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PnPLoc: UWB Based Plug & Play Indoor Localization

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***Abstract*—Enabling reliable indoor localization can facilitate several new applications akin to how outdoor localization systems, such as GPS, have facilitated. Currently, a few key hurdles remain that prevent indoor localization from reaching the same stature. These hurdles include complicated deployment, tight time synchronization requirements from time difference of arrival protocols, and a lack of mechanism to allow a pan-building seamless solution. This work explores ways in which these key hurdles can be overcome to enable a more pervasive use of indoor localization. We propose a novel passive ranging scheme where clients overhear ongoing two-way ranging wireless communication between a few infrastructure nodes, and compute their own relative location without transmitting any signals (preserving user privacy). Our approach of performing two-way ranging between infrastructure nodes removes a crucial timing requirement in traditional time-difference-of-arrival methods thereby relaxing the synchronization requirements imposed by previous techniques. We use ultra-wideband wireless (UWB) radios that can easily penetrate building materials so that spanning an entire floor of a large building with just a few infrastructure nodes is possible. We build working prototypes, including the necessary hardware, and demonstrate the plug-and-play nature of our proposed solution. Our evaluation in three indoor spaces shows 1-2 meter-level localization accuracy with areas as large as $2241\,m^2$. We expect our explorations to re-trigger interest in novel applications for indoor spaces based on fine-grained indoor location knowledge.**

***Index Terms*—TDoA, improved ranging, anchor deployment**

I. INTRODUCTION AND RELATED WORK

Indoor localization is a well-studied topic over many decades. Substantial progress has been made in this space—various technologies have been explored [1]–[3], various applications have been enabled [4], [5], and high accuracy has been achieved [6]. But when one looks around one does not find deployed solutions in most buildings today. One-off deployments surely exist, but the extent of deployment is nowhere close to what decades of research would suggest. This work is an effort to view indoor localization as an end-to-end system that encompasses deployment of infrastructure and localization of client devices under one integral solution. This means anyone—may it be a manager of a large building, or a home owner, or a localization researcher—can easily install the infrastructure devices and provide localization-as-a-service for novel applications without expending tremendous deployment effort. A set of desired properties [7] that our localization solution must meet are:

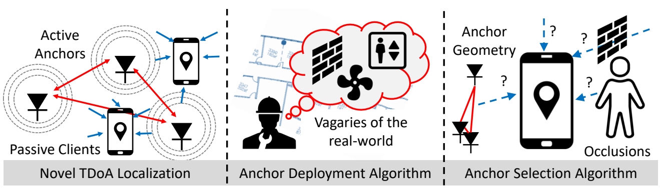

Fig. 1: PnPLoc creates an indoor localization system for passively listening clients. We focus on ease of deployment and large coverage in practical scenarios. Clients choose the anchor-set intelligently, improving accuracy.

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1) Scalability: the system should work for any number of clients in the space.
2) Privacy: the clients' location and identity should not be revealed to the infrastructure.
3) Easy deployability: the infrastructure should be easy to setup and maintain.
4) Large coverage: the solution should be able to span large spaces, thousands of square feet in area.
5) High accuracy: satisfying the requirements above, the solution must not sacrifice accuracy.

To meet the above desired properties, both hardware and software techniques must be carefully chosen. ***Which hardware should we use?*** Given that existing hardware on mobile phone, such as Wi-Fi and Bluetooth, has achieved limited success for localization in the real-world, mobile manufacturers have started exploring other options including ultra-wideband (UWB) radios [8]. UWB provides sub-meter ranging accuracy, due to its large bandwidth, and accurate multipath segregation capabilities even in complex environments. Recognizing its promise, mobile manufacturers are already incorporating UWB chips in their mobile phone offerings [9], and Google is already developing UWB stack for Android [10]. UWB based localization solutions have been extensively studied academically [4], [6], [11], all attesting to UWB's promise.

