Localization in Resource Constrained Sensor Networks using a Mobile Beacon with In-Ranging

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Abstract— **In this paper[1], We provide a mechanism for the problem of localization in resource constrained sensor networks by extending the principles of In-Range technique using a mobile beacon. The main advantage of this mechanism is that, it inherits all the advantages of In-Range technique, eliminates the need to deploy beacons in the sensor network and satisfy the requirements of localization algorithms for sensor networks. Location awareness of sensor nodes plays a critical role in most of the sensor network applications. Our mechanism assumes only a basic communication capability of sensor nodes and does not require any additional infrastructure. We employ a single mobile beacon equipped with a GPS receiver for localization. Each broadcast position of the mobile beacon acts as a stationary beacon at that point (known as a virtual beacon) thereby eliminating the need to deploy GPS equipped beacons in the sensor network. The motion of the mobile beacon localizes some of the sensor nodes, which in turn aid in localization of their neighbors using the iterative In-Range technique. Simulation results are presented to evaluate the performance of the proposed mechanism. An implementation on sensor network of MICA2 motes is used to evaluate the functionality of the proposed algorithm.**

Index Terms— **Wireless Sensor Networks, Localization, Mobile Beacon, In-Range Localization.**

I. Introduction

Location service is a basic service of many emerging applications in sensor networks. Most of the applications of sensor networks assume that the sensor nodes know their position. However such information can neither be pre-configured in sensors owing to their ad hoc and possibly random deployment nor can it be centrally disseminated because of absence of a centralized coordinator. Thus it is imperative that sensors infer their locations autonomously using a low cost infrastructure.

A process that enables the nodes of the sensor network to compute their locations is referred to as *Localization*. One method to determine the location of a node is through manual configuration. However, this is unlikely to be feasible for any large-scale deployment. Another method is Global Positioning System (GPS), which solves the problem of localization in outdoor environments for PC-class nodes. However, due to cost, it is not desirable to have a GPS receiver on each sensor node.

In past several years, a number of location discovery schemes have been proposed to eliminate the need of having a GPS receiver on every sensor node. Most of these schemes share a common feature: they use some special nodes called beacon[2] nodes (they are also called anchors or reference points), which already know their absolute locations via GPS or manual configuration, other sensors discover their locations based on the information provided by these beacon nodes.

In general, any beacon based positioning system consists of two components: one is the reference points (beacons), whose coordinates are known; the other is the ranging technique used to measure the distance between reference points and nodes. Most of the traditional ranging methods are based on Received Signal Strength (RSSI), Time of Arrival (TOA) Time Difference Of Arrival (TDOA), Angle of Arrival (AOA) etc. RSSI is usually very unpredictable since the received signal power is a complex function of the propagation environment. Hence, radios in sensor nodes will need to be well calibrated otherwise sensor nodes may exhibit significant variation in power to distance mapping. The mapping of power to distance varies unpredictably with time in a given environment, so it is not a practical solution for ranging. TOA using acoustic ranging will require an additional ultrasound source. TOA and RSSI are affected by measurement as well as non-line of sight errors. TDOA is not very practical for a distributed implementation. AOA sensing will require either an antenna array or several ultrasound receivers.

Although overall cost of beacon-based location discovery schemes is significantly less compared to having a GPS receiver on every sensor node, the cost for each beacon is still expensive. The density of the anchors depends on the characteristics and probably the budget of the network since GPS is a costly solution. However, to have a more robust and accurate positioning system, the number of beacon nodes

[1]Research work carried out under Summer Research Fellowships Programme 2005(SRFP 2005), offered by Jawaharlal Nehru Center for Advanced Scientific Research, Bangalore 560 064.

[2]A node in the sensor network that knows its location is termed as a beacon

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tend to increase. In most of the sensor networks, the location of sensor nodes would be static once they are deployed and therefore a beacon will have no role to play once it broadcasts its location information and the neighbors learn their locations using the broadcast information.

All the factors discussed above motivate us to create a simple, distributed, cost-effective, reliable, and accurate localization mechanism using a mobile beacon accompanied by In-Ranging [1]. The proposed mechanism eliminates the need to deploy stationary beacons in the sensor field, and is not dependent on any of the ranging techniques (RSSI, TDOA, TOA, or AOA) that have disadvantages as discussed above.

