Path Guiding Mechanisms for a Mobile Anchor Improving or Balancing Location Accuracies of Static Sensors in WSNs

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Abstract*—Location information is of utmost importance for most applications in wireless sensor networks. Recent localization schemes have been categorized into range and range-free based techniques. Obvious inclination is towards range free algorithms since they do not rely on special hardware that would be required in range based algorithms. In the most proposed range-free algorithms, nodes estimate their location using the geometric constraints imposed by the location of a mobile anchor. However, there is no discussion on how the mobile anchor moves so that the maximal location accuracies of all sensor nodes can be obtained with the constraint of energy consumption of a mobile anchor. This paper assumes that traditional range-free algorithms have been executed for a certain time period and the deployed sensors are with different location accuracies. We propose path guiding mechanisms that sensor nodes cooperatively guide the mobile anchor moving along an efficient path which can maximize the improvement of location accuracies or minimize the accuracy differences for all sensor nodes in a given WSN. Experimental study reveals that the proposed path guiding mechanisms effectively guide the mobile anchor moving along the efficient path and thereby saves time and energy consumptions for improving or balancing the location accuracies of all sensor nodes.

Keywords-WSN, localization, mobile anchor, path guiding, location estimates.

I. INTRODUCTION

Location awareness of sensor nodes plays a critical role in most of the sensor network applications such as coverage calculation, event detection, object tracking, and location aware routing. Sensor nodes have to be aware of their location to be able 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. One simple method for providing each sensor node with location information is manual configuration. However, it is not a feasible solution for a large scale sensor network. Equipping a Global Positioning System (GPS) receiver on each sensor node for providing the location information in an outdoor environment is also unlikely feasible because of its expensive hardware cost and considerable power consumption.

To eliminate the need of having GPS receiver on every sensor node, a number of location discovery schemes [1][2] have been proposed in recent years. These schemes share the common feature that some static beacon nodes (or called anchors) that are aware of their own location information are deployed in the WSN.

The common challenge of these schemes is that the location accuracy of each sensor node highly depends on the number and the deployed positions of the static anchors. To obtain high location accuracy, the number of anchor nodes tends to be increased, which increases the hardware cost. Another problem of static anchors is that they play no role after they broadcast the beacons [3].

To eliminate the need of static anchors, some other localization schemes are proposed for a resource constrained WSN. These localization schemes [3][4][5] are developed mainly based on a mobile anchor which is aware of its own location information by equipping with the GPS or other location support system. The mobile anchor moves and broadcasts its coordinates at some certain locations, which can be treated as virtual static anchors at those locations. Any static sensor that receives the mobile anchor’s coordinates is aware that its location is within the communication range of the mobile anchor. Therefore, the static sensor can identify that it is located within a location region. When a static sensor receives different coordinates from the mobile anchor, it can calculate its new estimate region by the intersection of all possible location regions based on the received coordinates. To simplify the calculation of the location region, most schemes use a square region which is a smallest square containing the circle that is centered at the beacon location with a radius of communication range. When the mobile anchor moves for a certain time, the sizes of rectangle regions of static sensors might different due to the received coordinates messages are different. At this moment, they have different location accuracies.

Though the mobile anchor-based localization schemes actually reduce the cost for deploying a number of static anchors over the WSN and enable the static sensors to be aware its location with a rectangle region, however, there is no discussion about the path guiding for the mobile anchor, especially when these schemes have been applied for a certain time and the static sensors have different location accuracy. We observe that the improvements on sensors’ location accuracies highly depend on the beacon location and the moving path of the mobile anchor. Let ER_s denote the estimate region of sensor s. Let the transmission range be r and the new beacon coordinates received by sensor s be (x, y). The new range-constraint of sensor s will be the square region R where the top-left and the bottom-right points are with coordinates $(x-r, y-r)$ and $(x+r, y+r)$, respectively. The new estimate region of sensor s is the intersection region of the old estimate region ER_s and the new range-constraint R. That also indicates that the improvement of the estimate region is the region area ER_s-R, which is contributed from the receipt of the new beacon. This concludes that given an estimate region ER_s of s, the improvement on estimate region of sensor s depends on the beacon location (x, y) of the mobile anchor. Therefore, finding the promising beacon locations and an efficient path that passes through these locations with minimal path length will be of great importance for improving the location accuracy of the WSN. This paper aims at developing path guiding mechanisms for the mobile anchor so that the improvements of location accuracies of all sensors in the given WSN can be maximized.

II. Network Emvironment & Problem Statement

2.1 Network Environment

We assume that a large number of static sensors have been randomly deployed in the given WSN. There exists a mobile anchor *m* that is always aware of its own location. The communication range of the mobile anchor and each static sensor are equal and is denoted by *r*. A beacon $b(x_m, y_m)_t$ that indicates the current location (x_m, y_m) of mobile anchor at time *t* will create a new range-constraint $R_t(x_m, y_m)=[(x_m-r, y_m-r), (x_m+r, y_m+r)]_t$. Each static sensor *s* has a rectangle estimate region $ER_{s,t}=[(x_{s,1}, y_{s,1}), (x_{s,2}, y_{s,2})]_t$ of its location at time *t*, where coordinates $(x_{s,1}, y_{s,1})$ and $(x_{s,2}, y_{s,2})$ denote the locations of top-left and bottom-right points of $ER_{s,t}$. The size of $ER_{s,t}$ can be evaluated by $|x_{s,2}-x_{s,1}|\times|y_{s,2}-y_{s,1}|$. Note that the estimate regions of all sensors need not to be equal. The estimate regions of all static sensors' locations are commonly initialized with the whole monitoring region.

