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Designing reduced beacon trajectory for sensor localization*

HUANG Wen-liang[1], LI Shi-jian[†‡1], LIU Duo[2]
([1]*School of Computer Science, Zhejiang University, Hangzhou 310027, China*)
([2]*Graduate School, Zhejiang University, Hangzhou 310027, China*)
[†]E-mail: shijianli@zju.edu.cn

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Abstract: Localization is one of the substantial issues in wireless sensor networks. The key problem for the mobile beacon localization is how to choose the appropriate beacon trajectory. However, little research has been done on it. In this paper, firstly, we deduce the number of positions for a beacon to send a packet according to the acreage of ROI (region of interest); and next we present a novel method based on virtual force to arrange the positions in arbitrary ROI; then we apply TSP (travelling salesman problem) algorithm to the positions sequence to obtain the optimal touring path, i.e. the reduced beacon trajectory. When a mobile beacon moves along the touring path, sending RF signals at every position, the sensors in ROI can work out their position with trilateration. Experimental results demonstrate that the localization method, based on the beacon reduced path, is efficient and has flexible accuracy.

Key words: Sensor network, Sensor localization, Mobile beacon, Virtual force
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INTRODUCTION

Wireless sensor networks will probably become the pervasive sensing (and actuating) technology in the future. For most applications of sensor network, sensed data should be with spatial and temporal coordinates, otherwise its use will be very limited. Because of this, sensor nodes have to be aware of their locations so as to specify where a certain event takes place. Therefore, the problem of localizing the sensors is of paramount importance for many classes of sensor network applications.

To solve the localization problem, it is natural to consider placing sensor manually or equipping each sensor with a GPS receiver. However, due to the large number of sensors, those two methods become either inefficient or costly. So researchers suggest many location methods based on the relation between sensors.

Many localization algorithms rely on the distances between nodes, which is known as the range-based localization. The estimation of distance is usually implemented by using signal strength decay, TOA, or TDOA for internode range estimation (Patwari *et al*., 2003). In another way, the range-free localization algorithms obtain position estimation by using a connectivity matrix of sensor instead of estimating distance between nodes (Doherty *et al*., 2001). Range-free methods need less computing and communication than range-based method, which leads to less energy consumption and longer system life. However, its localization accuracy is much lower. So, we pay more attention to range-based methods in this article.

In a sensor network with range-based localization method, some nodes are equipped with special positioning devices (e.g., a GPS receiver) that are aware of their locations. These nodes are called beacons. Other nodes that do not initially know their

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[‡] Corresponding author

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locations are called unknown nodes. Generally, an unknown node can estimate its location by range-based methods if three or more beacons are available in its 2D coverage field (Niculescu and Nath, 2004). Obviously, number and position of beacons have noticeable influence on the localization accuracy. Bulusu *et al.*(2000) and Savvides *et al.*(2001) showed that the localization precision increases with the increase of the beacons' number. The main problem caused by increased number of beacons is that the beacon is far more expensive than the rest of the sensor nodes. Even if only 10% of the nodes are beacons, the price of the whole network will increase by about tenfold (Sichitiu and Ramadurai, 2004). Another observation is that after the (stationary) unknown nodes have been localized, the beacons become useless. The aforementioned reason leads us to consider using a single mobile beacon to localize the entire network (Sichitiu and Ramadurai, 2004).

The main idea of localization with a mobile beacon is as follows (Patro, 2004; Sichitiu and Ramadurai, 2004; Sun and Guo, 2004). After sensor deployment, a mobile beacon traverses the sensor network while broadcasting beacon packets, which contain the coordinates of the beacon. Sensor nodes receiving beacon packets could infer their distance from a mobile beacon and use these measurements as constraints to construct and maintain position estimates. These methods have a common important question: "What is the optimal beacon trajectory and when should the beacon packets be sent?". To the best of our knowledge, this question has no answer within previous publications since the positions of unknown nodes could not be forecasted, therefore the beacon trajectory could not be designed according to the nodes locations.

The rest of this paper is organized as follows. In Section 2, we survey the related works in localization technologies, especially the methods based on mobile beacons. In Section 3, we discuss the optimal topology of beacon broadcasting positions, propose an improved topology (not optimal) of beacon positions, and bring forward two algorithms to obtain the reduced beacon trajectory in rectangular ROI and arbitrary shape ROI. Experimental results are given in Section 4 to demonstrate the performance of the proposed approach. Section 5 concludes the paper and outlines the directions for future work.

RELATED WORKS

Wang *et al.*(2005) showed some typical limitations within existing localization methods: (1) Unknown nodes should be neighbored to beacons so that too many beacons are needed, e.g., Cricket (Priyantha *et al.*, 2000), Cooperative Ranging (Savarese *et al.*, 2001); (2) Localization accuracy relies on the sensor deployment, e.g., DV-hop (Niculescu and Nath, 2001) is just applicable to dense isotropy network, and Convex Position Estimation (Doherty *et al.*, 2001) requires the beacons be deployed to the edge of the network. Especially, the major challenge in beacons localization is to make localization algorithms as robust as possible while using as few beacons as possible. Obviously, if we could advance efficient optimal beacon path algorithm, we would make mobile beacon based localization method more practical, and overcome these limitations.

