Pseudo Lateration: Millimeter-Wave Localization Using a Single RF Chain

Joe Chen*, Daniel Steinmetzer†, Jiska Classen†, Edward Knightly*, and Matthias Hollick†
*Rice Networks Group, Rice University, Houston, USA, {joe.chen, knightly}@rice.edu
†Secure Mobile Networking Lab, TU Darmstadt, Germany, {dsteinmetzer, jclassen, mhollick}@seemoo.tu-darmstadt.de

***Abstract*—While radio-based indoor localization schemes achieve decimeter-scale accuracy, they typically require precise reference measurements, multiple infrastructure nodes, or a multi-RF-chain anchor. In this paper, we propose Pseudo LATeration (PLAT), an indoor localization protocol that requires only a single RF chain infrastructure anchor and does not require prior knowledge of the environment. PLAT leverages the directionality and propagation characteristics of millimeter-wave transmissions to relax the requirement of multiple infrastructure anchors and RF chains by constructing pseudo anchors from reflected signal paths. By combining these pseudo anchors with time-of-flight measurements for distance estimation, PLAT can localize a user's device in indoors. Our evaluation reveals centimeter scale location accuracy for typical office environments. In testbed measurements and simulations, localization errors are centimeter scale for distances up to $1.5\,\mathrm{m}$ and beamwidths at or below $8.6°$. Although accuracy decreases to decimeter scale with additional propagation distance, we show that multiple reflection paths can mitigate this effect.**

I. Introduction

In this paper, we design, implement, and evaluate Pseudo LATeration (PLAT), a wireless indoor localization protocol that requires only a single infrastructure anchor (IA). This anchor uses a single RF chain and does not require prior environmental knowledge. PLAT eliminates the need for multiple IAs and RF chains, as employed by prior work, by substituting IAs with pseudo anchors (PAs) from environmental reflectors. These PAs are identified using sector diversity in a highly directional millimeter-wave environment that lacks the rich scattering and multipath effects common in bands below $60\,\mathrm{GHz}$. Moreover, with limited ability to penetrate obstacles in millimeter-wave bands, a client may often be in range of only a single access point (AP) for a WLAN deployment.

PLAT is a three-step localization protocol. First, the AP performs a sector-level sweep using a narrow beam, and the user's device reports the received signal strength (RSS) for each sector. Similar to IEEE 802.11ad, the AP transmits a short beacon in rapid succession in different sectors defined by codebook entries [1], [2]. In PLAT, the user reports the RSS for all overheard beacons, even for sectors not used for data. Consequently, the AP analyzes both line-of-sight (LOS) and reflected paths and selects sectors with high RSS for localization. Second, the user refines its received beam for the localization sectors and reports their angular offsets. As illustrated in Figure 1, the pairs of sectors and angular offsets between the AP and user define a directed set of LOS and NLOS paths over which communication is possible. The AP and user then cooperatively measure the time of flight for each localization sector. With all of this information, the AP estimates the locations of reflected paths and assigns them as PAs, replacing IAs in multilateration. Consequently, PLAT localizes the user by combining the the LOS path and reflected paths along with all of their angular offsets and times-of-flight.

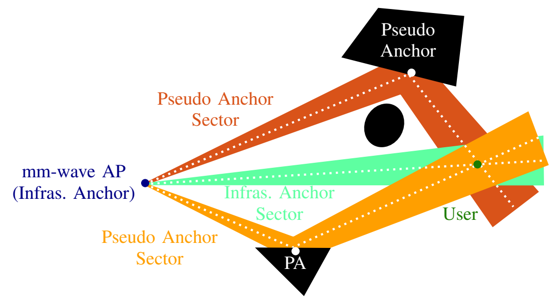


Fig. 1. Idealized scenario in which PLAT uses both the LOS path and NLOS pseudo anchors from existing environmental objects to localize a user.

To demonstrate PLAT's performance, we implement PLAT and evaluate its accuracy in over-the-air testbed experiments and simulations. The testbed provides traces from an office, while the simulation provides a ray-tracing analysis of custom environments. We compare PLAT against multi-anchor multilateration, and test several scenarios with varying degrees of beamforming inaccuracy and sector diversity. Our results indicate that PLAT achieves centimeter scale accuracy for close users for beamwidths at or below $8.6°$, and achieves decimeter scale for distances greater than $1.5\,\mathrm{m}$.

