Anchor-Guiding Mechanism for Beacon-Assisted Localization in Wireless Sensor Networks

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Abstract—Localization is one of the most important issues in wireless sensor networks (WSNs). In the most widely proposed range-free algorithms, nodes estimate location by employing the geometric constraints imposed by the location of the mobile anchor. However, none of them addresses how the mobile anchor moves to optimize the improvement of location inaccuracies and minimize the anchor’s movement. This paper assumes that previous range-free algorithms have been executed for a period of time and the deployed anchors are of different location inaccuracies. According to the size of the estimative region of each static sensor, an anchor-guiding mechanism is proposed to determine the beacon locations and construct an efficient path for the mobile anchor. Experimental study reveals that the proposed anchor-guiding mechanism effectively guides the mobile anchor to move along an efficient path, thereby saving the time required for improving or balancing the location inaccuracies of all sensor nodes.

Keywords—Wireless Sensor Networks; Mobile anchor; Path guiding; Location estimates

I. INTRODUCTION

Location awareness of sensor nodes plays a critical role in most sensor network applications such as coverage calculation, event detection, object tracking, and location aware routing. The sensor nodes have to be aware of their location to specify “where” a certain event takes place. Determining the physical location of the sensors after they have been deployed is known as the problem of localization.

Many mechanisms have been proposed to address the range-free localization problem [1-3]. These schemes [4-15] share the common feature of deploying beacon nodes (also called anchors) that are aware of their own location information in the WSN. All the other sensor nodes discover their locations based on the information provided by the anchors. The anchor-based localization schemes are categorized into static and mobile anchor techniques. The common challenge of static anchor schemes is that the location inaccuracies of each sensor node highly depends on the number and the deployed positions of the static anchors. To improve location inaccuracies, the number of anchor nodes tends to be increased, which adds to the localization cost. Another problem of static anchors is that they do not perform any other function after broadcasting the beacons [7].

To eliminate the need for static anchors, studies [4-15] propose some schemes based on a mobile anchor for a resource-constrained WSN. The mobile anchor is aware of its own location information with the use of GPS or other location support system. It moves and broadcasts its coordinates at some certain locations, which can be treated as virtual static anchors at those locations. Each static sensor that receives the mobile anchor’s coordinates is aware that its location is within the communication range of the mobile anchor. Therefore, static sensor can identify that it is located within a specific region. When a static sensor receives different coordinates from the mobile anchor, it can calculate its new estimative region by the intersection of all possible location regions based on the received coordinates. However, these studies do not consider how the mobile anchor moves and where the beacon should be broadcasted, especially when the static sensors have different location inaccuracies in the given WSN. To this end, this paper aims to develop an anchor-guiding mechanism for the mobile anchor to improve the location inaccuracies of all sensors and minimize the anchor’s movement.

The remaining part of this paper is organized as follows. Section 2 gives related work of localization mechanisms while section 3 illustrates the network environment and problem formulation of the proposed guiding mechanism. Section 4 details the proposed anchor-guiding mechanisms while section 5 analyzes the guiding efficiency of the proposed scheme. Section 6 investigates the performance of the proposed guiding mechanism and then the conclusion is given in section 7.

II. RELATED WORK

Localization with low cost and high accuracy is of utmost importance for most applications in WSNs. To eliminate the hardware cost such as a GPS device on each static sensor or even remove the requirement of deploying a number of static anchors in the WSN, a number of localization schemes [8-9] have been proposed for a resource-constrained WSN.

In studies [4-6, 8-11], a mobile anchor being aware of its own location is proposed to periodically move and broadcast a beacon with its current coordinate for improving the location inaccuracy of the nearby static sensors. Upon receiving the beacon message, the sensor node indicates that it is within the region of the circle centered at the coordinate of mobile anchor with a radius of \( r \), where \( r \) is the communication range of the mobile anchor. Therefore, the sensor node identifies that its location is within the circle region, which is referred to the estimative region. Based on the range-constraint of beacon messages, a static sensor that receives several different coordinates from the mobile anchor may reduce its estimative region by calculating the intersected estimative region of its neighbors and itself, hence improving the location inaccuracy. However, the range-constraint localization is mainly applied by those sensors that are actually one-hop neighbors of the mobile anchor.

Srinath T. V. [7] extends the range-constraint from one-hop to the two-hop neighboring sensors. Let \( A = \{a_1, a_2, \ldots, a_n\} \) denote the set of \( n \) neighbors of the mobile anchor and \( B \) denote those sensors that neighbor to sensor \( a_i \) in set \( A \). Upon receiving the location information from the mobile anchor, all sensors in set \( A \) calculate their estimative regions and then broadcast the regions to their neighbors. Since the two-hop neighboring sensors of mobile anchor cannot receive the location information from mobile anchor, nodes in set \( B \) have a location constraint that they are not located in the estimative region of \( a_i \). However, since nodes in set \( B \) neighbor to node \( a_i \), they have another constraint that they are located in the communication range of any possible location of \( a_i \). Based on these two constraints, nodes in set \( B \) can also derive their own estimative regions.
Utilizing different coordinates received from the mobile anchor might reduce the static sensor’s estimative region, consequently improving the location inaccuracy. However, it is complex and time consuming to calculate the intersection region of several circle regions. Some other studies [8-9] propose localization schemes applying a rectangle region instead of a circle region to simplify both the calculation and representation of the new estimative region. However, given a WSN, it is an essential requirement that the localization task should be completed under the constraint of the anchor’s remaining energy. The previous studies failed to address how the mobile anchor can achieve the optimal improvement of location inaccuracy for the WSN.

This paper presents an important observation that the improvement of sensors’ location inaccuracies highly depends on the beacon locations that determine the movement path of the mobile anchor. Let $ER_s$ denote the current estimative region of sensor $s$. Let the communication range of the mobile anchor be $r$ and the new beacon coordinate received by sensor $s$ be $(x, y)$. The new range-constraint of sensor $s$ will be the square region $R$ where the left-up and the right-down points are with coordinates $(x-r, y-r)$ and $(x+r, y+r)$, respectively. The new estimative region of sensor $s$ is the intersected region of the old estimative region $ER_s$ and the new range-constraint $R$. This also indicates that the improvement of the estimative region is the area $ER_s \cap R$, which is contributed from the receipt of the new beacon. As a result, given the $ER_s$ of sensor $s$, the improvement of the $ER_s$ highly depends on the new beacon location $(x, y)$. Therefore, there are two important tasks for a mobile anchor in improving the location inaccuracy of the WSN: determining the promising beacon locations and constructing an efficient path that passes through these locations with minimal path length.

