Combining Range-Based and Range-Free Methods: A Unified Approach for Localization

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ABSTRACT

Localization schemes used for positioning are currently based on either range-based or range-free principles. We propose a unified approach that combines the strengths of both methods while overcoming their limitations. Range-based methods rely on taking reliable measurements in which geometric techniques are then applied. These techniques are very susceptible to imprecision in captured measurements. Range-free methods do not consider the actual numerical sensor value, rather comparing magnitudes across sensors. These comparisons are not always reliable and may lead to an accumulation of errors. Our unified approach mitigates these effects by first using a range-based method to determine an approximate location followed by a range-free method to refine the positioning estimate further. Our experiments show the mean estimation error improves when applying our localization scheme to a Bluetooth system.

Keywords

Localization; Indoor Positioning

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols

1. INTRODUCTION

Positioning mobile devices in a wireless sensor network requires advanced localization schemes. Current principles are either range-based or range-free. Neither method in isolation provides a general solution that works well in a wide range of scenarios, especially for indoor settings. Common estimation techniques make use of trilateration, triangulation, fingerprinting and proximity [10].

Range-based methods are capable of achieving fine-grained precision. Distances are estimated using signal propagation models or timing methods. Assumptions are made about the environment in which they operate, thus they generally do not generalize well in dynamic environments. Range-free techniques make no assumptions that such information is available or valid. Binary decisions are used, e.g. is a user in range or is a user within a triangle. While range-free methods are robust, they are considered coarse-grained as the level of granularity they provide is bounded by the geometry formed. Consider the scenario presented in Figure 1a. The actual distances between the user node and beacons is $2m$, $5m$, $2m$ respectively, however using a signal propagation model the estimated distance calculated is $1m$, $4m$, $3m$. Based off the signal strengths, these beacons are most likely to be the closest and surround the node. Due to high sensitivity of the models, we do not assume the calculated position is accurate.

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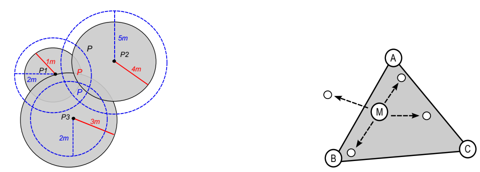


(a) Trilateration **(b) APIT InToOut Case**

Figure 1: Potential Issues Range-Based and Range-Free Methods Encounter

Range-free methods make use of information from neighboring nodes for localization. Approximate Point In Triangle Test (APIT) [9] overlays a geometry of triangles by joining location beacons. The key idea is to be inside or outside a triangle, the test is performed through a comparison of signal strengths of the received signals. Through a process of APIT aggregation, the position is estimated to be at the center of gravity of the triangles. This method is not without limitations, consider the scenario presented in Figure 1b. The scheme estimates incorrectly that the node is outside the triangle. This often occurs in cases when a node is close to the edges. When many neighboring nodes are clustered in one area, this will also cause a bias. In larger spaces, APIT tends to favor where nodes are more central as error accumulates.

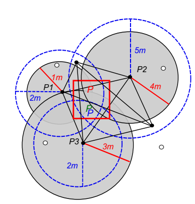


Figure 2: Combining Range-Based and Range-Free Method

In our unified approach, a bounding box is placed using the approximate location obtained by the range-based method as the center. Refinement is then achieved via APIT which can lead to a significant reduction of error. Consider the case presented in Figure 2, trilateration results in a position being above the actual position, a bounding box surrounds this point. Triangles are generated using location beacons, APIT is restricted to the search space within the bounding box which results in a refined position closer to the actual position. This does not necessarily work as well in reverse because range-free methods are susceptible to accumulation errors in large spaces.

To evaluate our approach, we developed a Bluetooth simulator. The ubiquity of Bluetooth makes it suitable for use in indoor positioning systems. Our results indicate we can achieve higher positioning accuracy when using our unified approach as opposed to when using either a range-based method or range-free method in isolation.

Our main contributions are as follows:

- Propose a unified approach to localization making use of both range-based and range-free methods;
- Provide an algorithm demonstrating the effectiveness of a unified approach;
- Demonstrate that our technique can achieve accuracies of under $1m$.

2. RELATED WORK

Localization is considered an important problem in which many techniques have been proposed. Current methods can be classified as either range-based or range-free. Recent research has focused on applying schemes in an indoor setting [8].