The remainder of this paper is organized as follows. First, we discuss our system model and protocol in Section II. Afterwards, we experimentally evaluate PLAT with a custom testbed (Section III) and via simulation (Section IV). Additional evaluation is available in [3]. We then classify the different existing techniques for indoor localization in Section V. Finally, we conclude the paper in Section VI.

II. PLAT Localization Protocol

In this section, we present PLAT, an indoor localization protocol that localizes a user using millimeter waves and only a single RF-chain device as the IA. In particular, we first describe the system requirements. Afterwards, we give a high level overview of how PLAT works. Finally, we discuss the three phases of PLAT in greater detail: extended sector level sweep, distance measurements, and the post-processing.

A. System Requirements

We consider protocol, device, and opacity constraints of a system architecture using commercially available off-the-shelf devices that are IEEE 802.11ad compliant at both the user and infrastructure. The key aspects that affect PLAT are as follows.

- *Codebook-based beamforming.* IEEE 802.11ad adopts codebook beamforming to reduce the overhead cost of beamforming. With a fixed beamforming codebook, devices employ a discrete set of virtual sectors and can rapidly switch beams within short beamforming interframe spacing (SBIFS) ($1\,\mu$s) [1]. Both link end points sweep among the sectors and adaptively select the strongest sender-receiver sector pair.
- *Single RF chain.* Codebook-based beamforming can be achieved with a single RF chain and multiple RF phase shifters. This design architecture reduces cost for large arrays achieving high directivity as analog-digital conversion is increasingly costly at higher frequencies.
- *No access to PHY signals.* Commercial devices cannot observe nor manipulate physical-layer information (e.g. raw radio signals and digitized baseband symbols).

B. Overview

PLAT localizes an indoor user with a LOS path and a moderate number of reflected paths. Unlike most prior work, PLAT uses non-line-of-sight (NLOS) reflections to make a refined location estimation. A fixed AP inside the service region serves as a single RF-chain IA with a known position and orientation. Instead of deploying additional IAs in the environment, PLAT infers the presence of PAs based on environmental reflectors that the AP and user can use to communicate. We consider PLAT as a localization protocol that is only run on demand and leave time optimization of the protocol as future work. PLAT features three stages: sectorwise sweeping, distance measurements, and a post-processing localization algorithm.

The AP discretizes the localization region into multiple virtual sectors. Each sector corresponds to the narrowest beamwidth defined in its codebook. APs typically have many antennas, making narrow beamwidths feasible. The AP does not require any prior knowledge of the environment. The user's beamforming codebook is assumed to be calibrated such that the user knows the angular offset between the center of the main lobe of each codebook entry's beamforming pattern. This calculation depends on the codebook implementation.

For ease of exposition, we assume the beamforming codebooks is based on a 1-D array of half-wavelength spaced antenna elements. Various beamwidths are generated by adding or removing active antenna elements. However, other beamforming codebooks are also applicable to PLAT. The remainder of this section describes each stage of PLAT in detail.

C. Extended Sector Sweep

To localize a user, PLAT first performs an extended sector level sweep between the AP and the user to establish which sectors to use for localization as shown in Figure 2a. This process is cooperative and is intended to establish as many non-contiguous sectors as possible. The AP beacons in each of its sectors while the user passively listens in pseudo-omnidirectional mode. Afterwards, the user reports both the sector ID and RSS for each sector it successfully decodes. The AP finds the RSS peaks and selects those as AP localization sectors—for a large planar surface like a wall, an RSS peak typically refers to a perfect reflection point, and for a smaller object, an RSS peak represents the sector pointing directly at the reflector. We collect the sector IDs of these AP localization sectors in set $L_A = \{L_{A0}, ..., L_{Ai}, ..., L_{A(N-1)}\}$, where N is the total number of selected localization sectors. The AP selects the sector with the strongest RSS as a reference sector and defines it as L_{A0}. This need not be the true shortest path sector. Afterwards, the AP sends L_A to the user.

Next, the user sweeps using its narrowest beam and pairs one of its sectors with each sector in L_A. In other words, the user must find its own set of localization sectors $L_U = \{L_{U0}, ..., L_{Ui}, ..., L_{U(N-1)}\}$. To find L_{Ui}, the AP beacons continuously in L_{Ai} while the user sweeps through its sectors, noting the RSS of each decoded beacon (Figure 2b).

