Title	Lighthouse: Precise 802.11-based Localization
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Publication date	2013-10
Publication information	Siddig, Abubakr, Ahmed Makki, and Chris J. Bleakley. “Lighthouse: Precise 802.11-Based Localization.” IEEE, October 2013. https://doi.org/10.1109/IPIN.2013.6817914.
Conference details	4th Indoor Positioning and Indoor Navigation (IPIN), Montbeliard, France, 28-31st October, 2013
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/5216
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Publisher's version (DOI)	10.1109/IPIN.2013.6817914

Lighthouse: Precise 802.11-based Localization

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***Abstract*—This paper proposes a novel approach to the problem of indoor location estimation based on IEEE 802.11 (WiFi) signals. The approach uses a rotating directional antenna at the Access Point (AP). The Mobile Device (MD) measures the variation of Received Signal Strength Indication (RSSI) with antenna Direction Of Emission (DOE). The observed DOE-RSSI signature is used as a fingerprint to search a map of previously measured DOE-RSSI signatures. The method has the advantage that it works with existing 802.11 cards and that it provides higher accuracy, for the same number of APs, than the conventional RSSI fingerprinting technique based on maps obtained using multiple omnidirectional APs. We report results obtained from an experimental testbed deployed in a typical office space. The Lighthouse algorithm achieved 85% and 95% success ratio in MD localisation over 20 possible positions using one AP and two APs, respectively. The success ratio achieved is, on average, +24% and +53% better than the conventional RSSI fingerprinting and directional beaconing methods, respectively.**

***Index Terms*—indoor localization, IEEE 802.11, positioning, direction of emission, wireless.**

I. Introduction

INDOOR localization has been the subject of increasing attention from researchers and developers in recent years. Since GPS does not work indoors, alternative solutions must be found. Location estimation using IEEE 802.11 (WiFi) transceivers is attractive due to their low cost and wide availability. Previous solutions have focused on the use of Received Signal Strength Indication (RSSI), or 'heat' maps, for position estimation [1]. RSSI is used since it is available at the application layer from all standards compliant 802.11 transceivers. However, to date, accuracy has been poor, i.e. of the order of several meters [1], [2], [3]. Higher accuracy is desirable for many applications including user navigation, object tracking and Human Computer Interfaces. Conventional RSSI location requires RSSI measurements from multiple Access Points (APs) to achieve reasonable results. This is unsatisfactory in typical deployments where the number of overlapping coverage cells is kept low to reduce deployment costs.

We introduce a novel technique, called Lighthouse, which seeks to improve the precision of 802.11-based localization and reduce the number of APs required for accurate positioning. The approach uses standard 802.11 transceivers at the AP and at the Mobile Device (MD). The technique is based on the use of rotating directional antennae at the AP(s). The MD measures RSSI variation with the AP antenna Direction Of Emission (DOE). The current DOE angle is sent from the AP to the MD as part of a normal data packet. The MD uses the recorded RSSI-DOE signature to search a database containing a map of previously recorded signatures. Each DOE can be thought of as giving a unique RSSI heat map. Thus a single AP gives rise to multiple heat maps, increasing localization accuracy and reducing the need for multiple APs. To the best of the authors' knowledge, this is the first paper to present experimental results using IEEE 802.11 RSSI-DOE signatures in a testbed network.

The remainder of this paper is organized as follows. In Section 2, we discuss previous work related to this paper. In Section 3, we introduce the problem statement. In Section 4, we describe the proposed algorithm. In Section 5, we detail the experimental method. In Section 6, we present the results. Finally, conclusions are drawn and future work suggested in Section 7.

II. Related Work

A number of researchers have proposed methods for indoor location estimation using 802.11 radio signals [1]. Herein, we consider two categories: RSSI-based techniques and Directional Beaconing techniques. We mainly focus on techniques designed for use with standards compliant 802.11 transceivers.