2.1 Range-Based Methods

Range-based methods consist of two phases, the ranging phase and the estimation phase. In the ranging phase, measurements are taken to estimate distance from sensors of known locations. The proceeding estimation phase uses the captured measurements and applies geometric techniques to estimate a position. Models based of the Received Signal Strength Indicator (RSSI) of a sensor can be used to measure distance. However due to issues relating to signal propergation, more robust timing methods including Time of Arrival (ToA) and Time Difference on Arrival (TDoA) can be alternatively used to measure distance.

In ToA, the one-way propagation time is measured, given the speed the signal travels is known, the distance can be then calculated. Geometric techniques including trilateration can then be performed. TDoA uses stations of known locations that broadcast at known times. The difference in distance is measured resulting in a number of locations forming a hyperbolic curve. Taking measurements from a second station combination will produce a second curve which intersects the first. A small number of possible locations are revealed producing a fix. Angle of Arrival methods (AoA) measure the angle between a node and location beacons. Directional antennas or an array of antennas are required. The angle the positioning device makes between two location beacons is measured, by using this angle to form two lines, the position is the intersection of these lines.

Small errors in measurements such as distance and time leads to the estimation accuracy dropping off rapidly. While range-based methods are considered to be a fine-grained method to localization, in the case of our unified approach that is intended for indoor scenarios, we use it to gain an approximate of where a user is located.

2.2 Range-Free Methods

Technique	Accuracy	Robustness	Scalability	Cost
Range-based	High	Low	High	Medium
Range-free	Medium	High	Low	Medium
Fingerprinting	Medium	High	Medium	High
Cellular	Low	High	High	Low

Table 1: Comparison of Different IPS Localization Schemes

Range-free methods make little to no assumptions about the environment in which they operate and rely upon error reducing methods such as aggregation. Well known range-free schemes proposed include Centroid [3], DV-HOP [13] and Amorphous [12] and APIT[9] which will be described in detail in Section 3.1.

Centroid works under the assumption coarse grained localization information is available from location beacons. The centroid of all the received location beacons in an area is then taken and used as the location estimate [3]. The authors found this method to work well outdoors with the mean estimation error never exceeded $2m$. In indoor settings, the performance accuracies range greatly between $4.6m$ to $22.3m$.

The DV-HOP and Amorphous algorithms share similarities borrowing from principles in classical distance vector routing. Broadcasts are sent throughout the network outwards scanning for location beacons. Nearby nodes that receive broadcasts track the hop-count in a table, increment it and forward it to surrounding nodes. Hop-count is then translated to physical distance. While DV-Hop uses the average single hop distance, Amorphous uses the Kleinrock and Slivester formula [11]. The final step performs trilateration to estimate a node's location.

Range-free methods are considered to be a robust coarse-grained approach, however in our unified-approach we use range-free methods to refine a position further.

2.3 Indoor Positioning Systems

Indoor Positioning Systems (IPS) aim to provide positioning and tracking of mobile devices or persons. A solution that is accurate, robust, scalable and cost effective is required for mainstream adoption. Table 1 compares different localization schemes across these criteria. In free space, radio multipath models work well in determining distance. This does not usually generalize to indoor situations except for in controlled settings [14] due to severe multipath propagation and signal attenuation caused by various objects.

Early work focused on centralized approaches that built upon client-server architecture [1, 6]. Computer workstations and bluetooth adaptors have been used as location beacons. The beacons constantly scan for mobile devices and readings are sent to a server for processing. Trilateration via RSSI has been demonstrated in [4] using values received from location beacons to locate a user holding a Bluetooth enabled device. Fingerprinting techniques take advantage of modern sensors being able to access online resources in order to compare and store readings. Microsoft RADAR [2] makes use of WLan technology and uses fingerprinting methods. RADAR creates a radio map of all access points in an area and corresponding signal strengths. Captured samples are compared to those on a radio map using a *kNN* Viterbi-like algorithm.