Which software protocol can enable our localization wish-list? The standardized two-way ranging (TWR) protocol [12], [13] achieves high localization accuracy by removing clock-drift errors in its formulation. However, our requirement of scalability and privacy precludes the use of TWR or any other protocol that requires the users' device to *transmit* signals for localization. We therefore focus on passive time-difference-of-arrival (TDoA) systems, where only anchors transmit and the user device can calculate its own location based on the receive time of anchor messages, satisfying our scalability and privacy requirements. However, passive-TDoA systems typically require time synchronization among anchor nodes [14], where the choice of synchronization method can affect the system cost and localization accuracy. Some commercial systems have proposed solutions where infrastructure devices are connected to a central clock-delivery system over wire [15], but doing so defeats the easy-deployability requirement. Wireless synchronization [16], [17] and asynchronous TDoA [18] solutions also exist, but they generally require all anchors to receive a common trigger, restricting solutions to a single collision domain, making them unsuitable for large deployments. Recently, concurrent ranging based TDoA systems [19], [20] have been developed that demonstrate high accuracy by employing nanosecond level scheduling of anchor messages, all observed as multiple signal arrivals in the channel impulse response (CIR) at the user's device. However, such systems **suffer from dynamic range problems** when there is a significant difference in the received signal strength from different anchors (see Fig. 2).

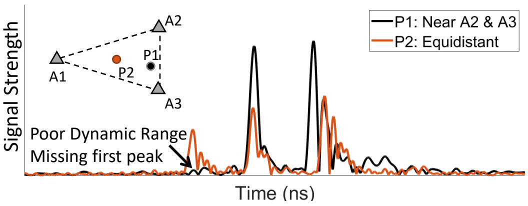

Fig. 2: Issues with concurrent ranging: Proximal anchors saturate CIR, making signals from farther-away anchors undetectable. This hampers large-scale deployment of SnapLoc [19].

In this work, we present PnPLoc, which proposes a novel underlying ranging protocol that provides the primitives to enable scalability, privacy, deployability, and large coverage, while providing comparable accuracy to existing works. We build a real-working prototype and deploy it in three large buildings spanning $695\,m^2$ ($7481\,sq.ft.$), $1208\,m^2$ ($13000\,sq.ft.$), and $2241\,m^2$ ($24122\,sq.ft.$). To the best of our knowledge, no other passive-client UWB localization scheme has been deployed to this scale.

Fig. 1 depicts our key contributions in PnPLoc:

1) A novel **time-difference of arrival (TDoA) algorithm** that removes strict timing requirements on anchor transmissions, and mitigates the effect of clock drifts thereby enabling accurate localization.
2) An **anchor deployment algorithm** that guides technicians when deploying anchors, and enhancing localization accuracy for user devices.
3) A real-time **anchor selection algorithm** to improve localization accuracy for mobile user devices.

Our contributions are central to fulfilling the requirements we outline above. Our completely wireless solution eliminates need of running synchronization cables between anchors. Our novel TDoA algorithm, for the first time, breaks away from a time-sensitive treatment of successive transmissions by anchors. This inherently allows a decoupling between executing time-difference of arrival algorithm and constraints on anchor placement; traditionally fully wireless approaches require all anchors to be within a single collision domain. Of course, while this decoupling is beneficial for expanding anchor coverage to service a large indoor space, arbitrary placement of anchors can dilute the localization precision obtained by user devices. Hence, an automated system which guides a technician to place the anchors appropriately is developed, imparting a **plug-and-play nature to our localization solution** (hence the name PnPLoc). Furthermore, while anchor deployment is a static and one-time activity, user's mobility continuously requires choosing a new subset of anchors for localization. Our method offers an opportunity for user device to choose the anchors it uses for localization. Most importantly, the solutions we present are not feasible without first upending the underlying time-difference of arrival (TDoA) protocol which forms the basis of the entire localization system, and has deep rooted implications for the choices we can make for anchor deployment and selection strategies.

We hope that through the innovations presented in this work, including the ease of deployment for technicians, a rich landscape of indoor location based applications and services can be enabled. We show in this paper that it is indeed possible to simultaneously achieve all the indoor localization goals set out above through algorithmic innovations.

We have already introduced several indoor localization systems and protocols. Here, we review the existing works on anchor deployment.

■ **Related Work in Large-scale Deployments:** Several works [21]–[24] have explored anchor placement methods to maximize the localization accuracy. Some [21], [22] only consider particular structure of anchors (e.g. in the corners). Some formulate an optimization problem and resorts to Bayesian [23] or evolutionary algorithms [24]. However, their generalizability to large buildings is limited due to the vagaries of the wireless channel. PnPLoc on the other hand, proposes an online heuristic method that can be generalized to any environment.