The rest of the paper is organized as follows; the next section provides an overview of the existing work on location discovery. In section III, we describe the proposed approach. Section IV describes the formulation. In Section V, we discuss the localization algorithm. In section VI, we evaluate our localization mechanism. In section VII, we provide the results. We conclude in section VIII. Finally, Acknowledgments are given in section IX.

II. Related Work

The localization scheme in [4] uses RSSI based distance estimates to beacons where as in [5] it is based on TOA with acoustic ranging and multilateration. Both of these methods have limitations as discussed in Section I. Recently, few schemes [6] [7] [8] have been proposed that employs mobile beacons for localizing sensor nodes. [6] uses four GPS equipped mobile beacons, which co-ordinate based on distance estimates using RSSI for localizing the sensor network. [7] uses a single mobile beacon and depends on RSSI for estimating distance between sensor nodes and the current position of the mobile beacon. Since both of these schemes are RSSI based, they have disadvantages as discussed in Section I. [8] proposes a localization scheme using a mobile beacon based on TOA, it also has disadvantages as discussed in Section I.

III. Proposed Approach

We propose a localization mechanism for the sensor networks using a GPS equipped mobile beacon accompanied by iterative In-Ranging technique. A mobile beacon moving according to Random Waypoint mobility model in the sensor network would broadcast its current position at regular intervals of time as defined by the mobility model. Each broadcast position can be considered as a stationary beacon at that point.

The basic premise of the proposed approach is that the sensor nodes in the transmission range of the mobile beacon can localize themselves to a disk centered at the location of the mobile beacon and radius equal to the transmission range of the mobile beacon. Once a node localizes itself by hearing the mobile beacon it can aid in localizing its neighbors using simple iterative In-Range technique.

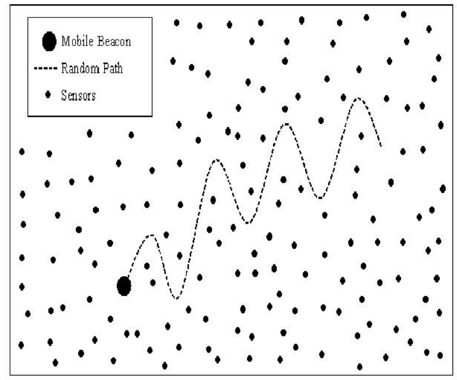

Fig. 1. Random movement of Mobile Beacon in the sensor network.

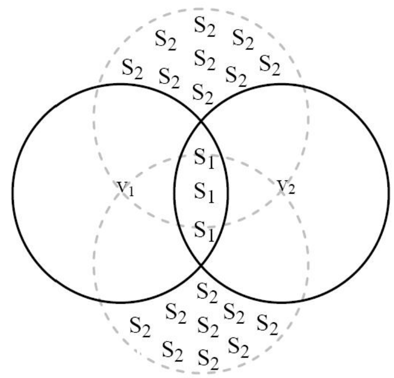

Fig. 2. Localization using Mobile Beacon with In-Ranging.

Since each broadcast position of the mobile beacon acts as a stationary beacon (known as a virtual beacon), the proposed concept eliminates the cost of stationary beacons by not having them to be deployed in the sensor network. This method has an advantage that it can increase the accuracy of localization of sensor nodes by having the mobile beacon for a longer duration in the sensor network, thereby producing large number of beacons. Random movement of the mobile beacon and localization process has been depicted in Fig. 1 and Fig. 2 respectively.

S_1 and S_2 are the two sensors with unknown locations. S_1 hears the mobile beacon at two locations V_1 and V_2. Thus S_1 gets localized to the region of intersection of two circles centered at V_1 and V_2 with the radii of circles equal to the transmission range of the mobile beacon. S_2 is does not hear the mobile beacon; since it is in the transmission range of the sensor S_1, S_2 gets localized to the region as shown in Fig. 2. This is the advantage of iterative In-Range localization. i.e., once a sensor gets localized it aids the other sensors in localization.