Bahl and Padamanabhan [4] suggested the use of radio frequency (RF) signal strength to locate and track users inside a building. Their system, called RADAR, used the measured signal strength from multiple APs to locate the user by comparing the measured signal strength with pre-stored data. Brunato and Battiti [5] proposed statistical methods to enhance localization based on RSSI measurements. In their work, location is determined based on a fingerprinting method that compares the observed RSSI-APID (Access Point ID) fingerprint with a pre-stored database of fingerprint and location pairs. To date, the accuracy of RSSI-APID methods have been limited by the nature of the RSSI heat maps, which are normally slowing varying with distance, and due to ambiguities in the signatures (i.e. similar signatures in different places) [6]. To ensure accuracy, multiple APs are typically needed. The method proposed herein improves accuracy by using multiple DOEs at a single AP.

Recently, the RSSI-based location estimation concept has been extended by exploiting additional information regarding the received Wi-Fi signal available at the Physical Layer [7], [8]. In the proposal, Channel State Information (CSI) is obtained directly from the 802.11 card hardware and is used as a signature for localization. CSI varies strongly with distance. Therefore, the method provides high level of precision. However, because the relationship between position and CSI is not well understood, the approach requires a very large number of measurements to build an adequate map. Most 802.11 cards do not make CSI information available to the higher layers in the stack. Therefore, at present, this method is specific to a single 802.11 card. The method proposed herein can be used with all 802.11 compliant cards.

Concurrently, a number of papers have published research on using Directional Beaconing (DB) for location estimation [9], [10], [11], [12]. This work is based on the concept of a rotating directional antenna at the AP or transmitter. The MD records the variation of signal strength with the transmitter DOE. The transmitter and MD are synchronized so that the DOE is known at the MD. In practice, the effect of rotating the antenna can be achieved electronically by beamforming [13]. Almost all work on DB, requires that the MD select the DOE giving maximum signal strength. Based on this, the bearing of the MD from the transmitter is determined. Bearings at multiple transmitters allow for positioning of the MD in 2D. The difficulty with this approach is that, in indoor environments, there is significant multi-path. This means that the maximum signal strength is frequently not associated with the true bearing angle from the transmitter to the receive. Herein, we propose to use an RSSI-DOE signature, measured for all DOEs, to determine position based on map look-up. This obviates the need for a determining the bearing angle.

The concept of DB with signal strength signal matching was previously proposed in [14], [15]. However, the papers only described simulation studies based on ray tracing using a 2.4 GHz beamforming model with single point experiment. In this paper, we focus on real-world experimental results using 802.11.

Some work has been done on location estimation by manually rotating the MD [16]. In addition, there has been work on estimating position by measuring the Direction Of Arrival (DOA) at the MD or AP [17]. In our view, rotating the MD antennae, either mechanically or electronically, by beamsteering an array, is not practical due to device size considerations. In addition, controlling DOE is lower complexity than estimating DOA and, as shown herein, can be used for localization.

III. Problem Statement

Herein, we consider the problem of determining which location a MD has been placed in from a set of pre-mapped reference points in a building. The MD position registration problem is important for security applications, warehouse management, tracking of medical personnel and patients in hospitals, interactive maps in exhibitions or galleries, and has been previously been addressed in [1]. The reference points are selected on a grid at 1 meter intervals at desk height. Location estimation is performed using 802.11 RSSI measurements obtained from 1 or 2 APs placed in the environment. The AP antenna is directional and can be rotated, either manually, mechanically or electronically, using beam switching or beamsteering. The MD is fitted with an electronic compass to improve accuracy.

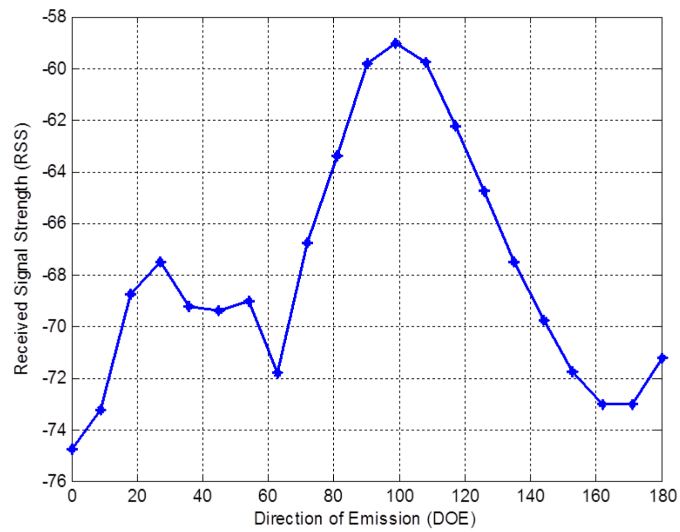


Fig. 1: A sample signature for one location where it shows change of RSS value with the direction of emission

IV. Proposed Algorithm

The Lighthouse algorithm has two modes - Mapping Mode and Localization Mode.

