On the Effects of Multiple Beacons on Localization for Wireless Sensor Networks

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Abstract

This paper concerns the simulation-based investigation of two localization protocols for wireless sensor networks, namely, RBC and MEC^2. In particular, for these two range-based protocols, that use information on inter-nodal distance and angle of arrival, we demonstrate their effectiveness in producing accurate localization as well as in containing the propagation of the localization error as the localization process progresses away from the beacon *(i.e., from the node that knows its exact location). Our aim here is threefold. We demonstrate the advantages of jointly using range and AoA for increasing localization accuracy. We show the effects of deploying multiple beacons on localization accuracy, and we quantify the improvements. We finally show the differences and possible improvements of manual beacon placement vs. scattering the beacons randomly among the network nodes.*

1. Introduction

Among the many problems tackled with by research on wireless sensor networks (WSNs) one is particularly close to the very nature of these networks, and to the very purpose for which they are deployed: *Localization*. Dealing with the issues related to endowing wireless sensor nodes with coordinates with respect to an absolute or relative system, localization becomes crucial for all those applications where reporting the sensed data without the place where the corresponding event has occurred would render the data itself useless. Most of the applications for WSNs require this important spatial information. Examples include environmental monitoring, asset tracking, independent assisted living and other medical applications, etc.

The Global Positioning System (GPS) is clearly one of the most well-known technologies for localization. Given the resource-constrained nature and the low cost of the sensor nodes, however, GPS is often not a viable option. A GPS device would require too much of the little energy that a sensor node usually has. Moreover, GPS does not work in many of the situations where a WSNs is useful, like monitoring environments characterized by heavy foliage, in indoor settings as well as in difficult, post disaster scenarios.

For this reasons, recent research on localization has focused on defining protocols that with little information allow the network nodes to estimate their coordinates [1]. When this information is only based on the knowledge of the coordinates of few selected nodes, called *beacons* (with GPS, or configured manually) and topological information (such as the number of hops from the beacons) the algorithms are categorized as *range-free*. When instead information on the inter-nodal distance, or on the angle of arrival (AoA) of the radio signal is available localization protocols are termed *range-based*. One of the main problems facing the design of localization protocols is to devise methods for reducing the *localization error*, simply defined as the distance between a node real and estimated coordinates. Range-free protocols often produce quite inaccurate localization, because the estimation of nodal coordinates depends on inter-beacon distance (both in hops and geographic) and on estimating the average hop-length, the distance from the beacons and applying multi-lateration techniques [2]. Despite range or angle measurements provide a better way to determine inter-nodal distance, range-based localization protocols that use either range or AoA achieve average localization errors that can be greater than $\frac{r}{2}$, where r is a node transmission range.

Recently, we have proposed a protocol that by jointly using both range and AoA measurements achieved increased localization accuracy [3]. Our protocol, termed Range-Based Centroid (RBC), starts from a single beacon and is able to localize all the network nodes with an accuracy that improves on that

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of methods based on the sole measurement of range (that usually require multiple beacons). In order to contain the propagation of the localization error while the process progresses away from the beacon, we have also proposes a new localization protocol that achieves even greater accuracy. In [3] we quantify the improvements of the proposed protocol, termed MEC^2 (for *Minimum Enclosing Circle Containment*) by simulations. We observe that MEC^2 keeps the localization error below 25% of the node transmission radius, with 20 to 30% improvements over RBC, and in general over common localization methods. We observe that combining range and angle of arrival produces better localization without requiring a higher number of beacons or extra hardware. The MEC^2 solution, for instance, achieves accuracy which is acceptable for most geo routing and location aware applications with just one beacon.

In this paper we contribute to the research on accurate WSNs localization methods by investigating the effect of deploying multiple beacons on the localization error as achieved by RBC and MEC^2. In particular we are interested in quantifying the improvements obtained with respect to the case with one beacon when we placed one, two or three extra beacons in the network deployment area. We them set to investigate the impact on the localization error of being able to manually place the beacons. Through extensive ns2-based simulations we demonstrate that, as expected, increasing the number of beacons benefits the localization process in terms of the overall accuracy. Our study also shows that, in general, placing the beacon manually also helps in achieving better localization, especially when the beacons can be placed inside the deployment area.