Besides Sichitiu and Ramadurai (2004), other researchers also noticed mobile beacon based localization. Dutta and Bergbreiter (2003) estimated the distance from a sensor node to a mobile object by ultrasound technology. Neighboring sensors cooperated to evaluate the distance between themselves by exploiting common tangent concept. As long as the node-to-node distances are available, the sensor position can be measured by range-based schemes. Sun and Guo (2004) proposed the probabilistic localization schemes with a mobile beacon by using TOA technique for ranging and using Centroid formula with distance information to calculate the sensor position. The above approaches still need integrating range information for localization. In another way, Galstyan *et al.*(2004) proposed a coarse-grained range-free localization algorithm to lower the uncertainty of the sensors' positions by using radio connectivity constraints, i.e., with each received beacon packet, the receiver location could be definitely bounded in the transmission area of the sender. Ssu *et al.*(2005) developed a novel localization mechanism by using the geometry conjecture, called "Perpendicular Bisector of a Chord", which uses two lines connecting the selected beacon positions as the chords, then, the intersection of the chords' perpendicular bisectors is taken for the sensor location.

The representative methods mentioned above bring us some useful ideas of localizing sensors with mobile beacons, but none of them discussed how to design an optimal beacon trajectory, other than Sichitiu and Ramadurai (2004) mentioned that: "the beacon trajectory should be designed in such a way that all possible positions are fully covered by at least three non-collinear beacons, and the 'grid' formed by the beacons should be as tight as possible (to increase the localization accuracy)". Recently, Koutsonikolas *et al.*(2007) showed three different deterministic beacon trajectories in a square ROI, and studied the tradeoffs between the trajectory resolution and the localization accuracy in the presence of 2-hop localization, but this method could not work well in an arbitrary ROI.

Extending Sichitiu's idea, we get several properties of the beacon trajectory. First, an arbitrary point should receive three non-collinear beacon packets at least when the beacon moves along the trajectory, so that an unknown sensor could be localized wherever it is. Second, the trajectory should be as short as possible while the number of sending positions in the trajectory, which is for a beacon to send a packet, should be minimized. Short trajectory will reduce the time needed to localize the sensors, and reduce the energy consumption of sensors and beacons. Based on this idea, designing an optimal beacon trajectory could be divided into two stages: (1) Find the minimal number and topology of beacon broadcasting positions triply covering ROI, which means each point in ROI could receive at least three beacon packets; (2) Find the shortest trajectory to tour the positions.

DESIGNING REDUCED MOBILE BEACON TRAJECTORY

In this section, we will describe our idea of obtaining the reduced beacon trajectory. First, we deduce the reduced number of positions for the beacon to send a packet (beacon position or sending position, position for short) according to the acreage of ROI. Second, we advance a method to get those positions in a rectangle ROI, and a novel method based on virtual force (Zou and Chakrabarty, 2004; Li S.J. *et al.*, 2005) to arrange the positions in an arbitrary shape ROI. Then we apply a TSP (travelling salesman problem) algorithm to the positions sequence to obtain the optimal touring path, which is the reduced beacon trajectory we want to obtain. When a mobile beacon moves along the reduced trajectory, and sends RF signals at every key position, the unknown sensors in ROI could calculate their positions with trilateration.

Topology of beacon broadcasting positions

For simplicity, we assume any sensor could infer the distance between itself and the mobile beacon according to the RSSI (radio signal strength indicator) of the beacon packets it received (Seidel and Rappaport, 1992). Considering the radio signal transmission losses in the air, we should predefine a broadcasting range of a beacon. The broadcasting area is a circle, with the beacon being its center and the broadcasting radius R_s as its radius. Only sensors within the range are assumed capable of receiving the packet sent by the beacon. Moreover, we assume that ROI is large enough compared with the broadcasting range, then the boundary effects can be ignored. Under these assumptions, finding optimal broadcasting positions has a corresponding geometry problem: how to find the minimal number and position of disks to triply cover ROI. The disk centers are even the optimal beacon broadcasting positions.

Some researchers (Huang and Tseng, 2003; Zhang and Hou, 2005; Ma and Yang, 2007) have drawn the following conclusions: as all sensors have the same sensing range, and sensors completely cover a certain ROI, minimizing the number of working sensors is equivalent to minimizing the overlap of sensing areas of all sensors. Meanwhile, to cover one crossing point of two disks with the minimum overlap, only one circle should be used and the centers of the three circles should form an equilateral triangle with sides of $\sqrt{3}r$, where r is the radius of the disks. Furthermore, for the whole network, if all Delaunay triangles with their vertices representing sensors are equilateral triangles with edge length of $\sqrt{3}r$, the coverage area of n sensors is maximum without coverage gap.

Based on these conclusions, we could know that if the Delaunay triangles composed of a set of beacon positions are equilateral triangles with the edge length of $\sqrt{3}r$, the set of positions is the minimal set covering ROI fully and without coverage gap, denoted as "optimal 1-coverage" for ROI. A partial enlarged optimal 1-coverage is presented in Fig.1, and the whole optimal 1-coverage is shown in Fig.2. Furthermore, we advance the definition of *k*-improved-coverage.

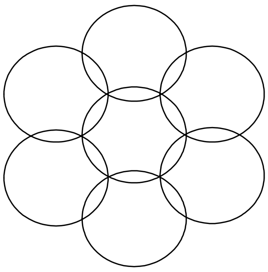


Fig.1 Partial enlarged optimal 1-coverage

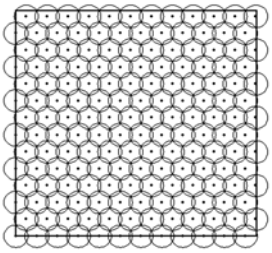


Fig.2 The whole view of optimal 1-coverage

Given a set of beacon positions B_k, in a 2D ROI, if B_k could be divided into K subsets $\{B_k^1, B_k^2, \ldots, B_k^k\}$, any two of which have no intersection.