In Mapping Mode, a reference MD is moved through the grid of locations over which positioning is to be performed. At each location, the MD orientation is rotated 360 degrees from North in steps of a_{MD} degrees. For each orientation, the MD logs its magnetic compass reading. In addition, the MD logs the observed RSSI-DOE signature from all visible APs. The APs are fitted with directional antennae which rotate in steps of a_{AP} degrees between 0 and 180 degrees, assuming they are fixed to a wall. The AP sends the current DOE, so that it is known at the MD. For each DOE and AP, the MD records the RSSI. Thus, the MD builds up a RSSI-DOE signature, as shown in Figure 1, which is unique to the MD location and orientation. This process is repeated for all locations on the grid. The RSSI-DOE signatures and their associated location and MD orientation are stored in an online database as the map and are made available to an MD in Localization Mode.

In Localization Mode, the MD seeks to determine its location. The MD reads its orientation from its electronic compass. For each AP, the MD obtains the DOE and measures the RSSI. It repeats this process for all DOEs to obtain the RSSI-DOE signature. The MD uses this signature to search the database for matching signatures with the same orientation. The best match is deemed to be the signature that minimizes the cost function. Two cost functions were considers: Mean Square Error (MSE) and Mean Absolute Difference (MAD). The mapped location associated with the matching signature is taken as the MD location estimate.

This signature measurement and search process can be repeated for all visible APs. The final location estimate is the one that minimizes the cost function across all signatures for all APs.

A flow chart illustrating the algorithm is provided in Figure 2 and pseudocode is provided in Algorithm 1.

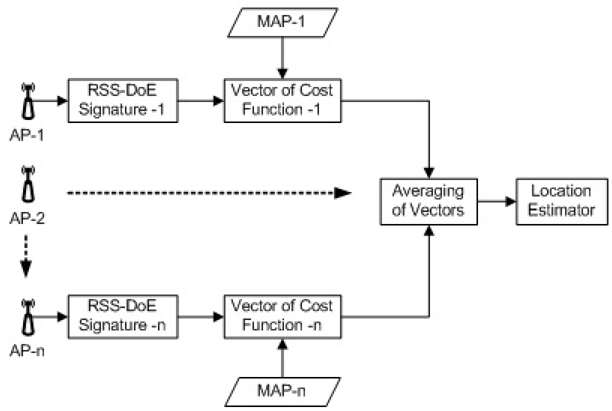


Fig. 2: Flow chart describes the Lighthouse algorithm at the MD end

Algorithm 1 Lighthouse Algorithm

```
Mapping Mode
MD logs its magnetic compass reading to determine
orientation;
Start rotating the AP(s) antenna(s);
MD logs the RSSI readings from all visible APs;
MD Builds up a RSSI-DOE signature for the location and
specifi orientation;
Repeat the Mapping Mode for different MD orientations for
the same location;
Repeat the Mapping Mode for different locations;
End Mapping Mode when data base is built for all
locations;
Localization Mode
MD reads its orientation;
MD logs the RSSI reading for each DOE;
MD builds the RSSI-DOE signatures for all visible APs;
MD to compare its signature with the database for
specific AP corresponds to its orientation;
MD to estimate its location based on minimum cost
function across all signatures for all APs;
Repeat Localization Mode until ended by user;
```

V. Experimental Platform

Lighthouse was evaluated on the 3rd floor of the 4-storey Complex and Adaptive System Laboratory at University College Dublin. Figure 3 shows the floor plan and Figure 4 is a photograph of the laboratory environment. The testbed space is a normal working environment. The tests were done at the weekend to facilitate access to the equipment.

The AP is a D-Link router (DIR-600) with a directional antenna (flat panel antenna - P2415T [18]) with beamwidth 34 degrees attached to a stepper motor (1.8 degrees step angle) that controls antenna rotation. During the experiments, the antenna was placed in two positions as shown in red in Figure 3. The arrows indicate DOE zero degrees for the two AP positions, then AP antenna is rotated anti-clockwise. Figure 5 shows the radiation pattern of the antenna and Figure 6 shows the AP, motor and antenna.

