Experiments on Localization of Wireless Sensors using Airborne Mobile Anchors

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Abstract — An important aspect of Wireless Sensor Network (WSN) operation is identifying the physical location of each sensor in 3-D space – a process known as localization where an anchor with known location determines the location of other location-blind nodes. In this paper, we present a detailed performance analysis of three scenarios: (1) localization of blind nodes using an airborne mobile anchor; (2) fixed ground anchors only; and (3) using the combination of fixed anchor and mobile anchors. Matlab simulations were carried out to explore the impact on localization error based on random and designated positions of mobile anchors, the number of mobile anchor positions used, and the variability of Received Signal Strength Indicator (RSSI) range measurements as part of the objectives of this experiment. Results show that a designated flight path is better than random anchor positions, and that localization error increases quickly with RSSI variability, while poor anchor geometry yields large errors. Somewhat surprisingly, adding ground-based anchors does not improve localization. Approximately 6 to 13 RSSI readings give the best localization accuracy.

Keywords—wireless sensor network, Received Signal Strength Indicator, localization, 3D, airborne mobile anchor, blind node.

I. INTRODUCTION

WSN applications are dominated by constrained resources such as energy, computing power, storage and communications bandwidth [1]. An important aspect of WSN operation is to know the geolocation of all the sensor nodes – a process known as localization. Automatically determining sensor position after deployment will improve the reporting of origin of events, routing etc. in indoor and outdoor applications, in areas such as environmental monitoring, target tracking and disaster relief operations.

This paper considers the motivating scenario where the sensor nodes are carried by an aircraft and are then dropped and randomly scattered within the sensing region [2]. These nodes are not guaranteed to land the right way up in a known orientation. A node could be upside down. It might be on the ground or at some non-zero elevation. The nodes should be lightweight and rugged enough to minimize the possibility of being damaged during their deployment [3]. The needs of low cost and rugged construction mean that the sensors are unlikely to be equipped with GPS.

Instead, localization will be achieved by using the same aircraft to act as a mobile position beacon. It will be equipped with GPS and will broadcast its position at regular intervals. The aircraft acts as a mobile anchor node. The sensor nodes’ positions are initially unknown, and so they are referred to as blind nodes. The blind nodes’ radios are equipped with RSSI which can be used to estimate their position from the mobile anchor positions. When sufficient beacon messages are received by each blind node from different mobile anchor positions, multilateration can be used by the blind nodes to localize themselves (multilateration is described in more detail below).

Figure 1: Airborne Mobile Anchor is used to localize the blind nodes.

RSSI is an inaccurate distance estimator [4], and errors in distance estimation are worse for larger distances. The accuracy of the multilateration localization also depends on the geometry of the anchor positions, and for this scenario, the geometry is not ideal, since all the anchor positions are in the same half-plane above the blind nodes. Normally, one would expect that using more distance estimates would improve the accuracy of localization, but this is not obviously the case here. The large errors associated with estimates of distance from low RSSI values means that using all readings may
degrade performance. The optimal mobile beacon path for best localization is also an open question.

Given these issues, this paper undertakes some simulation experiments which are designed to answer these main questions:

1. How does the localization accuracy vary with the number of mobile anchor positions used for multilateration?
2. How does the variability of RSSI estimates of distance affect localization accuracy?
3. Does the localization accuracy depend strongly on the position of the mobile anchor points (i.e. on the mobile anchor path)?
4. Is the localization performance significantly improved by adding some fixed anchor points at ground level to improve the multilateration geometry?

II. BACKGROUND

A. Localization Methods

There are many techniques for localization such as beacon based distribution, hybrid localization, interferometry ranging based localization which are discussed in [5]. The comparison of appropriate tools and techniques used in mobile sensor network localization was discussed extensively in [6].

Localization schemes can be grouped into range-free and range-based schemes [7]. Range-free schemes use network connectivity to support coarse node position estimation with simple measurements. Range-free approaches include geometry conjecture, DV hop and centroid. In contrast, range-based schemes are based on estimates of either distance or angle. These schemes require more expensive hardware in their implementation and typically are more accurate than range-free schemes. Techniques use measurements such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA) and Received Signal Strength Indicator (RSSI). Among these metrics, RSSI information is available with most modern radio receivers and this makes it practical to be used in many WSNs. However, RSSI is not a particularly accurate or stable estimator of distance, and this introduces complexity into RSSI-based Localization [4]. In this paper we consider multilateration using RSSI-range based distance estimation, since this gives the best accuracy without significant additional hardware.

Localization in stationary WSNs (where the nodes are not moving) typically uses several static anchor nodes with known position to assist the localization of the static blind nodes (those whose position is not known). Anchor nodes typically are more expensive nodes that self-locate using GPS, and this contributes to higher system cost [8]. Often the self-localizing feature of the anchors is not needed after all blind nodes have been localized. An alternative is to use a self-localizing mobile node which can move through the deployment space and provide many anchor positions during localization, and which can then be reused elsewhere afterwards.