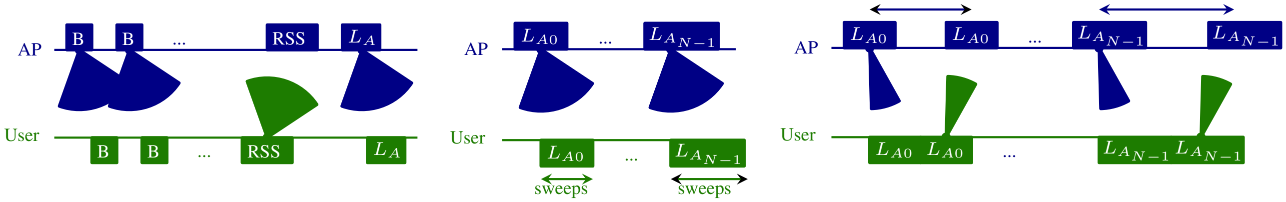
Afterwards, the user reports the angular offset (α_i) between the user sectors with respect to the strongest AP sector L_{A0}. For example, α_0=0° because L_{U0} pairs with L_{A0}. Additional information about the user's orientation is not needed. In contrast, since the AP is often a stationary entity in the room, we assume that the 0° sector's orientation is known at the AP. Accordingly, we define θ_i as the angular offset between the AP's 0° sector and the center of the localization sector L_{Ai}. An example is shown in Figure 3 where $\phi_i = \theta_i - \theta_0$.

In the event that the user is very close to the AP and the NLOS sector is weak (e.g. poor reflection materials or long propagation distance from the reflector), the LOS path may dominate the NLOS path, despite beamforming in the NLOS sector. When this occurs for a NLOS sector, the user will direct its beam at the LOS orientation for the NLOS localization sector as well. PLAT removes the NLOS sector when it detects this in order to not affect the localization accuracy.

D. Distance Measurements

After selecting localization sectors, the AP and user now have a set of communication paths. Finally, PLAT measures the approximate distance between the AP and user along each of these communication links with time difference of arrival techniques. The set of distances are defined as $D = \{d_0, ..., d_i, ..., d_{(N-1)}\}$. The AP sends a series of bits to the user on one channel, and the user simply reflects those bits back towards the AP on a second channel as shown in Figure 2c. The time difference between when the AP sends the bits and when it receives the response serves as the round-trip time (RTT) used to measure the distance. For the example in Figure 3, d_0 is directly measured via RTT, whereas $d_{AP,i}$ and $d_{PU,i}$ are not directly measurable. Nonetheless, $d_i = d_{AP,i} + d_{PU,i}$ is also directly measured.

For evaluation purposes only, we assume that users are able to measure the time of arrival with a precision of within $1\,\mathrm{ns}$. This is a modest assumption that reduces the uncertainty of



(a) Infrastructure anchor sweep (b) User sweep (c) Distance measurements

Fig. 2. An example timeline of PLAT transmissions between the AP and user. (a) The AP beacons "B" in all of its sectors. The user reports the observed RSS by sector ID, and the AP selects the localization sectors L_A. (b) For the chosen localization sectors, the AP continuously beacons while the user sweeps through its sectors. (c) A rapid bit exchange is used to measure the distance along each localization sector.

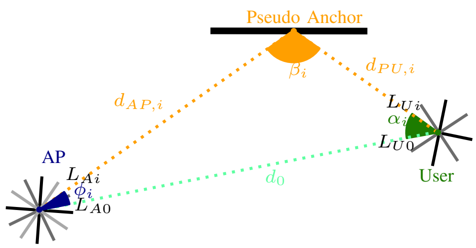


Fig. 3. An example of an AP and user who have established the LOS sector along with one NLOS sector numbered i. The NLOS sector corresponds with a pseudo anchor. PLAT measures ϕ_i, α_i, d_0 and d_i to find the user.

any distance measurement to within 15 cm. Currently, off-the-shelf chips by DecaWave known as Scensor (DW1000) are able to achieve an accuracy of 10 cm with time of flight measurements [4], so a time of flight to distance accuracy of 15 cm is a feasible assumption. The fundamentals of distance measurements and distance bounding can be found in other works [5], [6]. If the processing time at the user is fixed and known, the RTT uncertainty may be less than 1 ns by calibrating the two devices to account for this time.

E. Post-Processing Localization

With the angular offsets at the AP (ϕ_i) and user (α_i) for all localization sectors from Section II-C, and the distances from Section II-D, PLAT can now localize the user.

