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Adaptive Path Planning for Randomly Deployed Wireless Sensor Networks[*]

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In this paper, we propose an adaptive path planning scheme considering the length of movement path and number of beacon messages of a mobile beacon for its energy efficiency, where the sensor nodes are randomly deployed. Contrary to the previous studies that utilize mobile beacons (nodes sending beacon messages) only on the basis of a random movement method or predefined static movement paths, the proposed scheme provides energy-efficient and adaptive movement path construction with low computational complexity. The movement path also includes beacon positions in which the mobile beacon broadcasts beacon messages containing the information of its current position. The random movement methods are not concerned about the energy of the mobile beacon. In randomly deployed environments, it is not easy to obtain precise field information for static movement path decisions. Thus, we propose the adaptive path planning scheme which can operate without this information in randomly deployed wireless sensor networks, and improve the energy efficiency of the mobile beacon. The candidate areas that limit the search space are devised so as to provide low complexity. The performance evaluation shows that the proposed scheme reduces the movement distance and number of beacon messages of the mobile beacon by comparison with other methods.

Keywords: mobile beacon, adaptive path planning, energy efficiency, randomly deployed WSNs, candidate areas

1. INTRODUCTION

The location of a sensor node has intrinsic value, and can be used to improve the quality or utility of other information as well. Location information plays a pivotal role in understanding events detected in a sensor field, enabling further processing and aggregation for higher-level location-based services (LBS) or applications such as in-door/outdoor monitoring, target tracking, geographic routing protocols, interference control with signal strength regulation, location-based multicast, *etc*. Therefore, localization for obtaining the physical or logical position of nodes is one of the most critical research topics in wireless sensor networks (WSNs). Conventional localization literature focuses on how to use the range information or network connectivity to estimate a node's position. However, with the advance of mobile devices and the growing interest in movable robots,

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recent studies have considered other issues for movable devices, such as path planning for mobile beacons, target tracking, and navigation.

The majority of localization schemes aim for fully localized networks (*i.e.*, globally rigid networks) where every sensor node can obtain its own unique position, and at least three beacon messages are needed for each sensor node. Without the support of mobile beacons, localization schemes require many static beacons with a uniform distribution in order to guarantee that all sensor nodes receive a sufficient number of beacon messages for localization. This approach has several problems; the use of a large number of static beacons is a high-cost factor, and it is not easy to distribute them uniformly.

A notable solution used in recent studies on the localization problem is a mobile beacon-based approach applying a few mobile beacons. The mobile beacon is a kind of sensor node containing more energy and capacity than an ordinary sensor node and generally has longer transmission range than sensor nodes. (In this paper, we assume that the range of mobile beacon is longer than two times of that of sensor node.) The mobile beacon is used not only for supporting localization but also for conducting manifold roles (*e.g.*, sink node) throughout a system. Hence the energy efficiency of mobile beacon is an important factor for the system. To this end, path planning schemes are proposed by many researchers for reducing beacons' energy consumption, which direct a mobile beacon where to go and when to send a beacon message.

In this research area, random movement strategies and predefined path planning schemes have been proposed. However, the above strategies have some problems; in the former strategies the movement distance is too long and there are numerous beacon messages, and both kinds of schemes require advance knowledge of the field shape. In general, the sensor nodes are randomly deployed, and the prior information of the shape cannot always be obtained. In this case, the existing schemes are not available. Moreover, sensor nodes are scattered in inaccessible terrains or disaster areas [1], and a ground beacon [2-4] (mobile beacon which moves on the surface) cannot be located in these environments. On the other hand, an aerial beacon [5-9] (mobile beacon which flies through the air) is more useful than a ground one for approaching inaccessible areas, and a few methods are proposed for aerial beacon-based localization systems.

In this paper, we propose an Adaptive Path Planning (APP) that provides beacon positions in which a mobile beacon sends beacon messages. Contributions of the paper are listed as follows,

- The APP can be operated without any prior information of the field shape.
- We suggest candidate areas where a mobile beacon should transmit beacon messages. The areas guarantee a reception of beacon message regardless of the real position of a sensor node. The candidate areas for both beacon types, ground and aerial beacons, are devised. They also are useful for low computational complexity. A mobile beacon chooses the nearest position in candidate areas as a next beacon point iteratively.
- The proposed planning scheme also reduces the movement distance and number of beacon messages of a mobile beacon to decrease the energy consumption. It is the main goal of the APP. The decrease of number of beacon messages can lead to reduced reception energy consumption of sensor nodes.