III. NETWORK ENVIRONMENT AND PROBLEM STATEMENT

3.1 Network Environment

Let the monitoring region be the region where users are interested to monitor. To totally understand what events occur in the monitoring region, a large number of sensors will be deployed in the region to detect the event and report their sensing information via multi-hop routing. This paper considers that a large number of static sensors have been randomly deployed in the monitoring region. Assume that localization schemes proposed in [4-15] have been applied to the monitoring region for a while such that all sensors might have different initial estimative regions. During the execution of the existing localization schemes, the mobile anchor can also collect the information of estimative regions of these sensors. Herein, we notice that our work is complementary to the existing studies [4-15] and can be applied after each sensor has an initial estimative region.

In addition, the mobile anchor $m$ that is always aware of its own location information by GPS or other location support system. The communication ranges, denoted by $r$, of the mobile anchor and all static sensors are equal. Consider that the mobile anchor $m$ broadcasts a beacon at location $(x_m, y_m)$ at time $t$. The beacon $b(x_m, y_m)$ that indicates the current location $(x_m, y_m)$ of mobile anchor at time $t$ will create a new range-constraint $R_s(x_m, y_m) = \left\{(x, y) | (x-x_m)^2 + (y-y_m)^2 \leq r^2\right\}$.

We assume that each static sensor $s$ has an initial rectangle estimative region $ER_s = \left\{(x, y) | (x-x_s)^2 + (y-y_s)^2 \leq r^2\right\}$, of its location at time $t$, where coordinates $(x_s, y_s)$ and $(x_s, y_s)$ denote the locations of left-up and right-down points of $ER_s$. The size of $ER_s$ can be evaluated by $|x_{s,2} - x_{s,1}| \times |y_{s,2} - y_{s,1}|$.

3.2 Problem Formulation

A beacon $b(x_m, y_m)$, broadcasted by the mobile anchor $m$ at time $t'$ will create a new range-constraint region, called broadcasting rectangle $R_b(x_m, y_m)$, to those static sensors neighboring to the mobile anchor. Upon receiving the beacon at time $t > t'$, the sensor $s$ will recalculate its estimative region by Exp. (1).

$$ER_s = ER_{s, r} \cap R_b(x_m, y_m)$$

Figure 1 depicts an example of the calculation of $ER_s$. When sensor $s$ receives a beacon $b(x_m, y_m)$, the dotted rectangle in Fig. 1 represents the estimative region $ER_s$ of sensor $s$ at time $t$ while a new range-constraint $R_b(x_m, y_m)$ is represented by the solid square. The sensor $s$ uses the received beacon information and applies Exp. (1) to determine the new estimative region $ER_s$ (depicted by the shadow region). To simplify the calculation of $ER_s$, a solid square is used instead of the dotted circle. As shown in Fig. 1, since the area size of $ER_{s, r}$ is smaller than that of $ER_s$, the location inaccuracy of sensor $s$ can be improved.

$$|x_{s,2} - x_{s,1}| \times |y_{s,2} - y_{s,1}| > |x_{s,2} - x_{s,1}| \times |y_{s,2} - y_{s,1}|$$

In the randomly deployed WSN, the estimative regions of sensors might be different because these sensors receive several different beacons from the mobile anchor $m$. The locations where the mobile anchor broadcasts beacons will result in different improvements on the location inaccuracy of WSN. Let $bef_{s(x_m, y_m)}$ and $bef_{s(x_m, y_m)}$ denote the benefits of sensor $s$ and all sensors obtained from the beacon $b(x_m, y_m)$, respectively. If a static sensor $s$ with the estimative region $ER_s$, receives a beacon $b(x_m, y_m)$ from mobile anchor $m$, the improvement of its location inaccuracy can be measured by Exp. (2).

$$bef_{s(x_m, y_m)} = ER_s - ER_{s, r} = |ER_s - (ER_s \cap R_b(x_m, y_m))|$$

Let $N(m)$ denote the sensors that neighbor to the mobile anchor $m$. Expression (3) shows the total benefits obtained from the beacon.

$$bef_{s(x_m, y_m)} = \sum_{s \in N(m)} bef_{s(x_m, y_m)}$$

3.3 The Investigated Problem

This paper aims at developing a guiding mechanism that constructs a path passing through all beacon locations to obtain maximal benefits and minimize the movement of the mobile anchor. Assume that the proposed guiding mechanism constructs a path $p$ passing through $k$ beacon locations $l_1 = (x_1, y_1), l_2 = (x_2, y_2), \ldots, l_k = (x_k, y_k)$, where there are $i$ turns on path $p$. When the anchor arrives at beacon location $l_i$, the mobile anchor will stop to broadcast a beacon and then move or turn toward the next beacon location along path $p$. Let $E_m$ denote the total energy consumption of the mobile anchor in
the anchor guiding process. The $E_m$ can be derived by the energy consumptions required for moving along path $p$, for stopping and broadcasting the beacons, and for making turns. Let $e_p$, $e_{stop}$, $e_{beacon}$ and $e_{turn}$ denote the energy consumptions for mobile anchor moving per unit distance, stopping once, broadcasting a beacon, and making a turn, respectively. Let $|p|$ denote the length of path $p$. Furthermore, assume that there are $i$ turns and $k$ stops for broadcasting $k$ beacons on path $p$. The $E_m$ can be represented by Exp. (4).

$$E_m = \text{energy consumption for moving in the path} + \text{energy consumption for stopping and broadcasting the beacons} + \text{energy consumption for making turns}$$

$$= |p| \times e_p + k \times (e_{stop} + e_{beacon}) + i \times e_{turn}$$

Let $E_s$ be the initial energy of mobile anchor. The total benefit of the anchor’s movement and beacons should be maximized under the constraint $E_m \leq E_s$. The total benefit $Total_{bef}$ is calculated as shown in Exp. (5).