PLAT considers the localization sector with the shortest measured distance to be the LOS path. This need not be the sector with the strongest RSS. If L_{A0} and L_{U0} are not already the sectors with the shortest measured distance, all angular offsets α_i are adjusted so that the sector with the shortest measured distance is the point of reference. For an AP beamwidth of B_{AP}, PLAT nominates multiple linearly spaced candidate orientations for the LOS sector (centered at θ_0). We define candidate j as the user position at the geometric angle of θ_{0j} between the APs and the candidate j, where θ_{0j} is constrained as $\theta_0 - 0.5B_{AP} \leq \theta_{0j} \leq \theta_0 + 0.5B_{AP}$. With the measured LOS distance d_0 and θ_{0j}, candidate user position j can then be calculated using geometry as $X_j = AP_x + d_0 cos(\theta_{0j})$ and $Y_j = AP_y + d_0 sin(\theta_{0j})$. The set of these candidate positions is defined as $C = \{C_0, C_1, ..., C_j, ..., C_{(M-1)}\}$ where M is the total number of candidates and $C_j = (X_j, Y_j)$. In contrast to a laser-like beamwidth, the point-to-point distances for PLAT can be large. The goal of PLAT is to identify which candidate position is the most likely location of the user.

If N localization sectors are available, then $N-1$ localization sectors are NLOS created by PAs. In an ideal scenario in which beamwidths approach zero and time of flight measurements are perfect, PLAT can calculate the exact position of the ith PA as $P_i = (P_{xi}, P_{yi})$ ($i > 0$ indicates a NLOS localization sector). We first assume that the PA is created by a 1st order reflection, which creates the triangular geometry shown in Figure 3. Geometry can then be used to calculate each localization sector's propagation distance as $d_{AP,i} = d_0 \frac{sin(\alpha_i)}{sin(\beta_i)}$ and $d_{PU,i} = d_0 \frac{sin(\phi_i)}{sin(\beta_i)}$. where β_i is the only unknown angle in the triangle. With these distances, the position of the PA can be calculated as $P_{x,i} = AP_x + d_i cos(\theta_i)$ and $P_{y,i} = AP_y + d_i sin(\theta_i)$ where AP_x and AP_y are the (x,y) coordinates of the single known IA at the AP.

This process can be repeated for all PAs. However, in a system with non-negligible beamwidths, error in the true LOS orientation (θ_0, ϕ_i) and angular offset at the user (α_i) cause errors when approximating P_i. Therefore, we construct a minimization problem over θ_0, ϕ_i, and α_i.

For a given candidate position C_j and user beamwidth of B_U, the user's angular offset ($\alpha_{i,k}$) can be any angle within $\alpha_i - B_U \leq \alpha_{i,k} \leq \alpha_i + B_U$, such that $\alpha_{i,k} > 0$. The upper bound on $\alpha_{i,k}$ is B_U (i.e. when the LOS orientation and NLOS orientation are both half a beamwidth from the center). For each $\alpha_{i,k}$, PLAT calculates $\hat{d}_i$, and the absolute difference between the measured distances and the geometrically calculated distance as $\delta d_i = |\hat{d}_i - d_i|$. This process is repeated for all $\alpha_{i,k}$, and the minimum Δd_i represents the best PA$_i$ position for the candidate position C_j. This entire process is repeated for all PAs for the candidate position C_j. To approximate the probability that the user is at C_j, we sum the absolute errors for all localization sectors for a candidate as ϵ_j.

By the end of the process, each candidate position C_j has its own ϵ_j. PLAT assumes that the candidate position with the smallest ϵ is the most probable position for the user.

III. PLAT Testbed Evaluation

As a proof of concept, we implement PLAT on a custom millimeter-wave testbed in an office and localize a user at several test points. We also use the data to test accuracy as a function of the number of available localization sectors.