II. PnPLoc System Design

PnPLoc is designed as an indoor localization system that uses wireless anchor nodes installed in the infrastructure to help users navigate through the indoor space. The user is expected to carry a passive wireless listener, also **called as tag**. Whereas currently we have developed a custom tag, we expect it will be soon embedded inside mobile phones as the uptake of UWB-enabled mobile phones increases. This section describes the various design decisions we make that define the PnPLoc system. We start with an overview of PnPLoc, followed by detailed description of each of its components.

A. Design Overview

The end-to-end localization we wish to enable through PnPLoc comprises three main components: (1) A TDoA protocol that allows tags to localize by only overhearing TWR messages between anchors (Section II-B), (2) A real-time anchor deployment guidance system which tells technician where to place the next anchors for better client localization

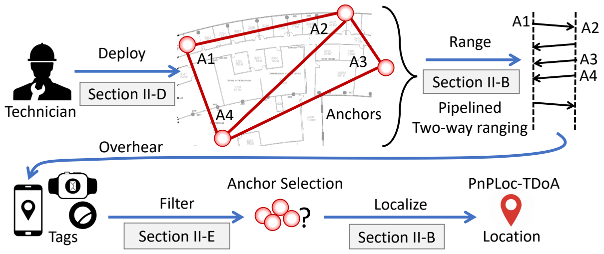

Fig. 3: PnPLoc guides the technician to deploy anchors to improve localization accuracy. Anchors exchange messages with each other which are passively overheard by user devices called tags. Tags localize themselves after filtering out low quality anchors signals for the current location.

accuracy (Section II-D), and (3) An on-device anchor selection strategy to utilize only high-quality signals for tag localization (Section II-E). Fig. 3 shows the interplay between these components.

We develop a new time-difference of arrival protocol where anchors do not just transmit wireless beacons. They also actively receive signals from other *anchors* and respond. This two-way communication between anchors provides unique opportunities to cancel out clock drifts between participating devices. Removing clock synchronization requirements has a significant advantage in adding flexibility to the deployment of anchors and extending coverage and therefore is **a major contribution of this work**.

We intend to simplify the process of deploying anchors by taking advantage of the two-way communication between anchors. The placement of a new anchor is determined dynamically by accounting for the geometry of existing anchors and the signal quality of communication between the new anchor and the existing ones. A technician can simply carry a monitoring device and move around an indoor space to explore a feasible location for the next anchor. The anchor or a supporting device will continuously update to show the technician the suitability of that location for deploying the next anchor. After deployment, user devices, or tags, will overhear communication between multiple anchors. Tags dynamically choose the anchor-set used to compute their own location. This choice allows to account for dilution of precision and signal quality experienced by the tag for each anchor's transmissions, with the intent of obtaining the best possible location accuracy.

Next, we present details of each of the above aspects and build the case for our design decisions through carefully crafted real-world experiments.

B. PnPLoc-TDoA: A synchronization free, passive tag TDoA protocol

Our novel TDoA protocol can be summarized as follows. Anchors perform TWR between themselves. Clients overhear these TWR message exchanges occurring between multiple anchor-pairs. Anchors embed their own location in the TWR messages, which allows the client devices to deduce their own locations, without sending any message.

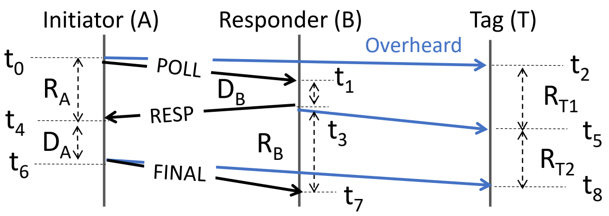

Fig. 4: Timing diagram of the PnPLoc TDoA scheme.

Consider the setup shown in Fig. 4 where anchors A and B perform two way ranging [25], with A as the initiator and B as the responder. A Tag, T passively captures the data exchanged by the two nodes and infers its own time-difference-of-arrival (TDoA) from A and B. We now formulate the TDoA based on this overheard message exchange and derive the clock-drift error based on this formulation.