Definition 1 B_k is considered to be a *k*-improved-coverage to the ROI, if each subset B_k^i (i=2,…,n) is optimal 1-coverage for ROI.

The *k*-improved-coverage is not an optimal coverage pattern, but it is good enough and has already been applied in broadcasting protocols of ad hoc network. The 3-improved-coverage is suitable for localizing in a sensor network, so we concern only the 3-improved-coverage problem in this article.

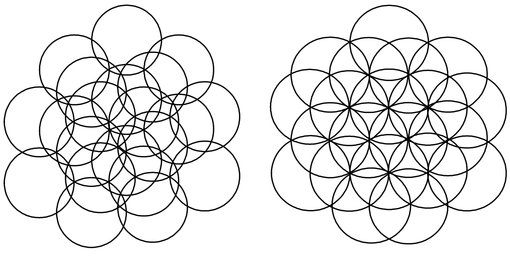
There are many existing topologies of sensor forming the 3-improved-coverage, such as the topology in Fig.3a. For most cases, the relations of positions cannot be described in a single way. Consequently, an arbitrary topology is difficult to be translated into a set of coordinates in practice. So, we only consider a special 3-improved-coverage, named "equal-distance 3-improved-coverage". As shown in Fig.3b, the beacon positions of equal-distance 3-improved-coverage form equilateral triangles, with edge length being R_s.

While beacon positions form equal-distance 3-improved-coverage, meanwhile the ROI is large enough to ignore the boundary effects, thus every position could be considered as a common vertex of 6 equilateral triangles. So, we obtain Eqs.(1) and (2) to calculate the number of beacon positions:

$$Triangle\_num = acreage\_ROI \Big/ \left(\frac{1}{2} \times \frac{\sqrt{3}}{2} R_\mathrm{s}^2 \right), \quad (1)$$

$$Beacon\_position\_num = \frac{1}{6} \times 3 \times Triangle\_num, \quad (2)$$

where *Triangle_num* means the number of equilateral triangles to triply cover the ROI, and *Beacon_position_num* means the number of needed beacon positions.



(a) (b)

Fig.3 3-optimal-coverage (partially enlarged). (a) An arbitrary 3-optimal-coverage; (b) Equal-distance 3-optimal-coverage

Equal-distance 3-improved-coverage can be easily translated into a set of coordinates. Because of the convenience in implementation, we will concentrate on how to achieve this topology in ROI in the next subsection.

Reduced mobile beacon trajectory

In the previous subsection we analyzed the improved beacon position topology, equal-distance 3-improved-coverage. Obviously, we need a good algorithm to convert the topology into a set of coordinates in ROI, especially when the ROI is large or with irregular shape. In this subsection, we shall advance two algorithms to find the coordinates set for equal-distance 3-improved-coverage, one for the rectangular ROI, another for the irregular ROI. Based on the coordinate set, we could obtain the reduced beacon trajectory by TSP algorithm.

1. Designing reduced mobile beacon trajectory for rectangular ROIs

For a rectangular ROI with acreage $A \times B$, we could quickly compute the coordinate of beacon position with algorithm "BETER". The algorithm is simple and efficient, except for some deficiencies: it needs more beacon positions to cover ROI and cannot be used in the case of arbitrary shape ROI.

Algorithm 1 Beacon rEduced Trajectory in rEctangular ROI: BETER

Assume the vertexes of the ROI are (0,0), (*A*,0), (0,*B*), (*A*,*B*), and the broadcasting radius is R_s. Then the position number in every line (*PN–L*) is A/R_s, and that of lines (*NL*) is $1+2B/(\sqrt{3}R_s)$.

Step 1: Compute the *x*-coordinate of beacon position, the *j*th beacon position in the *i*th line, denoted as X_{ij}.

```
for $i$=1 to $NL$ do
  for $j$=1 to $PN–L$ do
    if $i$ is odd then
      $X_{ij}=(j-1)R_s$;
    else if $i$ is even then
      $X_{ij}=A-(j-1)R_s$;
    end if
    if $X_{ij}>A$ then
      $X_{ij}=A$;
    else if $X_{ij}<0$ then
      $X_{ij}=0$;
    end if
  end for
end for
```

Step 2: Compute the *y*-coordinate of beacon position, the *j*th beacon position in the *i*th line, denoted as Y_{ij}.

```
for $i$=1 to $NL$ do
  for $j$=1 to $PN–L$ do
    $Y_{ij}=(i-1)\times(\sqrt{3}/2)\times R_s$;
    if $Y_{ij}>B$ then
      $Y_{ij}=B$;
    end if
  end for
end for
```

Step 3: Based on TSP algorithm, we can tour all beacon positions, and obtain the optimal beacon trajectory.

2. Designing reduced mobile beacon trajectory for arbitrary ROI

To obtain the reduced mobile beacon trajectory for arbitrary ROI, we should first put some beacon positions [see Eq.(1)] to the ROI, and deploy them to form equal-distance 3-improved-coverage.