2.2 Problem Statement

A beacon $b(x_m, y_m)_{t'}$ broadcasted by the mobile anchor at time *t'* will create a new range-constraint region to those static sensors neighbor to the mobile anchor. Any sensor node *s* that receives the beacon at time *t'*>*t* will recalculate its estimate region by the formula

$$ER_{s,t'} = ER_{s,t} \cap R_{t'}(x_m, y_m). \quad (1)$$

Figure 1 depicts an example of calculation of the $ER_{s,t'}$ when sensor *s* receives a beacon $b(x_m, y_m)_{t'}$. The dotted rectangle in Fig. 1 represents the estimate region $ER_{s,t}$ created by sensor *s* at time *t*. If sensor *s* receives the beacon $b(x_m, y_m)_{t'}$ from mobile anchor *m*, a new range-constraint $R_{t'}(x_m, y_m)$ which is represented by the dotted circle is formed. The sensor *s* applies the information of the beacon and formula (1) to calculate the new estimate region $ER_{s,t'}$ (represented by the shadow region). For simplicity of calculation, a solid square is used in stead of the dotted circle. As shown in Fig. 1, since the area size of $ER_{s,t'}$ is smaller than that of $ER_{s,t}$, the location accuracy of sensor *s* has been improved.

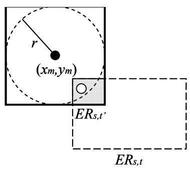


Figure 1: An example for illustrating the calculation of new estimate region $ER_{s,t'}$ of sensor *s* when it receives a beacon $b(x_m, y_m)_{t'}$ from mobile anchor *m*.

In the randomly deployed WSN, the estimate regions of sensors might be different since they receive different beacons from mobile anchor. The locations where mobile anchor broadcasts beacons will result in different improvements on the location accuracy of WSN. Let $bef_{s,(x,y)}$ and $bef_{(x,y)}$ denote the benefits of sensor *s* and all sensors obtained from the beacon $b(x_m, y_m)_{t'}$. If a static sensor *s* with the estimate region $ER_{s,t}$ receives a beacon $b(x_m, y_m)_{t'}$ from mobile anchor *m*, the improvement of its location accuracy can be measured by

$$bef_{s,(x,y)} = ER_{s,t} - ER_{s,t'} = ER_{s,t} - (ER_{s,t} \cap R_{t'}(x_m, y_m)). \quad (2)$$

Let $N(m)$ denote those sensors that neighbor to the mobile anchor *m*. The total benefits obtained from the beacon is

$$bef_{(x,y)} = \sum_{s_i \in N(m)} bef_{s_i,(x,y)} \quad (3)$$

The following gives the problem statements of this work.

Problem formulation

Given a WSN with a predefined energy constraint E_c, where E_c denotes the maximal allowed energy consumption of mobile anchor for localization, we aim at developing a guiding mechanism that construct a path which passes through as more as possible the most promising beacon locations for obtaining maximal benefits under the given constraint. Let mobile anchor *m* moving for a path length $|p|$ and having *k* turns and *i* stops for broadcasting *i* beacons during the movement consume $E_m=|p|\times e_p+i\times(e_{stop}+e_{beacon})+k\times e_{turn}$ where e_p, e_{stop}, e_{beacon} and e_{turn} denote the power consumption for moving a unit distance, stopping then moving, broadcasting a beacon, and making a turn, respectively. The proposed guiding mechanisms aim at constructing a path *p* passing through *k* positions $l_l=(x_l, y_l)$, …, $l_k=(x_k, y_k)$ such that the total benefit of the anchor's movement

$$Total\_bef = \sum_{l \le i \le k} bef_{(x_i, y_i)}$$

can be maximized under the constraint $E_m \le E_c$.

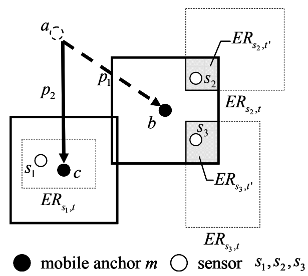


Figure 2: Mobile anchor moves along path p_1 and broadcasts a beacon at location *b* will contribute more benefits to the localization than moves along path p_2 and broadcasts a beacon at location *c*.

Figure 2 shows an example that the mobile anchor moves along different paths and broadcasts beacons at different locations result in different contributions to the location accuracy of the WSN. At time *t*, the three static sensors s_1, s_2 and s_3 have estimate regions $ER_{s_1,t}$, $ER_{s_2,t}$ and $ER_{s_3,t}$, respectively, which are represented by the dotted rectangles in Fig. 2. 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 accuracy of sensor s_1 since the range-constraint $R_{t'}(x_c, y_c)$ can not reduce the area of $ER_{s_1,t}$. Furthermore, the range-constraint also can not help for improving the estimate 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 accuracies of sensors s_2 and s_3. As shown in Fig. 2, the resultant estimate regions of sensors s_2 and s_3 are $ER_{s_2,t'}$ and $ER_{s_3,t'}$ respectively. Compared with the $ER_{s_2,t}$ and $ER_{s_3,t}$, the new estimate regions are quit smaller than the original ones.

