

Two Practical Considerations of Beacon Deployment for Ultrasound-Based Indoor Localization Systems

Chun-Chieh Hsiao^{*a, d} and Polly Huang^{a, b, c}

^aDepartment of Electrical Engineering

^bGraduate Institute of Communication Engineering

^cGraduate Institute of Networking and Multimedia

National Taiwan University (NTU), Taipei 10617, Taiwan, R.O.C.

^dDepartment of Computer Information and Network Engineering

Lunghwa University of Science and Technology (LHU), Taoyuan 33306, Taiwan, R.O.C.

*d94921013@ntu.edu.tw

Abstract

In this paper, two practical considerations of beacon deployment for ultrasound-based indoor localization systems are presented. In an indoor environment, beacons are deployed incrementally on the ceiling in order to localize the listeners in between the ceiling and the floor. We first propose a water-drop shaped radio model for the beacon to replace commonly assumed spherical radio model in order to provide true coverage of the listeners. Obstacles in the indoor environment are then considered to take into account the line-of-sight restrictions and thus to enable practical beacon deployment. Although when taking into these two considerations, the number of deployed beacons required tends to be high, it would otherwise be impossible to provide true coverage of the listeners in the indoor environment utilizing ultrasound-based localization.

1. Introduction

Indoor localization has become more important as many applications such as asset tracking, virtual presence, and smart space [1] [2] [3] emerge. There are two types of radios commonly used for localization in indoor environments, namely radio frequency (RF) and ultrasound. Though RF is the more popular media for localization in indoor environments, its localization precision is usually poor. Ultrasound can provide higher localization precision. It, however, suffers from the line-of-sight restrictions. Beacon placement thus becomes challenging for ultrasound-based indoor localization in environments with various obstacles such as desks and chairs.

Another essential problem in beacon placement is coverage, i.e., localization of every target in the

environment. There are two common assumptions when beacon deployment algorithms are devised: (1) a spherical radio model for the sensing range and (2) free space for the deployment environment.

Replacing the spherical model with a realistic radio model for the ultrasound sensor and adopting a heuristic based on [4], we find the deployment plan turns out very different in both the number of beacon required, as well as the placement, in a case study where room BL-621 in our department building is measured.

Furthermore, we take into consideration the furniture and other obstacles in BL-621. The deployment algorithm is extended and the resulting deployment plan is even more different. Depending on the height of the tracking target, the number of beacon required to cover the room decreases with the height. In particular, the amount decreases from 157 to 67 as the height increases from 0 cm to 150 cm.

This paper is organized as follows. Section 2 describes the base-line algorithm used for beacon deployment. The extension of the algorithm by utilizing the realistic ultrasound model is demonstrated in Section 3. Section 4 describes how the algorithm is further extended to take into account the obstacles in the environment. Finally, in Section 5, we conclude our work.

2. Ultrasound-based Indoor Localization

2.1 Localization Using Trilateration

In this paper, sensor nodes with beacons in an indoor environment are deployed on the ceiling to provide accurate 3D positions of the sensor nodes (listeners) that can move around in the indoor environment in between the floor and the ceiling. A

beacon on the ceiling can simultaneously transmit RF and ultrasound signals to the listener as in [5]. Since the transmitted RF signal propagates at the speed of light in the air ($\approx 3 \times 10^8$ m/s), it arrives almost immediately at the listener. The transmitted ultrasound signal will arrive at the listener much later since it has to propagate in the air at the speed of sound (≈ 346 m/s with a temperature of 25°C in dry air). The time difference of the arrival times for the transmitted RF and ultrasound signals is thus approximately equal to the propagation time of the transmitted ultrasound signal. The listener can then derive the distance from the beacon by multiplying the ultrasound propagation time by the speed of sound. Since the location of the beacon is known when the beacon was deployed, the listener must be located at the surface of a sphere that is centered at the beacon and with a radius of the derived distance from the beacon to the listener. In 2D, distances from three beacons with known locations are needed to derive the listener's location as shown in Figure 1. The process in which the location of a listener is determined by utilizing the information of the beacon's known locations and the distances from the beacons to the listener is called *trilateration*.