To deploy the beacon positions, we could consult the presented methods to deploy sensors. The virtual force based method (Zou and Chakrabarty, 2004; Li *et al*., 2006) is a typical one, which assumes that the sensors could compare the distance between them and their neighbors within a threshold distance. The attractive (resp. repulsive) virtual forces are applied to the neighbor sensors if the distances are greater (resp. smaller) than the threshold. Then, the sensors move to their new positions according to the force imposed on them. This process is repeated until all the sensors have obtained their new locations, where the forces on them are smaller than a predefined threshold. Then, we obtain the expected deployment.

In this article, the virtual force algorithm adjusts the beacon positions according to the relative distance between one position and its neighbors compared to a threshold distance. We assume that position *j* exerts attractive force on position *i* ($\boldsymbol{F}_{ij}$) when the distance between them (d_{ij}) is larger than the predefined threshold D_{th} but smaller than C_{th}, and repulsive force when $d_{ij}<D_{\text{th}}$. D_{th} can be calculated from the user defined beacon position density. Obviously, $D_{\text{th}}=R_s$ according to Section 3.1. C_{th}, which could be used to reduce the computing complexity, is the upper limit of distance among beacon positions. We set $C_{\text{th}}=1.2R_s$. So, the virtual force between beacon positions can be expressed as follows:

$$\boldsymbol{F}_{ij}=\begin{cases}0, & d_{ij}>C_{\text{th}},\\ (W_{\text{Ass}}(d_{ij}-D_{\text{th}})^{\beta_1},\alpha_{ij}), & D_{\text{th}}\le d_{ij}\le C_{\text{th}},\\ (W_{\text{Rss}}(d_{ij}^{-\beta_2}-D_{\text{th}}^{-\beta_2}),\alpha_{ij}+\pi), & d_{ij}<D_{\text{th}},\end{cases} \quad (3)$$

where, α_{ij} is the orientation (angle) of a line segment from beacon position *j* to *i*; W_{Ass} and W_{Rss} are constant coefficients, measuring the quantity of attractive and repulsive forces, respectively; β_1 and β_2 are constants that can be adjusted according to the physical properties of a beacon, commonly, $\beta_1=\beta_2=2$. Repulsive forces make the beacon positions disperse to improve coverage, while attractive forces keep enough density of the beacon positions to avoid blind areas and disconnectivity.

Moreover, a beacon position *i*, which is near to the ROI boundary, could receive the repulsive force from ROI boundary, denoted as $\boldsymbol{F}_{i\text{b}}$:

$$\boldsymbol{F}_{i\text{b}}=-\frac{\boldsymbol{P}_i\boldsymbol{P}_{\text{cen}}}{|\boldsymbol{P}_i\boldsymbol{P}_{\text{cen}}|}\cdot W_{\text{b}},\quad \text{if } d_{i\text{b}}<C_{\text{b}}, \quad (4)$$

where $d_{i\text{b}}$ is the distance between position *i* and the ROI boundary, when $d_{i\text{b}}$ is less than the predefined threshold C_{b}, the ROI boundary applies a repulsive force on the position *i*; $\boldsymbol{P}_i\boldsymbol{P}_{\text{cen}}$ is a vector from the ROI center to position i; W_b is constant coefficient measuring the quantity of repulsive forces, which is usually a big number. The total force exerted on position i is the vector addition of all the forces discussed above:

$$\boldsymbol{F}_i = \sum_{j\neq i;j=1}^{N} \boldsymbol{F}_{ij} + \boldsymbol{F}_{ib}. \tag{5}$$

To avoid useless movement, a single maximum number of moving steps, denoted as *MaxStep*, is introduced. In each iteration, a position would be adjusted according to the orientation and magnitude of the total force exerted on it. The new location is calculated as follows:

$$x_{\text{new}} = \begin{cases} x_{\text{old}}, & \left|\boldsymbol{F}_{xy}\right| \le F_{\text{th}}, \\ x_{\text{old}} + \dfrac{F_x}{F_{xy}} \cdot MaxStep, & \left|\boldsymbol{F}_{xy}\right| > F_{\text{th}}, \end{cases} \tag{6}$$

$$y_{\text{new}} = \begin{cases} y_{\text{old}}, & \left|\boldsymbol{F}_{xy}\right| \le F_{\text{th}}, \\ y_{\text{old}} + \dfrac{F_y}{F_{xy}} \cdot MaxStep, & \left|\boldsymbol{F}_{xy}\right| > F_{\text{th}}, \end{cases} \tag{7}$$

where F_{xy} is the total force exerted on the beacon position; F_x and F_y are x- and y-coordinate forces, respectively; $(x_{\text{new}}, y_{\text{new}})$ is the new location.

When the distance, which a position is to move in a single step, is less than a certain threshold F_{th}, the position is thought to reach a steady state, and the approximate distances between the position and its neighbors are very close to D_{th}, i.e. R_s.

When every beacon position has reached the steady state, the positions are thought to have achieved optimal deployment. Then, we can tour every position based on a certain TSP algorithm to obtain the optimal beacon trajectory. The whole process is described in Algorithm 2.

Algorithm 2 Beacon rEduced Trajectory in Arbitrary ROI: BETAR

Step 1: Calculating the number of beacon positions, denoted as *PN*, according to acreage of ROI based on Eq.(2).

Step 2: Randomly getting *PN* points in ROI as the initial coordinates of beacon positions.

Step 3: Working out the optimal coordinates of beacon positions based on VF algorithm.

Step 4: Based on a TSP algorithm and the result of Step 3, touring every coordinate of beacon positions, and getting the reduced beacon trajectory.