The rest of the paper is organized as follows. In the next section we describe RBC and MEC^2. In Section 3 we present the results of our simulations. Finally, Section 4 concludes the paper.

2. RBC and MEC^2

The Range-Based Centroid (RBC) solution for node localization works as follows. There is an initial set up phase in which each node gets to know its hop distance h from the beacon, the identity of its neighbors at distance $h-1$ from the beacon and the measurements of range and AoA from these neighbors. (We assume that each node is equipped with a compass, which allows consistent measurements of the AoA.) The beacon starts the localization process by broadcasting its (exact) coordinates to its one hop neighbors (layer 1 nodes). Based on the (possibly faulty) measurements on range and angle, each neighbor of the beacon is able to compute its own (estimated) coordinates, which in turn are broadcast to the nodes that are two hops away from the beacon (layer 2 nodes). The generic node V at level h receives estimated coordinates from its u neighboring nodes one hop closer to the beacon (upstream neighbors). By using the measurements to each of such neighbors i and the coordinates (x_i, y_i) they sent, V computes its estimated coordinates (x_V, y_V) as the average over the estimated coordinates (x_V^i, y_V^i) with respect to each neighbor (centroid, as in [4]), i.e., for a node V in the plane, $(x_V, y_V) = \frac{1}{u}\sum_{i=1}^{u}(x_V^i, y_V^i)$.

Clearly, the localization error increases while the localization process progresses away from the beacon, given that a node h hops away from the beacon computes its coordinates based on faulty measurements and on imprecise coordinates (error propagation).

Based on RBC we propose a localization method that effectively contains the propagation of the localization error experienced by RBC. We assume that each node is aware of an upper bound on measurement errors on the real distance d between two nodes (ε_d, expressed as a percentage of d), and on the AoA α (ε_α, an absolute value). These two bounds allow a node to compute the area in which its real coordinates can be found.

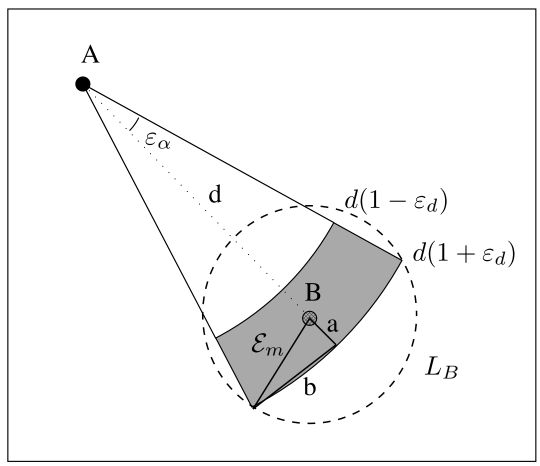


Figure 1. $\mathcal{E}_m$ and corresponding localization area

Let us consider two nodes A and B as in Figure 1, where A is the beacon. The shaded area is where B can be located based on the known bounds on the measurement errors and A's coordinates. We approximate this area with a circle L_B centered on the unknown real position of B. We term L_B the *localization area* of node B. The radius $\mathcal{E}_m$, called *measurement error radius*, is obtained as the norm of the vectorial sum of the errors on distance and angle, and represents the error due to measurements.

$$\mathcal{E}_m = \left\| \overrightarrow{d}\,\varepsilon_d + 2\,\overrightarrow{d}\,sin\frac{\varepsilon_\alpha}{2} \right\| \qquad (1)$$