1) Experimental Setup: As shown in Figure 4, our custom-built millimeter-wave testbed combines a commercial VubIQ transmitter/receiver pair [7] with two Wireless open-Access Research Platform (WARP) boards [8]. WARPLab and our

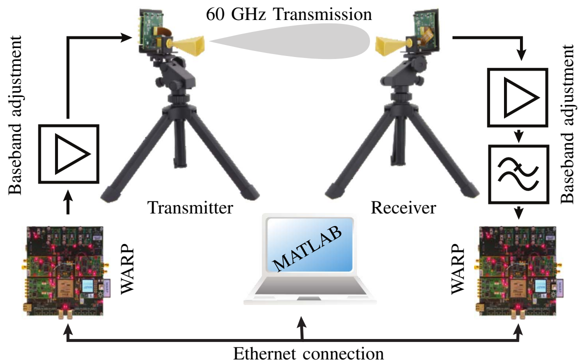


Fig. 4. Hardware setup showing the interconnection of WARP and the millimeter-wave transceivers.

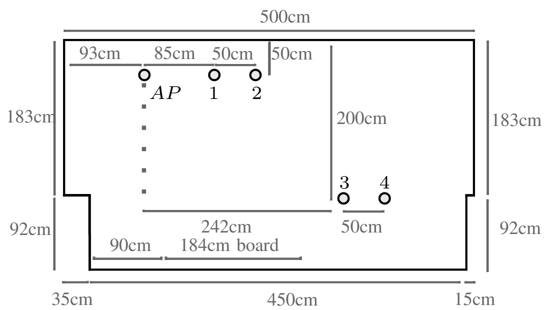


Fig. 5. The office environment used for testing PLAT. Measurements are taken on top of the office desks (100 cm above the ground). The AP rotates $180°$ whereas the receiver is stationary. The walls are made of plasterboard.

custom circuitry handles the baseband, while the VubIQ transmits and receives in the $60\,\mathrm{GHz}$ band. Since WARP's clocking limitations lead to inaccurate distance measurements, noisy distance measurements are fed to the testbed to complete the localization instead of over-the-air measurements. The accuracy of these distance measurements are varied based on existing round-trip distance measurement literature [9].

The testbed features two rotating tables with sub-degree precision and a Cinetics linear rail with sub-millimeter precision. This setup allows for accurate positioning and rotation of the transmitter and receiver during experimentation.

We deploy the wireless millimeter-wave transmitter at one end of an office shown in Figure 5. We then deploy the receiver in several positions in the room to collect RSS traces at different positions. The peaks of these RSS traces are chosen as localization sectors and run through the PLAT localization algorithm. The localization distances are calculated geometrically (not over the air) from the known office environment of the room for evaluation purposes only. Prior to localizing with PLAT, all distance measurements are perturbed with a random amount of normally distributed noise ($\mu = 0$, $\sigma = 3.75\,\mathrm{cm}$), which corresponds to the $15\,\mathrm{ns}$ assumption from Section II-D.

The AP (transmitter) uses a narrow beamwidth of $7°$. During the AP's sweep, the user (receiver) uses a wide beamwidth of $80°$ to collect as many alternate paths as possible. During the user's sweep, the AP maintains its $7°$ beamwidth, and the user narrows its beam to a $20°$ beamwidth. The AP's sweep

TABLE I

LOCALIZATION ERROR FOR 4 OFFICE POSITIONS WITH TESTBED MEASUREMENTS AVERAGED OVER 100 TRIALS (WITH 95% CIS).

Position	**Error for 3 Sectors (cm)**	**Error for 2 Sectors (cm)**	**LOS Distance (cm)**
1	4.87 ± 0.40	4.62 ± 0.44	85
2	4.69 ± 0.53	5.45 ± 0.50	135
3	4.87 ± 0.54	11.73 ± 1.48	285
4	4.87 ± 0.46	18.62 ± 2.03	328

is conducted in increments of $5°$ via the electronic rotating table, and the user averages 100 RSS values for each swept sectors. The user's device sweeps at $10°$ steps.

For comparison purposes, we remove the localization sector with the weakest RSS in a separate data set to observe how accuracy scales with number of localization sectors available.

2) Experimental Results: Table I shows the results when combining the testbed RSS traces with the perturbed geometrically calculated distance measurements. For the maximum number of reflectors (3), localization accuracy is on the centimeter scale for the given test positions, which is comparable with many indoor localization schemes. Larger distances will introduce more error to PLAT due to sector expansion. This trend is visible when using only 2 localization sectors. However, the results also show that additional localization sectors provide higher resolution, as the localization error is nearly unaffected by LOS distance when using 3 sectors. This mimics the effect that localization improves with additional IAs in traditional techniques, such as multilateration and fingerprinting. On the other hand, PLAT's PAs are completely passive and do not require any additional infrastructure.