The proposed scheme uses sensor nodes' support but each sensor node receives and transmits a few messages for localization. The APP also adopts a new technique, viz. range check, which can generate more localizable nodes for distributed localization schemes. This technique tries to obtain a unique position using bilateration and two-hop neighbor information.

The remainder of this paper is organized as follows. Section 2 discusses related work, and the detailed operation of the proposed scheme is described in section 3. In section 4, the results of the performance evaluation are presented. The conclusion is discussed in the last section of this paper.

2. RELATED WORK

Localization studies deal with many different issues, such as location estimation using range or connectivity information, sensed event-based localization [5, 10], analysis of localization error bounds [11, 12], schemes for ranging bias models [13], underwater sensor localization [14], target tracking [15], *etc*. As mentioned above, many recent studies focus on other issues, especially the movement policy of a mobile beacon. In this section, we classify the related literature on mobile beacons into two groups including random movement-based schemes and static path planning-based schemes.

2.1 Random Movement-Based Schemes (Non-Specific Strategies)

In random movement-based schemes, mobile beacons generally follow the random waypoint model and transmit beacon messages periodically. Most of the schemes are not concerned about the mobile beacons' energy and assume that they always have enough. The authors in [2] suggest a range-free scheme using mobile beacons, and apply a geometrical conjecture (perpendicular bisector of a chord) to calculate the node position. Some anchor (beacon) nodes equipped with GPS roam the sensing field. They also suggest a range-based method for obstacle-tolerant localization, which exploits the characteristics of concentric circles to select chords. They further extend their idea to three-dimensional environments with aerial anchors (beacons) [9]. However, these papers do not provide a specific movement strategy for mobile beacons. It is also reported that the position of the beacon and measured RSSI are used to calculate the node position [3]. The beacon trajectory is mentioned. However, they only list some of the required properties of the movement path of the mobile beacon. They also fail to propose any specific movement strategy for determining the path of mobile beacon nodes.

The aforementioned schemes are well-known localization methods using mobile beacons. A common advantage is that the operation is simple, and the responsibility of each sensor node is confined to reception of beacon messages and position estimation. However, the sensor nodes have to receive a number of beacon messages for estimation of their position, and the localization scheme in [2] needs a short beacon interval, resulting in energy inefficiency. In short, the previous work does not focus on the path decision of the beacon nodes and assumes that they have abundant energy capacity.

2.2 Static Path Planning-Based Schemes

On the other hand, Static Path Planning (SPP)-based schemes predefine the movement path and period of the beacon messages. This requires that the schemes need advance knowledge of the network field shape in order to decide the start/end points and each beacon point of the path. Static path planning is easily applied to an aerial beacon's movement policy.

In path planning schemes, a mobile beacon's movement path is directly related to the performance of the localization scheme. Two important evaluation criteria for selecting a movement path are the length of the curve required for beacon energy efficiency and the collinear beacon points required for unique position estimation of the sensor nodes. The authors in [16] propose a localization scheme in which the trajectory (path) of a mobile beacon matches a Hilbert space filling curve. They also justified utilizing a Hilbert space filling curve by comparing it to other known types of curves based on the two criteria. The Scanline and Peano curves were selected as comparison targets. According to their analysis, the Hilbert and Scanline curves have the same length and are shorter than the Peano curve. In addition, Scanline may not result in collinear beacon points.

Three deterministic trajectories, SCAN, DOUBLE SCAN, and HILBERT, are evaluated in [17] via the RSSI-based localization algorithm proposed in [3]. It is shown that SCAN is the best trajectory at fine resolutions, while HILBERT outperforms SCAN when the resolutions are larger than the transmission range. In addition, the authors present the tradeoffs between the resolution of trajectories and accuracy of localization for a two-hop localization scheme using beacon messages from other sensor nodes. When the sensor nodes have moderate speed and the resolution is very large (3 times the transmission range), the two-hop localization achieves better accuracy of localization than the one-hop localization.