IV. Formulation of Localization mechanism using a Mobile Beacon

Consider a randomly deployed sensor network in a geographical region $\mathcal{A}$; The sensors are indexed by $i\epsilon\{1,2,...,N\}$(N being the number of sensors in the deployment area) and the virtual beacons by $i\epsilon\{N+1, N+2, ..., N+M(t)\}$ at any instant of time t ($M(t)$ represents the number of virtual beacons generated till time t). We say that a transmission can be "decoded" by a sensor when its signal to interference ratio (SIR) exceeds a given threshold β. The *transmission-range* is then defined as the maximum distance at which a receiver can decode a transmitter in the absence of any co-channel interference. We denote the transmission range of sensors and that of the mobile beacon by R_0. The sensors within a distance of R_0 from i will be called its neighbors. The set of neighbors of i will be denoted by N_i and their count by n_i. By the location of sensor we mean its co-ordinates and denote it compactly by v_i.

A localization set for a sensor i is a subset of the region of deployment. Let $X_i(t,n)$ denote the localization set for the sensor i at time t after n iterations of In-Range localization. Thus the initial localization set, $X_i(0,0) = \mathcal{A}$ for all $i\epsilon\{1,2,..,N\}$. $D(v,r)$ denotes a disk of radius r centered at v. O denotes the origin. If G and H are two sets, $G+H$ denotes the set addition, i.e., $G+H = \{g+h | g\epsilon G, h\epsilon H\}$.

We assume that each sensor would maintain a list of neighbors. When the mobile beacon broadcasts location information, the sensors within the transmission range of the mobile beacon would add the current location of mobile beacon to their neighbor list, thus generating virtual beacons.

The following gives the iterative localization scheme. n is the number of iterations and t is the time. For $n \geq 0$, $t \geq 0$ and $i = 1,2,...,N$.

$$Y_i(t,n+1) = \bigcap_{k\epsilon N_i} (X_k(t,n) + D(0,R_0)) \quad (1)$$

$$X_i(t,n+1) = X_i(t,n) \cap Y_i(t,n+1) \quad (2)$$

If i is in the range of k, i is certainly in the region $(X_k(t,n) + D(0,R_0))$. Since this property holds for each neighbor of i, i is localized to $\bigcap_{k\epsilon N_i}(X_k(t,n) + D(0,R_0))$. Thus, it follows that at any instant of time t, the localization set of i after $(n+1)$ iterations is the intersection of its localization set after n iterations and $\bigcap_{k\epsilon N_i}(X_k(t,n) + D(0,R_0))$.

Let $\mathscr{L}(X)$ denote a measure of set X; in one dimension it is the length of X. Define, $\chi_i(t,n) = \mathscr{L}(X_i(t,n))$, which we call the *localization error* of sensor i in time t and iteration n. $\chi_i(t,n) = 0$ for all virtual beacons. Let $\underline{\chi}(t,n) = (\chi_1(t,n), \chi_2(t,n), ..., \chi_N(t,n))$ and consider the vector valued process $\{\underline{\chi}(t,n); n \geq 0, t \geq 0\}$ which we call the *localization process*. Note from (2) that for each i, $\chi_i(t,n)$ is non-increasing with t and n.

The performance measures which are of interest include

- $\overline{\chi}(t,n) = \frac{1}{N+1}\sum_{i=1}^{N}\chi_i(t,n)$
- $v(t,n) = \frac{1+\sum_{i=1}^{N} 1_{\{\chi_i(t,n)<A\}}}{N+1}$, where $1_{\{.\}}$ denotes the indicator function.

Thus by definition, $\overline{\chi}(t,n)$ is the average localization error in the network at the time t with iteration constant n. $v(t,n)$ is the fraction of nodes localized at the instant of time t with iteration constant n.

V. Localization Algorithm

There are several requirements that a localization mechanism should satisfy;

- It has to be distributed: centralized approach requires high computation at selective nodes to estimate position of nodes in the whole network.
- It should be robust: the localization algorithm should be able to localize with failure or loss of nodes.
- The localization algorithm should be very accurate and scalable.

The localization algorithm presented in this paper satisfies all the above requirements and gives very accurate results.
Here are the assumptions made:

- There is a mobile beacon, which is GPS enabled.
- The mobile beacon can move according to the RWP mobility model.