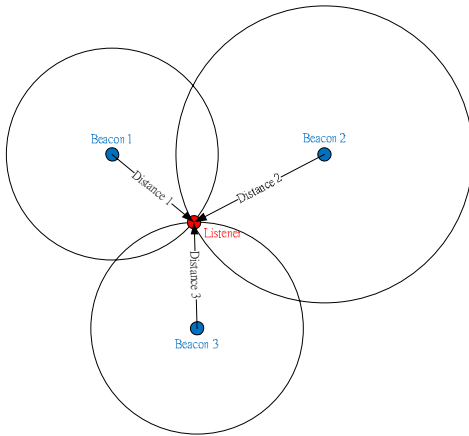


Figure 1. Demonstration of trilateration.

In 3D, the actual position of the listener can be derived with distances from at least four beacons. However since the listener can only be located below the ceiling, distances from three beacons would be sufficient to calculate the listener's location.

2.2 Heuristic for Beacon Deployment

In this paper, our goal is to deploy the least number of beacons to locate the listeners so as to achieve minimal system cost. For the deployment of beacons, we used an algorithm similar to the one used in [4]. The pseudo code of our algorithm is as shown in Figure 2.

Algorithm 1. Beacon Deployment Algorithm

```

for each candidate beacon
    calculate its initial  $N_p$ 
set the coverage of each potential listener to be 0
put all candidate beacons in a list  $L_{cb}$ 
until the coverage of all potential listeners are at least 3
    sort  $L_{cb}$  with  $N_p$  in a non-increasing order
    select and delete a beacon from the head of the sorted  $L_{cb}$ 
    update the coverage of the potential listeners that are covered by the selected beacon
    update the  $N_p$  in the  $L_{cb}$ 
output deployed positions of the selected beacons

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Figure 2. Beacon deployment algorithm.

In the beacon deployment algorithm the beacons are deployed progressively to provide at least 3-coverage of each listener. By 3-coverage of a listener, we mean that the listener is within radio range of three beacons, or in other words, the listener is covered by three beacons. In the literature [4] [6], a spherical model is usually used to represent the radio range of a radio transmitter (a beacon in our case). All the candidate beacons are assumed to be located at the grid points in a predefined grid. All the potential listeners are also assumed to be located at the grid points in another predefined grid. For each of the candidate beacon, its initial popularity N_p , the number of potential listeners that are within the candidate beacon's radio range and are not yet of 3-coverage, is first calculated. Then, each time a candidate beacon is selected if it has the greatest number of N_p . The deployment or selection process proceeds progressively and terminates when all listeners are at least of 3-coverage.



Figure 3. A photo of our lab BL-621 in NTU BL Building.

2.3 Case Study

As an example, we take one of our labs, BL-621 as shown in Figure 3, as the test environment. The dimension of this lab is $648 \text{ cm} \times 569 \text{ cm} \times 254 \text{ cm}$. In this example, the potential listeners are assumed to be located on the 10-cm grid on the floor and the candidate beacons are located on the 30×30 grid on the

ceiling. With a spherical model of 5-m radio range, the deployed beacons would be as shown in Figure 4.

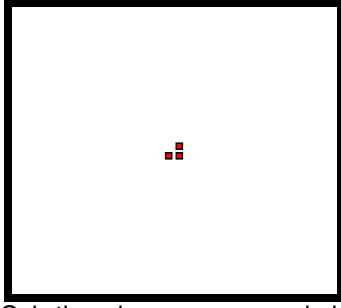


Figure 4. Only three beacons are needed for our lab using a spherical model with radio range of 5 meters.

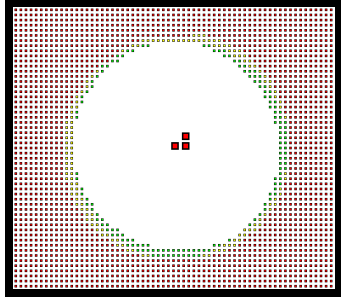


Figure 5. The uncovered listeners are shown as green, yellow and red respectively when they are covered by only 2, 1, and 0 beacons respectively.