$$Total_{bef} = \sum_{i \in \mathcal{E}_i} \text{bef}_{s_i(x, y)}$$

Figure 2 shows an example of a mobile anchor moving along different paths and broadcasting beacons at different locations resulting in different contributions for improving the location inaccuracy of the WSN. At time $t$, the three static sensors $s_1$, $s_2$ and $s_3$ have estimative regions: $ER_{s_1}, ER_{s_2}$ and $ER_{s_3}$, respectively, which are represented by the dotted rectangles in Fig. 2. Assume that the current location of mobile anchor is $a$. In case that mobile anchor moves along path $p_2$ and broadcasts a beacon at location $c=(x_c, y_c)$, the new range-constraint $R_t(x_c, y_c)$ does not help for improving the location inaccuracy of sensor $s_1$ since the range-constraint $R_t(x_c, y_c)$ cannot reduce the area of $ER_{s_1}$. Similarly, the range-constraint $R_t(x_c, y_c)$ cannot help in improving the estimative regions of sensors $s_2$ and $s_3$. On the contrary, if mobile anchor moves along path $p_1$ and broadcasts a beacon at location $b=(x_b, y_b)$, the range-constraint $R_t(x_b, y_b)$ significantly improves the location inaccuracies of sensors $s_2$ and $s_3$. As shown in Fig. 2, the resultant estimative regions of sensors $s_2$ and $s_3$ are $ER_{s_2}$ and $ER_{s_3}$, respectively. Compared with the $ER_{s_1}$ and $ER_{s_3}$, the new estimative regions are quite smaller than the original ones, hence contributing the maximal benefits for localization.

According to (3), Exp. (7) shows the total benefit obtained from the beacon $b(x_b, y_b)$.

$$bef_{s_1(x_c, y_c)} = bef_{s_2(x_b, y_b)} + bef_{s_3(x_b, y_b)}$$

This observation motivates us to investigate the anchor guiding mechanism for obtaining the maximal improvement on location inaccuracy of the WSN and minimizing the movement of the mobile anchor.

IV. THE GUIDING MECHANISM

This section presents the proposed guiding mechanism for mobile anchor to contribute the maximal benefits for localization. The guiding mechanism mainly consists of four phases: Identifying Promising Region Phase (IPRP), Weighting Phase (WP), Beacon Locations Selection Phase (BLS), and Path Construction Phase (PCP). The first phase, called Identifying Promising Region Phase (IPRP), aims to analyze the relation between the estimative regions and the communication ranges of static sensors, and thereby the promising region of each sensor can be determined. Then, the Weighting Phase (WP) partitions the promising region into a number of regular grids and determines the weight of each grid. Third, according to the weight of each grid, the Beacon Locations Selection Phase (BLS) selects some of the most promising grids where the mobile anchor broadcasts beacons at those locations can significantly contribute benefits for improving the location inaccuracy of the WSN. Herein, we notice that the selection of beacon locations should satisfy the minimal movement constraint. Hence, this phase also presents two policies to achieve different goals according to the requirement of localization in either minimizing or balancing the location inaccuracies of all sensors. Finally, the Path Construction Phase (PCP) creates the shortest path for passing through all promising grids determined in BLS. The following details each phase of the proposed guiding mechanism.

4.1 Identifying Promising Region Phase (IPRP)

This phase aims to identify the promising region of each sensor. A promising region of sensor $s$ at time $t$, denoted by $PR_{s,t}$, is a rectangle region, where a mobile anchor broadcasting a beacon at any location of this region might improve the location inaccuracy of sensor $s$.

A beacon can help sensor $s$ recalculate its new estimative region [4-15] if sensor $s$ can receive the beacon from mobile anchor. That is, the mobile anchor should be located within the communication range of sensor $s$. However, the mobile anchor only has the knowledge that sensor $s$ falls in the estimative region $ER_{s}=[(x_{s1}, y_{s1}), (x_{s2}, y_{s2})]$. Since sensor $s$ might be located at any point belonging to its estimative region $ER_{s}$, and the mobile anchor should fall in the communication range of sensor $s$, the promising region $PR_{s,t}$ will be determined by extending the boundaries of estimative region $ER_{s}$ with length $r$ which is the communication range of sensor $s$. As shown in Fig. 3, the mobile anchor can determine the $PR_{s,t}$ whose boundaries is marked by solid rectangular region. As a result, the mobile anchor can simply determine $PR_{s,t}$ by applying the coordinates of left-up and right-down points of $ER_{s}$. Let coordinates $(x_{s1}, y_{s1})$ and $(x_{s2}, y_{s2})$ denote the locations of left-up and right-down points of $ER_{s}$, respectively, the $PR_{s,t}$ can be calculated by Exp. (8).
However, the promising region might include a helpless region that the new range-constraint \( R_s(x_m, y_m) \) totally covers the \( ER_s \), and hence cannot reduce the area size of \( ER_s \). For example, as shown in Fig. 1, since the area size of \( ER_s \) is smaller than that of \( ER_s \), the location inaccuracy of sensor \( s \) can be improved. Nevertheless, if the estimative region \( ER_s \) is fully covered by the new range-constraint \( R_s(x_m, y_m) \), the new estimative region \( ER_s \) will be \( ER_s \cap R_s(x_m, y_m) = ER_s \). As a result, the location inaccuracy of sensor \( s \) cannot be improved by beacon \( b(x_m, y_m) \). The following gives the formal definition of helpless region and uses the Fig. 4 to illustrate how to determine the helpless region of each sensor.

\[
PR_{s,t} = \left[ (x_{s,1} - r, y_{s,1} - r), (x_{s,2} + r, y_{s,2} + r) \right]
\]

![Diagram showing the relationship between \( PR_{s,t} \) and \( ER_s \)](Image)

Figure 3: The promising region of sensor \( s \) can be determined by the constraint that the mobile anchor is located within the communication range of sensor \( s \).