It should be noted that the virtual force method greatly adds to the flexibility of the mobile beacon method in the following aspects: (1) After carefully defining the forces between beacons and these between boundary and beacons, BETAR algorithm can adapt to various shapes of ROI and finally find the appropriate beacon positions in it. (2) If some applications need more precise location, we can increase the beacon signal density by adding a certain number of beacons and decease the balance distance (D_{th}) between beacons. Then, executing the virtual force method again and we will obtain the new beacon positions. (3) The sensor nodes generally obey some probability distribution, for instance, the sensor nodes distributed by rocket always obey normal distribution, with the landing point as their center. So, if we make the area, where nodes more likely appear, as "hot area" and generate relatively stronger attractive forces to the beacon positions, the hot area and surrounding area will attract relatively dense beacon positions and the localization accuracy of sensors in the hot area will be improved.

3. Multiple beacons touring path

For accelerating sensor localization, multiple beacons were always applied to the process. In this subsection, we will introduce an algorithm in brief for calculating the touring paths of multiple mobile beacons.

Finding the reduced touring path for multiple mobile beacons is a typical MTSP (multiple travelling salesmen problem), and the beacons are the travelling salesmen in MTSP. The MTSP can be stated as follows. There are m salesmen who must visit n cities, and each salesman is defined to start and end at the same city. In this problem, each city must be visited exactly once by only one salesman and its objective is to find the minimum of total distances travelled by all salesmen. In this paper, we concern a special kind of MTSP with two features: (1) the beacons are not necessary to return to the starting point; (2) the path length of every beacon should be approximately equivalent, so the beacons could finish their journey with approximately the same time.

Referring to the method mentioned by Dang and Jin (1998), we resolve the problem of reduced touring path for multiple mobile beacons in the following three steps:

Step 1: Calculating the reduced path $P1$ for a single beacon.

Step 2: According to BN, the number of beacons, dividing $P1$ into BN sub-paths, making the length of every sub-path almost equal.

Step 3: Applying TSP algorithm to optimize every sub-path. The optimized sub-paths are the reduced touring paths for the corresponding beacons.

4. Distance estimate based on RSSI

Using the widely used receiving-signal strength based methods (RSSI) (Liu *et al.*, 2004; Shi *et al.*, 2005; Li X.L. *et al.*, 2005), a sensor can calculate the distance between itself and a beacon based on the RF signal it received.

The RSSI based localization methods can be divided into two types (Lymberopoulos *et al.*, 2005): the map-based and the distance prediction based, and we adopt the latter. The process is: given the degree of the sending signal (which can be preconcerted), the sensor calculates the transmission loss of the signals and converts the loss to distance with the signal transmission model (mostly empirical model). When the distance measuring is completed, the node position can be decided by using algorithms such as the trilateration method, maximum likelihood estimation, etc.

For convenience, the interior space transmission loss model (Seidel and Rappaport, 1992) is adopted in the simulation.

$$L(dB) = PL(d_0) + 10\eta\log_{10}(d/d_0) + FAF, \quad (8)$$

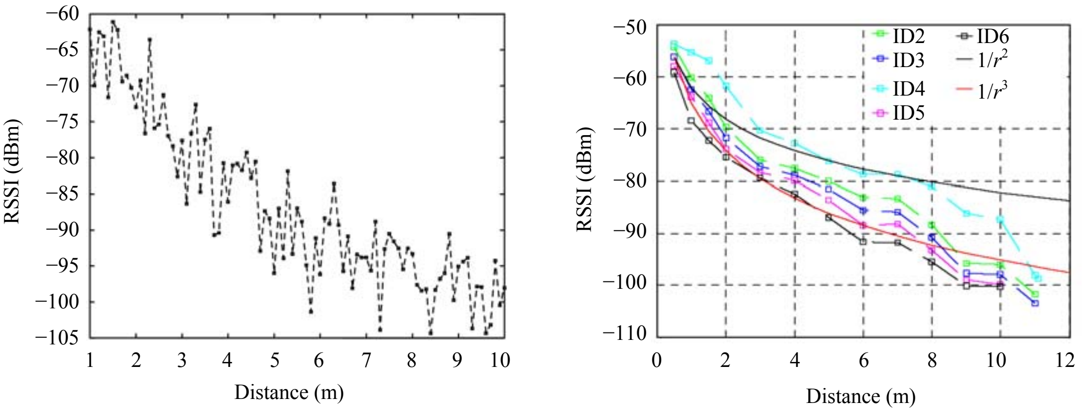
$$RSSI(d) = P_{\mathrm{T}} - L(dB), \quad (9)$$

where P_{T} is the transmission power which is generally 4 dBm (Yedavalli *et al.*, 2005). $L(dB)$, which needs to be predicted here, is the loss value of the position d meters from the emission source. $PL(d_0)$ is the path loss of the position 1 m from the antenna, the typical value of which is 55 dB; η is the path attenuation index, and in outdoor conditions it can take the value η=4; FAF is the appending value of path attenuation, its value is 8 dB for glass, 10~15 dB for partition walls, and 20~30 dB for pre-fabricated sheets. Also in some cases it is replaced by a random value X_σ drawn from a Gaussian distribution with mean 0 and variance σ^2 which denotes the random interference factors. Its value is related to the electric wave frequency and environment conditions, and the simulation results can be found in (Hashemi, 1993; Yedavalli *et al.*, 2005), and in outdoor conditions it can take the value σ=5.

EXPERIMENTS

In the following parts, we do some simulation experiments of the BETER and BETAR algorithms to verify their performance, and the character of each algorithm is analyzed as well.

