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Lighthouse: Accurate 802.11 Localization using Directional Beacon Fingerprinting

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Abstract—In this paper, we propose a novel method for indoor location estimation using an unmodified Mobile Device (MD) in an IEEE 802.11 Wireless Local Area Network. In this method, Directional Beaconing is combined with Fingerprinting whereby the WiFi Access Points (APs) transmit narrow beam width signals at a small number of fixed Direction Of Emissions (DOEs) and the MD records the Received Signal Strength Indicator (RSSI) for all in-range APs and all DOEs. These observations give a DOE-RSSI signature at the MD for each AP. The location of the MD is determined using a K-Nearest Neighbor algorithm which finds the best matching DOE-RSSI signature in a pre-stored map. The method improves on previous omnidirectional Fingerprinting methods by increasing the number of RSSI maps available per AP. A testbed network was deployed in an office building and its performance was evaluated. The results show a reduction in mean location error from 2.87 m to 1.64 m (43% improvement) for the proposed method compared with conventional omnidirectional RSSI fingerprinting, when using 3 APs in a positioning space of 12 m by 13.5 m.

Index Terms—indoor localization, WLAN, IEEE 802.11, WiFi, positioning, direction of emission, location estimation.

1 Introduction

The extensive use of Mobile Devices (MDs) such as smart phones, tablets and laptops, has increased demand for Location Based Services, such as pedestrian navigation, user tracking and location-enhanced user communication. The Global Positioning System (GPS) [1] is used extensively outdoors but fails indoors due to attenuation of the Radio Frequency (RF) signals by the building fabric. RF-based positioning indoors has proven to be challenging due to tight cost requirements, signal attenuation with distance, non line of sight events and multipath. High accuracy indoor positioning has been demonstrated using ultra wide band and ultrasonic systems [2], [3]. However, these systems require special hardware in the MD and are not currently widely deployed.

In contrast, devices supporting IEEE 802.11 Wireless Local Area Network (WLAN or WiFi) transceivers are common in indoor environments. As a consequence, much research has been conducted on determining indoor location using WiFi signals [4]. A popular approach is to locate a MD by recording the Received Signal Strength Indicator (RSSI) for all in-range Access Points (APs) and using this vector (or fingerprint) of RSSI measurements to find the best matching location in a pre-stored map [5]. This approach has the advantage that all standards compliant 802.11 devices make their RSSI readings available at the application layer. However, to date, the accuracy of these methods has been limited by the nature of the RSSI signature, which is normally slowly varying with distance and can be ambiguous (i.e. similar signatures are observed in different places) [6].

Recently, researchers have proposed increased use of physical layer information to enhance positioning accuracy. In [7] and [8], Channel State Information (CSI) was obtained from a 802.11 card and used as an enhanced signature for localization. However, access to CSI information at the application layer is not mandated by the standard and is only supported on a small number of cards.

Researchers have also investigated use of directional (or angle) information for indoor positioning. Direction Of Arrival (DOA) methods seek to estimate the bearing angle of the MD or AP based on the angle of signal arrival corresponding to maximum RF power. ArrayTrack [9] estimates the DOA of the signal from the MD at the AP using an antenna array. SpinLoc [10] relies on the MD user's body to partially block the RF signal and effectively create a directional antenna. The user rotates their body to obtain a profile of varying RSSI with orientation. While illustrating the potential for using directionality in a location system, the requirement to rotate the body is not satisfactory in many applications.

Directional Beaconing (DB) methods [11], [12], [13], [14] are based on control of the Direction Of Emission (DOE) of the RF signal. DB methods sweep a narrow RF beam from an AP over the signalling space. The MD detects the timing of maximum received signal strength. The DOE at the time of the maximum received signal strength is then associated with the bearing angle of the MD from the AP. In experiments, the beam is often rotated mechanically. However, DOE control can be achieved electronically by beamsteering at an antenna array [15].

The difficulty with most previous DOA and DOE based location techniques is that they seek to associate the peak received signal strength with the bearing angle between the AP and MD. This assumption is valid in free-space but leads to significant angulation errors in environments with strong multi path components, such as indoors. One research group considered the use of DB with signal strength matching to circumvent this problem [16], [17]. The work focused on ray tracing-based simulation studies for a single point using a 2.4 GHz beamforming model and did not include real-world experiments.