Nodes A and B perform asynchronous double-sided TWR by exchanging three messages `POLL`, `RESPONSE`, and `FINAL` (refer Fig. 4), while the response delay D_A, D_B and reception intervals R_A, R_B, R_{T1}, R_{T2} are measured. The timestamps are embedded in the messages, which can be decoded by the tag. And B's measurements of R_B and D_B are embedded into the `RESPONSE` message of the next ranging cycle, or by exchanging one more packet in the same cycle (not shown).

The tag can estimate its TDoA (T_{AB}) from A and B, using any of the following three formulations:

$$T_{AB} = \frac{D_A R_{T1} - R_{T2} R_A}{R_A + D_A} + \rho_{AB} \tag{1}$$

$$T_{AB} = \frac{R_B R_{T1} - R_{T2} D_B}{R_B + D_B} - \rho_{AB} \tag{2}$$

$$T_{AB} = \frac{D_A R_{T1} - R_{T2} R_A + R_B R_{T1} - R_{T2} D_B}{2(R_{T1} + R_{T2})} \tag{3}$$

Note that since the locations of the anchors nodes A and B are known, so is the propagation delay between them (ρ_{AB}), which leads to the solution for the TDoA of T using only passively overheard data. Of course, ρ_{AB} is invariant for static anchors and may also be present as a part of the messages exchanged in the next A-B ranging.

We now show the derivation of the Equation (1) assuming exact knowledge of all time-gaps, devoid of any clock drifts. Later we will relax this assumption and derive the clock-drift based theoretical error for this scheme and demonstrate how it is minimal in practical situations and can be ignored.

Denoting the Time-of-Flight (ToF) between AB, AT, and BT as ρ_{AB}, ρ_{AT}, and ρ_{BT}, respectively, and the TDoA of A and B's messages at T as $T_{AB} = \rho_{BT} - \rho_{AT}$, we can obtain the following relations:

$$R_{T1} = \rho_{AB} + D_B + T_{AB} = R_A - \rho_{AB} + T_{AB}, \tag{4}$$

$$R_{T2} = \rho_{AB} + D_A - T_{AB} = R_B - \rho_{AB} - T_{AB}, \tag{5}$$

where D_A, D_B are the response delays, calculated by individual devices and communicated in message exchanges, and

R_A, R_B and R_{T1}, R_{T2} can be precisely measured. Rearranging the equations above leads to:

$$D_A = R_{T2} - \rho_{AB} + T_{AB}, \tag{6}$$

$$R_{T1} = R_A - \rho_{AB} + T_{AB}. \tag{7}$$

Multiplying eq. (6) and eq. (7) gives:

$$\begin{aligned} & D_A R_{T1} && (8) \\ & = (R_{T2} - \rho_{AB} + T_{AB})(R_A - \rho_{AB} + T_{AB}) \\ & = R_{T2}R_A + (-\rho_{AB} + T_{AB})(-\rho_{AB} + T_{AB} + R_{T2} + R_A) \\ & \therefore D_A R_{T1} - R_{T2}R_A \\ & = (-\rho_{AB} + T_{AB})(-\rho_{AB} + T_{AB} + R_{T2} + R_A) && (9) \end{aligned}$$

From eq. (6) we can obtain $T_{AB} = -R_{T2} + \rho_{AB} + D_A$, which substituted into eq. (9), leads to:

$$\begin{aligned} & D_A R_{T1} - R_{T2}R_A \\ & = (-\rho_{AB} + T_{AB})(-\rho_{AB} - R_{T2} + \rho_{AB} + D_A + R_{T2} + R_A) \\ & = (-\rho_{AB} + T_{AB})(D_A + R_A) \end{aligned}$$

$$\therefore T_{AB} = \frac{D_A R_{T1} - R_{T2}R_A}{D_A + R_A} + \rho_{AB} \tag{10}$$

Similarly eq. (2) can be obtained. Summing up eq. (10) and eq. (2) and using the fact that $R_A + D_A = R_B + D_B = R_{T1} + R_{T2}$ is always true, we obtain eq. (3).

Equations 1, 2 and 3 assume a global clock recording the various transmit and receive times exactly. However, real clocks are far from ideal.