The benefits improved by sensors s_2 and s_3 are calculated in below.

$$bef_{s_2,(x_b,y_b)} = ER_{s_2,t'} - ER_{s_2,t}$$
$$bef_{s_3,(x_b,y_b)} = ER_{s_3,t'} - ER_{s_3,t}$$

According to (3), the total benefits obtained from the beacon $b(x_b, y_b)_{t'}$ are

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

This observation motivates us to investigate the anchor guiding mechanisms for obtaining the maximal improvement on location accuracy of the WSN under the energy constraint.

III. THE GUIDING MECHANISMS

This section presents the guiding mechanisms for mobile anchor to contribute the maximal benefits for localization. The guiding mechanisms consist of four phases. The first phase, called *Identifying Promising Region Phase* (or *IPRP*), aims to analyze the relation between the estimate region of static sensors and the communication range, and thereby the promising region can be determined. Then the *Weighting Phase* (or called *WP*) partitions the promising region into several regular grids and determines the weight of each grid according to its contribution to the location accuracy of sensor s if a beacon is broadcasted at the grid. Thirdly, the *Beacon Locations Selection Phase* (or called *BLSP*) selects some most promising grids where the mobile anchor broadcasting beacons at those locations can significantly contribute benefits to the location accuracy of the WSN. Note that the selection of beacon locations should satisfy the predefined energy constraint. There are two schemes presented to achieve different goals according to the requirement of localization is either maximizing benefit of the WSN or balancing the location accuracies of all sensors in the WSN. Finally, the *Path Construction Phase* (or called *PCP*) creates the shortest path for passing through all promising grids determined in *BLSP*. The following details each phase of the guiding mechanisms.

Identifying Promising Region Phase (*IPRP*)

The goal of this phase is to identify the promising region. A *promising region* of sensor s, denoted by PR_s, is a location region that the mobile anchor broadcasting a beacon at any location of the region can improve the location accuracy of sensor s. The PR_s should be bounded by the communication range of sensor s since the sensor has to receive the beacon broadcasted from the mobile anchor. Therefore, the PR_s can be determined by moving along the edges of the $ER_{s,t}$. The estimate region $ER_{s,t}$ and the communication range of sensor s are depicted by the dotted rectangle and cycle, respectively, as shown in Fig. 3. In Fig. 3, the PR_s is represented as the solid rectangle. Let coordinates $(x_{s,1}, y_{s,1})$ and $(x_{s,2}, y_{s,2})$ denote the locations of top-left and bottom-right points of $ER_{s,t}$, the PR_s can be calculated by the following formula:

$$PR_{s,t} = [(x_{s,1} - r, y_{s,1} - r), (x_{s,2} + r, y_{s,2} + r)]_t$$

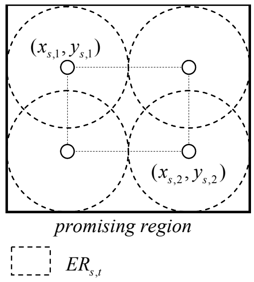


Figure 3: The *promising region* of sensor s can be determined by the fact that the mobile anchor is located with the communication range of sensor s.

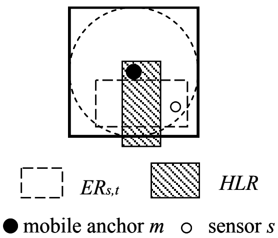


Figure 4: The promising region of sensor s excludes the subregion where the range-constraint contains the estimate region of sensor s.

However, the promising region might include a helpless region that the new range-constraint $R_{t'}(x, y)$ can not reduce the area of $ER_{s,t}$. Figure 4 shows an example to illustrate the helpless region, called HLR_s of sensor s. When the mobile anchor broadcasts a beacon $b(x, y)_t$ at location (x, y) in the region, the range-constraint $R_t(x, y)$, represented as the solid rectangle, totally cover the estimate region of s, which does not help for improving the location accuracy of sensors s. Therefore, the PR_s should exclude the helpless region. Formula (4) reflects this fact.

$$\begin{aligned} PR_{s,t} &= [(x_{s,1} - r, y_{s,1} - r), (x_{s,2} + r, y_{s,2} + r)]_t \\ &-[(x_{s,2} - r, y_{s,2} - r).(x_{s,1} + r, y_{s,1} + r)]_t \end{aligned} \quad (4)$$

Weighting Phase (*WP*)

For evaluating the improvement of the location accuracy of sensors s, the whole monitoring region of WSN will be partitioned into a number of regular grids in this phase. A virtual coordinates system can be constructed for the grid-based WSN. Let $g(x, y)$ denote the grid located at the xth row and yth column of grids. Each grid $g(x, y)$ of PR_s will be assigned with a weight value by sensor s according to its contribution to the location accuracy 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. The grids located out of the PR_s are assigned with zero values by sensor s because that it has no contribution to the location accuracy of sensor s.