In [18], two static path types, CIRCLES and S-CURVES, are proposed for mobile beacons in order to enable more sensor nodes to be localized accurately while shortening the path length. A good trajectory has to provide at least three non-collinear beacon messages per sensor, and involve a low complexity, short movement length, and small number of beacon transmissions. This paper is motivated by the fact that straight lines result in collinear points, and more direction changes effectively results in fewer collinear points during localization. Therefore, CIRCLES consists of a sequence of concentric circles centered within the deployment area, and S-CURVES consist of S curves instead of straight lines. It is shown that the localization accuracy of these schemes is better than that of other existing schemes, *i.e.*, SCAN and HILBERT.

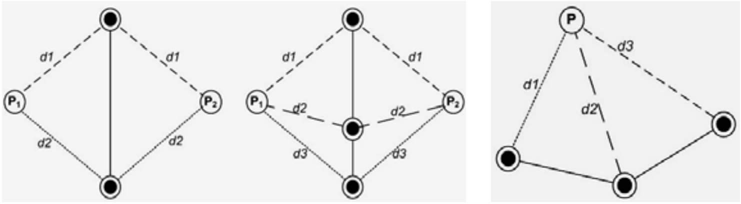
Both random movement-based schemes and SPP-based schemes require information about the shape of sensing field. In the random movement-based schemes, mobile beacons continue moving in the sensing field, and the SPP-based schemes require this information in order to decide their paths. However, as mentioned above, it is not easy to accurately decide the area of the sensing field in randomly deployed WSNs. This limitation can be overcome via the simple support of sensor nodes using a few message receptions and transmissions. Moreover, there is the potential for improvement with this type of support, via reduction of the length of the movement path and number of beacon transmissions of the mobile beacon.

3. ADAPTIVE PATH PLANNING FOR MOBILE BEACON

First of all, we describe the preliminaries of how to estimate the positions of sensor nodes. The network environment and detailed description of the proposed path planning scheme follow.

3.1 Preliminaries

To estimate the node's position, the distances and/or angles between nodes are needed in range-based localization. The distance measurement utilizes signal metrics such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Received Signal Strength (RSS). RSS is widely used in localization research [19, 20], and we utilize it here in order to obtain the distance information between sensor nodes or between each sensor node and a mobile beacon. Most of the existing localization systems apply trilateration or multilateration in order to calculate the node position. Trilateration finds the intersection point using three distances from three neighbors. Multilateration uses more than three distances in order to improve robustness against the ranging error. Because the ranging error is not the main focus of our work, we apply trilateration for the simulation. Fig. 1 (a) shows the ambiguity position problem when there are only two non-collinear reference nodes. The node cannot determine its own position between P_1 and P_2. As shown in Fig. 1 (b), node (P) needs to know at least three distances from non-collinear neighbors to find the unique position.



(a) Non-rigid. (b) Rigid.

Fig. 1. Trilateration.

APP-GB was introduced in [4] as MBAL (Mobile Beacon-Assisted Localization), and we conduct an additional simulation to compare the performance with SPP-based schemes in this paper. APP-AB is an extended version with newly derived candidate areas.

3.2 Detailed Description of Adaptive Path Planning

APP-GB and APP-AB minimize the length of the movement path of a mobile beacon with low computational complexity. It consists of three phases: reference movement, sensor localization, and movement path decision.

3.2.1 Reference movement phase and sensor localization phase

More details about the first two phases are explained in [4], which we summarize in this paper. The mobile beacon node determines the coordinates of the three beacon points of the first phase, which comprise a regular triangle, as shown in Fig. 2. It broad casts each beacon message including information on the positions of the three initial beacon

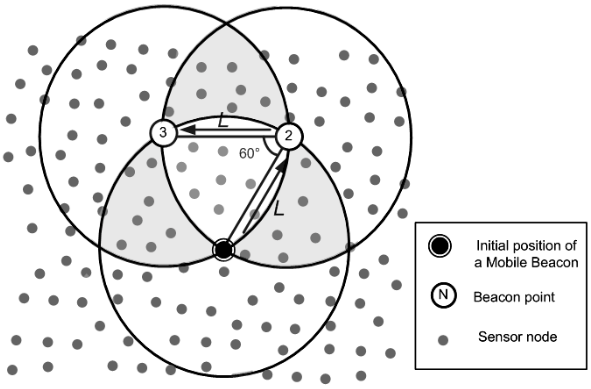


Fig. 2. Reference movement of mobile beacon.

points. This information helps the sensor nodes in the intersection area (gray areas in Fig. 2) of the two beacon ranges to find their own location using simple calculation [21]. The length of the regular triangle of the aerial beacon is shorter than that of the ground beacon, because the beacon nodes have the same transmission range. The aerial beacon should follow the limited length of the regular triangle, expressed as:

$$L_{AB} \le \sqrt{R_{AB}^2 - H_{AB}^2}, \tag{1}$$

where R_{AB} is the transmission range of the beacon, and H_{AB} is the height of the aerial beacon. To account for the signal range irregularity, its lower bound can be used.