In mobile localization, RSSI-based localization techniques can be categorized as probabilistic and deterministic methods. Deterministic localization provides a simple algorithm with acceptable performance. The range for a specific RSSI reading is taken as the most likely value across many calibration experiments. Probabilistic techniques use more information from the spread of range vs RSSI measurements. For example, ranges with higher errors are given less weight in the calculation of the solution. Despite the fact that probabilistic localization offers superior performance, the computational complexity is a challenge as it requires a higher number of RSSI samples taken per position in the calibration phase [8]. Thus it affects the training time and cost. In probabilistic methods, a Bayesian decision process is used to estimate the most likely position of blind nodes in the sensing area.

For this set of experiments, deterministic multilateration is used, and future work will look at probabilistic localization.

B. Range estimation

Range estimation from RSSI is based on a Log Normal Shadowing model used as parameterized propagation model. Parameters are determined based on experimental measurements at known distances and include probabilistic variations.

The path loss in dB for a given distance, d, (i.e. the RSSI for a 0 dB transmitter) is given by:

\[ PL(d) = PL(d_0) + 10 \cdot n \cdot (\log d/d_0) + VX \cdot \sigma \]  

(1)

Where \( d_0 \) is the reference distance used for the experimental measurement \( PL(d_0) \), \( n \) is the path loss index (depends on environment, typically between 2 and 4), \( \sigma \) is the zero mean Gaussian variable and \( VX \) is the standard deviation of the variations.

Then, given an RSSI path loss, \( PL(dx) \) at unknown distance, \( dx \) can be estimated as:

\[ dx = 10 \cdot \left[ \frac{((PL(dx)) - PL(d_0))}{10 \cdot n} \right] \]  

(2)

Note that RSSI is typically provided as an integer value so there is an additional quantization error introduced. For these experiments, parameters for the CC2420 ZigBee module are used from results published in [9], giving values of \( d_0 \) is 1m, \( PL(d_0) \) is -30.44dB, and \( n \) is 3.567. In [10] typical VX values are around 1.5dB. In these experiments, three different scenarios of RSSI variability are chosen, a low variability scenario with \( VX \) is 1dB, a medium variability scenario with \( VX \) is 2dB and a high variability scenario with \( VX \) is 5dB. Note that the CC2420 has a sensitivity of around -94dB, so values of RSSI less than this value are not detected [11].
C. Deterministic Multilateration

Multilateration is a well-known technique which solves the unknown position of a blind node, \([x, y, z]\) using \(n\) beacons numbered 1..\(n\), at positions \([x_i, y_i, z_i]\) and at estimated distance \(r_i\) from the blind node.

We can define a matrix \(A\) with \(n-1\) rows of the form
\[
\begin{bmatrix}
(x_n - x_i) & (y_n - y_i) & (z_n - z_i)
\end{bmatrix}
\]
(3)

We can define a column range vector, \(r\), with each row of the form
\[
\frac{1}{2}((x_n^2 + y_n^2 - r_n^2) - (x_i^2 + y_i^2 - r_i^2))
\]
(4)

Then we solve for the blind node position
\[
\begin{bmatrix}
x
y
z
\end{bmatrix}^T = \hat{x}
\]
(5)

By solving the matrix equation
\[
A \hat{x} = r
\]
(6)

Giving
\[
\hat{x} = A^+ r
\]
(7)

Where \(A^+\) is the pseudo inverse, \((A^T . A)^{-1} . A^T\)
(8)

If there are more beacons than are required for a solution, the least-square error solution is provided by this method.

III. PERFORMANCE EVALUATION

A. Simulation Setup

Preliminary investigation was carried out to simulate typical localization scenarios as mentioned above. Simulation using Matlab was used to build a statistical model of RSSI versus distance for various scenarios, based on previously published work [9].

Experiments are carried out in a simulated space which is 50m x 50m x 50m. Blind node localization is independent for each node, so the experiments consider there is just one blind node placed on the ground at \(x=25\)m, \(y=25\)m, \(z=0\)m.

This node makes distance estimates to 15 mobile anchor positions based on RSSI from the mobile anchor beacons. For these experiments, it is assumed that the beacon positions are exact. Future work will seek to quantify the beacon position errors caused by GPS. To investigate the effect of different numbers of anchor points on localization accuracy, the best \("N"\) anchor points are chosen, with \(N\) varying from 4 (the minimum needed for a solution) to 15 (total available beacons). For these experiments "best" corresponds to the \(N\) highest RSSI measurements, since smaller RSSI measurements typically give higher range estimate error. For these experiments, the geometry of the chosen \("N"\) beacons is not considered, but this factor will be investigated further in future work.

The following experiments are undertaken.

**Experiment 1:** 15 mobile anchor points are chosen at random in the airspace above the blind node.

**Experiment 2:** 15 mobile anchor points are chosen along a pre-determined flight path which is between 1 and 10 metres above the ground. (Note that any planar flight path, such as constant height, leads to flip ambiguity in localization, so the height is varied). Figure 2 shows the anchor points, and one example of the actual and estimated blind node position.