In this work, we introduce Lighthouse, a novel method for indoor location estimation based on Directional Beacon Fingerprinting. The method utilises APs with narrow beam widths and DOE control. Unlike DB methods, Lighthouse does not need to estimate the bearing of the MD with respect to the AP, rather it relies entirely on RSSI fingerprint matching over all available DOEs. The APs switch DOE at a fixed rate between a number of DOEs. The MD obtains a DOE-RSSI signature for each AP, i.e. a vector containing the observed RSSI for each DOE. The location of the MD is then determined by finding the position in a pre-stored map which best matches the observed DOE-RSSI signature. The advantage of the proposed method is that multiple RSSI map layers are available for each AP, i.e. one for each DOE. When compared with previous approaches, the proposed method offers higher accuracy with the same number of in-range APs due to the extra map layers. Lighthouse works with existing, standards compliant, WiFi MDs. Previously, the authors of this paper published a conference paper outlining the basic Lighthouse concept but the work was orientation-dependent and focused on localization to the nearest map reference point [18]. To the best of the authors' knowledge, this is the first paper to present experimental location estimation results using DOE-RSSI signatures in a testbed network.

The reminder of this paper is organized as follows. In section 2, we describe the Lighthouse method. In section 3, we detail the experiment method used to evaluate the proposed localization method. In section 4, we present and discuss the results. In section 5, we conclude the paper and suggest future work.

2 Proposed Method

The Lighthouse method relies on APs with directional antennas whose DOE can be controlled. In the general method, it is assumed that the DOE of a particular AP transmission can be determined at the MD and its RSSI independently measured. In practice, there are a number of ways to achieve this. DOE control at the AP can be achieved by utilizing an array of fixed directional antennas, or by beamsteering an antenna array. DOE identification at the MD can be achieved by associating each DOE with a unique physical AP or virtual AP. In this way, packets from a given DOE have a unique SSID. Alternatively, a single SSID may be used for all DOEs and the time of switching DOE may be shared between the AP and MD as data.

DOE control allows the MD to obtain multiple RSSI readings from a single AP - one for each DOE. The DOE-RSSI signature S for a given position is a matrix of RSSI readings where each row corresponds to an AP and each column corresponds to a DOE:

$$S(x,y) = \begin{bmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,D} \\ \vdots & \vdots & \ddots & \vdots \\ r_{A,1} & r_{A,2} & \cdots & r_{A,D} \end{bmatrix} \tag{1}$$

where $r_{a,d}$ is the RSSI reading at MD position (x, y) for AP a and DOE d. There are A APs in range and D DOEs for each AP.

A complete map M consists of S measured at all grid positions. An AP map consists of S measured for all APs at all grid positions for one AP only, i.e. each signature is a row vector. A map layer L is S measured at all grid positions for one AP only and for one DOE only, i.e. each signature of L is an elementary RSSI value:

$$L = \begin{bmatrix} S(1,1)[a,d] & S(1,2)[a,d] & \dots & S(1,Y)[a,d] \\ \vdots & \vdots & \ddots & \vdots \\ S(X,1)[a,d] & S(X,2)[a,d] & \dots & S(X,Y)[a,d] \end{bmatrix} \tag{2}$$

where $S(x, y)[a, d]$ is the RSSI signature of AP a for DOE d at position (x, y), i.e. the RSSI value $r_{a,d}$ in signature $S(x, y)$.

The Lighthouse method operates in two stages - Mapping and Localization.

During Mapping, M is obtained by moving a reference MD over a grid of known locations in the positioning space. At each grid point, the signature S is measured by averaging RSSI over N observations. To allow for any directionality in the MD antenna, RSSI must be averaged over a number of MD orientations as part of this process. The complete map M is then stored in an online database.

During localization, an MD in the positioning space seeks to determine its location. The MD obtains RSSI readings for all in-range APs for all DOEs to give an observed signature $\hat{S}$. Averaging can be performed over time to reduce the effects of noise. To estimate the location of the MD, the observed signature is compared with the map using a K-Nearest Neighbor (KNN) algorithm [19].

The database is searched for the K closest matching grid points in the database in terms of their Euclidean distance e:

$$e(x,y) = \frac{1}{AD} \sum_{a=1}^{A} \sum_{d=1}^{D} (\hat{S}(x,y)[a,d] - S(x,y)[a,d])^2 \tag{3}$$

The co-ordinates of the K closest matching grid points are then averaged to obtain the final MD position estimate (p_x, p_y):

$$\begin{aligned} p_x &= \frac{1}{K} \sum_{k=1}^{K} x_k \\ p_y &= \frac{1}{K} \sum_{k=1}^{K} y_k \end{aligned} \tag{4}$$

where (x_1, y_1) is the grid point with the minimum error $e(x_1, y_1)$, (x_2, y_2) has the second lowest error and so on.