In the second phase, several sensor nodes are changed from an unknown node to a reference node, after obtaining its position using three beacon messages sent during the first phase. Then the reference nodes broadcast beacon messages containing their position information to their neighbors. Consequently, location broadcasting of the reference nodes increases the number of reference nodes recursively. To increase the reference node ratio more efficiently, we have devised a range check technique. This helps a sensor node to find the unique position using two beacon messages based on two or more-hop neighbor's location information. In [4], a full explanation of the technique for general networks is provided. Even though the technique utilizes the location information on three or more hop neighbor nodes, no significant performance improvement is achieved. Therefore, we set a hop-count limit of two for the range check technique.

3.2.2 Movement path decision phase

After the above two phases, nodes that do not know their own position, viz. reQuest Nodes (QNs), request additional beacon messages to the mobile beacon, including the location information of the received messages. To receive request messages, the mobile beacon can apply any of the on-demand or geographic routing protocols. Two-QN, One-QN, and Zero-QN are request nodes which received two, one, and zero beacon messages, respectively. Unlike static path planning schemes, the beacon analyzes the aggregated request messages, and determines its next beacon points adaptively and iteratively in order to provide additional beacon messages.

In general minimization problems, the following formulations are used; Eq. (2) is for minimizing the movement distance, and Eq. (3) is for the minimization of energy consumption.

$$L_{total} = \min\left(\sum_{i=1}^{n} d(P_{i-1}, P_i)\right), P_i \in P_{MB}, \tag{2}$$

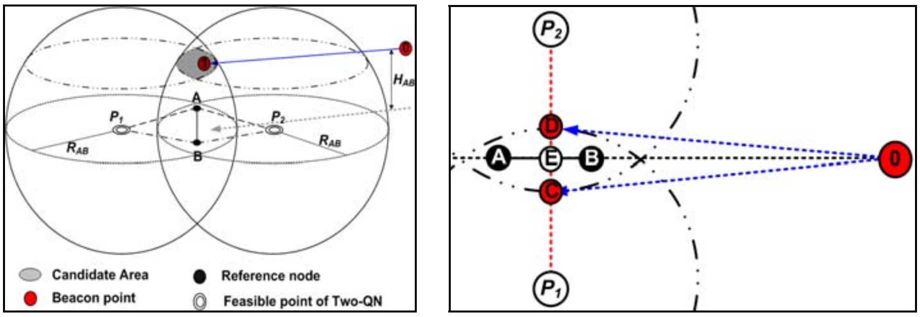
$$E_{total} = \min\left(\sum_{i=1}^{n} (E_M \cdot d(P_{i-1}, P_i)) + (n+1) \cdot E_B\right), \tag{3}$$

where
P_{MB}: sequential set which is the movement path of the mobile beacon, and each element is the beacon point,
$d(P_{i\text{-}1}, P_i)$: Euclidean distance between two points,
E_M: movement energy consumption per unit distance,
E_B: transmission energy consumption per beacon message.

The formulations look like the traveling salesman problem (TSP) which can be solved by algorithms for NP-hard problem. However, the algorithms cannot be applied because a mobile beacon may not have all instances to solve Eqs. (2) and (3) at the beginning of the movement path decision phase. As a Zero-QN changes its state to One-or Two-QN and sends a request message, the number of instances for the problem is increased frequently during the movement of the mobile beacon. Therefore, we should find the next beacon positions iteratively with updated request messages.