To accelerate testing, twenty Acer notebooks (Aspire One

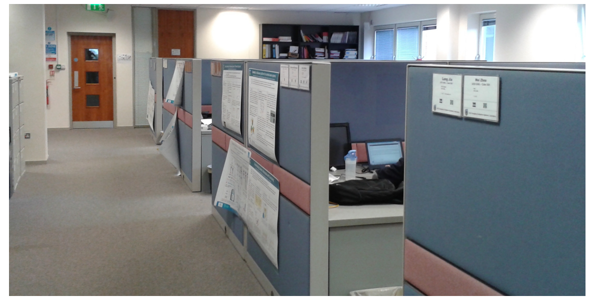


Fig. 4: Laboratory environment

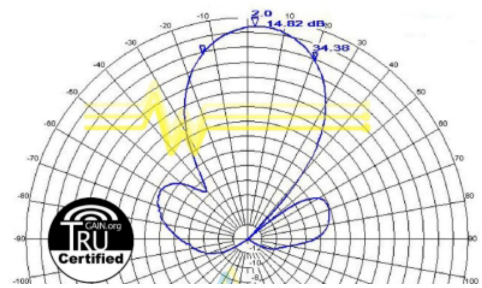


Fig. 5: Directional antenna radiation pattern [18]

Series - ZG5) were used as MDs for the experiment. The notebooks were distributed in twenty positions marked in blue in Figure 3. The distance between adjacent notebooks was 1 meter, in most cases. All notebooks ran Windows with inSSIDer for RSSI logging. Each RSSI reading is averaged over 10 seconds (i.e. 3 readings from the software). Other platforms offer different updates rates depending on the WiFi card, e.g. 5 readings in 10 seconds. A shorter measurement time can be achieved by logging RSSI for each packet [4].

VI. Results

Four evaluations were conducted: RSSI-DOE signature variation, impact of AP rotation step size, impact of MD orientation step size, and a comparative study with previously proposed methods.

A. RSSI-DOE Signature Variation

Figure 7 shows the signatures obtained for various MD locations. Figure 7(a) shows the signatures for 8 locations using AP1. Figure 7(b) shows the same locations using AP2.

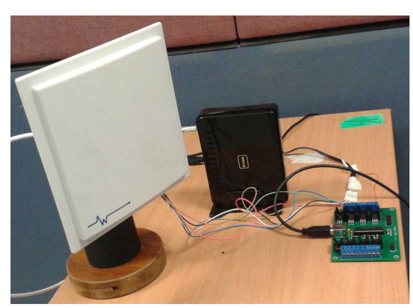


Fig. 6: AP unit

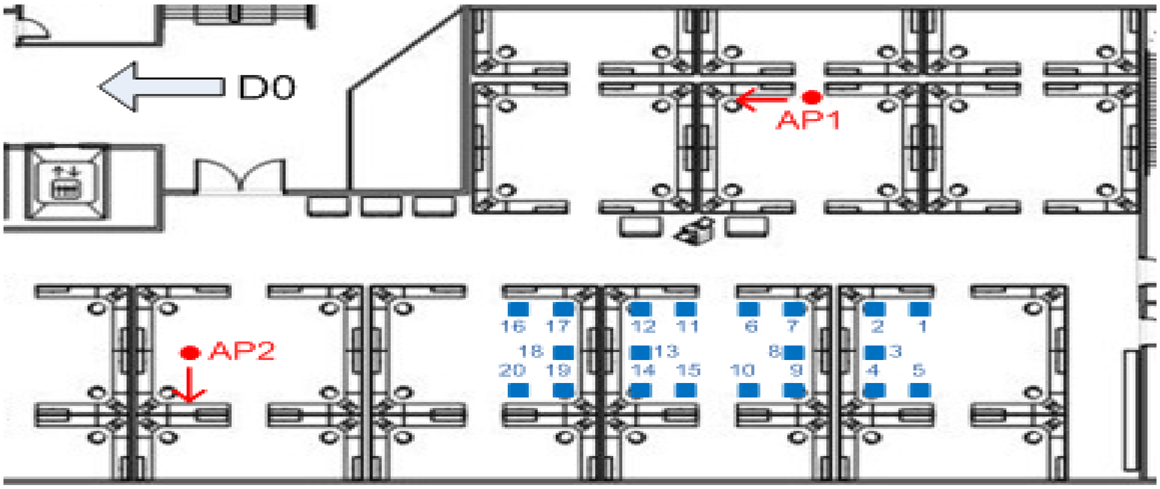


Fig. 3: Floor plan where tests took place (D0 is the reference direction)