Let $p_{s,g(x,\ y)}$ and $bef_{s,g(x,y)}$ denote the probability that the mobile anchor is within the communication range of sensor s and the improvement of location accuracy of sensor s, respectively. Since the $bef_{s,g(x,y)}$ can be measured by the difference of $ER_{s,t}$ to $ER_{s,t'}$, the $GB_{g(x,\ y)}$ to sensor s can be determined by

$$GB_{s,g(x,y)} = p_{s,g(x,y)} \times bef_{s,g(x,y)} = p_{s,g(x,y)} \times (ER_{s,t} - ER_{s,t'}) \quad (5)$$

Let $N_c(R)$ be the number of grids that mobile anchor can communicate with sensor s in region R_s. Let $N_e(R)$ be the number of grids in region R. Then, the $GB_{s,g(x,\ y)}$ can be calculated by

$$GB_{s,g(x,y)} = p_{s,g(x,y)} \times bef_{s,g(x,y)} = \frac{N_c(ER_{s,t'})}{N_e(ER_{s,t})} \times N_e(ER_{s,t} - ER_{s,t'}) \quad (6)$$

The Grid Benefit of grid $g(x, y)$ is the summation of all benefits assigned by those sensors that grid $g(x, y)$ belongs to their estimate regions. The following formula calculates the Grid Benefit of grid $g(x, y)$.

$$GB_{g(x,y)} = \sum_{\forall s \ni g(x,y) \in ER_s} GB_{s,g(x,y)} \quad (7)$$

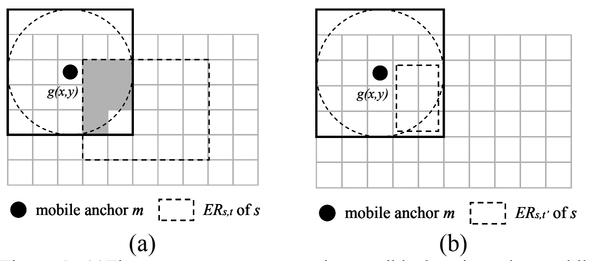


Figure 5: (a)The gray area represents the possible locations that mobile anchor m can communicate with sensor s. (b)The new estimate region $ER_{s,t'}$, denoted by the dotted rectangle, is evaluated according to the new range-constraint.

Figure 5 shows an example to illustrate the calculation of $GB_{s,g(x,\ y)}$. In the following, we assume that the mobile anchor broadcasts a beacon at grid $g(x, y)$ and discuss the contribution of the beacon to sensor s. In Fig. 5(a), the new range-constraint is depicted by the solid rectangle and the original estimate region $ER_{s,t}$ of sensor s is presented by the dotted rectangle. Since sensor s is possible located in any grid of $ER_{s,t}$, 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, $N_c(R)$ is 5 (the number of grids in the gray region). Since the number of grids in $ER_{s,t}$ is $N_e(ER_{s,t})$=4×5=20, we have $p_{s,g(x,\ y)}$= 5/20 which indicates the probability that the mobile anchor located at grid $g(x, y)$ can communicate with sensor s. In case that the sensor receives mobile anchor's beacon, it applies (1) and calculates its new estimate region $ER_{s,t'}$ presented by the dotted rectangle as shown in Fig. 5(b). The number of grids in $ER_{s,t'}$ is 6. Therefore, the $bef_{s,g(x,y)}$ is 20-6= 14 grids. Then, the Grid Benefit to sensor s can be calculated by

$$GB_{s,g(x,y)} = p_{s,g(x,y)} \times bef_{s,g(x,y)} = 0.25 \times (20 - 6) = 3.5.$$

Notice that one grid might belong to more than one promising regions. That is, a beacon at grid $g(x, y)$ might improve several sensors' location accuracies. To aggregate all benefits on the same grid, each sensor s in the monitoring region should transfer $GB_{s,g(x,\ y)}$ to the mobile anchor, for all $g(x, y) \in PR_s$. After obtaining the estimate regions sent from all sensors, the mobile anchor will create a record for each grid of the monitoring region for storing its Grid Benefit. Each record of Grid Benefit consists of *Total_GB* and many *Each_GB* fields. If the mobile anchor broadcasting a beacon at grid $g(x, y)$ can improve the location accuracy of sensor s, the set {sensor s, $GB_{s,g(x,\ y)}$} will be appended in the *Each_GB* filed and the value of $GB_{s,g(x,\ y)}$ will be added into the *Total_GB* field. Finally, the *Total_GB* field maintains the value of $GB_{g(x,\ y)}$ for each grid $g(x, y)$.

Beacon Locations Selection Phase (*BLSP*)

This phase introduces how the mobile anchor selects beacon locations for obtaining maximal benefits in executing localization task. First of all, we would like to presents a concept that any two beacon locations should be far away with a certain distance. Let the mobile anchor broadcast a beacon at grid $g(x, y)$ at time t', as shown in Fig. 6. Let the new range-constraint improve the location accuracy of sensor s. We observe that the area of helpless region of sensor s will be changed and increased with the size of $ER_{s,t'}$. The new helpless region should be derived so that mobile anchor should select the beacon location outside the helpless region.