Prior work on millimeter-wave indoor propagation has shown that 2 or more NLOS paths are available inside a typical conference room from multiple positions [10]. Furthermore, since PLAT does not need to know what causes the NLOS reflection, it can use of any object inside the room to create reflectors, such as cups or even mobile phones [11].

IV. PLAT SIMULATION EVALUATION

We also use our millimeter-wave simulator to simulate PLAT in a conference room environment. This combines the link budget and path loss models from the 802.11ad conference room channel models [12] with ray-tracing.

1) Simulation Setup: The simulator AP discretizes an empty room with plasterboard [13] walls into virtual sectors (Figure 6). This topology is non-optimal for PLAT, as the AP loses a potential reflector by being placed against a wall. The tested user positions are uniformly distributed in a grid spaced by $20\,\mathrm{cm}$. Beamforming is accomplished using a linear 1-D array of antenna elements with half wavelength spacing as a proof of concept. The number of antenna elements in the beamforming array on both parties is varied between 4 and 32 antenna elements depending on the experimental goal, which produces beamwidths between 4.3–$36°$ (IEEE 802.11ad minimum beamwidth is $\sim 3°$ [1]).

The AP uses PLAT as outlined in Section II. We fix the user beamwidth at $17.4°$ (8 ant. elements) and vary the AP

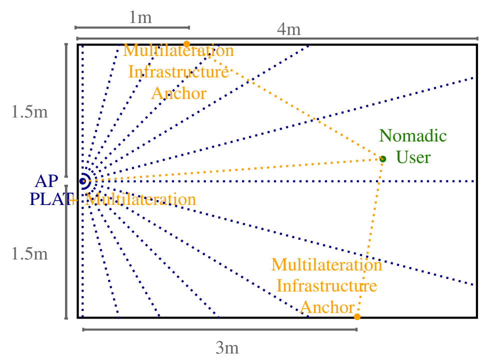


Fig. 6. Simulation topology. The AP discretizes the room into multiple uniformly distributed sectors from $-90°$ to $90°$. The angular step size equals the AP beamwidth, and the user is considered stationary during localization.

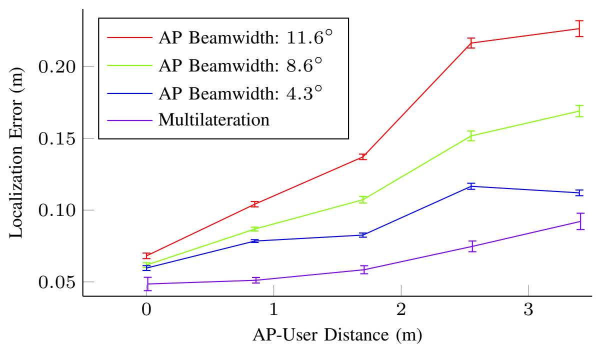


Fig. 7. Accuracy comparison for PLAT vs the traditional solution of multilateration with three IAs. Users are partitioned into bins based on their distance from the AP. Error bars represent the 95% confidence intervals.

beamwidth. All distances are perturbed by a random amount of normally distributed noise ($\mu = 0$, $\sigma = 3.75\,\mathrm{cm}$).

We also deploy 3 IAs for multilateration in the same environment (Figure 6). The user's position is calculated based on the Gauss-Newton algorithm, and the initial guess is the center of the overlapping regions created by each IA's distance measurement. Like for PLAT, no prior information about the environment is needed for multilateration.

2) Simulation Results: Figure 7 shows the localization error for different AP beamwidths along with multilateration for comparison. Each tested user position is partitioned into 5 bins based on AP-user distance, and the average error for the entire bin is plotted at the shortest distance within the bin.

The results indicate that PLAT achieves centimeter scale accuracy for AP beamwidths at or below $8.6°$ for clients within $1.5\,\mathrm{m}$ from the AP. For distances greater than $1.5\,\mathrm{m}$, PLAT achieves decimeter scale accuracy. A wider beamwidth introduces more error than a narrow beamwidth. Closer users tend to have less error because PLAT nominates candidate positions that are within the beamwidth of the LOS sector. This creates an upper bound on the error that PLAT can achieve. As distance increases, the upper bound on errors also rises.