TABLE I: Location classification success ratio (%) using various DOE step sizes and cost functions.

Cost Function		Step Size - Degrees				
		9	18	36	45	54
MSE	AP1	88%	88%	82%	79%	65%
MAD	AP1	89%	87%	86%	83%	64%
MSE	AP2	91%	92%	93%	91%	85%
MAD	AP2	91%	92%	94%	94%	84%

P1-9 refer to the MD locations as numbered in the floor plan. In all cases, the MD orientation was towards North. It can be seen that the signatures are distinct and different, even for adjacent locations such as P1 and P2. Offsets in RSSI strength due to varying AP-MD range can be seen, for example, when comparing the signatures for P1 and P2 with AP2. It can also be noted that MDs at similar bearing angles at the AP show different peaks in their signatures due to multipath, e.g. P3 & P8 at AP2. This illustrates the problems associated with peak detection in conventional DB.

B. AP Rotation Step Size

Figure 8 shows signatures taken for a single location using 3 different step sizes (9 degrees, 18 degrees and 36 degrees). Naturally, the smaller the step size, the more fine grained the signature. However, there is considerable redundancy in the information obtained when the step size is less than the beamwidth of the AP antenna. Table 1 shows the percentage of the correct location classification using 5 different step sizes (9, 18, 36, 45 and 54 degrees). All 20 MD locations, a single MD orientation and a single AP location were used. The overall success ratio is almost the same for step sizes less than the antenna beamwidth, this accuracy drop noticeably at and above 45 degrees. In the remainder of the experiments, a step size of 9 degrees was used in order to eliminate the effects of limited step size.