The helpless region of sensor \( s \) is the region where mobile anchor located at any location within the region to broadcast a beacon cannot improve the location inaccuracy of sensor \( s \). That is, the new range-constraint created by mobile anchor will fully cover sensor \( s \)'s estimative region. Thus, if the mobile anchor can evaluate the helpless region, it should not broadcast the beacon in that region. Figure 4 shows an example of the helpless region of sensor \( s \) at time \( t \), denoted by \( HLR_{s,t} \). Let the coordinates of left-up point and right-down point of \( ER_s \) be \((x_{s,1}, y_{s,1})\) and \((x_{s,2}, y_{s,2})\), respectively. Let the location of mobile anchor be \((x_m, y_m)\) and the coordinates of left-up point and right-down point of \( R_s(x_m, y_m) \) be \((x_{s,1}^{m,1}, y_{s,1}^{m,1})\) and \((x_{s,2}^{m,1}, y_{s,2}^{m,1})\), respectively. The \( HLR_{s,t} \) can be easily calculated based on the information of the five coordinates. In case that the rectangle region \( R_s(x_m, y_m) \) fully covers the region \( ER_s \), the intersection operation as depicted in Exp. (1) will equal to the original region \( ER_s \), resulting that the beacon is helpless to improve the location inaccuracy of sensor \( s \). Therefore, the condition that \( ER_s \) is fully covered by \( R_s(x_m, y_m) \) is necessary for deriving the \( HLR_{s,t} \). That is to say, Exps. (9), (10), (11), and (12) hold.

\[
\begin{align*}
(x_{s,2}^{m,1} - r, y_{s,2}^{m,1} - r) \leq (x_m, y_m) \\
(x_{s,1}^{m,1} + r, y_{s,1}^{m,1} + r) \geq (x_m, y_m)
\end{align*}
\]

![Diagram showing the condition for \( HLR_{s,t} \)](Image)

Figure 4: The condition that \( HLR_{s,t} \) is fully covered by \( R_s(x_m, y_m) \) is necessary for deriving the \( HLR_{s,t} \). That is, the Exps. (9), (10), (11), and (12) hold.

4.2 Weighting Phase (WP)

This phase aims at partitioning the whole monitoring region into a number of regular grids and proposes a weighting system that assigns each grid with a weight to represent the benefit obtained by broadcasting a beacon at each grid. A virtual coordinates system can be constructed for the grid-based WSN. Let \( g(x, y) \) denote the grid located at the \( x \)th row and \( y \)th column of grids. Each grid \( g(x, y) \) of \( PR \) will be locally assigned with a weight value according to the contribution to the location inaccuracy of sensor \( s \) if a beacon is broadcasted at that grid. The weight value assigned in grid \( g(x, y) \) is called Grid Benefit of \( g(x, y) \) (or \( GB_{g(x,y)} \)), which will be used to guide the mobile anchor for maximizing the total benefit of the anchor’s movement. Any grid located out of the promising region of sensor \( s \) is assigned with zero value because there is no contribution to the location inaccuracy of sensor \( s \).
Let \( p_{g(x,y)} \) and \( \text{bef}_{g(x,y)} \) denote the probability that the mobile anchor is within the communication range of sensor \( s \) and the improvement of location inaccuracy of sensor \( s \), respectively. Since \( \text{bef}_{g(x,y)} \) can be measured by the difference of \( \text{ER}_{s,t} \) to \( \text{ER}_{s,t}' \), the \( GB_{g(x,y)} \) to sensor \( s \) can be determined by Eq. (25).

\[
GB_{g(x,y)} = p_{g(x,y)} \times \text{bef}_{g(x,y)} = p_{g(x,y)} \times (\text{ER}_{s,t} - \text{ER}_{s,t}')
\]  

(25)

Let \( N_s(R) \) be the number of grids that mobile anchor located at those grids can communicate with sensor \( s \) in region \( R \). Let \( N_s(R) \) be the number of grids in region \( R \). Then, the \( GB_{g(x,y)} \) can be calculated by Eq. (26).

\[
GB_{g(x,y)} = \frac{N(\text{ER}_{s,t})}{N(\text{ER}_{s,t}')} \times N(\text{ER}_{s,t} - \text{ER}_{s,t}')
\]  

(26)

The Grid Benefit of grid \( g(x,y) \) is the summation of all benefits assigned by those sensors that grid \( g(x,y) \) commonly belongs to their promising region. Let \( N \) denote the set of sensor nodes in the monitoring region. Expression (27) calculates the Grid Benefit of grid \( g(x,y) \).

\[
GB_{g(x,y)} = \sum_{\forall x,y,N_s(g(x,y) \in PR)} GB_{g(x,y)}
\]  

(27)

Figure 5 shows an example to illustrate the calculation of \( GB_{g(x,y)} \). In the following, we assume that the mobile anchor broadcasts a beacon at grid \( g(x,y) \) and discuss the contribution of this beacon to sensor \( s \). In Fig. 5(a), the new range-constraint is depicted by the solid rectangle and the original estimative region \( \text{ER}_{s,t} \) of sensor \( s \) is represented by the dotted rectangle. Since sensor \( s \) is possibly located at any grid of \( \text{ER}_{s,t} \) the gray region marked in Fig. 5(a) represents those grids that are within the communication range of the mobile anchor located at \( g(x,y) \). Therefore, \( N_s(\text{ER}_{s,t}) = 5 \) (the number of grids in the gray region). Since the number of grids in \( \text{ER}_{s,t} \) is \( N_s(\text{ER}_{s,t}) = 4 \times 5 = 20 \), we have \( p_{g(x,y)} = 5/20 \) which indicates the probability that the mobile anchor located at grid \( g(x,y) \) can communicate with sensor \( s \). In case the sensor receives the mobile anchor’s beacon, it applies Exp. (1) and calculates its new estimative region \( \text{ER}_{s,t}' \) represented by the dotted rectangle as shown in Fig. 5(b). The number of grids in \( \text{ER}_{s,t}' \) is 6. Therefore, the \( \text{bef}_{g(x,y)} \) is 20-6=14 grids. Then, the benefit of grid \( g(x,y) \) can be calculated by

\[
GB_{g(x,y)} = p_{g(x,y)} \times \text{bef}_{g(x,y)} = 0.25 \times (20 - 6) = 3.5.
\]

4.3 Beacon Locations Selection Phase (BLSP)

In this phase, the mobile anchor selects beacon locations for obtaining maximal benefits in executing localization task. First of all, we would like to present a concept that any two beacon locations should be far away from each other at certain distance. Let the mobile anchor broadcast a beacon at grid \( g(x,y) \) at time \( t \) and then broadcast another beacon at grid \( g(x,y) \) at time \( t' \) with a certain distance, as shown in Fig. 6. Let the new range-constraint improve the location inaccuracy of sensor \( s \). We observe that the area of helpless region of sensor \( s \) will be changed and increased with the size of \( \text{ER}_{s,t} \). The new helpless region should be derived so that the mobile anchor can select the beacon location outside the helpless region.