Algorithm 1: Localization Mechanism using the Mobile Beacon

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1) Select an initial point (source) for the mobile beacon.
2) Select the next point (destination) as defined by the RWP mobility model.
3) The mobile beacon would move from the source to the destination with a velocity as defined by the RWP mobility model.
4) The mobile beacon would broadcast the current location information to the sensors and the sensors in the transmission range of the mobile beacon would add the current location of the mobile beacon to their neighbor list (flags this entry as a virtual beacon).
5) Execute the In-Range localization algorithm at each sensor.
6) Repeat steps 1-6 till the desired accuracy in terms of localization parameters are obtained.

VI. Evaluation

Localization algorithm can be evaluated based on some parameters which we call them as localization parameters. Some of the localization parameters include time of localization, error of localization and percentage localization.

Time of localization can be defined as the time taken to localize a sensor network. The cardinality of set of potential locations of sensor nodes can be taken as measure of error.

The mathematical models for the localization parameters depend on the distribution of sensors and also the virtual beacons generated by mobile beacon. In this paper We model the sensor network with large number of randomly distributed sensors with the sensing radius R_0 as a set of points in $[0,1]^2$ generated by a two dimensional poisson point process of intensity n and assume that the beacons generated by the mobile beacon follows a similar poisson point process. The above assumption is valid since we can define a mobility model that determines the movement of the mobile beacon. For example if RWP mobility model, the distribution of beacons in the sensor field would be uniform. Here are some of the results based on the above assertions.

Theorem 1: If $lim_{n\rightarrow\infty}\frac{NR_0^2}{logN} > 8$, we can divide $[0,1]^2$ into layers; such that all the nodes in a layer i are connected to at least one node in the layer $(i-1)$.

Proof: Partition $[0,1]^2$ into $\frac{cN}{logN}$ squares of equal size where $c < 1$. Since $r > 2\sqrt{2}\sqrt{\frac{logN}{N}}$, we can see that, every node is connected to all the other nodes in its own square and adjacent squares.

Starting from some square we label as 0, we iteratively label every square in $[0,1]^2$. In step $i \in \{1, ..., \sqrt{\frac{cN}{logN}}\}$, we label with i, every unlabeled square that adjoins a square labeled $i-1$ horizontally, vertically or diagonally. We will refer to the union of all squares with the same label i as layer i.

We now iteratively label all N nodes in the grid. We choose a node in layer 0 and label it 1. In step 0, we label the rest of the nodes in layer 0 with numbers greater than 1. In step i, we label all nodes in layer i with numbers larger than every label in layer $(i-1)$.

Every node in layer 0 with label greater than one has an edge connected to 1. By construction, a node labeled m in layer i $(i > 0)$ has edges to at least one node in layer $(i-1)$ with the label less than m.

■

Claim 1: For some $R_0 \in O(\sqrt{\frac{logN}{N}})$, with a high probability, all the sensors in $[0,1]^2$ are localized by $O(\sqrt{\frac{N}{logN}})$ time if a beacon is placed anywhere in $[0,1]^2$.

Proof: We set R_0 and partition $[0,1]^2$ into labeled squares as in the proof of Theorem 1 such that the beacon is placed in the square labeled 0. We say a layer is localized when all the sensors in that layer have determined their potential locations. Assuming the In-Range localization takes place in a single constant-time step, layer 0 will be localized in a single constant time step. Additionally, given layer i localized, In-Range method will localize layer $(i+1)$ in a single constant-time step. Therefore, all the layers will be localized in at most $O(\sqrt{\frac{N}{logN}})$ steps and our claim is established.

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Claim 2: Let MB_{RN} represent the number of points in the transmission region of the mobile beacon. For some $R_0 \in O(\sqrt{\frac{logN}{N}})$, with a high probability, average cardinality of the set of potential locations of all the sensor nodes in the sensor network is at most equal to MB_{RN}, provided beacons are placed on $[0,1]^2$ by a Poisson point process of intensity $O(\frac{N}{logN})$.

Proof: If $R_0 \in O(\sqrt{\frac{logN}{N}})$, the Poisson point process places beacons in the sensing region of a sensor at the rate of $\lambda \ \alpha \ \frac{N}{logN}R_0^2 \ \alpha \ 1$. Since we expect $O(1)$ beacons connected to every sensor, with high probability, we will have average cardinality of the set of potential locations of all the sensor nodes less than or equal to the number of points that constitutes the transmission radius of the mobile beacon. ■

TABLE I
EVALUATION OF THE PROPOSED ALGORITHM.