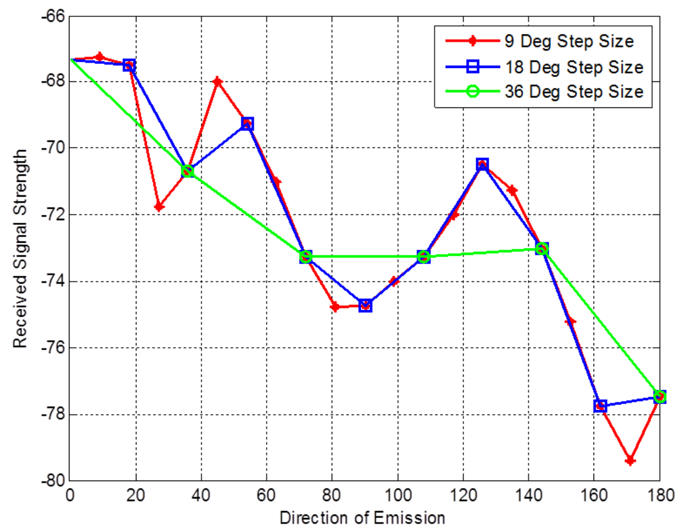


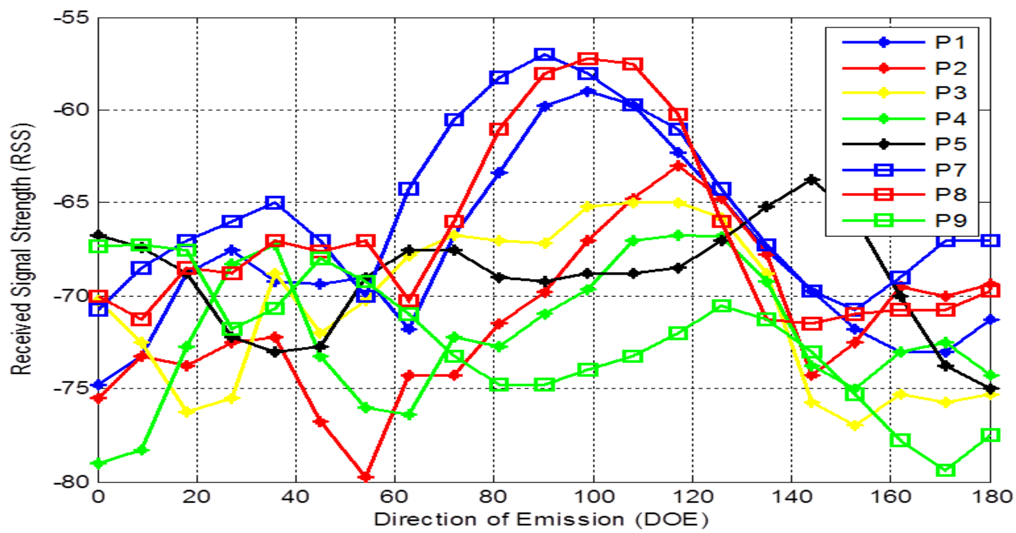
Fig. 8: Effect of step size on signature pattern.

C. MD Orientation

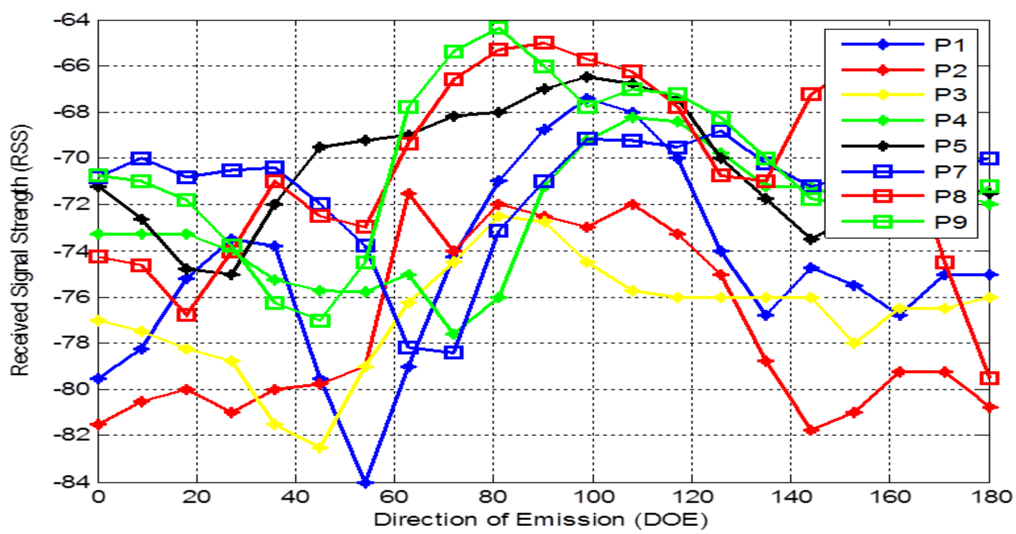
An experiment was conducted to investigate the effect of MD orientation. Figure 9 shows the RSSI-DOE signatures obtained for 8 different MD orientations, starting at the reference direction D0 as in Figure 3 and rotating 45 degrees anti-clockwise at a time. This change in signature is due to the fact that the MD antenna is not truly omnidirectional. As a consequence RSSI changes as it rotates.

D. System Comparison

The accuracy of the Lighthouse algorithm was compared with that of conventional RSSI fingerprinting [4], [19] and conventional Directional Beaconing [12]. For the RSSI fingerprinting method, an omni directional AP was used to obtain a single RSSI measurement per location for each AP. For the DB method, the maximum RSSI taken to be associated with the direct path between the AP and the MD. The intersection between readings from two APs was used to estimate the location of the MD. Since the beamwidth of the directional



(a)



(b)

Fig. 7: Signatures of adjacent locations. (a) using AP1. (b) using AP2. DOE with respect to AP1 and AP2 vectors in Figure 3 where increasing angle is an anti-clockwise.

antenna is 34 degrees, and the step size of the rotation is 9 degrees, we assume a margin error of ±20.5 degrees, i.e. if an estimation falls in the intersection of AP1 and AP2 cones, it is considered to be successful. The Lighthouse and RSSI-only tests were carried out using AP1-only, AP2-only and APs1&2 together. The results are based on 20 MD locations. A single MD orientation was used. For each AP, the measurements were performed 4 times. and k-fold cross validation method was performed. The results obtained are summarized in Table 2.