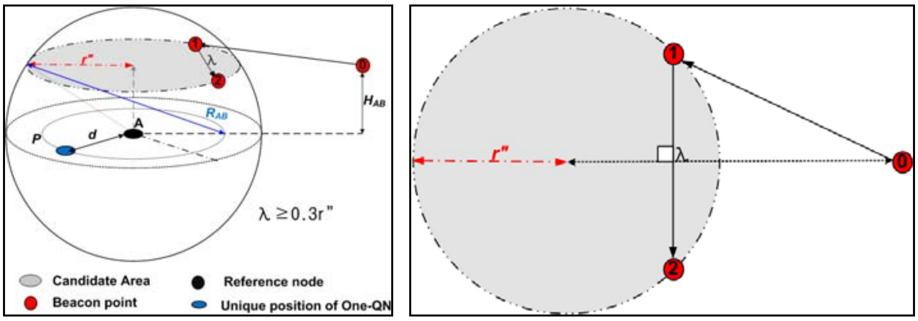
The search space is needed to be limited as small as possible. To this end, we propose candidate areas of QNs in order to reduce the domain size for low computational complexity. In candidate areas, every beacon message can be successfully delivered to the corresponding request node. The following describes the candidate area of each QN group for the aerial beacon. The candidate areas of the ground beacon are described in [4].

Candidate area of Two-QN for aerial beacon: Two-QN has two feasible points by bilateration, *e.g.*, P_1 and P_2 in Fig. 3 (a). The sensor node is located on either P_1 or P_2, and it cannot know the real position between them. The candidate area has to be designed to guarantee a reception of beacon message, no matter where the sensor node is located between the feasible points. Hence the candidate area consists of the intersection area which is gray colored part in Fig. 3 (a). Because Two-QN needs an additional beacon message, one beacon point is selected in the candidate area, and it must not be located on the perpendicular plane containing reference nodes A and B in order to avoid the ambiguity problem. In Fig. 3 (b), four points (A, B, P_1, and P_2) are corresponding positions at height H_{AB} to the positions in Fig. 3 (a). For example, the coordination of A is $(x, y, 0)$ in Fig. 3 (a) and (x, y, H_{AB}) in Fig. 3 (b). If the current beacon is located on the extended line of $\overline{AB}$ as shown in Fig. 3 (b), the beacon has to choose another point instead of the nearest point. To this end, we provide two candidate points C and D, which are cross points between the line of P_1 and P_2 and two circles, as shown in the figure. Hence the beacon selects one of the candidate points randomly. In the following simulation, a crossing point between a line of points 0 and E in Fig. 3 (b) and a boundary of the candidate area



(a) Two-QN. (b) Ambiguity case of Two-QN.

Fig. 3. Candidate areas of the aerial beacon.



(a) One-QN. (b) Plane figure of candidate area of One-QN.

Fig. 4. Candidate areas of the aerial beacon.

is chosen, while points *C* or *D* is selected for the ambiguity cases.

In the proposed method, Two-QN does not use trilateration to achieve faster computation, but compares the distances between each feasible point and the beacon point with the distance from RSSI. To guarantee a sufficient candidate area size, the height of the aerial beacon is limited. More details on the height limitation are described in the next subsection.

Candidate area of One-QN for aerial beacon: All feasible positions that can be located by One-QN consist of a circle with the reference node at its center *A*. As shown in Fig. 4 (a), the gray circle at height H_{AB} is the candidate area of One-QN, and its radius can be derived considering the maximum distance between a sensor node and a mobile beacon. Hence we can formulate the following equation.

$$(d(P, A) + r'')^2 + H_{AB}^2 = R_{AB}^2. \tag{4}$$

Therefore, the radius of One-QN is expressed as:

$$r'' = \sqrt{R_{AB}^2 - H_{AB}^2} - d(P, A). \tag{5}$$

The unique position of One-QN (P) is unknown, but the distance between P and reference node A can be obtained using the RSSI of the message.

One-QN needs two more beacon points and the perpendicular plane containing them must not cross the position of reference node A. Under this condition, the beacon points can be located on the line or interior of the candidate area. We select two positions that have distance λ (the length between two beacon points, which is sufficient for error tolerant estimation of the node position). The threshold (λ) was previously used in [3] for chord selection and this concept is used here as the constraint of the two beacon points. In the simulation, 30% of r'' is used as the length between the two beacon points. In the following simulation, we select two beacon points for One-QN as shown in Fig. 4 (b). Hence, from now on, we do not use candidate areas but candidate beacon points for One-QNs and Two-QNs to determine the next beacon position.

The proposed scheme excludes the handling of Zero-QN, because its real position can be possibly located in too large area and it may not have appropriate candidate areas. In terms of possibility or efficiency, the handling Zero-QN is impossible to be considered. However, Zero-QN can be changed into One-QN or Two-QN at run-time, and it will operate as One-QN or Two-QN.