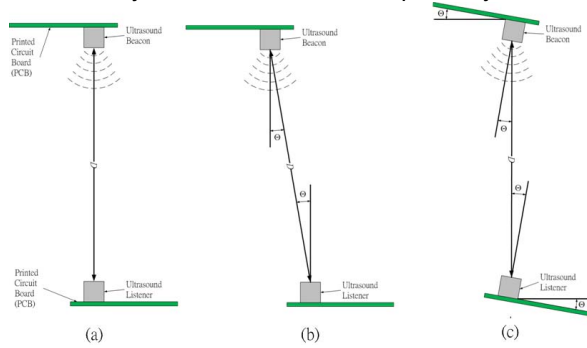


Figure 6. (a) Initial placement of an ultrasound beacon and an ultrasound listener facing each other with a distance D (b) Move the ultrasound listener such that the distance remains D however the angle between the normal direction of the PCB and the line connecting the beacon and the listener is Θ (c) The equivalent of (b) with rotation only.

However after deploying the beacons in the lab, we find that many listeners cannot be localized because they are actually not covered by at least three beacons. The uncovered listeners are as shown in Figure 5. The percentage of total covered listeners is only about 40%. The reason why around 60% of listeners are not covered is that the spherical model we use is too idealistic. The radio range of the ultrasound beacons is rather far from being spherical. A more realistic model

is thus proposed in the next section to overcome this problem.

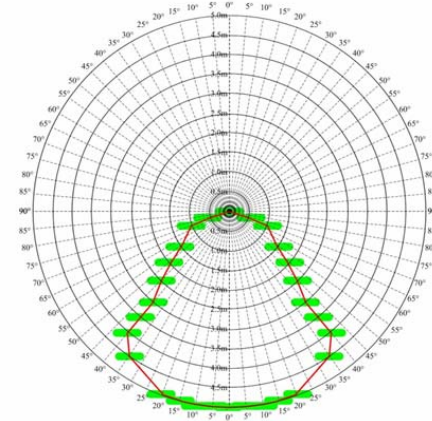


Figure 7. Directional model of ultrasound transmission.

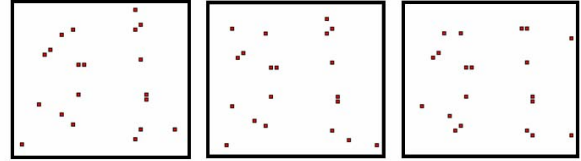


Figure 8. 20 beacons are deployed in three different runs using modified beacon deployment algorithm with water-drop model to provide 3-coverage for each listener.

3. Water-Drop Radiation Model

3.1 Field Measurement of Water-Drop Radiation Model

In the field measurement, initially an ultrasound beacon and an ultrasound listener are placed facing each other with a distance D as shown in Figure 6 (a) to check whether the listener can derive the distance D . The listener is then moved such that the distance between the beacon and the listener remains the same however the angle between the normal direction of the PCB and the line connecting the beacon and the listener is Θ as shown in Figure 6 (b). The same check as in (a) is performed to see whether the listener can derive the distance D . For the ease of measurement, the configuration of the listener and the beacon in Figure 6 (c) is used instead of (b). In Figure 6 (c), both the beacon and the listener only need to rotate with an angle Θ and do not have to move any more. By the results of our field measurement, we have observed that the ultrasound transmission is highly directional as shown in Figure 7. Only when the listener is inside the water-drop shaped area enclosed by the solid line can the listener derive distance measurement value from the beacon.

3.2 Case Study Revisited

Due to the directional model of ultrasound transmission, it is thus necessary to modify the radiation model used in our beacon deployment algorithm to utilize water-drop shaped model instead of spherical model. Algorithm 1 in section 2.1 is modified accordingly. In particular, for the calculation and the update of popularity N_p , we substitute the spherical model with the water-drop model based on our measurement. By applying the modified beacon deployment algorithm in the same test environment as in section 2.1, the number of beacons required increases to 20, as opposed to the 3 beacons derived using the naïve spherical model. Three sampled beacon deployments with 20 beacons using realistic