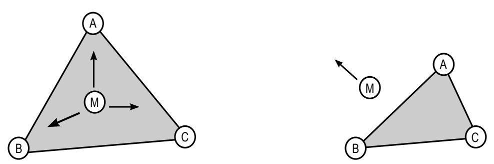
Inspired by cellular routing techniques, indoor positioning has also been achieved by placing beacons in non-overlapping locations [5]. Tadley Systems developed an IPS called Topaz combining the strengths of both Bluetooth and Infrared (IR). Bluetooth is used to determine what room a user is in using a proximity detection algorithm then Infrared determines the position within the room. Another system provided by indoo.rs uses iBeacon and has been demonstrated to work for large scale IPS.

3. PROBLEM STATEMENT

The position of a node n in space needs to be determined through the use of a localization scheme that makes use of available information. Audible location beacons are a special case in which their location is known and provide location information to querying nodes. For example a location beacon may advertise its (X,Y) position to all nodes in range. Neighboring nodes surround n, however their location is not known. Signal strength relative to n and audible location beacons is known. The localization scheme is required to utilize information provided by both surrounding neighbor nodes and audible location beacons to improve estimation accuracy.

3.1 APIT

APIT was designed to perform well when radio patterns are irregular and nodes are placed randomly. Given three location beacons are present: A, B, C, the aim is to determine whether a point M with an unknown position is inside the triangle $\triangle ABC$ or not. The perfect Point in Triangle Test (PIT) provides a theoretical solution to this problem.



(a) Proposition I **(b) Proposition II**

Figure 3: P.I.T Propositions

Propositon I states if M is inside triangle $\triangle ABC$, when M is shifted in any direction, the new position must be nearer to (further from) at least one anchor A, B or C (Figure 5a). Propositon I states If M is outside triangle $\triangle ABC$, when M is shifted, there must exist a direction in which the position of M is further from or closer to all three anchors A, B and C (Figure 5b).

The issue arising from this solution is that the movement of nodes is required and is infeasible to implement. The APIT algorithm approximates the PIT test without requiring any node movement. The departure test is run on each neighbor to determine if M is further away from an anchor than a neighbor. APIT is formally defined as follows: If no neighbor of M is further from/closer to all three anchors A, B and C simultaneously, M assumes that it is inside triangle $\triangle ABC$. Otherwise, M assumes it resides outside this triangle.

APIT runs on every combination of triangles formed via location beacons. APIT aggregation is then run by using a grid SCAN algorithm, each grid cell is incremented or decremented based on whether an intersecting triangle passes or fails the APIT test. The center of gravity of the grid area that has the maximum values is the location estimate.

3.2 Mean Estimation Error

To measure accuracy, the estimation error is calculated by taking the Euclidean distance between the actual user position and the estimated position. Accuracy can vary depending on position, to account for this multiple measurements are taken to determine the mean estimation error (MSE). i is the sample index and n the number of samples taken in a setting.

$$MeanEstimationError = \sum_{i=1}^{n} EstimationError_i / n$$

4. OUR UNIFIED APPROACH

The unified approach we propose makes use of the range-based trilateration using signal magnitudes to calculate distances combined with the range-free APIT algorithm [9] which is used for further refinement.

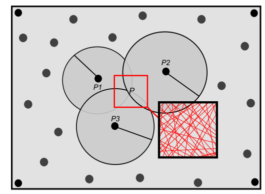


Figure 4: Unified Approach

Initially the three closest beacons are determined using the signal magnitudes. Distance estimates are calculated to each of these three location beacons via a signal propagation model. In the case presented in Figure 4, the location beacons are $P1$, $P2$, $P3$. The node the algorithm is attempting to position is assumed to be somewhere within these beacons, the position need to be narrowed down further.

Trilateration is performed using these estimates. It can be seen that these circles intersect at a point, the center of gravity of the intersection is considered the location estimate. The resulting location from the trilateration is used as the center point to create a bounding box Bm which is indicated by the red box. It is assumed that the location estimate could be refined further within the bounding box

The APIT algorithm is applied to the entire scene. For each formed triangle, it is determined whether the node that needs to be positioned is inside or outside each triangle. A grid is then overlaid on top of the scene for which APIT aggregation is run. Triangles within the red bounding box are clipped using the Sutherland-Hodgman algorithm [15], resulting in a list of polygons. Triangle edges terminate at the edge of the box. All polygons inside the bounding box that intersect with any grid cell with the maximum SCAN index value are taken and the intersection between these polygons is found.