When $K = 1$, the algorithm is equivalent to placing the MD at the closest matching grid point. For larger, K the algorithm averages the position estimates across multiple grid points with closely matching signatures. This improves robustness to the spatial and temporal variability in the RSSI readings.

A heat map is a graphic representation of a map layer. The physical map of the positioning space is superimposed with the colorized RSSI at each grid position. Increasing

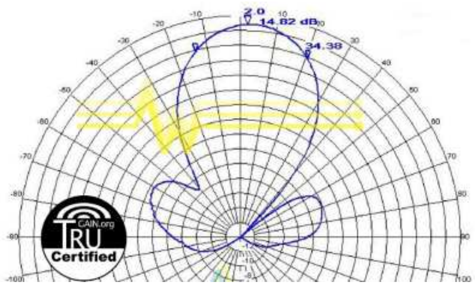


Fig. 1: Directional antenna radiation pattern [20]

RSSI variation with distance allows the MD to determine its position with greater accuracy. Using a directional antenna increases RSSI variation with distance in a small region whereas use of multiple directional antennas allows high RSSI variation with distance over more of the positioning space.

3 Experimental Method

The following paragraphs describe the experimental set-up and method used to evaluate the performance of the Lighthouse method.

The evaluation platform consisted of:

- APs: D-Link DIR-600.
- Omni-directional antenna.
- Directional antennas: Flat panel P2415T [20], beam width 34 degrees. Figure 1 shows the radiation pattern.
- MDs: Acer notebook (Aspire One Series - ZG5) with Atheros WLAN card and Linux Mint OS.
- Data collection: tshark tool [21]. RSSI reading per packet with beacon period of 20 ms
- Data processing: offline using Matlab

Two floors in the 4-storey Complex and Adaptive System Laboratory at University College Dublin were used for experiments:

- The ground floor consists of 4 walled offices and an open plan area, see Figure 2. The positioning space was 12.3x13.5 m.
- The third floor consists of open plan desk space. The positioning space was 23x13.5 m. The third floor was used in two configurations, see Figure 3.

In all experiments, the existing office WiFi infrastructure continued to operate as normal. The experiments were conducted during the weekends to facilitate access. The experiments took place over several weeks.

Initially, an experiment was conducted to determine the number of DOEs to be used. For this purpose, a directional antenna was attached to a stepper motor allowing variation of the DOE, see Figure 4a. The stepper motor has minimum step size of 1.8 degree, and the total angular sweep covered in the experiment was 180 degrees. Two APs were placed on the 3rd floor in configuration 1 and five maps were constructed for the 20 grid locations. The five maps were constructed using DOE step sizes of 9, 18, 36, 45 and 54 degrees. An MD was introduced and its location on the grid

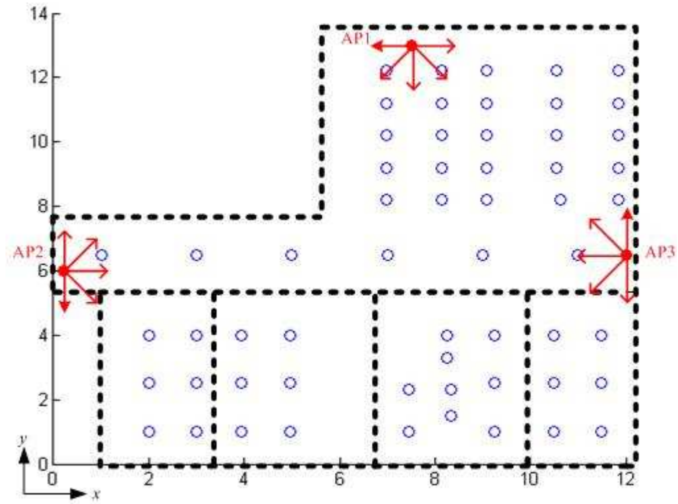


Fig. 2: Ground floor plan: walls (dots), grid locations (blue), APs (solid red). Arrows indicate DOE, solid arrow indicates 0 degrees.