water-drop shaped model are as shown in Figure 8. In all three deployments, every listener can be covered by at least three beacons and can thus be localized. When a more realistic radiation is considered, a significantly higher number of beacons are needed to provide true full coverage of localization to the listeners. In addition, when we compare the deployments in Figure 8 and Figure 4, there is a substantial amount of beacons needed to cover the corners and borders in the space.

3.3 Scaling Property

We examine further with the beacon deployment required for spaces with different sizes. This will allow us to observe how the beacon requirement scales to the size of the deployment space. Considering square-shape space, we start from a space with 5 meters in width, 5 meters in length, and 2.54 meters in height. The area of the space is then increased from 25 square meters incrementally to 250 square meters. The deployment results are as shown in Figure 9 in which results of the original beacon deployment algorithm are included for comparison. As can be observed in Figure 9, using either the spherical or the water-drop model, the number of beacons required increases as the size of the deployment space. However, the growth rate in the water-drop case is significantly higher than that in the spherical case. This demonstrates the limitation of the spherical model. Deployment algorithms assuming the spherical model not only under-estimate the number of beacons required in practice. The discrepancy grows larger as the size of the deployment space.

The squared area in the smallest space is of 25 m² and is formed by a 5 m by 5 m square. The squared area in the largest space is of 250 m² and is formed by a 15.8 m by 15.8 m square.

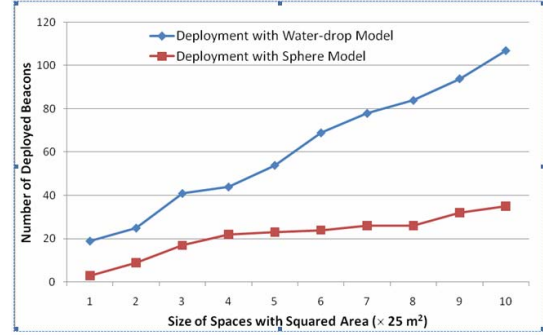


Figure 9. Number of deployed beacons using beacon deployment algorithms with water-drop model and sphere model versus size of spaces with squared area.

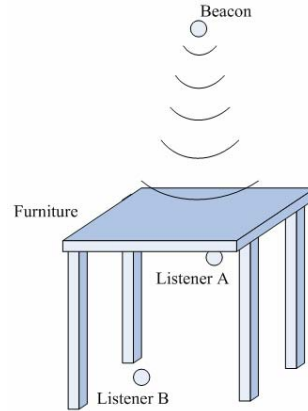


Figure 10. Ultrasound signal blocked by a piece of furniture. Both listeners A and B cannot receive ultrasound signal from the beacon due to line-of-sight constraint.

4. Obstacles

4.1 Problems with Obstacles

When beacon deployment is derived using the algorithm in section 3 with water-drop model, another problem emerges when the beacons are deployed in a room with furniture such as desks and chairs inside. Since the ultrasound wave from a beacon can be blocked by the furniture (obstacles) due to line-of-sight constraints as shown in Figure 10, some listeners can no longer receive the ultrasonic signal from this beacon even though the listeners are within radio range of this beacon. If too many ultrasonic signals are blocked by the obstacles in the environment, it is easy for a listener to receive less than 3 ultrasonic signals such that this listener can no longer be localizable.

4.2 Solutions

To overcome the problem of ultrasonic signals being blocked by the obstacles in the environment, the obstacles in the environment should be taken into consideration in the deployment planning process, i.e.