The following presents how the mobile anchor determines the new helpless region. As shown in Fig. 6(a), \( \text{ER}_{s,t} \) is denoted by the dotted rectangle. When a mobile anchor broadcasts a beacon at grid \( g(x_1,y_1) \) at time \( t_1 \), the \( \text{ER}_{s,t} \) is changed to \( \text{ER}_{s,t}' \) that is sized \( m \times n \). In Fig. 6(b), mobile anchor moves from \( g(x_1,y_1) \) to \( g(x_2,y_2) \) with a certain distance. The new range-constraint cannot improve the location inaccuracy of sensor \( s \). In Fig. 6(c), the shadow region shows the new helpless region formed due to the change of \( \text{ER} \) of sensor \( s \) from \( \text{ER}_{s,t} \) to \( \text{ER}_{s,t}' \). This indicates that the beacon broadcasted at any location of the shadow region will not form a new range-constraint which will totally cover the \( \text{ER}_{s,t}' \). The width and length of the new helpless region are \( 2r-m \) and \( 2r-n \), respectively. Therefore, assume that the new \( \text{ER}_{s,t}' \) has been constructed by sensor \( s \) because of receiving a beacon from mobile anchor at location \( g(x_1,y_1) \) at time \( t_1 \). Expression (28) gives the evaluation of the new helpless region.

\[
H_{LR_{s,t}} = [(x_1,y_1),(x_1 + (2r - m),y_1 + (2r - n))]
\]  

(28)
beacon locations. The following presents the two selection policies. Let $G$ denote the set of selected grids for broadcasting beacons. Let $S_i$ denote the set of sensors whose sizes of estimative regions can be reduced if the mobile anchor broadcasts a beacon at grid $g(x_i, y_i)$. The $ER_i$ denotes the set of new estimative regions of sensors belonging to set $S_i$ after these sensors receiving the beacon broadcasted at grid $g(x_i, y_i)$. Furthermore, let $HLR_i$ denote the set of new formed helpless regions derived according to the $ER_i$.

A. Benefit-Based Selection Policy

The Benefit-Based Selection (BBS) policy aims at maximizing the benefits in executing the localization task. That is, the BBS scheme selects one grid that has optimum benefit at a certain time. It only considers those grids whose benefit values are larger than the predefined benefit threshold $\sigma$. Herein, we notice that the benefit threshold $\sigma$ is a user defined value. The smaller value of $\sigma$ represents the larger number of beacon locations, leading to a longer path length and higher energy consumption for the mobile anchor. In the Performance Study section, the value of $\sigma$ is set to 10. Let there be $k$ grids $g(x_i, y_i), 1\leq i\leq k$, satisfying Exp. (29).

$$GB_{g(x_1,y_1)} \geq GB_{g(x_2,y_2)} \geq \cdots \geq GB_{g(x_k,y_k)} \geq \sigma \tag{29}$$

The following gives the BBS procedure.

**Benefit-Based Selection Procedure**

**Input:** grid $(x_i, y_i)$

**Output:** beacon locations

1. $G = \{g(x_i, y_i)\}; \ \ \ \ \ HLR = \{HLR_i\}$
2. FOR $i = 2 \ \ \ \ \ \ \ \ \ \ k$
3. IF $(x_i, y_i) \notin HLR$
4. $G = G \cup \{g(x_i, y_i)\}$
5. $HLR = HLR \cup \{HLR_i\}$
6. END IF
7. END FOR

Initially, in line 1, the first grid $g(x_1, y_1)$ that has the highest priority is selected in set $G$. Since the new grid $g(x_1, y_1)$ is selected, this implies that there is a new beacon broadcasted at grid $g(x_1, y_1)$. The new beacon will construct one or more new estimative regions, which result in a new helpless region set called $HLR$. Therefore, the new helpless region set $HLR$ should be recalculated to avoid the subsequently selected grids falling in $HLR$. Line 2 checks whether or not the subsequent $k-1$ grids can be selected in $G$. In line 3, if the considered $i$-th grid $g(x_i, y_i)$ does not fall in the new helpless region set $HLR$, it is selected in set $G$, as shown in line 4. Line 5 recalculates the new helpless region set $HLR$ according to Exp. (28).

Figure 7 is an example illustrating the BBS policy. Each solid square represents the current estimative region of each sensor. The threshold is set to 10 in this example. Therefore, those grids that are marked with gray color are considered as the candidates for broadcasting the beacons. Initially, the grid with maximum benefit 15 is selected. Then the grid with the second highest benefit 13 is considered. Since this grid does not belong to the helpless region of any sensor, it is selected and is included in set $G$. The next grid will be selected if it has the maximal benefit among the unchecked grids and it does not belong to the set of helpless regions. As a result, the selected grids are marked with dotted squares as shown in Fig. 7.

B. Distance-Based Selection Policy

The Distance-Based Selection (DBS) policy aims at minimizing the moving distance and thus saves the energy consumption in executing the localization task. The DBS policy selects the next grid that has minimal distance to the current selected grid. Let mobile anchor $m$ be located at grid $g(x_m, y_m)$ currently. Let there be $k$ grids $g(x_i, y_i) \geq \sigma, 1 \leq i \leq k$, that satisfy $dist(g(x_m, y_m), g(x_i, y_i)) \leq dist(g(x_m, y_m), g(x_{i-1}, y_{i-1})) \leq \cdots dist(g(x_m, y_m), g(x_1, y_1))$, where $dist(g(x_m, y_m), g(x_i, y_i))$ denotes the distance between grids $g(x_m, y_m)$ and $g(x_i, y_i)$. The DBS algorithm is the same as BBS algorithm except that it selects grids according to the distances of the selected grids. The following gives the DBS procedure.