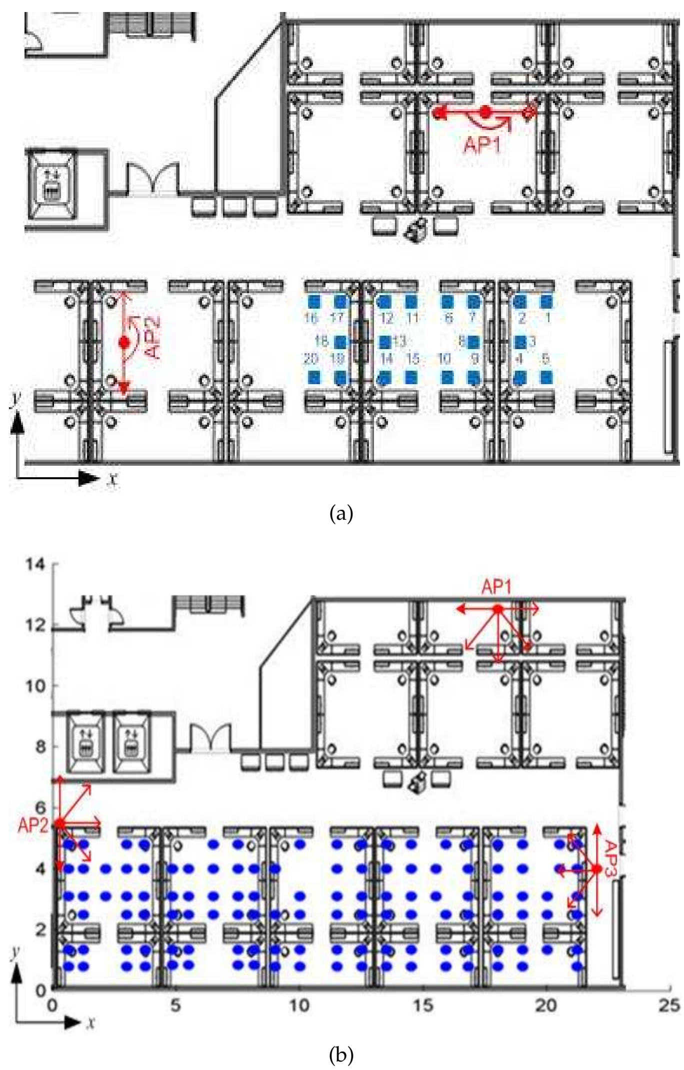
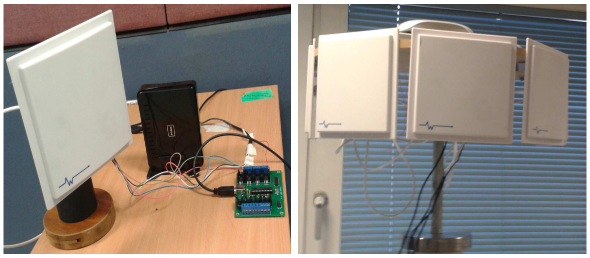


Fig. 3: Third floor plan: grid locations (blue), APs (solid red). Arrows indicate DOE, solid arrow indicates 0 degrees. (a) configuration 1; (b) configuration 2.



(a) (b)

Fig. 4: Directional AP antennas: (a) motorized, (b) multi-antennas.

determined using the five maps. The variation in location error with DOE step size was evaluated. Based on these results, the DOE step size was fixed for the later experiments.

A portable unit with 5 fixed directional antennas, was constructed and used for the remainder of the experiments, see Figure 4b. Each antenna was connected to a D-Link AP with unique SSID to distinguish between the DOEs at the MD. All were set to the same transmission channel and transmission power level. The multiple antennas prototype had several advantages over the single motorized directional antenna. Firstly, time synchronization was no longer needed, reducing complexity, and secondly mechanical rotation was no longer needed, speeding up the measurement and improving reliability.

A fingerprint map was constructed for the third floor configuration 2 (Figure 3b) using 3 APs and 118 grid locations with approximate 1 meter between grid points. Location estimation was performed for 18 MD locations with random positions, random orientations and random heights (1-1.5 m). Reference data was collected zone-by-zone over several weeks and after that the test point data was collected. The accuracy of the location estimates was assessed in terms of their 2D position error in meters. The effects of using various K values (1-8) and various combinations of APs was studied. The variation of the RSSI measurements with time was recorded to estimate the time period required for averaging.