The following presents how the mobile anchor determines the new helpless region according to the $ER_{s,t'}$. As shown in Fig. 6(a), the $ER_{s,t'}$ is sized $m \times n$. During the movement of mobile anchor from location $g(x, y)$ to location $g'(x, y)$, any beacon broadcasted by the mobile anchor is helpless as shown in Fig. 6(b). This is because that the new range-constraint formed from the that beacon will totally cover the $ER_{s,t'}$. Therefore, the segment from $g(x, y)$ to $g'(x, y)$ is the edge of the helpless region. The width of this segment can be easily derived by $2r$-m. Similarly, the length of the helpless region can be calculated by $2r$-n. Therefore, given a beacon location and the new constructed estimate region $ER_{s,t'}$, the helpless region of sensor s can be derived.

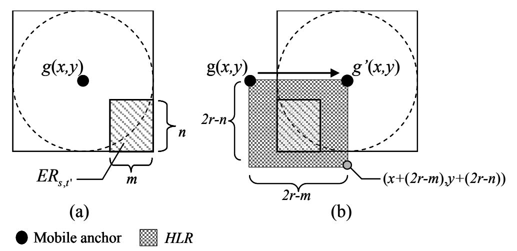


Figure 6: Mobile anchor broadcasts a beacon at grid $g(x, y)$ so that a new estimate region $ER_{s,t'}$ of sensor s has been formed. Let the $ER_{s,t'}$ is sized wiht $m \times n$. The helpless region to $ER_{s,t'}$ will be the gray rectangle.

This study proposes two mechanisms, called benefit-based and accuracy-based grid selection schemes, for mobile anchor selecting beacon locations. The following presents the two selection schemes. Let G denote the set of selected grids for broadcasting beacons. Let S_i denote the set of sensors whose sizes of estimate regions can be reduced if the mobile anchor broadcasts a beacon at grid $g(x_i, y_i)$. Let ER_{S_i} denote the set of new estimate 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_{S_i} denote the set of new formed helpless regions derived according to the ER_{S_i}.

A. Benefit-Based Selection Scheme

The *Benefit-Based Selection* (or *BBS* in short) scheme aims at maximizing the benefits in executing the localization task. That is, the *BBS* scheme selects one grid that has maximal benefit at a time. It only considers those grids whose benefit value is larger than the predefined benefit threshold σ. Let there are k grids $g(x_i, y_i)$, $1 \le i \le k$, satisfy $GB_{g(x_1,y_1)} \ge GB_{g(x_2,y_2)} \ge \cdots \ge \sigma$. The following gives *BBS* algorithm.

Benefit-Based Selection Scheme

$G = \{g(x_1, y_1)\}$
For $i = 2$ to k
IF $(g(x_i, y_i) \notin \bigcup_{j=1}^{i-1} HLR_{S_j})$
$G = G \bigcup \{g(x_i, y_i)\}$
End for

B. Accuracy-Balancing Based Selection Scheme

The *Accuracy-Balancing Based Selection* (or *ABS* in short) scheme aims at improving the location accuracy based on fairness. That is, the grids selection for broadcasting beacons is based on the policy that mobile anchor will improve more accuracies for those sensors with larger sizes of estimate regions. Let $ER_s.bef$ denote the total benefits of the selected grids in estimation region ER_s of sensor s. Let G_s denote the set of selected grids in region ER_s. We have

$$ER_s.bef = \sum_{g(x,y)\in G_s} GB_{g(x,y)} \tag{8}$$

To balance the sizes estimate regions of sensors $s_1, \ldots, s_k$, the *ABS* aims to satisfy the following property.

$$ER_{s_1}.bef : ER_{s_2}.bef : \ldots : ER_{s_k}.bef = |ER_{s_1}| : |ER_{s_2}| : \ldots : |ER_{s_k}| \tag{9}$$

Based on this policy, the sizes of estimate regions of k sensors will be likely equal, which implies that their location accuracies are similar. Let s_{max} be the sensor whose size of estimate region is maximal. The *ABS* scheme first selects as more as possible grids in region $ER_{s_{\max}}$ and use $ER_{s_{\max}}.bef$ as the absolute value to derive how many benefits should be obtained in the other estimate regions according to (9). The following introduces the grid selection procedure for region $ER_{s_{\max}}$. Assume that there are k grids $g(x_i, y_i)$, $1 \le i \le k$, in the region $ER_{s_{\max}}$ and they satisfy $bef_{g(x_1,y_1)} \ge bef_{g(x_2,y_2)} \ge \cdots \ge bef_{g(x_k,y_k)}$. The following gives the *ABS* procedure.

Accuracy-Based Selection Procedure($ER_{s_{\max}}$ **)**

$G = \{g(x_1, y_1)\}$
$ER_{s_{\max}}.bef = 0$
For $i = 2$ to k\{
IF $(g(x_i, y_i) \notin \bigcup_{j=1}^{i-1} HLR_{S_j})$\{
$ER_{s_{\max}}.bef = ER_{s_{\max}}.bef + bef_{g(x_i,y_i)}$
$G = G \bigcup \{g(x_i, y_i)\}$
\}
\}

The *ABS* procedure depicts how to selects grids for the estimate region $ER_{s_{\max}}$. In executing the selection procedure, a grid $g(x_i, y_i)$ will be collected in set G if it does not located in the helpless region of sensor $s_{\max}$. The benefits of all selected grids will be added into $ER_{s_{\max}}.bef$. When the *ABS* procedure running for region $ER_{s_{\max}}$ is completed, another *ABS* procedure will be activated running for the estimate region with the largest size in the remaining estimate regions. The operations are similar with those done for region $ER_{s_{\max}}$. However, the grid selection for this region should satisfy property (9) so that all estimate regions can have same size after executing the *ABS* procedure on each estimate region.