**Distance-Based Selection Procedure**

**Input:** grid $(x_i, y_i)$

**Output:** beacon locations

1. $L = \{g(x_1, y_1), g(x_2, y_2), g(x_3, y_3), \ldots, g(x_r, y_r)\}; \ \ \ \ r = 1$
2. $HLR = \{HLR_i\}$
3. WHILE $L \neq \emptyset$
4. Let $DIS(r, t) = \min DIS(r, s)$, where $r \neq t$ and $g(x_r, y_r) \in L$
5. $G = G \cup \{g(x_r, y_r)\}$
6. $HLR = HLR \cup \{HLR_i\}$
7. $L = L - \{g(x_r, y_r)\}; \ \ \ \ r = t$
8. END WHILE

Let $L$ denote the set of remaining candidates for beacon locations. The mobile anchor $m$ initially selects $g(x_1, y_1)$. Then it treats the selected grid $g(x_1, y_1)$ as $g(x_m, y_m)$ and repeats the DBS selection operations until $L = \{\emptyset\}$. Let $d_{ij}$ denote the value of entry $DIS_{x,y}(i, j)$ which represents the distance between grids $g(x_i, y_i)$ and $g(x_j, y_j)$, for $1 \leq i, j \leq k$. The following gives the DBS procedure. Since the $g(x_1, y_1)$ is selected for being a beacon location, the DBS algorithm looks at the first row ($r = 1$) of $DIS$ matrix to find the grid with minimal distance to $g(x_1, y_1)$. We assume that entry $DIS(r, t)$ has a minimum value in row $r$. Therefore, the grid $g(x_r, y_r)$ will be selected. This indicates that the mobile anchor will broadcast a beacon at grid $g(x_r, y_r)$. Then, the DBS procedure will further select the next grid by checking the $t$-th row, which records the distances of grid $g(x_r, y_r)$ to other grids. The WHILE loop will be terminated once all grids in set $L$ have been checked.
4.4 Path Construction Phase (PCP)

This phase presents how the mobile anchor constructs the path that passes through those beacon locations selected in the BLS. The path construction aims at obtaining maximal benefits and minimizing the movement in executing the localization task. The energy consumption of the mobile anchor, say $E_m$, will be evaluated in the phase. Let mobile anchor $m$ moving for a path length $|p|$ and having $i$ turns and $k$ stops for broadcasting beacons during the movement consume $E_m=|p|\times e_p + k\times (e_{stop} + e_{beacon}) + i\times e_{turn}$. Let $G$ be the set of the grids selected from BLS and $g(x_m, y_m)$ be the current grid location. Let $P$ denote the constructed path which starts at $g(x_m, y_m)$ and ends at $g(x_s, y_s)$. Let $EG_{a,b}$ denote the edge which starts at $g(x_s, y_s)$ and ends at $g(x_b, y_b)$. The constructed path will be extended by connecting as many new edges as possible. Note that each extended edge will have maximal benefit-cost ratio so that the total improvement of location inaccuracy is optimal. The following gives the PCP algorithm.

Figure 8 shows an example illustrating the PCP phase. As shown in Fig. 8(a), assume that there are four grids $a$, $b$, $c$ and $d$ selected in the BLS phase and they have benefits 15, 10, 11 and 13, respectively. In the path construction phase, mobile anchor $m$ is located at the grid $g(x_m, y_m)$. We assume $15/\text{dist}(g(x_m, y_m), a)> 10/\text{dist}(g(x_m, y_m), b)>11/\text{dist}(g(x_m, y_m), c)>13/\text{dist}(g(x_m, y_m), d)$. Therefore, the mobile anchor constructs the edge connecting grids $g(x_m, y_m)$ and $a$, as shown in Fig. 8(a). The energy consumption for moving from $g(x_m, y_m)$ to $a$ is evaluated. Then PCP algorithm continues executing the next WHILE loop and compares the values of ratios $10/\text{dist}(a, b), 11/\text{dist}(a, c), 13/\text{dist}(a, d)$. As shown in Fig. 8(b), the edge connecting grids $a$ and $b$ is constructed in the path and the energy consumption for moving from $g(x_m, y_m)$ to $b$ passing through $a$ is evaluated. Similar operations will be executed by mobile anchor for constructing a path that obtains as many benefits as possible under the energy constraint $E_m$.

Path Construction Phase Algorithm (PCP)

**Input:** beacon locations

**Output:** path $P$

1. $g(x_r,y_r)=g(x_m,y_m)$
2. $P=EG_{a_m}$; $E_p=0$
3. Let $\text{dist}(EG_{a_m})=\text{dist}(g(x_r,y_r),g(x_i,y_i))$
4. WHILE($G \neq \emptyset$)
   5. $g(x_i,y_i)=\max\{GB_{(x_i,y_i)/\text{dist}(EG_{a_m})}, g(x_i,y_i)\} \in G$
   6. IF($x_i=x_r$ or $y_i=y_r$) $\text{turn}=0$
   7. ELSE $\text{turn}=1$
   8. $P=P+EG_{a_i}$; $g(x_i,y_i)=g(x_r,y_r)$
   9. $E_m=E_m+(\text{dist}(EG_{a_i})\times e_p) + e_{stop} + e_{beacon} + \text{turn}\times e_{turn}$
10. $G=G-\{g(x_i,y_i)\}$
11. END WHILE

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smaller, leading to a lower location inaccuracy. Hence, if a scheme is able to achieve a smaller value \( \lambda \) for each estimate region, the scheme has higher performance for localization. Recall that the area size of \( EBR \) is \( t^t i/4 \). The area size of the estimative region of each sensor after applying the proposed \( BBS \) policy will be \( t^t \lambda \) while the eliminated area size of the estimative region of each sensor from the \( EBR \) after applying the proposed \( BBS \) policy will be \( (t^t i/4 - \lambda) \). Let required location accuracy (\( RLA \)) be a user predefined value and be defined by \( (t^t i/4 - \lambda)^t \), as shown in Exp. (30).

\[
RLA = \frac{t^t i/4 - \lambda}{t^t i/4} \tag{30}
\]

The larger value of numerator of \( RLA \) represents that the estimative region is reduced more significantly. Therefore, if a scheme achieves higher \( RLA \), the scheme is with higher localization performance.

Let \( RLA = 1 - \delta \), where \( 0 \leq \delta \leq 1 \). The constraint of the grid size, \( d \), can be derived as shown in Exp. (31).

\[
RLA = \frac{t^t i/4 - \lambda}{t^t i/4} = 1 - \delta \Rightarrow d^t = \frac{\delta^t}{\lambda} \tag{31}
\]

For example, the value of \( RLA \) is set to 0.9, where \( \delta \) is 0.1. We set 1-\( \delta \) for the value of \( RLA \) but not \( \delta \) since it is able to simplify the Exp. (31). This also indicates that the grid size has an upper bound if a certain location accuracy 1-\( \delta \) is required. Since the small grid size will increase the movement distance in the \( BBS \) policy, the maximal value of \( d \) will be considered in the analysis to reduce the movement distance while the predefined \( RLA \) constraint can be satisfied.