Finally, the accuracy of the Lighthouse method was compared with that of conventional RSSI fingerprinting using an omnidirectional antenna on the ground floor with 3 APs, 58 grid points and 24 random MD test points.

4 Results and Discussion

The following paragraphs present and discuss the results of the experiments described in Section 3.

Figure 5 shows an example of a DOE-RSSI signature measured on the third floor using the rotating directional antenna. It can be clearly seen that there is a measurable change in RSSI at the MD as DOE varies at the AP.

Table 1 lists the variation in location classification accuracy with DOE step size using the rotating directional antenna on the 3rd floor in configuration 1 (as shown in Figure 3a). Accuracy is expressed as the percentage of times that the MD is located at the true grid point ($K = 1$). The results were obtained using one AP at a time. For each test, a number of measurements were made at the same location, over various times of day, over a few weeks. K-fold cross validation was applied to one data, whereby one data set was taken as localization data while all others were averaged and taken as a reference map. This process was repeated for all experiments. As can be seen, there is little improvement in accuracy below a step size of 45 degrees. We believe that the effectiveness of reducing step size is limited by the beam width of the antenna. Based on these results, 5 DOEs were used in the later experiments: 0, 45, 90, 135 and 180 degrees.

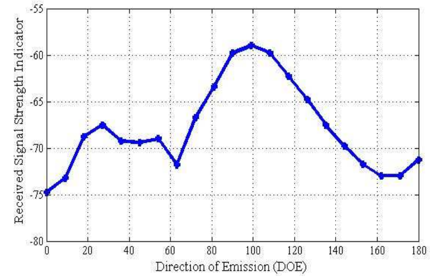


Fig. 5: A sample signature for one location where it shows change of RSS value with the direction of emission

TABLE 1: Location classification success ratio (%) using various DOE step sizes.

	Step Size - Degrees				
	9	18	36	45	54
AP1	88%	88%	82%	79%	65%
AP2	91%	92%	93%	91%	85%

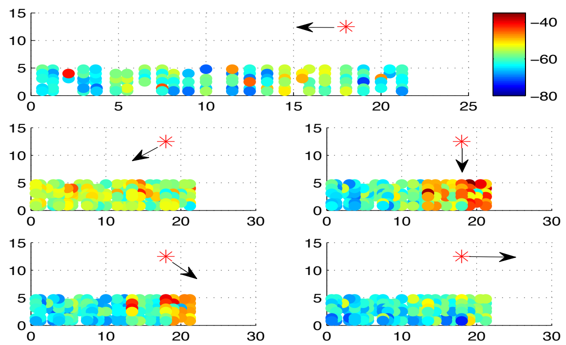
Figure 6 shows the heat maps obtained for the third floor with configuration 2. Heat maps are shown for all layers, i.e. all 3 APs and all 5 DOEs. As would be expected, points closer to the APs and in line with the assiciated DOE show greatest RSSI. Comparing APs, it is clear that the maps for AP2 and AP3 show greater point-to-point variation and so were expected to provide better location estimation results. It can be seen that, for many grid points, there is significant change in RSSI for different DOEs at the same MD location for the same AP. This observation supports the utility of the DOE approach for increasing mapping information without increasing the number of AP locations.

Based on these maps, location estimates were obtained for test MDs positions. Table 2 lists the mean location error obtained for various values of K. Due to Geometric Dilution of Precision, AP3 outperforms AP2 which outperforms AP1 in most cases. Significantly for the Lighthouse method, one well placed AP provides very good accuracy - almost as good as all 3 APs. Our observation is that the main advantage of using 3 APs is in reducing the maximum error; from 7 m in the case of one AP only to 5 m in the case of two APs, and to 4 m in the case of all three APs. Overall, $K = 6$ seems a reasonable choice in terms of obtaining good accuracy. Unless otherwise stated, this value was used for the remainder of the experiments.

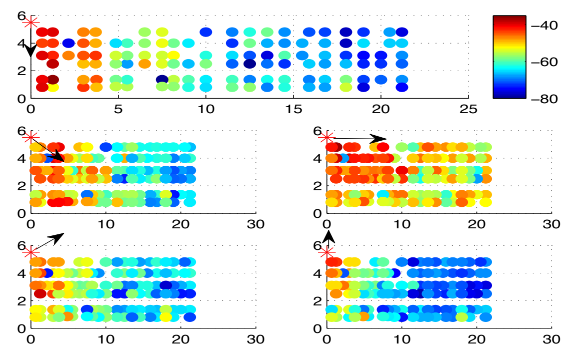
Cumulative Distribution Functions (CDFs) for the location error on the 3rd floor, configuration 2, are shown in Figure 7. The graphs show how the error varies with the

TABLE 2: Location Mean Error in Meters using various K-Neighbors (based on third floor testbed).