Beacons	Sensing Radius	Time/Avg Cardinality
$O(1)$	$O(\sqrt{\frac{logN}{N}})$	$O(\sqrt{\frac{logN}{N}})\ (Time)$
$O(\frac{N}{logN})$	$O(\sqrt{\frac{logN}{N}})$	$<= MB_{RN}(Avg\ Cardinality)$

VII. Results and Discussion

We simulated the proposed mechanism on a computer to evaluate its performance by generating a set of poisson points, which represent the positions of sensor nodes. We then simulated RWP mobility model and used In-Range localization scheme to localize the sensor network using the virtual beacons generated by the mobile beacon. In the simulation, we take a rectangular region of 100X100 and we generate 2000 poisson points which represent the position of the sensors. Each virtual beacon is generated after 47 seconds. The transmission range of the sensors and that of the mobile beacon was set to 5 units.

Fig. 3 shows the variation of localization error with time for the proposed localization scheme (with one iteration of In-Ranging). Fig. 4 shows the variation of percentage localization with time for the proposed localization schemes (with one iteration of In-Ranging).

The proposed concept of mobile beacon was implemented as distributed asynchronous algorithm on TinyOS using nesC. Implementation was verified for its functionality on a sensor network of resource constrained MICA2 motes. Existing TinyOS CSMA/CA based B-MAC (Berkeley MAC) implementation was used by mobile beacon to broadcast its current position to sensor nodes. Sensor nodes used Tinyos MultiHop module built on the top of B-MAC to convey the localization information to the base station. A toy car was used to carry the mobile beacon in the sensor field.

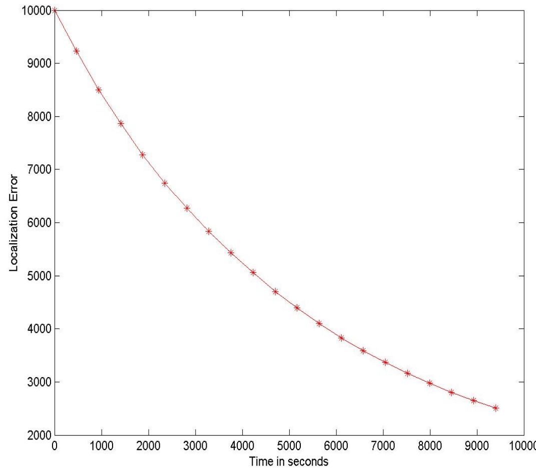

Fig. 3. Variation of Localization Error with time

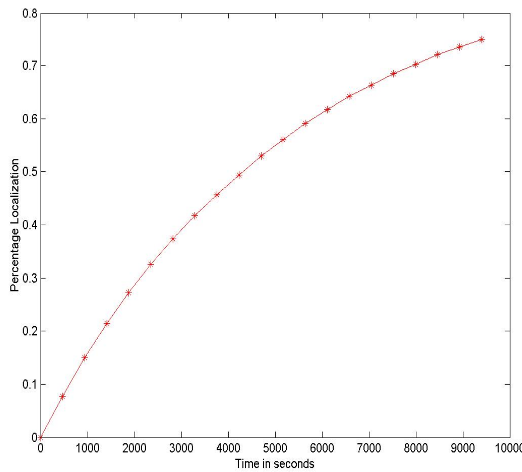

Fig. 4. Variation of Percentage Localization with time

VIII. Conclusions

In this paper, we addressed the problem of localization by proposing a new algorithm for localization which extends the principles of In-Range localization. The algorithm proposed addresses most of the basic requirements of a localization algorithm for sensor networks. The algorithm is distributed, robust, scalable, fault tolerant, accurate, and relies only on a basic communication capability of sensor nodes. It eliminates the need to deploy stationary beacons in the sensor network.

We also studied the computational complexity and accuracy of the proposed algorithm, which exploits that the accuracy of localization is a function of the distribution of beacon positions obtained by using the mobile beacon. A test implementation on a sensor network of resource constrained MICA2 motes reveals that proposed scheme could be easily implemented as distributed asynchronous algorithm in resource constrained wireless sensor networks. Simulation results show that the localization mechanism works well in the real sensor networks.

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