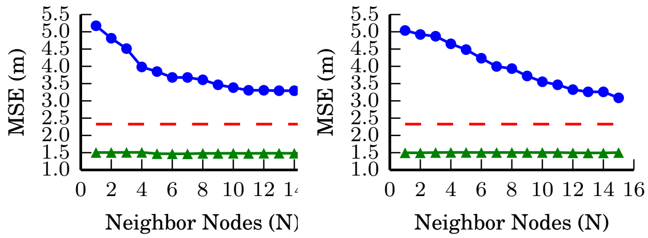
The center of gravity of the resulting polygon is used as the new refined positioning estimate.This has the effect of refining the initial position obtained by the range-based to be closer to the actual user position using information provided by surrounding neighboring nodes.

5. EXPERIMENTS

To evaluate our approach, we developed a Bluetooth simulator in Java for the purposes of testing and comparing different localization schemes. The simulator allows for Bluetooth location beacons and Bluetooth nodes to be placed arbitrary in a room.

5.1 Indoor Scenario

The indoor scenario we considered for testing was to position a node in a $10m$ x $10m$ room. This a good candidate room size as many Bluetooth devices have a maximum range of $10m$. Roms in



(a) Random Placement **(b) Uniform Placement**

Figure 5: Performance of Localization Schemes

indoor settings rarely have an area larger than $10m^2$ unless considering larger floor spaces like hall ways and office spaces. In these cases additional location beacons can be deployed. In the indoor setting we tested, 100 location estimates are captured across the entire $10m$ x $10m$ space effectively covering every position a user can stand in a room.

5.2 Location Beacon and Node Placement

Four real beacons were placed in the corners of the room. The ubiquity of mobile smart phones makes it realistic to consider that there would be devices nearby that could be used for refinement by a range-free component. In our experiments, we increased the neighboring nodes from 1 to 15 and test if an increase leads to better positioning accuracies. Two configurations for placing neighboring Bluetooth nodes surrounding the user Bluetooth node is considered. Random placement and Uniform placement.

5.3 Signal Strength Simulation

For each Bluetooth node, perceived RSSI values are calculated for each location beacon that can be sensed via the path loss equation by setting the distance value to be the Euclidean distance between the location beacon and the respective node. To add some interference, the propagation constant was set to $n = 2.2$. As evidenced in ZigBee wireless networks and transceivers [7], this propagation constant represents what would occur in a retail store. This simulates what happens in real scenarios where signal attenuation occurs due to various objects in a room.

Through experimental evaluation of multiple real Bluetooth devices, we found the RSSI value tends to be -51 when placed $1m$ from one another. Thus, $RSSI_0 = -51$ was set in the simulator when calculating RSSI based off path-loss. When taking range-based estimations, the localization algorithm assumes $n = 2.0$ as the exact environment in which we are operating is not known.

5.4 Evaluation

In our evaluation we tested RSSI Trilateration and APIT in isolation and compared the accuracy achieved to our proposed unified approach. the difference in performance. It can be seen in Figure **??** and Figure **??** that the unified approach performed better than when using either RSSI Trilateration or APIT in isolation. The red dashed line indicates RSSI Trilateration, because neighboring nodes and virtual beacons are not considered by this method, it always produces a consistent MSE of $2.30m$ in every case. Our unified approach achieves a MSE of just under $1m$ in some cases.

Increasing neighboring nodes leads to improved performance in a logarithmic like trend when only using APIT. However in the Unified approach the effect of increasing nodes is negligible. This is because the bounding box restricts the search space to the point where looking at just one neighbor node is enough to refine within the box further. Our results suggest, there only needs to be at least 1 neighbor distributed around the room to achieve high accuracy.

6. CONCLUSIONS AND FUTURE WORKS

In this paper, we proposed a unified approach to localization. The key contribution of this work is combining a normally considered fine-grained range-based methods to get a rough estimate with a course-grained method to refine further within smaller search space can improve positioning results. Our experimental results indicate that using our unified approach produces more accurate location estimates than when using either approach in isolation.

At present we are in the process of implementing our IPS based on our proposed unified localization scheme on top of the Android platform and will be evaluated by taking location estimates at known locations and comparing where the IPS estimates the user to be. In future work we plan on working on an algorithm to determine the optimal configuration of beacons in larger spaces when using our localization scheme.

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