the coverage area should be calculated with the obstacles in place when selecting the candidate beacons. To take into account the effect of the obstacles, a 3D modeling tool, Autodesk 3ds Max, is used to construct the 3D model of the indoor environment along with the obstacles. Take one of our labs in NTU, BL-621 as shown in Figure 3, as an example; its constructed 3D model is as shown in Figure 11.

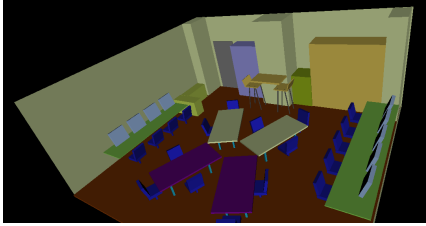


Figure 11. 3D model of one of our labs in NTU, BL-621 constructed using Autodesk 3ds Max.

After the 3D model of the indoor environment with obstacles is built, it is used to calculate the list of listeners that are actually covered by each candidate beacon. The list of listeners visible to a candidate beacon is referred to as the beacon's covering list (L_{cov}). The L_{cov} 's are used to calculate N_p in the beacon deployment algorithm.

To obtain L_{cov} 's, all the listeners within the radio range of each candidate beacon are first included in the candidate beacon's L_{cov} . Then a line is drawn between the beacon and each of the listeners in the beacon's L_{cov} 's to test whether the line intersects any obstacle in the indoor environment. If the line intersects with any of the obstacles, the ultrasound signals transmitted by the beacon will be blocked by that obstacle and the listener will no longer be able to receive the ultrasound signals. The corresponding listener will be thus excluded from the candidate beacon's L_{cov} . After all the listeners are tested, only the listeners remain in the L_{cov} will receive the ultrasound signals from the candidate beacon and can thus derive the distance from the beacon. A further check is necessary to see whether each of all listeners appears in at least three L_{cov} 's. If any listener fails to appear in at least three L_{cov} 's, it means that this listener cannot receive signals from at least three candidate beacons and thus cannot be localized. This listener will then be marked and deleted from all the L_{cov} 's. After the preprocessing stage, the selection of the candidate beacons can proceed as before until all the unmarked listeners can receive signals from at least three beacons.

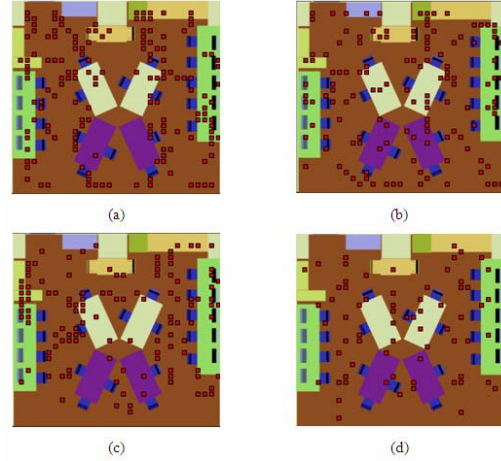


Figure 12. Beacon deployment with consideration of obstacles and with listeners at different height: (a) 157 beacons for listeners at height of 0 cm (on the floor); (b) 131 beacons for listeners at height of 45 cm (around knees); (c) 121 beacons for listeners at height of 100 cm (around waist); (d) 67 beacons for listeners at height of 150 cm (around shoulder).

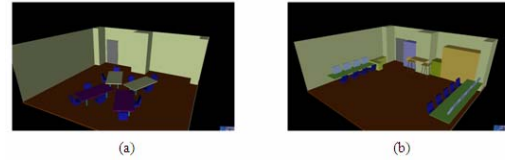


Figure 13. (a) Furniture in the center area only (b) Furniture in the surrounding area only.

4.3 Case Study Revisited