Case 1 Setting some key parameters [see Eqs.(8) and (9)] related to RSSI, and comparing the simulation result by using those parameters with the real instance. Here we take the values: P_{T}=−5 dBm, η=4 (outdoor), $PL(d_0)$=55 dB, X_σ with mean 0 and variance σ=5. Fig.4 shows the simulation results. Corresponding practical experiments with 433 MHz MICA2 sensors can be seen in (Alippi and Vanini, 2004). Those sensors are equipped with several CC1000 radio transmitters and receivers with the transmitting power being −5 dBm. Comparing our simulation experiments with the practical ones in



(a) (b)

Fig.4 RSSI in simulation (a) and practical experiment (b) (Alippi and Vanini, 2004)

(Alippi and Vanini, 2004), we find our parameters are in better agreement with the actual situation. Hence it is credible to do subsequent experiments with those parameters.

Case 2 Selection of the beacon positions and path in a rectangle area. This experiment mainly examines the performance of the BETER algorithm in a rectangle ROI, with the parameters as follows: the ROI rectangle size 20×20, beacon broadcasting radius R_s=3. According to the ROI size, we could calculate the number of beacon positions, it is about 72. The number of sensors to be located is 60, evenly distributed in the ROI. Fig.5 shows the result. We could conclude from Fig.5 that the beacon positions worked out based on the BETER can effectively triply cover the ROI.

Case 3 Selection of the beacon positions and path in a random area. This experiment mainly examined whether BETAR could effectively select beacon position in a random ROI. Parameters used in the experiment are: the ROI (which can be substituted with any other shape) shape is a circle with radius of 10, the number of sensors obtained based on the ROI size is 40, beacon broadcasting radius is R_s=3, other key parameters are: C_{th}=1.2R_s, D_{th}=R_s. The sensors to be located are evenly distributed in the ROI, with the number being 60. Fig.6 shows the result.

Fig.6 shows that the beacon broadcasting positions could compose a series of equilateral triangle grid that covered the ROI fully and triply. This fact clearly proved that the virtual force method could find beacon broadcasting positions effectively and properly. Comparing to the sensing radius, the resulting localization error is 70% or so. However there are still several sensors that have not been located correctly (see Fig.6). After analyzing the experimental data, we find the reason lies in that these sensors are at the boundary of ROI, where the beacons are spare due to the virtual forces exerted by the boundary, and could not receive enough beacon packets to locate themselves. It is known from numbers of experiments that the localization results of the sensors around the

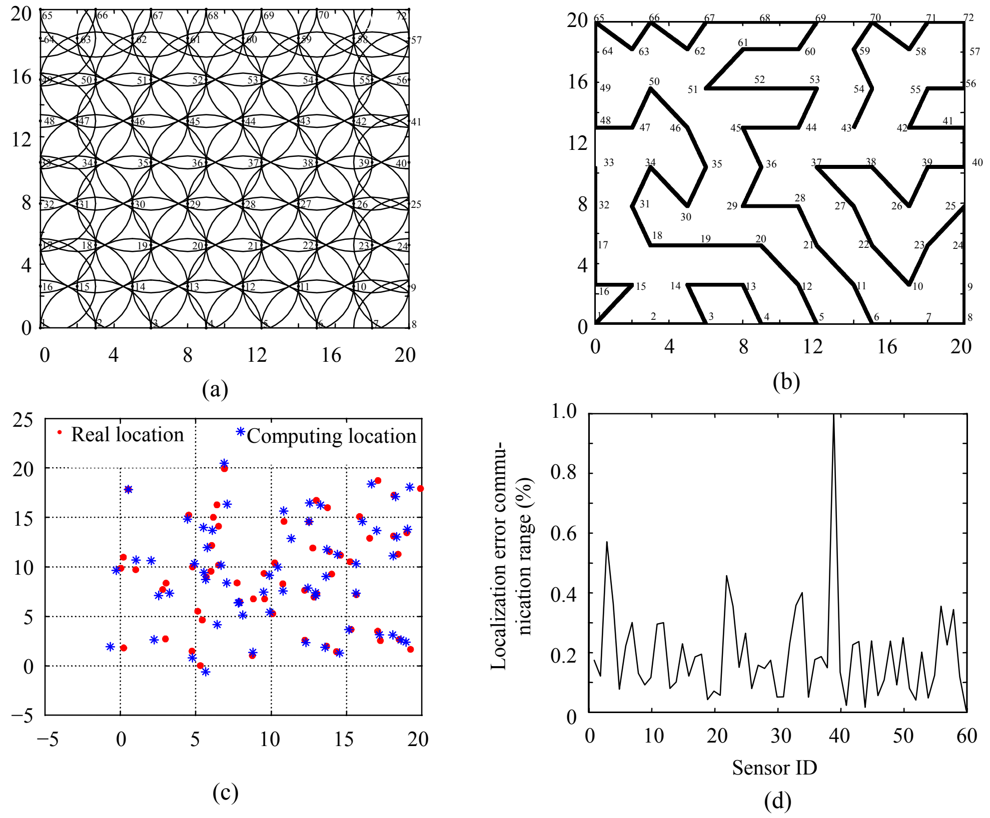
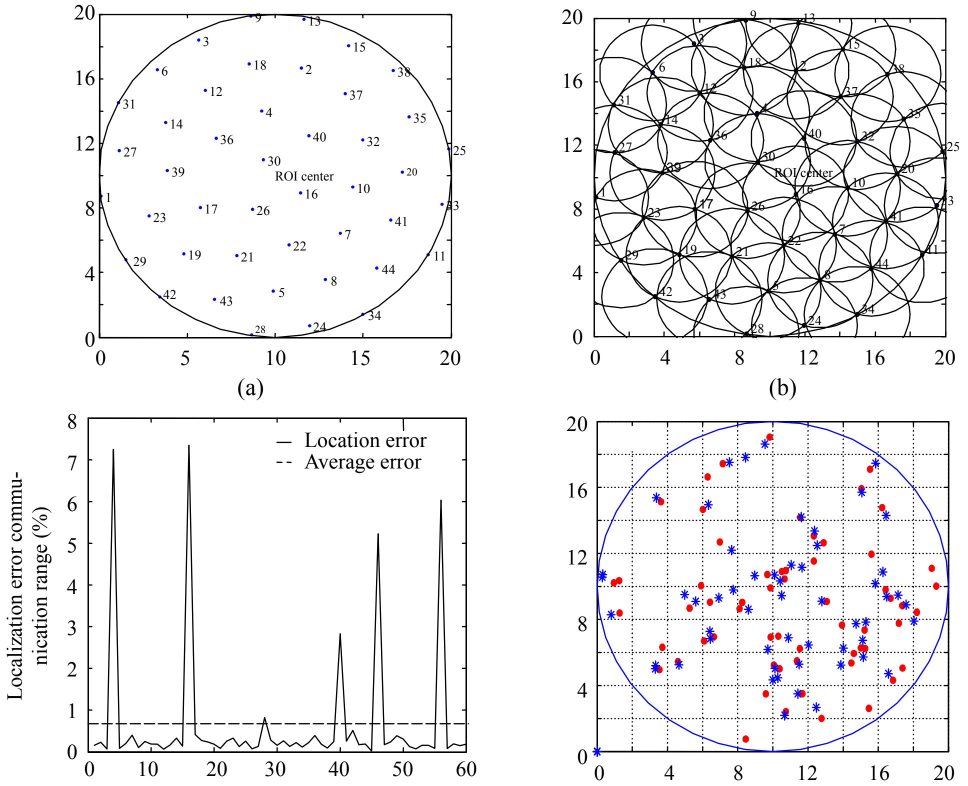