Determining the next beacon position for constructing movement path: In each iteration after the second phase,

1. Construct a set of candidate beacon points from candidate areas for the current QNs as described above.
2. Find the nearest beacon:
   A. For Two-QN, the distance to a beacon point from the current beacon position is calculated.
   B. For One-QN, the distance between two beacon points is added to the distance to one of the beacon points from the current beacon position.
3. Move to the nearest beacon point and broadcast a beacon message.
4. Receive additional request messages from new Two-QNs or One-QNs.

In the step 4, the mobile beacon set a timer for waiting request messages. If request messages are arrived after the expiration of the timer, they could be covered after the next iteration. The mobile beacon set the timer again when it does not receive any request messages after the expiration. When a Zero-QN node changes its group to One- or Two-QN, the node has to send an additional request message. Newly localized nodes also report to the beacon node. The proposed method is operated iteratively until there is no request node.

3.2.3 Height limitation of aerial beacon

When the width of the candidate area of Two-QN, $d(P_1, P_2)$, has the maximum length, the height of the beacon position must satisfy the following condition:

$$H_{\text{MAX}} \le \sqrt{R_{AB}^2 - R_{SN}^2}\,. \tag{6}$$

In Fig. 4 (a), the range of the candidate area of One-QN is derived by Eq. (5) and diminishes as the height of the aerial beacon increases. Therefore, the range must be a positive length in order to guarantee the candidate area of One-QN. In order to satisfy this condition, the height of the aerial beacon also must satisfy the condition given by Eq. (6). Therefore, when the height of the aerial beacon is fixed, the aerial beacon must be located at a lower height than H_{MAX} for all request nodes.

4. PERFORMANCE EVALUATION

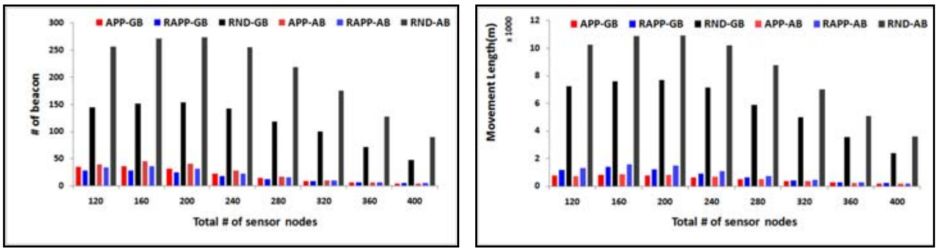
The simulation environment is as follows; the field size is 200m × 200m, the beacon node radii R_{AB} and R_{GB} are 50m, the sensor node radius R_{SN} is 20m, and the height of the aerial beacon H_{AB} is 30m. The number of sensor nodes is between 120 and 400 (the smallest value signifies a sparse network). In wireless sensor networks, a large number of sensor nodes are generally deployed. In [4], we merely compared APP-GB with random movement, and an additional comparison is conducted with static path planning in this paper.

First, we conduct a comparison of APP-GB, APP-AB, and the random movement-based methods. As mentioned above, the random movement-based method applies the random waypoint model, and the mobile beacon broadcasts beacon messages periodically. When the beacon message interval has the same length as the beacon node radius, the movement length of the random movement-based method has the shortest distance [4]. Therefore we choose a 50m and 40m beacon message interval for the ground and aerial beacon, respectively. Second, we choose static path planning schemes as comparison targets. The movement length and number of beacon messages are derived in order to determine the performance of the schemes. Finally we show some examples of the movement path and beacon points.

4.1 Random Movement-Based Method vs. APP and RAPP

We conduct a performance comparison of APP and Random APP (RAPP) with the random movement-based methods. As mentioned above, APP chooses its next beacon point by finding the nearest beacon point, whereas Random APP selects next beacon point randomly among candidate point. In other words, RAPP only utilizes the proposed candidate areas. We provide the same reference movement phase to the random movement-based method for the fair comparison.

The two main metrics for the performance evaluation are the movement length and number of beacon messages. As shown in Fig. 5, APP-AB yields similar results to APP-GB, even when the aerial beacon has a shorter range on the surface. The aerial beacon’s transmission range is 40m on the surface, which is shorter than that of the ground beacon. The figure also shows that APP-AB yields much better performance than the random movement-based method using an aerial beacon (RND-AB). Compared to RND-AB, APP-AB reduces the number of beacon messages from 256.1 to 39.2 and reduces the movement length from 10,245.1m to 726.5m with 120 stationary nodes. This is a better improvement than that achieved by APP-GB. For example, with 400 sensor nodes, the ratios of the number of beacon messages between APP and RND are 4.3/47.7 (about



(a) Number of beacon messages. (b) Movement length.