Lighthouse provides very good results with only one AP. With two APs, there are only two errors. Lighthouse provides a large improvement in accuracy over conventional RSSI fingerprinting when only one AP is used, giving a +47% mean improvement. When both APs are used the improvement, +24%, is still significant but less so due to the improving accuracy of the conventional method. DB performs poorly in comparison to the RSSI due to its sensitivity to multi-path. There is little difference between the accuracy of MSE and MAD. Thus MAD is preferred due to its lower computational complexity. It can be seen that, in both cases, the results obtained using AP2-only are better than those obtained using AP1-only. This may be due to the more central (with respect to the grid) positioning of AP2.

VII. Conclusion

This paper proposed a novel method for 802.11 based indoor location based on the use of RSSI-DOE signatures. The paper presented the results of experiments conducted using a testbed network. The proposed Lighthouse algorithm achieved an average success ratio of 85% over 20 locations when using one AP for positioning and 95% when using two APs. The success ratio achieved is much greater than that obtained using

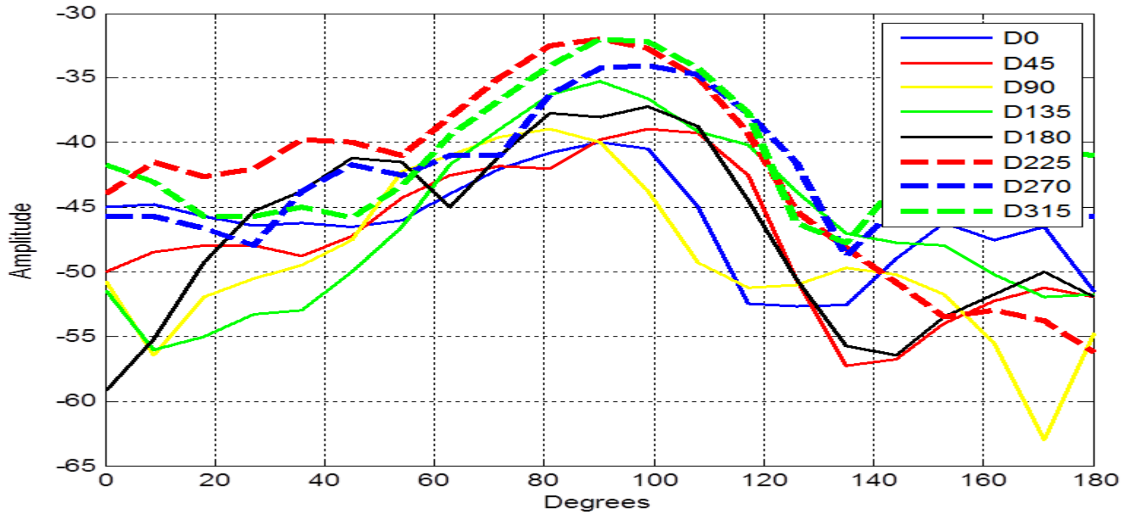


Fig. 9: Signatures obtained at a single location with varying orientation (MD orientation with respect to D0 vector on Figure 3, where increasing angle is an anti-clockwise).

TABLE II: Location classification success ratio (%) - Comparison table using 9 deg. step size

	Cost	AP1	AP2	AP1&2
Lighthouse	MSE	88%	91%	97%
	MAD	89%	91%	98%
RSS Fingerprinting	MSE	37%	47%	73%
	MAD	37%	47%	74%
Directional Beaconing		NA	NA	44%

a conventional RSSI signature method and a conventional Directional Beaconing method, +24% and +53% respectively.

In future work we plan to investigate the use of: mobile phones instead of laptops as MDs; alternative cost functions; narrower beamwidths; map prediction using ray tracing models; and beamforming rather than physical rotation of the AP antenna. In addition, we plan to study the real time implementation of large scale maps while minimizing computational complexity.

Acknowledgment

This publication has emanated from research conducted with the financial support of Science Foundation Ireland under Grant Number SFI/11/US/I2220.

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