Fig.5 Beacon position and path choosing concerning the rectangle ROI. (a) Beacon positions and coverage in the rectangle area; (b) Beacon touring path; (c) Localization result (the sensors' real location and the computed location); (d) Localization error



(a) (b) (c) (d)

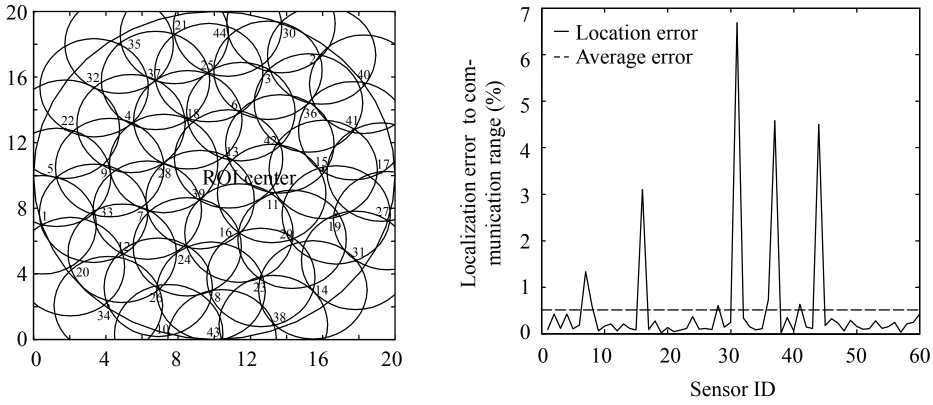
Fig.6 A group of beacon positions obtained with virtual forces method. (a) Beacon positions; (b) Beacon signal coverage for ROI; (c) Location errors; (d) Localization result, where dots mean the real locations and asterisks refer to the computing locations

boundary are not precise enough or even fail, which is an inherent limitation of virtual forces algorithm. Nevertheless, the localization error can be decreased to 55% by adding 10% (that is 4% in the experiment) beacon broadcasting position as shown in Fig.7. Additionally, we showed in Fig.8 how to convert the path of a single beacon into sub-paths for 3 beacons with the method of Section 3.2.3.

Case 4 Comparing the beacon position number and touring path length of BETER, BETAR and Helix (Sun and Guo, 2004) in the same size ROI rectangle (20×20). Helix is a typical beacon path, which is described as $l=\sqrt{3}R_{\mathrm{s}}\theta/(4\pi)$ in this paper. The starting point of the helix, which is also the center of ROI, is the first beacon position. Every beacon position is apart from the former position with the distance R_{s}. The parameters of BETER and BETAR are the same as mentioned before.