As shown in Exp. (32), let \( L \) and \( W \) denote the length and width of the given monitoring area. Herein, we assume that \( L = kW \) since the length \( L \) can be represented as \( k \) times the width \( W \) where \( k \geq 1 \) is a constant value.

\[
W = eR = \frac{e\sqrt{\lambda}}{\sqrt{\pi\delta}} \quad \text{and} \quad L = kW = \frac{ke\sqrt{\lambda}}{\sqrt{\pi\delta}}. \tag{32}
\]

Let the average benefit of each beacon be \( u \) grids by applying the \( BBS \) policy and the number of the deployed static sensors in the monitoring region be \( n \). Let \( g_{\text{remove}} \) denote the number of grids in each \( EBR \) that are removed from the anchor’s beacon by applying the \( BBS \) policy. The \( g_{\text{remove}} \) can be evaluated by Exp. (33).

\[
g_{\text{remove}} = n \left( \frac{L}{d} \right)^2 - n \lambda. \tag{33}
\]

Since each beacon contributes the average benefit of \( u \) grids by applying the \( BBS \) policy, the number of beacon, say \( t \), required to achieve the requested location accuracy is shown in Exp. (34).

\[
t = \left[ \frac{g_{\text{remove}}}{u} \right] = \left[ n \left( \frac{L}{d} \right)^2 - n \lambda \right] = \left[ n \left( \frac{\lambda}{\delta} \right) - n \lambda \right] \tag{34}
\]

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distance of the BBS policy is longer than that of the Snake-Like policy in horizontal direction. Since \( L = kW \) and \( k \geq 1 \), Exp. (37) can be further simplified to Exp. (40) which indicates that the moving distance of the proposed BBS will be shorter than the Snake-Like approach. This guarantees that the result presented in Exp. (40) is always valid for a rectangle monitoring region.

When \( \frac{L}{t} > d \), \( \frac{t}{d} < \frac{L}{d} \)

\[
\frac{D_{\text{snake-like}}}{D_{\text{BBS}}} = \frac{k(W + d)}{d\sqrt{k^2 + t^2}} > \frac{k(W + d)}{d\sqrt{k^2 + \left(\frac{kW}{d}\right)^2}} = 1
\]

VI. PERFORMANCE STUDY

This section compares the performance results of the proposed Anchor-Guiding Mechanism (AGM) with the Snake-Like [14-15] and Random movements [3] using the Giomasim simulator [16]. The GloMoSim simulator is a library-based sequential and parallel simulator for wireless networks. The major reason for us to select GloMoSim as our simulator is that our proposed guiding mechanism and the compared approaches can be simply programmed using PARSEC language which is a C-based parallel simulation language. We use GloMoSim simulator to investigate the performance results in terms of the impact of network density and localization time on location inaccuracies (described in Section 6.1), the impact of energy consumption and thresholds on location inaccuracies (described in Section 6.2) as well as the impact of energy consumption and thresholds on balance index (described in Section 6.3).

In the simulation study, the benefit-based and distance-based anchor-guiding policies applied in AGM are denoted by BB-AGM and DB-AGM, respectively. In executing the Snake-Like and Random movements, the time-based and distance-based policies are applied for mobile anchor to determine when or where a beacon should be broadcasted. In Random movements, the mobile anchor broadcasts a beacon every time unit. Let \( \beta \) denote the distance of two parallel trajectories of the Snake-Like movement. The value of \( \beta \) is set at 2 and 4 to observe its impact on the performance of Snake-Like movement.

The network environment is described below. The size of the monitoring region is 300 units x 300 units. A number of static sensors, ranging from 20 to 100, are randomly deployed in the WSN. The monitoring region is partitioned into 300x300 grids. The communication radius is 10 units. The mobile anchor is located at the left-up corner of the monitoring region and moves at a constant speed and stops to broadcast a beacon for localization. The energy consumptions required for constant-speed movement for a unit distance, broadcasting a beacon, making a turn, and stop-then-start are 0.98W, 0.017W, 3W, and 0.7W, respectively.

6.1 The Impact of Network Density and Localization Time on Location Inaccuracies

In literature, many location-aware applications highly rely on each sensor’s accurate location, rather than on an estimative region. To fit the existing applications, the estimation region of each sensor should be transferred to an estimate location. The estimate location of sensor \( s \), denoted by \( (x_{\text{est}}, y_{\text{est}}) \), is the cross point of the two diagonal lines of \( ER \).

The location error of a sensor \( s \) can be measured by Exp. (41).

\[
P_{\text{error},s} = \sqrt{(x_{\text{est}} - x_{\text{real}})^2 + (y_{\text{est}} - y_{\text{real}})^2}
\]

where \((x_{\text{real}}, y_{\text{real}})\) is the real location of sensor \( s \). Hence the mean location error of the WSN can be derived by Exp. (42).

\[
P_{\text{error}} = \left( \sum_{i=1}^{n} P_{\text{error},s_i} \right) / n
\]

where \( n \) denotes the number of static sensors deployed over the monitoring region.

Figure 12 measures the impact of network densities and the time spent for localization on the location error. All mechanisms have a common feature. When the network density is fixed, the mean location error decreases with the localization time. However, the proposed anchor-guiding approaches DB-AGM and BB-AGM outperform the Snake-like and Random movement mechanisms in terms of mean location error in all cases of the network density and the localization time. When the mean location error and network density are fixed, the proposed approaches require shorter localization time than the other two mechanisms. This is because the approaches of the proposed DB-AGM and BB-AGM guide the mobile anchor along the path that passes through the most promising locations for broadcasting beacons.

Figure 12 also depicts that the proposed approaches have lower mean error, especially in the case of high network density. The major reason is that the number of beacon locations increases with the number of sensors, which significantly improves the location inaccuracies of the sensors. On the other hand, the mean error of Snake-like mechanism increases with the network density. The trajectory and beacon locations of the Snake-like movement do not change with the network density. Therefore, the maximal path length that the mobile anchor could exert before its energy exhaustion will be a constant. However, the number of sensors that are not visited by the mobile anchor increases with the network density. Therefore, there are more sensors obtaining no location information in a higher network density, and hence the mean error of Snake-like movement mechanism increases. Moreover, a higher \( \beta \) value will result in a lower mean error.
by applying the Snake-like movement. The major reason is that a higher $\beta$ value makes the beacon locations cover a larger area size, which results in a lower mean error. Regarding the Random movement mechanism, the trajectory of the mobile anchor’s movement is randomly determined. When the network density is increased, the number of sensors that do not receive any beacon from mobile anchor increases, which results in a higher mean error.