Path Construction Phase (*PCP*)

This phase presents how the mobile anchor constructs the path that passes through those beacon locations selected in *BLSP*. The path construction aims at obtaining maximal benefits under the predefined energy constraint E_c in executing localization task. Let mobile anchor m moving for a path length |p| and having k turns and i stops for broadcasting beacons during the movement consume $E_m=|p|\times e_p+i\times(e_{\text{stop}}+e_{\text{beacon}})+k\times e_{\text{turn}}$. Let G be the set of the grids selected from *BLSP* 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 $g(x_e, y_e)$. Let $EG_{a,b}$ denote the edge which starts at $g(x_a, y_a)$ and ends at $g(x_b, y_b)$. The constructed path will extend by connecting new edges as more as possible if the energy consumption of the path for the mobile anchor is not greater than E_c. Note that each extended edge will has maximal benefit-cost ratio so that the total improvement of location accuracy is the optimal. The following gives the path construction algorithm.

Path Construction Algorithm

$g(x_e,y_e)=g(x_m,y_m)$
$P= EG_{m,e}$
$E_m=0$
Flag=*true*
WHILE (Flag) and ($G \neq \phi$) \{
Let $dist(EG_{e,i})=dist(g(x_e,y_e), g(x_m,y_m))$
$g(x_t,y_t)=\max\{GB_{g(x_i,y_i)}/dist(EG_{e,i})\}$, where $g(x_i,y_i)\in G$
IF $((x_e= x_t)$ or $(y_e= y_t))$ *turn*=0

ELSE $turn$=1
IF (E_m+($dist(EG_{e,t})$ ×e_p)+e_{stop}+e_{beacon}+$turn$×e_{turn}≦E_c)
{ P=P+$EG_{e,i}$
$g(x_e,y_e)$=$g(x_t,y_t)$
E_m= E_m +($dist(EG_{e,t})$/e_p)+e_{stop}+e_{beacon}
G =G –{$g(x_t,y_t)$} }
ELSE Flag=*false* }

Figure 7 shows an example for illustrating the *PCP* phase. As shown in Fig. 7(a), there are four grids *a*, *b*, *c* and *d* with benefits 15, 10, 11 and 13, respectively, selected in the *BLSP* phase. In the path construction phase, mobile anchor is located at the grid $g(x_m, y_m)$. We assume 15/$dist(g(x_m, y_m), a)$> 10/ $dist(g(x_m, y_m), b)$> 11/$dist(g(x_m, y_m), c)$> 13/$dist(g(x_m, y_m), d)$. Therefore, the mobile anchor constructs the edge connecting grids $g(x_m, y_m)$ and *a*, as shown in Fig. 7(a). The energy consumption for moving from $g(x_m, y_m)$ to *a* is evaluated. Then *PSP* continues executing the next while loop and compares the values of ratios 10/ $dist(a, b)$, 11/ $dist(a, c)$, 13/ $dist(a, d)$. As shown in Fig. 7(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 more as benefits under the energy constraint E_c.

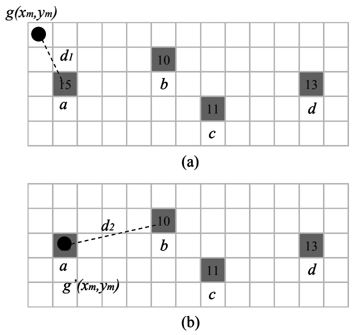


Figure 7: An example for illustrating the *PCP* phase. (a)The edge connecting $g(x_m, y_m)$ and *a* is constructed. (b) Another edge that connects grids *a* and *b* is constructed.

IV. Performance Study

This section compares the performance results of the proposed *Path Guiding Mechanisms* (or *PGM* in short) with the *snake-like* [7] and *random* movements using Glomosim simulator [6]. In the simulation study, the benefit-based and accuracy-balancing-based path guiding mechanisms are denoted by *BB-PGM* and *AB-PGM*, 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. That is, the mobile anchor broadcasts a beacon every 300 time units or every constant distance of 1.5r.

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

A. The Impact of Network Density and Localization Time on Mean Position Error

In literature, many location-aware applications highly rely on each sensor's accurate location, rather than an estimate 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_{est}, y_{est}), is the cross point of the two diagonal lines of ER_s. The position error of a sensor s can be measured by the following formula:

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

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

$$P_{error} = (\sum_{i=1}^{n} P_{error,s_i}) / n$$

where n denotes the number of static sensors deployed in the WSN.