Fig. 5. Comparison: APP, RAPP and RND.

0.09%) with the ground beacon and 4.4/90.1 (about 0.05%) with the aerial beacon, and the ratios of the movement lengths between APP and RND are 197.3/2385.0 (about 0.08%) with the ground beacon and 184.7/3604.6 (about 0.05%) with the aerial beacon.

RAPP also shows much better performance than RND. Compared to APP, the differences of the number of beacon messages are small (below 7 for a ground beacon and below 5.5 for an aerial beacon). However, the differences of the movement lengths are changed up to 590m for a ground beacon and 730m for an aerial beacon. Hence we can conclude that APP shows the best performance in general. Regardless of the total number of stationary nodes or the type of beacon nodes, our proposed methods outperform the random method. The energy efficiency of the beacon nodes is substantially increased.

4.2 Static Path Planning vs. APP-GB/AB

We choose HILBERT, which is the representative static path planning scheme, as a target to compare the movement distance to APP-GB/AB. The target has the same distance as SCAN and a shorter distance than that of Peano. In the SPP-based schemes, predefined movement paths are applied in simulation tests, and the analysis of the movement length and number of messages coincides with the test results. According to [16], the results of the 200m × 200m field shape are derived as follows.

Scale of the grid (s) for *GB* and *AB* is expressed as:

$$s_{GB} = \sqrt{2/5}\cdot R_{GB} = 10\sqrt{10},\ s_{AB} = \sqrt{2/5}\cdot R_{AB} = 8\sqrt{10}. \tag{7}$$

Order of the Hilbert curve (m) for *GB* and *AB* is expressed as:

$$m_{GB} \geq \left\lceil \log_2\left(\frac{\max\left(height, width\right)}{s_{GB}}\right)\right\rceil = 2,\ m_{AB} \geq 3. \tag{8}$$

Grid side size (S) for *GB* and *AB* is expressed as:

$$S_{GB} = s_{GB}\cdot 2^{m_{GB}} = 80\sqrt{10},\ S_{AB} = s_{AB}\cdot 2^{m_{AB}} = 64\sqrt{10}. \tag{9}$$

Length of the Hilbert curve for *GB* and *AB* is expressed as:

$$L_{GB}^{Hilbert} = (2^{m_{GB}} - 2^{-m_{GB}}) \cdot S_{GB} = 630\sqrt{10},\ L_{AB}^{Hilbert} = 504\sqrt{10}. \tag{10}$$

Hence, the number of beacons is 64, and the movement distance is about 1,992.2m and 1593.8m for the ground and aerial beacon, respectively. Moreover, without precise area information, the distance and number of beacons can be increased. As shown in Fig. 5, APP-GB shows that the number of beacons is less than 34.7 (< 64) and the movement distance is less than 762.5m (< 1992m). APP-AB also achieves better performance than the static path planning schemes. The authors in [18] claim that their proposed path planning generates shorter distances than HILBERT. CIRCLES and S-CURVES have distance ratios 83.2% and 97.7% that of HILBERT, respectively. However, even the longest distances of APP-GB and APP-AB are less than 50% of HILBERT's movement distance. The results are summarized in Table 1.

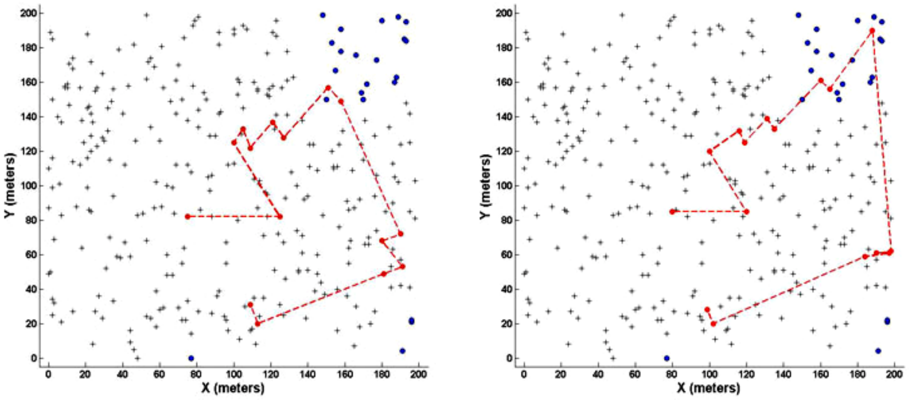
Table 1. Hilbert for ground/aerial beacons vs. APP-GB/AB.

