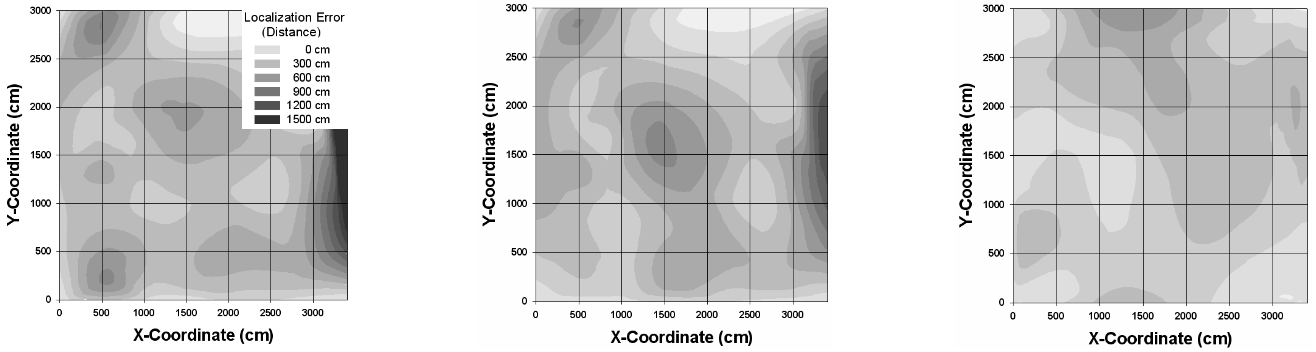
(a) (b) (c)

Fig. 12. Localization error in grid topology for (a) DV-Hop, (b) HCRL without hop subdivision, and (c) HCRL with hop subdivision



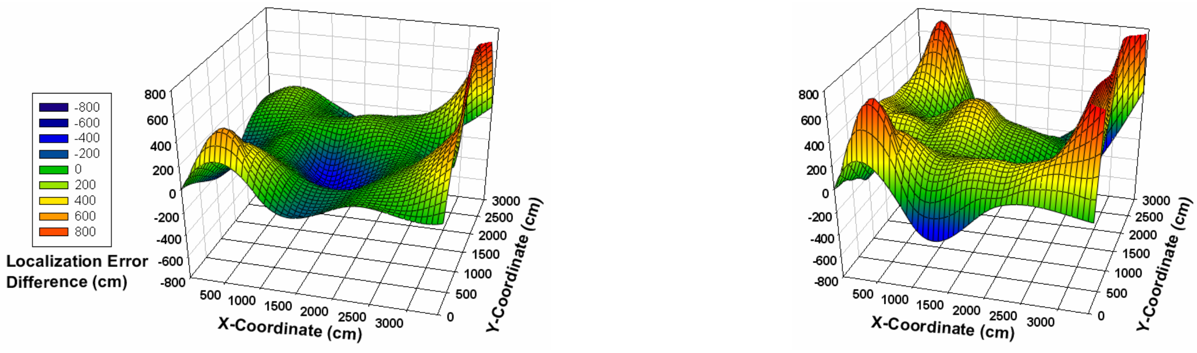
(a) (b)

Fig. 13. Localization error difference in grid topology between DV-Hop and (a) HCRL without hop subdivision, (b) HCRL with hop subdivision



(a) (b) (c)

Fig. 14. Localization error in random topology for (a) DV-Hop, (b) HCRL without hop subdivision, and (c) HCRL with hop subdivision



(a) (b)

Fig. 15. Localization error difference in random topology between DV-Hop and (a) HCRL without hop subdivision, (b) HCRL with hop subdivision

The HCRL algorithm, which can be improved through the one-hop subdivision technique, provides better localization accuracy than the conventional scheme with still less communication overhead. With the RSS-cutoff mechanism, we also achieved drastic reduction in transmission overhead which is required for the reliable link determination.

In future work, we plan to develop an environment-independent HCRL scheme. The hop-count which is based on the communication range varies greatly, even if the distance between nodes is regular, with environmental conditions such as obstacle presence, ground material, or landform. We will explore a mechanism that adaptively determines the appropriate hop-counts in accordance with environmental conditions.

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