6.2 The Impact of Energy Consumption and Thresholds on Location Inaccuracies

The location inaccuracy of sensor $s$ at time $t$, noted as $LI_{s,t}$, is denoted the area size of estimative region $ER_{s,t}$. Hence, the unit of the location inaccuracy is square meters. The smaller size of $ER_{s,t}$ represents that sensor $s$ has a smaller estimative region, which also indicates that the maximal distance from the real location of the sensor to any point in $ER_{s,t}$ is smaller.

Let $LI_{WSN,t}$ denote the location inaccuracy of WSN at time $t$ and it can be measured by Exp. (43).

$$LI_{WSN,t} = \sum_{s=1}^{n} LI_{s,t}$$

(43)

A smaller value of $LI_{WSN,t}$ represents a lower location inaccuracy of WSN at time $t$. Therefore, the ratio of localization inaccuracy, called localization efficiency, of mobile anchor from time $t$ to $t'$ is measured by $1-LI_{WSN,t'} / LI_{WSN,t}$. In the best case, each sensor has a location point at time $t'$, implying that the value of $LI_{WSN,t'}$ is zero. In the worst case, the mobile anchor does not help to reduce the size of estimation region of any sensor and hence the value of $LI_{WSN,t'} / LI_{WSN,t}$ is equal to 1 and thus the localization efficiency is equal to zero. Therefore, the value of localization efficiency is normalized between zero and one, and a larger value indicates better localization efficiency.

Figure 13 also depicts another result that the proposed approaches and the other two mechanisms under the constraint of the energy consumption for obtaining the maximal benefits in localization.

Figure 13 compares the localization efficiencies of the proposed approaches and the other two mechanisms under the constraint of the energy consumption for the anchor’s movement. In general, the localization efficiency is increased with the number of beacons broadcasted by mobile anchor at the locations where can obtain higher benefit. However, the mobile anchor consumes more energy for its movements and broadcasting beacons. That is the major reason that the localization efficiency of static sensors is increased with the energy consumptions of the mobile anchor. As shown in Fig. 13, the proposed approaches have larger values than the Snake-like and Random movement schemes and thus outperform them in terms of localization efficiency. Moreover, BB-AGM has a better performance than DB-AGM because the benefit-based policy always guides the mobile anchor moving along the path that passes through the beacon locations for obtaining the maximal benefits in localization.

Higher mean location errors may cause more routing error. In the experiments, the well known GPSR [17] is applied to construct routes from randomly selected sources to destinations. GPSR is one of the famous location-aware routing protocols [17]. By applying this routing protocol, the source node or forwarding node selects its neighboring sensor that is the closest to the destination node as the next data forwarder. This operation will be repeatedly executed until the data reaches the destination node.

Figure 15 shows that BB-AGM achieves lower routing error than DB-AGM and Random movement since the benefit-based policy guides the mobile anchor to obtain the maximal benefits and thus reduces the mean location error in localization under energy constraint. Figure 16 shows the snapshot obtained by applying the BB-AGM approach on the WSN for 1000 time units. In Fig. 16, the hollow and solid
nodes represent the estimate and real locations of sensors, respectively. Since the estimated location of each sensor is very close to real location, the proposed BB-AGM effectively improves the location inaccuracies of all sensors in the monitoring region.

![Figure 15: Comparison of routing error of the proposed approaches and Random movement under various threshold values. The constraint of mobile anchor’s remaining energy is set at 10 kW.](image)

6.3 The Impact of Energy Consumption and Thresholds on Balance Index

In the experiments, a Balanced Index $BI$, as shown in Exp. (45), is used to measure the balance of the sensors’ location inaccuracies:

$$BI = \left( \sum_{i=1}^{n} \frac{1}{\alpha} \sum_{j=1}^{n} \left( |ER_{ij} - |ER_{ij}| | \right) \right) / \left( 2n^2 |ER_{mean}| \right)$$

(45)

where the $ER_{mean}$ denotes the mean value of the sizes of all sensors’ estimative regions. A smaller value of $BI$ indicates that the sizes of estimative regions of all sensors are likely equal.

Figure 17 compares the proposed approaches with the Snake-like movement mechanism. All of the compared movements have a common feature that the $BI$ value decreases with the energy consumption. The proposed approaches have a smaller value of $BI$ and thus have a better performance in terms of balancing the location inaccuracies of the WSN. Moreover, the proposed BB-AGM saves significant energy than DB-AGM and Snake-like movement for achieving the same value of $BI$. The proposed BB-AGM aims at moving to the grid with maximal grid benefit, it has fewer impact by the value of $\alpha$. However, applying the other three mechanisms will result in a larger distance between the visited grids and hence the mobile anchor consumes more energy for movement. As a result, the BB-AGM approach outperforms the other three mechanisms in terms of the beacon benefits as shown in Fig. 19.

Figure 18 shows the $BI$ changed in each beacon by applying BB-AGM is smaller than the other mechanisms. Referring to Fig. 15, since the DB-AGM consumes more energy than BB-AGM when the anchor moves for balancing the location inaccuracies of the sensors, the BB-AGM approach will significant improves the sizes of estimative regions and results in smaller routing error. Furthermore, a higher threshold value applied by the anchor can have better performance in terms of location inaccuracies of the sensors.
and routing error when the energy constraint of the mobile anchor is considered.

![Figure 19: Comparison of BB-AGM, DB-AGM, and Snake-Like in terms of beacon benefits by varying the value of α.](image)

![Figure 20: Comparison of BB-AGM, DB-AGM, and Snake-Like in terms of $BI$ by varying the value of $\alpha$.](image)

VII. CONCLUSIONS

To our knowledge, this is the first study that applies the mobile anchor to improve the location accuracy under the condition that all sensors are with different sizes of estimative regions. Firstly, the monitoring region is partitioned into grids and each grid is assigned with a weight value representing the localization benefit. Then the BB-AGM and DB-AGM approaches are proposed to select promising grids for broadcasting beacons so that the goals of minimizing and balancing the location inaccuracies of all sensors can be reached. Finally, a path construction algorithm is proposed to construct a path passing through the beacon locations and minimize the anchor’s movement. Simulation results reveal that the proposed mechanism outperforms the Snake-Like and Random movements and hence obtains better results in terms of mean location error, localization efficiency and balance index.

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