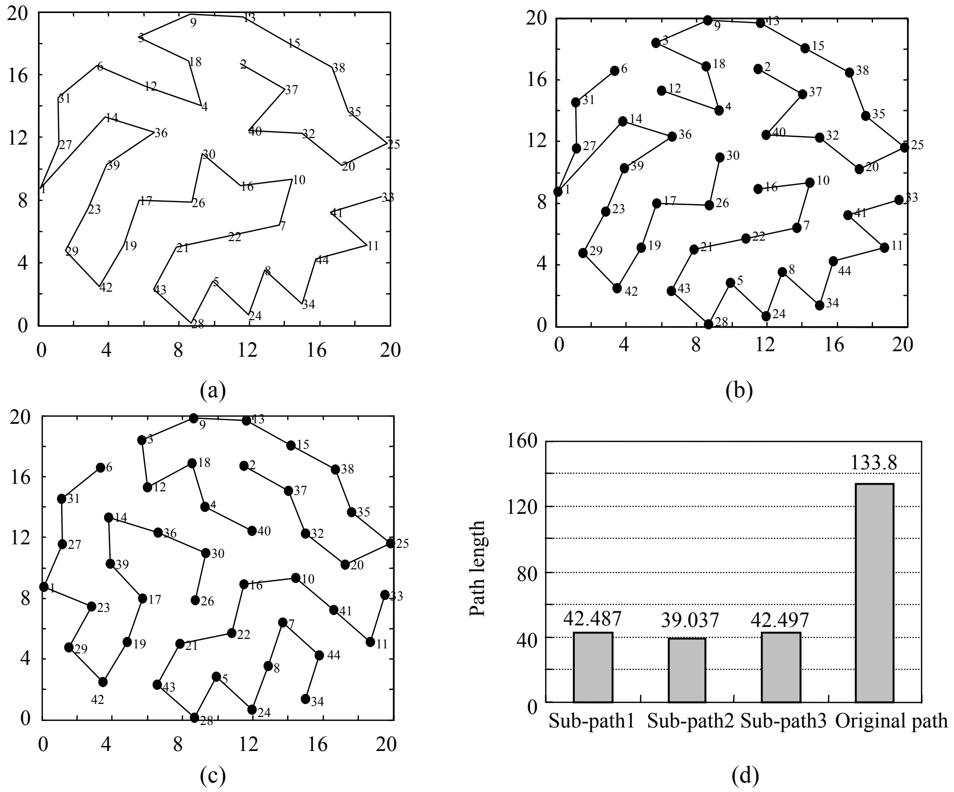
Considering the result in Case 4 with former experiments (Fig.9), it is obvious that the localization accuracy of BETER for rectangle areas is slightly better than those of BETAR and Helix, while the number of broadcasting positions and length of the path of BETAR are significantly less than their counterparts of BETER. The position number and path length of Helix are less than those of BETER and BETAR, but the beacon signals of Helix trajectory cannot cover rectangular ROI efficiently, so its localization result is much more inexact than those of BETER and BETAR.

Hence the BETER algorithm holds well in ROI rectangles for the condition that requires more in localization accuracy while less in localization time and energy consumption, and Helix can do well in a discal ROI, while BETAR is good for the condition that needs comparatively shorter time, less energy consumption, and lower localization accuracy. Moreover, BETAR can be applied to different shapes of ROI, while the other two can not.



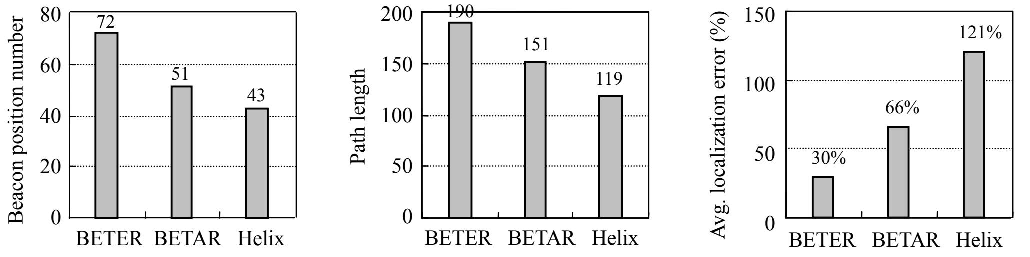
(a) (b)

Fig.7 Localization results after adding 4 beacon positions. (a) Beacon coverage; (b) Improved localization effect



(d)

Fig.8 Touring beacon positions by 3 beacons. (a) The path of a single beacon; (b) Dividing a 1_beacon path into 3 parts; (c) Getting 3 optimal paths for beacons; (d) Comparing sub-path with the original path



(a) (b) (c)

Fig.9 Localization results of BETER, BETAR and Helix. (a) Position number; (b) Path length; (c) Localization error

CONCLUSION

In this paper we present a simple beacon broadcasting position selection method (i.e. BETER) for rectangle ROI, and a novel method (i.e. BETAR) for arbitrary ROI based on virtual forces algorithm. The sensors localization experiments proved that our methods can effectively solve the position selection problem for the mobile beacon. Moreover, we introduced the idea of designing mobile beacons path based on optimal position touring by a TSP algorithm. For simplicity, "expected deployment"+"optimal touring"="expected path". The idea could easily be combined with the present location algorithms (Bulusu *et al.*, 2001; Yick *et al.*, 2004; Ssu *et al.*, 2005) based on beacon deployment, and obtain groups of beacon paths that meet different performance requirements. Thus, the practicability of the mobile beacon method is greatly extended.

The future research may focus on: (1) improving and completing the algorithm in this paper for more complicate terrain with other location methods (different distance and angle measuring methods); (2) considering how to adaptively design beacon paths based on a dynamically obtained ROI, since current beacon position selection is based on conditions of given ROI size, shape and terrain, etc.; (3) studying and improving the localization methods presented in the energy aspect, as decreasing energy consumption is a great problem in sensor network; (4) forming and optimizing a set of constraint conditions for beacon path design and presenting beacon path planning rules which are of general application based on different kinds of beacon location methods.

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