Together with its estimated coordinates node B transmits also its measurement error radius to its neighbors in layer 2. These neighbors (possibly) receive multiple coordinates and radii, and compute their own coordinates and a *localization radius*, which is a function of the measurement errors and the received coordinates. This radius bounds the localization error from above. (In the case of neighbors of the source the localization radius coincides with the measurement error radius.) More specifically, a generic node V that is h hops away from the beacon receives coordinates (x_i, y_i) and localization radii $\mathcal{E}_i$ from all its u neighbors in layer $h-1$. From each of the received coordinates, given the measurement to the neighbors, V computes its possible estimated coordinates (x_V^i, y_V^i). At this point, instead of averaging on the estimated coordinates (as in RBC), node V considers (x_V^i, y_V^i) as the center of a circle L'_i whose radius $\mathcal{E}'_i$ is given by the localization radius $\mathcal{E}_i$ of neighbor i increased by the measurements error radius $\mathcal{E}_m$ (see Figure 2).

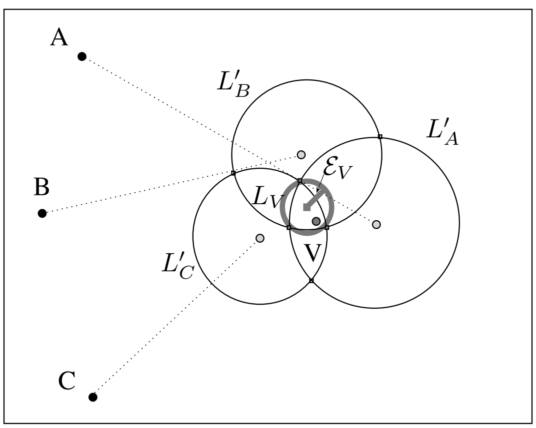


Figure 2. Localization area in MEC^2

Each of the circles L'_i, $i = 1, \ldots, u$, covers an area where the actual coordinates of node V are surely to be found. It is clear that V resides in the intersection of such circles. Node V's final estimated coordinates are therefore computed as the center of the smallest circle that contains all the points common to the intersection of the bigger circles (minimum enclosing circle, or MEC).

The MEC (thicker circle in Figure 2) is V's localization area L_V, whose radius $\mathcal{E}_V$ is sent by V to all its neighbors in layer $h+1$ along with its estimated coordinates.

We notice that the complexity of computing the MEC of a set with $O(u)$ points is $O(u)$, i.e., there is only quite a limited added complexity with respect to the simple centroid computation.

3. Simulation Results

RBC and MEC^2 have been implemented by using the CMU wireless extension to the network simulator ns2 [5]. The scenarios we consider comprise WSNs with n homogeneous nodes, where n belongs to the set $\{50, 100, 200, 300, 400\}$. Since we kept the deployment area fixed (a square of size 1400m) we obtained networks with increasing densities. The node transmission radius r is set to 250m. Measurement errors on distance have been modeled by adding to the Euclidean distance d between two nodes a percentage of d randomly chosen in $[-\varepsilon_d, \varepsilon_d]$, $\varepsilon_d \in [5\%, 50\%]$. Measurement errors on the angle are modeled by adding to the actual angle α a value randomly chosen in $[-\varepsilon_\alpha, \varepsilon_\alpha]$ where $\varepsilon_\alpha \in [5°, 45°]$. In the experiments below we consider three pairs of measurement errors, namely,$\langle \varepsilon_d = 5\%,\ \varepsilon_\alpha = 5° \rangle$ (which corresponds to good measurements), $\langle 25\%, 20° \rangle$ (medium measurement errors), and $\langle 50\%, 45° \rangle$ (high measurement errors).

As mentioned, in this paper the metric we investigate is the localization error, i.e., the distance between a node real and estimated coordinates. We normalize this error the nodal transmission range r. We consider both the error per level, i.e., the error that affects the nodes at the same hop distance from a beacon, and the average localization error over all nodes. We perform two sets of experiments. The first concerns the effect on the error of the use of up to four beacons instead of one. The second set of experiments explores the possible improvements that can be obtained by placing the beacons manually, being able to decide where to put them, instead of placing them randomly. Both alternatives are interesting and realistic. Having access to the deployment area one can take advantage of positioning the few beacons in places that allow more accurate node localization. If the area is instead not accessible, beacons can be either scattered as if they were like all other nodes, or placed along the area perimeter.