The results of beacon deployment considering obstacles in the same indoor environment used in section 2 and 3, namely BL-621, and considering listeners at different height are as shown in Figure 12. As can be seen in Figure 12, the number of beacons is significantly larger than the one in Figure 8 in order to compensate the ultrasound signals that are blocked by the obstacles. The number of deployed beacons for listeners at height of 0 cm, 45 cm, 100 cm, and 150 cm are 127, 111, 101, and 47 more than the one needed for the same environment without obstacles in Figure 8 respectively. The percentages of the potential listeners at height of 0 cm, 45 cm, 100 cm, and 150 cm that are not covered by the corresponding deployed beacons are 6%, 26%, 3% and 3% respectively. The reason of the huge number of uncovered listeners at height of 45 cm is that when the listener is right under the tables at that height like the listener A in Figure 10 it would be very difficult if not impossible for any beacon's ultrasound signal to reach that listener. Consequently, that listener is unlikely to be localized since it cannot receive ultrasound signals from more than three beacons.

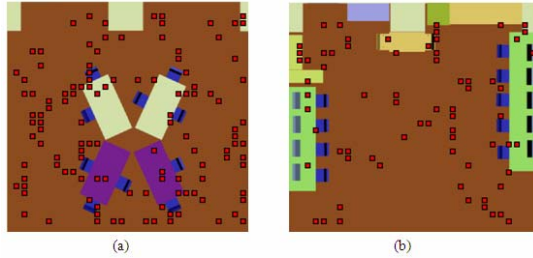


Figure 14. Beacon deployment when furniture is present in (a) the center area (b) the surrounding area.

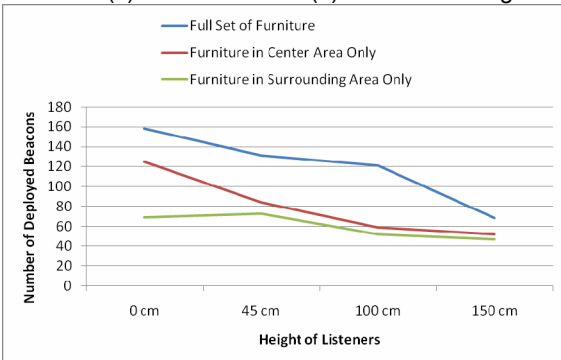


Figure 15. Number of deployed beacons for different sets of furniture.

4.4 Effect of Furniture Distribution

Two more indoor environments with different setting of furniture as shown in Figure 13 are examined further to observe how the location of the furniture in the environment affects the beacon deployment plan. The deployments for environments with two different furniture settings when the listeners are at the height of 0 cm are shown in Figure 14. As can be seen in Figure 14, when only the centered/surrounding furniture is present, the beacons tend to be deployed toward the surrounding/center to avoid the obstacles. The numbers of deployed beacons for different sets of furniture including full set of furniture are as shown in Figure 15. As can be observed in Figure 15, the obstacles in the center area affect more than the ones in the surrounding area especially when the height of the listeners is low.

5. Conclusions

Radio model and environmental obstacles play a critical role in determining how many and where to place the beacons for localization. Using a realistic radio model, we discover that (1) more beacons are needed to provide full coverage of the listeners since the covering space of an ultrasound transmitter is smaller than a perfect sphere and (2) the number of required beacons grows linearly with the size of the

space. Taking into consideration of the obstacles, we find that (1) many more beacons are needed to localize the listeners since the ultrasound signals can be blocked by the obstacles in the environment, (2) the requirement of beacons grows about inversely proportionally with the height of the listeners since when the listener is higher the less effect the obstacles will have to block the ultrasound signal from beacons, and (3) the placement of the obstacles have significant impact on the beacon deployment especially when the listener is lower. The cost of deploying for a smart, interactive room is approximately US\$ 7,000 in order to locate listeners at height of 150 cm, around the height of one's shoulder, in our lab BL-621 with full set of furniture when an about US\$ 100 sensor node is used as a beacon or a listener.

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