	Movement length (m)	Number of beacon messages
APP-GB	197.3-762.5	4.4-34.7
HILBERT for GB	1992.2	64
APP-AB	184.7-726.5	4.4-39.3
HILBERT for AB	1593.8	64

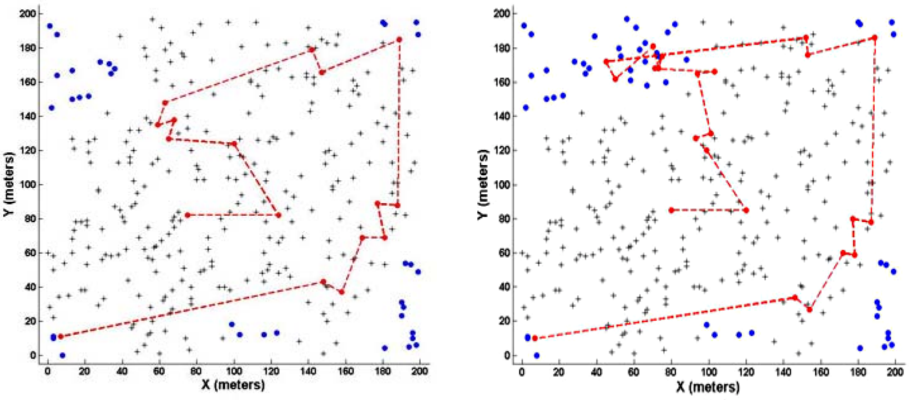
4.3 Simulation Results of APP-GB/AB

Some simulation results of APP-GB/AB are illustrated in Fig. 6. 300 sensor nodes are randomly deployed in the sensing field. The dotted polygonal line is the path of the mobile beacon. Each red circle linked by the dotted line indicates a beacon point. A mobile beacon moves along the line and broadcasts a beacon message at each beacon point. The three initial beacon points in the middle of the field are generated during the reference movement phase, which are linked by two consecutive dotted line segments. These points are located as a regular triangle, and the length of the triangle of the ground beacon node is longer than that of the aerial beacon node. The blue-colored nodes are the request nodes, which need one or more beacon messages. The cross nodes are the reference nodes that have information of their own positions in advance of the last phase of APP-GB/AB. We can find that a request node may make subsequent request nodes recursively, which generally appear at network boundaries, as shown in Fig. 6. The two tangled points on the movement path are generated according to the selection order of the two beacon points of One-QN.

The first case, Figs. 6 (a) and (b), have the same request node set, which is not the general case. They have different radii on the surface: 50m and 40m for the ground and aerial beacon nodes, respectively. The difference between the radii of the two beacon nodes translate into a different set of initial reference nodes. However, in this case, sensor nodes' self localization compensates for it and generates the same request node group. Despite having the same request nodes, the paths of the two beacon nodes differ, due to the difference between the transmission radii on the surface. On the other hand, the second case, Figs. 6 (c) and (d), show different request node groups, and there are more request nodes in APP-AB. Consequently, the two beacon nodes have different paths.



(a) APP-GB, case 1. (b) APP-AB, case 1.



(c) APP-GB, case 2. (d) APP-AB, case 2.

Fig. 6. Examples of test results.

5. CONCLUSION

We advocated specific movement strategies that are not used in current mobile beacon-assisted localization approaches, as a viable solution for coping with the resource constraints of mobile beacon nodes. Taking into account the fact that there are still concerns about energy and computing resources for mobile beacons, the proposed scheme reduces the excessive overhead of the mobile beacon nodes. Moreover, the proposed range check is a simple but effective technique for obtaining the unique position of sensor nodes. Our performance evaluation establishes that a specific movement strategy is an essential requirement for energy efficient mobile beacons in mobile beacon-assisted localization.

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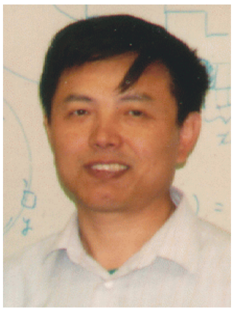

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