**Experiment 3:** 4 fixed anchors are placed on the ground at the corners of the area, at positions \((0,0,0), (0,50,0), (50,0,0), (50,50,0)\) and these are used to localize the node at \((25,25,0)\).

**Experiment 4:** The 4 fixed anchors plus the 15 mobile anchors are all used to localize the blind node. The best \(N\) distance estimates out of the total 19 estimates are used. Only the best 15 positions will be shown in the graph.

**Experiment 5:** This repeats experiment 4, but with the blind node in a poor geometrical position. The node is placed outside the 50m x 50m x 50m space at position \((-10,-10,0)\).

Figure 2: Actual and estimated blind node’s location on the ground with designated position of anchor node.

For each individual experiment, a large number of trials are conducted and the average localization error calculated. For experiment 1, each trial chooses different random anchor positions. For the other experiments, the anchor positions are fixed across all trials – the only variability between trials is the RSSI-based distance estimates. It was found that 100 trials were sufficient to get a stable average error.
B. Results

Figure 3(a) shows the results for experiment 1. Anchor positions are chosen randomly in the 50m x 50m x50m space, resulting in many long distances and large RSSI errors. (For high RSSI variability, 15 beacon readings could not be achieved, hence the missing value there). There is no clear pattern to the results.

Figure 3(b) shows the results when a fixed set of 15 anchors below 10 metres in height are chosen. The pattern here is clearer, and is similar for each level of variability. The error is reasonably high for the best 4 anchors, decreases as more anchors are used up until about 13 anchors for RSSI variability of 5dB. The number of anchor increases with high variability, then as additional “poorer” anchors are used, the error increases again. This clearly shows that “more anchors are not always better”. There are a number of anchors that yields the minimum error for a given variability and standard deviation. Compared to Figure 3(a) it also shows that a designated flight path closer to the ground gives better accuracy.

Figure 4 shows the results of experiment 3 with 4 fixed anchors at the corner of the area. Results with 4 fixed anchors are better than the best 4 mobile in figure 3(b) in term of localization error for different RSSI variability. Figure 3(b) shows the localization error of 8 and 18 metre for 1dB and 2dB, while the localization error in Figure 4 reduced at 2.2 and 4.7 metre respectively. This is because the four fixed anchors are better positioned for localizing the blind node which is located in the middle. However the localization error would increase for other layouts.

Figure 5 shows the results of combining the 4 fixed anchors and the 15 dedicated mobile anchors, and choosing the best N results. Only the best 15 anchor’s positions are shown in graph suggesting that the rest of anchor’s positions are impracticable. Also, the result is not much comparable with localization using mobile anchor. Apparently, the optimal number of mobile anchor’s position is 6 to 13 positions while 6 to 14 positions using combination of anchors. However, localization using combination of anchors does not show dramatic changes of error as it is almost similar to mobile anchor for all variability. Thus adding some fixed anchor points at ground level is unnecessary.
Figure 6 compares the results of fixed (4 only), mobile (best 4 to 15) and fixed and mobile (best 4 to 15). 6(a) shows low variability, 6(b) shows medium variability, 6(c) shows high variability results. The error from the combination of anchors is comparable to the case of mobile anchors only, in that it can perform better or worse depending on the geometry.

Figure 7 shows the results when the node is away from the expected sensor space. Due to poor geometry and being only able to reliably see 10 anchor points, error is very high at around 80 metres at high variability for the best four anchor position.

IV. CONCLUSION

From preliminary analysis of RSSI versus distance based on three different scenarios, it can be observed that the localization error varies between these three scenarios.

Random mobile anchor positions gave poor localization accuracy results. A designated, planned flight path gave much better results.

Anchor geometry plays an important part in localization performance, thus the best N (number of anchor’s position) is not necessarily the closest N. For example, using the four fixed anchors alone gives better accuracy than using the “best” four from fixed and mobile anchors. Future work will need to consider choosing anchors based on geometry.

Less variability in RSSI readings obviously gave better results. For the best results the average localization error was about 2m for 1dB variability in RSSI, about 6m for 2dB variability and about 13m for 5dB variability. Thus, it shows that the variability of RSSI estimates the distance will affect the localization accuracy.

The fixed anchor scenario gave better results than the mobile anchors for low variability, most likely because of significantly better geometry; however localization with only fixed anchors was not possible at high RSSI variability. Here, we only considered the fixed anchor in ideal locations, but this not likely in a real scenario where there is no control over the
node locations. Therefore, localization with a mobile anchor is preferred. Somewhat surprisingly, the combined setup of fixed and mobile anchors did not provide any significant improvement in accuracy, due to the combination of poor anchor geometry, suggesting that the mobile anchor beacons are sufficient.

Also somewhat surprisingly, more anchor readings are not necessarily better. The results showed that approximately 6 to 13 anchor readings gives the best compromise between the reduction of errors from more readings and the increase in solution error by including low RSSI values. This suggests more work is needed on how best to combine multiple RSSI readings. Alternatives include the current “best N”, perhaps using all readings above a threshold, perhaps using probabilistic methods to weight readings differently.

REFERENCES