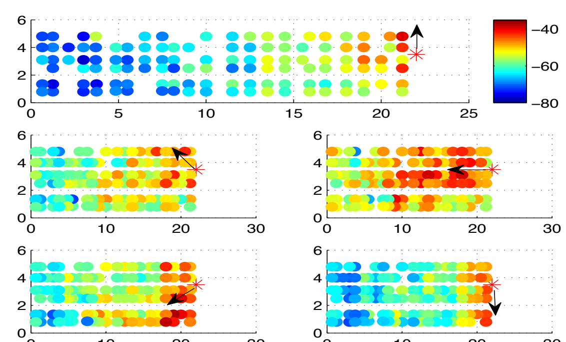
	1	2	3	4	5	6	7	8
AP1	3.75	3.85	3.52	3.60	3.45	3.25	3.13	3.16
AP2	3.85	3.25	3.21	3.05	2.94	3.02	3.03	3.10
AP3	2.88	2.55	2.26	2.20	1.98	2.03	2.05	2.19
AP1&2	3.40	3.18	2.97	2.93	3.04	2.94	2.86	2.76
AP2&3	2.33	2.04	2.15	2.07	2.02	2.11	2.03	2.10
AP1&3	2.22	2.44	2.27	2.36	2.29	2.32	2.37	2.33
AP1&2&3	2.40	1.97	2.14	2.17	1.98	1.90	2.00	2.02



(a)



(b)



(c)

Fig. 6: Heat map for the 3rd floor, configuration 2: (a) AP1, (b) AP2, (c) AP3. The asterisks (*) indicate the AP location and the arrow shows DOE for that layer.

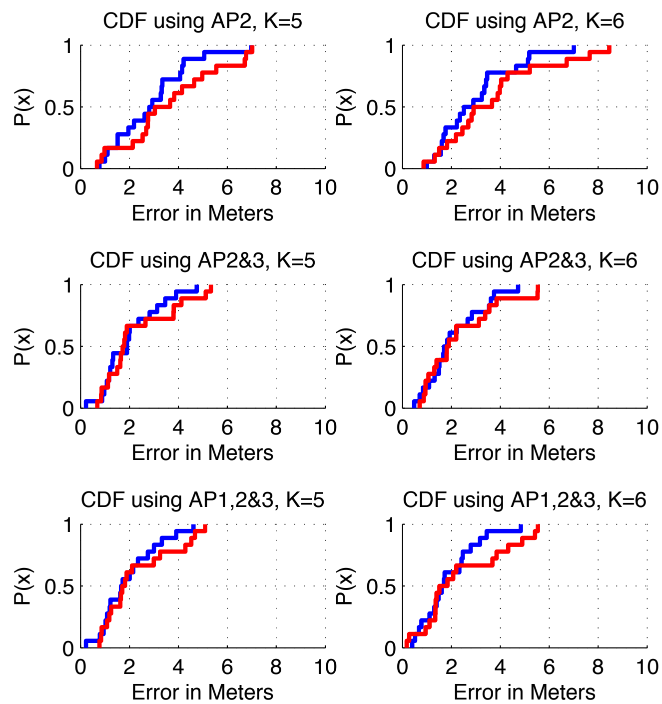


Fig. 7: CDF of location error, 3rd floor: 118 grid points (blue), 59 grid points (red).

APs used and the number of reference points used to build the map. The plots show that there are very few large errors, in 90% of cases the error is below 4 meters, except when using only one AP where the error is around 6 meters. Also, interestingly, there is little difference in using 118 grid points, rather than 59 grid points, i.e. 1 m versus 2 m grid point separation. This points the way towards lower density mapping.

Figure 8 shows mean location estimation error variation with time. It takes about 600 RSSI measurements (12 s) for the error to converge to its long term average. However, the mean error is within 20 cm of its long term average within 1 s.