Each point in the figures below is obtained by averaging over 250 network topologies for each n. This corresponds to a statistical confidence of 95% and to a 5% precision.

3.1. Experiments with increasing number of beacons

In our first set of experiments we are interested in studying how the localization error grows as the localization process progresses away from the beacon (i.e., the average localization error per layer) in the case that one, two, three and four beacons are deployed. In case of multiple beacons, a node choses the closest as the beacon of reference to compute its coordinates according to RBC and MEC^2. For instance, if a node is distant k hops from beacon A and h hops from beacon B, with $k > h$, it will compute its coordinate based on its neighbors at distance $h-1$ from beacon B (if $h = k$ one beacon is chosen randomly, or selecting the one beacon with the lowest ID).

A summary of the obtained results is as follows (the numbers refer to the case with one beacon deployed randomly. We observed similar trends for randomly deployed multiple beacons).

1) *The localization error increases as the distance from the beacon increases*. For instance, for networks with 100 nodes (fairly sparse), with medium measurement errors, nodes three hops from the beacon experience an error which is below 15% of r for both protocols. Nodes 7 hops from the beacon suffer an error of 20% (MEC^2) or higher (RBC). This percentages decrease with network density.
2) *The higher the measurement error, the higher the localization error*. For instance, in dense networks ($n = 400$) for $\langle \varepsilon_d = 50\%, \varepsilon_\alpha = 45° \rangle$ the localization error is 45% of r for nodes that are 7 hops away from the beacon. The error decreases to only 19% of r when $\varepsilon_d = 25\%$ and $\varepsilon_\alpha = 20°$.
3) *The localization error increases as the network density increases*. Since the estimated coordinates of a node are computed as the average over the estimated coordinates (or "the centers of circles") from neighboring nodes, the more the neighbors, the more accurate the estimation. For instance, when $n = 100$ nodes 6 hops from the beacon suffer an average error which is 24% of r (for medium measurement errors). Nodes the same distance from the beacon in networks with 400 nodes suffer a lower error (18% of r).
4) *MEC^2 is more effective than RBC in containing the propagation of the localization error*. More important, as the distance from a beacon increases the improvements of MEC^2 over RBC become more noticeable. RBC yields localization errors that are up to 22% higher than those obtained by using MEC^2 for nodes that are 6 hops away from the beacon. The MEC^2 improvement increases to 34% for nodes in the seventh layer.
5) *Using information on both range and AoA with just one beacon is effective in containing the localization error to under 25% of the nodal transmission range r*. This happens for medium measurement errors on range and AoA. Even in the worst case considered, however, in sparse networks, errors are always below 62% of r (for RBC. MEC^2 is always below 50% of r).

Improvements obtained by using multiple (randomly placed) beacons are depicted in Fig. 3.

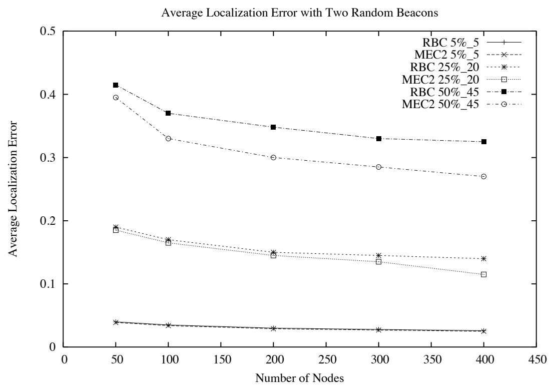
In all cases, we observed that MEC^2 leads to smaller localization errors than RBC. In particular, the improvements in accuracy of MEC^2 over RBC are up to 18%, 13% and 9% for networks with two, three and four beacons, respectively. For both RBC and MEC^2, as the number of beacons increases, the average localization error decreases, as expected, because multiple beacons reduce the hop distance between a node and its chosen beacon.