Since there is no error in the position of the IA, Three IA LOS multilateration is always more accurate than PLAT. In contrast, PLAT must infer the position of each PA. Nonetheless, PLAT comes within 10–$15\,\mathrm{cm}$ of the accuracy of multilateration for all bins. However, prior multilateration techniques were designed for bands below 6 GHz. Since multiple APs are often not in the same room as the user, the LOS distance is not guaranteed to be measured. This can create localization errors on the order of decimeters (roughly 10–$40\,\mathrm{cm}$) for multilateration, even with NLOS suppression algorithms [14].

Note that localization errors at close positions are almost indistinguishable. At close range, potential PAs are often masked by the LOS sector because the LOS and the NLOS sectors are very close. Because transmissions are conducted with a finite codebook and non-negligible beamwidth, PLAT must localize these users with only a single sector (i.e. it simply assumes that the user is in the center of the LOS sector). Narrower beamwidths lead to more localization sectors on average. The upper limit on the operating distance depends on the AP beamwidth, and centimeter scale accuracy is achievable at nearly all points in the simulated environment for narrow beamwidths, such as $4.3°$.

V. Related Work

Existing work falls into three main categories: multilateration, angle-of-arrival, and RF fingerprinting. In the remainder of this section, we discuss works in each category along with object tracking in millimeter-waves.

A. Multilateration

In multilateration, multiple IAs are deployed which periodically announce their own location. Based on the difference in time-of-arrival, the user is able to infer its position.

Early work using multilateration focuses on multi-sensor ad-hoc systems where multiple nodes are available as potential anchors [15]. Recent work focuses on tackling the implicit assumptions of multilateration, such as perfect anchor position availability [16], and optimizing time difference of arrival accuracy [9], [17], [18]. Lights can also be used as IAs [19].

Unlike multilateration, PLAT uses highly directional millimeter-waves and only uses a single IA with a single RF-chain. Our protocol also uses distance measurements across NLOS paths instead of trying to suppress NLOS effects.

B. Angle-of-Arrival (AoA)

This technique identifies the LOS path by accessing physical layer signals and then applying algorithms such as MUSIC [20]. Afterwards, time of arrival information is used to estimate the position of the user. Recent work focuses on suppressing multipath indoors through multi-IA deployments [21], or moving the user to multiple positions [22].

Unlike angle-of-arrival (AoA), PLAT only uses a single RF chain and does not compute phase offsets. Instead, it uses the 802.11ad sector sweep mechanism to infer directional information. Furthermore, PLAT does not suppress multipath and instead relies on the presence of multipath to create PAs, allowing PLAT to localize with only a single anchor with no prior knowledge of the localization environment.

The Triangulate-Validate algorithm uses a sectorized approximation of AoA and prior knowledge of environmental reflectors to find the user [23]. PLAT uses a similar sectorized approximation, but in contrast uses over-the-air distance measurements instead of prior environmental knowledge.

C. RF Fingerprinting

This method involves wardriving the service region to create a location database. When wardriving at a discrete location, the database lists the RSS of all IAs that can be heard. The accuracy of this method depends on the granularity of the wardriving and the diversity of the IA positioning. Some popular methods include HORUS [24] and SPOT [25]. A floorplan, along with historical fingerprints of the same user, can also help refine the accuracy of fingerprinting [26].

First, PLAT does not require any prior environmental knowledge. Second, PLAT only relies on one existing IA, whereas fingerprinting relies on the diversity of multiple existing IAs.

D. Millimeter-Wave Object Tracking

Prior work has suggested using the short wavelength of millimeter-waves for object tracking. Examples include pen tracking via phase changes [27], and detecting larger known objects for robotic motion [28]. In contrast, PLAT solves a localization problem, where the user being tracked has at least one radio device, which allows PLAT to only use a single infrastructure device. This is a different problem than tracking an object of known material and shape.

VI. Conclusion

Localization with a single-RF-chain infrastructure anchor and without any prior environmental knowledge is still an unsolved challenge. In this work, we propose PLAT, an indoor localization protocol that leverages the propagation characteristics of millimeter waves. PLAT relaxes the requirement of multiple localization anchors and RF-chains for multilateration by replacing infrastructure anchors with pseudo anchors from signal reflections. Our evaluation based on testbed experiments in an office and customized simulations with the 802.11ad conference room channel model shows that PLAT achieves centimeter scale accuracy within a range of $1.5\,\mathrm{m}$ and decimeter scale at greater distances. Under a scenario where only a single LOS IA is available, PLAT's accuracy is comparable to existing localization protocols, but PLAT does not require additional RF chains nor prior environmental knowledge.

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