Figure 9 shows the CDFs of the location error obtained for Lighthouse and the conventional omnidirectional RSSI method on the ground floor with $K = 5$ and $K = 6$. Table 3 provides the mean error measurements for the same experiment. These CDFs show that when using 3 APs the median error is 1.8 m and 2.4 m for Lighthouse and the conventional

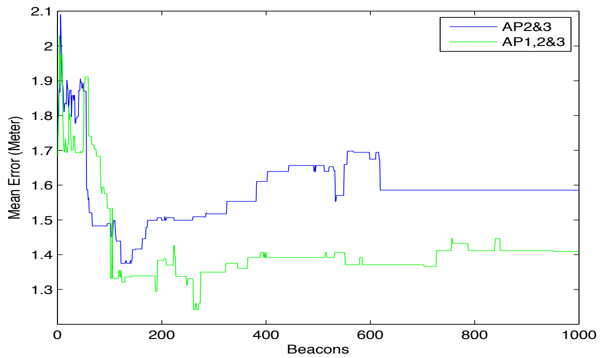


Fig. 8: Mean error versus time, 3rd floor.

TABLE 3: Comparison table for mean error in location estimation

	Lighthouse (5 directional antennas)	Conventional (1 omnidirectional antenna)	Improvement (meters)	Improvement (%)
AP1	2.48	3.04	0.56	18%
AP2	3.87	4.95	1.07	22%
AP3	2.18	3.86	1.68	43%
AP1&2	1.99	3.19	1.20	38%
AP2&3	1.85	3.55	1.70	48%
AP1&3	1.99	3.27	1.29	39%
AP1&2&3	1.64	2.87	1.23	43%

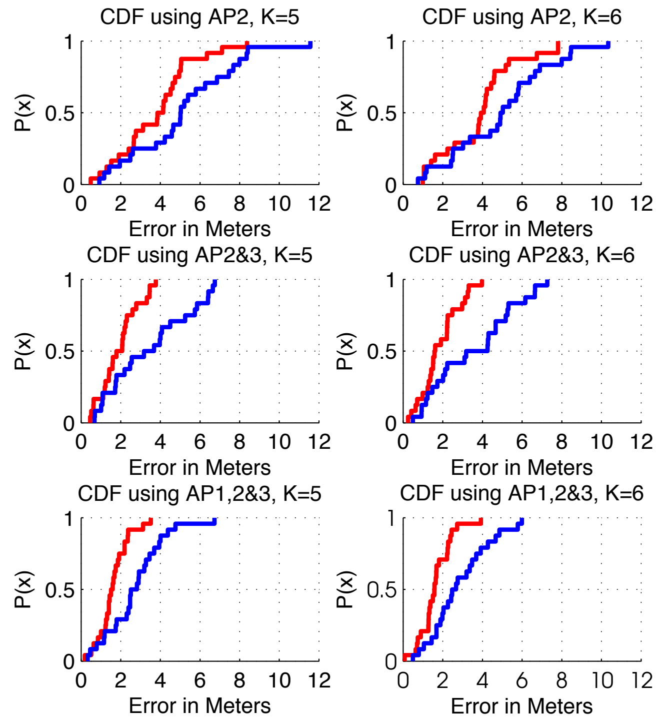


Fig. 9: CDF of location error, ground floor: Lighthouse (red), conventional (blue).

method, respectively. This is a 25% improvement. As can be seen from the CDFs, the improvement in accuracy is greater above the 50% point due to the increased robustness arising from the increased number of map layers. These plots also show that the maximum error is kept below 4 meters when using the Lighthouse method.

5 Conclusions

In this paper, we proposed Lighthouse, a Directional Beacon Fingerprinting WiFi location method. The technique uses 802.11 standard compliant MD devices. Directional antennas and DOE control are used at the APs to enable the MDs to obtain DOE-RSSI signatures. The DOE-RSSI signatures are used to estimate location by matching the observed signatures to a pre-stored map. This paper presented the results obtained from three testbed networks including both open plan and internally walled office environments. The proposed method achieved a mean error of 1.64 m in comparison to an error of more than 2.87 m using the conventional omnidirectional RSSI method when using 3 APs in a 12 by 13.5 m space (see Table 3. Parameter settings for the method were studied and the results obtained were presented. The paper also considered the effectiveness of the technique when using low density maps and low numbers of in-range APs.

In future work, we propose to investigate the utility and effectiveness of DBF in accelerated map construction. We also plan to investigate the use of beamforming for DOE control.

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