Figure 8 measures the impact of network densities and the time spent for localization on the position error. All mechanisms have a common feature. With the energy constraint, when the network density is fixed, the mean position error decreases with the localization time. However, the proposed path guiding mechanisms *BB-PGM* and *AB-PGM* outperform the *snake-like* and *random* movement mechanisms in terms of mean position error in all cases of the network density and the localization time. When the mean position error and network density are fixed, the proposed mechanisms require smaller localization time than the other two mechanisms. This is because that the proposed *BB-PGM* and *AB-PGM* guide the mobile anchor along the path that passes through the most promising locations for broadcasting beacons.

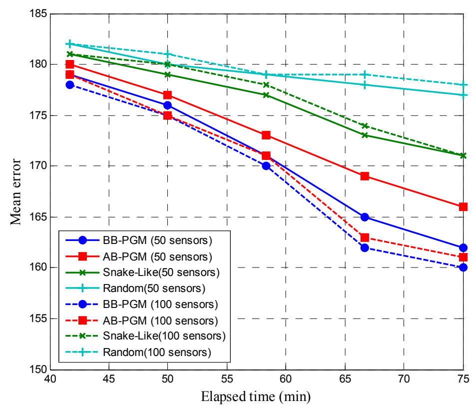


Figure 8: The impact of network densities and time spent for localization on the position error.

Let $LA_{s,t}$ and $LA_{WSN,t}$ denote the location accuracies of sensor s and WSN at time t, respectively. The value $LA_{s,t}$ is measured by the area size of $ER_{s,t}$ and the location accuracy of the WSN is measured by

$$LA_{WSN,t} = \sum_{i=1}^{n} LA_{s_i,t}$$

A smaller value of $LA_{WSN,t}$ represents a higher location accuracy of WSN at time *t*. Therefore the localization efficiency of mobile anchor from time *t* to *t'* is measured by $1\text{-}LA_{WSN,t'}/LA_{WSN,t}$. In the best case, each sensor has an location point at time *t'*, implying that the value of $LA_{WSN,t'}$ 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 $LA_{WSN,t'}/LA_{WSN,t}$ is equal to 1 and thus the localization efficiency is equal to zero. Therefore, the value localization efficiency is normalized between zero and one, and a larger value indicates a better localization efficiency. Figure 9 compares the localization efficiencies of the proposed *BB-PGM*, *AB-PGM* and the other two mechanisms under the constraint of the energy consumption for anchor's movement. The proposed *BB-PGM* and *AB-PGM* have larger values than the other two mechanisms and thus outperform the *snake-like* and *random* movement schemes in terms of localization efficiency. Moreover, the *BB-PGM* has a better improvement than *AB-PGM* since the benefit-based path guiding mechanism always guide the mobile anchor moving along the path that passes through the beacon locations for obtaining the maximal benefits in localization. Figure 10 also depicts another result that the proposed mechanisms *BB-PGM* and *AB-PGM* consume much fewer energy than the other two mechanisms to meet the requirement of a given expected localization efficiency.

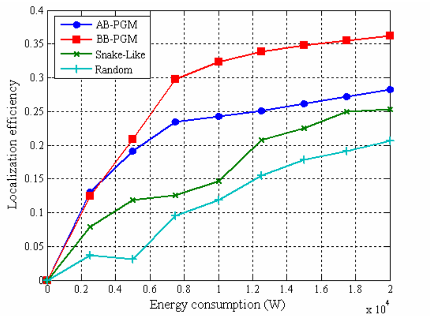


Figure 9: *BB-PGM* and *AB-PGM* achieve higher localization efficiency than the other two mechanisms under the energy constraint.

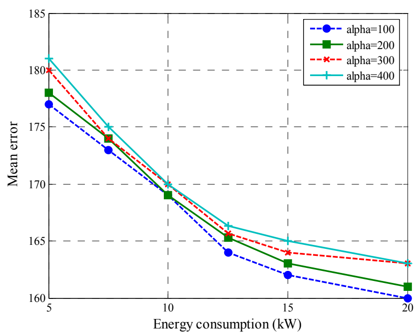


Figure 10: The impact of threshold values on the anchor's energy consumption as well as the mean position error.

In the *benefit-based mechanism* (*BB-PGM*), the accuracies of sensors whose sizes of estimate regions are bigger than the predefined threshold value should be improved. Figure 10 discusses the impact of threshold values on the anchor's energy consumption as well as the mean position error. In case that the mean position error is fixed, the energy consumption of *BB-PGM* decreases with the threshold value. A high threshold value indicates that fewer sensors are required to be improved their location accuracies and thus fewer locations should be visited by mobile anchor, thereby saving the mobile anchor's power consumption.

B. Performance Comparison in terms of Balance Index

The proposed *accuracy-balanced mechanism* (*AB-PGM* in short) aims to balance the location accuracies of all sensors under the constraint of energy consumption. In the experiment, a *balanced index BI*, as shown in below, is used to measure how balanced of the sensors' location accuracies.

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

where ER_{mean} denotes the mean value of the sizes of all sensors' estimate regions. A smaller value of *balance index* indicates that the sizes of estimate regions of all sensors are similar. Figure 11 compares the proposed *AB-PGM* with the *snake-like* and *random* movement mechanisms. Three mechanisms have a common feature that the *BI* value decreases with the energy consumption. The proposed *AB-PGM* has a smaller value of *BI* and thus has a better performance in terms of balancing the location accuracies of the WSN. Moreover, the proposed *AB-PGM* saves significant energy than the other two mechanisms for achieving the same value of *BI*.