Fig. 3(c) shows the overall localization error for the two protocols in the case of medium measurement errors. The improvements in localization accuracy with respect to the case with one beacon for MEC^2 (RBC) is 26% (21%) when using two randomly placed beacons, 30% (25%) when using three randomly placed beacons, and 35% (29%) when deploying four beacons randomly.

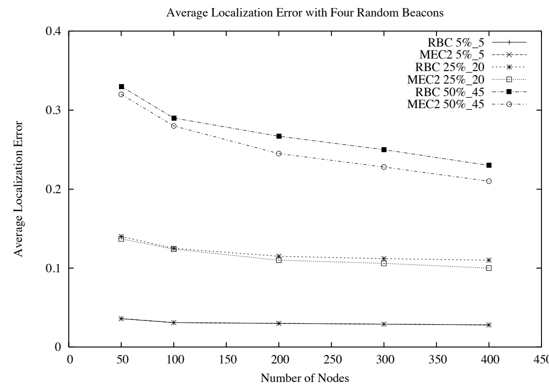
3.2. Experiments with different beacon placements

It might be sometimes possible to place the beacons in specific positions of the network deployment area. With this second batch of experiments we investigate how much this has an effect on the localization error. More specifically, we place one beacon at the center of the deployment area. When having two beacons, we place them at two opposite corners of the area. Three beacons are placed at the center and at two opposite corners. Finally, four beacons are placed at the four corners.

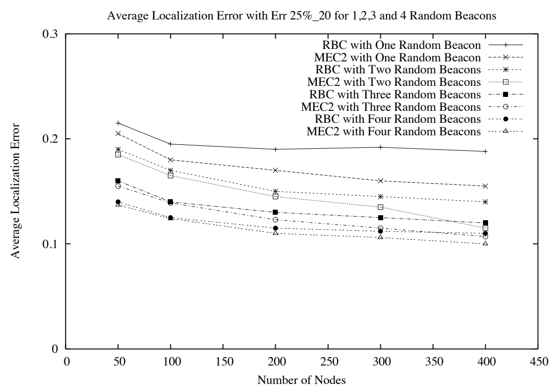
In general, with manual placement what one is after is the decreasing of the hop distance between a node and the beacon that the node use for localization. We noticed that this is obtained when a beacon is placed in the center of the deployment area. We have performed several sets of experiments that confirm this observation. Here we show the improvements



(a) 2 beacons



(b) 4 beacons



(c) Comparison (medium errors)

Figure 3. Localization error for networks with increasing number of beacons

Table 1. Improvements over 1 random

	RBC	MEC^2
1 manual	14%	19%
2 random	21%	26%
2 manual	9%	11%
3 random	25%	30%
3 manual	35%	40%
4 random	29%	35%
4 manual	16%	18%

on localization accuracy of the different beacon deployments with respect to the case of one beacon deployed randomly. These improvements are shown in Table 1. There is always an improvement, as expected. However, we notice that, while for one and three beacons manually placed the improvements are better than those in their random counterparts, in the case of two and four beacons, placed at the corners, the improvements are worse than those obtained by placing the beacons (randomly) inside the network area. In the latter cases we observe that the average hop distance between a node and its beacon is higher for beacons manually placed than for those scattered randomly, which explains the better improvements in the random placements. This prompts us to future research, where *optimal* beacon placement will be investigated.

4. Conclusions

In this paper we have explored the impact of using multiple beacons on localization accuracy for WSNs of increasing number of nodes and densities. In particular, we have performed a wide set of ns2-based experiments that show the improvements in localization accuracy achieved by two localization protocols, RBC and MEC^2, when increasing the number of beacons from one to four. We also started a discussion on the importance of where to place the beacons, when possible, and how much beacon placement impacts localization accuracy.

Acknowledgments

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