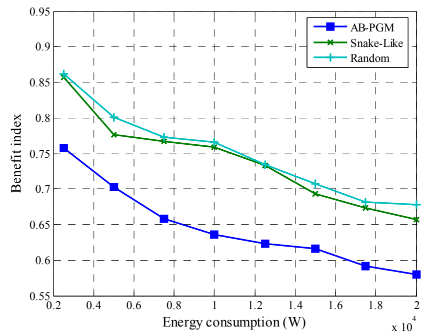


Figure 11: *AB-PGM* achieves higher balance of the location accuracies of all sensors under the constraint of energy consumption

In the following, we discuss and detail the performance results based on the scenarios.

C. A Look on the Physical Scenarios

Figure 12 shows the snapshot in the scenario that the number of deployed sensors is 50 and the proposed *BB-PGM* is applied for 10k time units. The hollow and solid nodes represent the estimate and real locations of sensor nodes, respectively. Since the estimate location of each sensor is very close to real location, the proposed mechanism effectively improve the location accuracies of all sensors in the WSN.

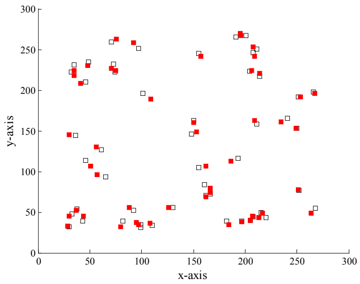
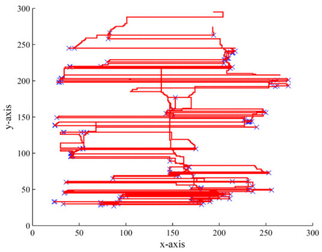
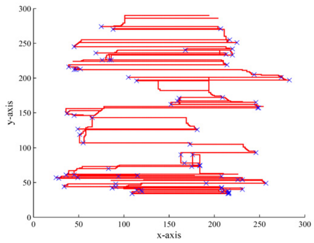


Figure 12: The snapshot of the simulation scenario.



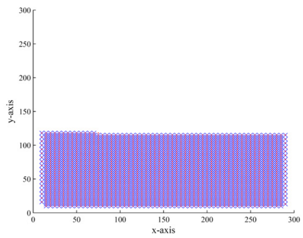
Total Benefit=9286
BI=0.57
Path length=14128 units

Figure 13(a): The path and the beacon locations by applying the proposed *BB-PGM*.



Total Benefit=8247
BI=0.46
Path length=14428 units

Figure 13(b): The path and the beacon locations by applying the proposed *AB-PGM*.



Total Benefit=11136
BI=0.67
Path length=2029 units

Figure 13(c): The path and the beacon locations by applying the *snake-like* movement mechanism.

Figure 13 depicts the paths and the beacon locations by applying *BB-PGM*, *AB-PGM*, and *snake-like* movement mechanism. A common value of energy constraint is applied in all mechanisms. The star points in Figs. 13(a), 13(b), and 13(c) represent the beacon locations by applying *BB-PGM*, *AB-PGM*, and *snake-like* movement mechanism, respectively. As shown in Fig. 13(a), applying *BB-PGM* causes that mobile anchor broadcasts beacons at those star points that have significant benefits for improving the sizes of estimate regions. Therefore, the total benefit is maximal. Applying the *AB-PGM* causes that mobile anchor broadcasts beacons at those locations such that the sizes of estimate regions of all sensors can be similar. Although the benefits obtained in Fig. 13(b) is smaller than that in Fig. 13(a), however, the *BI* value of *AB-PGM* is smaller than that of *BB-PGM*. This also indicates that the *AB-PGM* takes into account the fairness of the location accuracies of all sensors in the WSN. The *snake-like* movement only visited a half of monitoring region because of the limitation of energy constraint. Overall, the proposed *BB-PGM* and *AB-PGM* outperform the *snake-like* and *random* movement schemes in terms of total benefit, balance index, and path length under the same constraint of energy consumption.

V. CONCLUSIONS

Accurate location information is important for most applications in wireless sensor networks. Recently, many localization schemes that use mobile anchor to provide or improve the location estimate regions for static sensors have been proposed. However, these schemes mainly focus on how the static sensors reduce their estimate regions. However, different sensors might have different degrees of requirements for improving their location accuracies since they might have different sizes of estimate regions. To our knowledge, this is the first study that discusses how static sensors guide the mobile robot to construct an efficient moving path and determine the beacon locations. Firstly, the monitoring region is partitioned into grids and each of which is assigned with a weight representing the localization benefit. Then *BB-PGM* and *AB-PGM* are proposed to select grids for broadcasting beacons so that the goals of maximizing benefit of localization and balancing the location accuracies of all sensors can be achieved, respectively. Finally, a path construction algorithm is proposed to construct a path passing through the beacon locations under the constraint of energy consumption of mobile anchor. Simulation results reveal that the proposed mechanisms outperform the *snake-like* and *random* movements and hence obtain better results in terms of position mean error, localization efficiency and accuracy balance index.

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