In reality, the clock of A, B and T have drifts, which we denote as δ_A, δ_B, and δ_T. A global time duration Y will be measured by a device's imperfect clock with drift δ_Y as $\hat{Y} = (1+\delta_Y)Y$. Each of the $R_A, R_B, D_A, D_B, R_{T1}, and, R_{T2}$ measurements are thus measured by those respective devices through the different drift values.

Based on eq. (1), the measured $\hat{T}_{AB}$ which incorporates the various clock drifts is :

$$\begin{aligned} \hat{T}_{AB} &= \frac{\hat{D}_A \hat{R}_{T1} - \hat{R}_{T2}\hat{R}_A}{(\hat{D}_A + \hat{R}_A)} + \rho_{AB} \\ &= \frac{(1+\delta_T)(D_A R_{T1} - R_{T2}R_A)}{(D_A + R_A)} + \rho_{AB} \end{aligned}$$

The measurement error due to clock drift is:

$$\hat{T}_{AB} - T_{AB} = \frac{\delta_T(D_A R_{T1} - R_{T2}R_A)}{(D_A + R_A)} = \delta_T(T_{AB} - \rho_{AB}).$$

Similarly, the measurement error due to clock drift of the other equivalent equations can be derived to be $\delta_T(T_{AB} + \rho_{AB})$ and $\frac{1}{2}\left[(\delta_A + \delta_B)T_{AB} + (\delta_B - \delta_A)\rho_{AB}\right]$, respectively. A key observation from these expressions is that the **measurement error is a product of extremely small quantities** (drift and propagation delays).

At a maximum, UWB devices have a permissible clock drift of up to 20 ppm according to IEEE 802.15.4 [12]. Assuming the largest possible drift, the error is in the order of a few pico-seconds ($< 1\,mm$) and is not dependent on any specific protocol requirements, such as $D_A = D_B$ [12]. Therefore, the estimated $\hat{T}_{AB}$ can accurately represent the actual TDoA T_{AB}. Thus, our new TDoA scheme, called PnPLoc-TDoA, removes tight synchronization requirements that exist in traditional TDoA. This novel TDoA formulation in PnPLoc is expected to have significant impact in enabling a variety of localization schemes in the future, similar to how Decawave's improved TWR formulation [25] did, which has now been accepted into the IEEE 802.15.4z standard and forms the bedrock for several novel localization solutions [4], [26], [27].

Every anchor always shares its own location in both the `POLL` message and the `RESPONSE` message, which will help the tag compute its location from the measured TDoA. When a tag has collected 3 or more TDoA measurements from different anchor pairs, the tag computes its location based on Levenberg-Marquardt method [28].

How does PnPLoc-TDoA enable all of our desired system properties? The underlying ranging protocol *must* satisfy all of the desired properties of the final localization system (necessary condition), though the ranging protocol alone may not be sufficient to realize those properties in the final system. In PnPLoc-TDoA, the tag T never sends any messages, and calculates its TDoA based on only overheard information. This enables PnPLoc to remain privacy preserving, and scalable to an unbounded number of tags. We have removed tight synchronization requirements between anchors and any overheard TWR can be utilized for localization. This means anchors no longer need to be within one collision domain, allowing extensibility of coverage. Continuous TWR between anchors allows dynamic addition of anchors to the system, without pausing the system.

C. Anchor Messaging

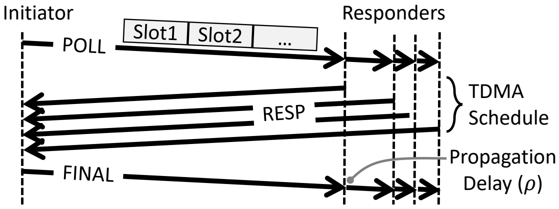

Fig. 5: Pipelined TWR with TDMA slots.

PnPLoc uses a pipelined two-way ranging scheme (see Fig. 5), which enables a single initiator to receive responses from multiple responders during each ranging cycle. The initiator sends a `POLL` message with a TDMA slot schedule selecting the order that the responders are allowed to send `RESPONSE` in this cycle. To allow the anchor network to expand, the TDMA schedule reserves a slot for new devices.

The anchor devices take turns to initiate TWR. The TWR messages are used in: (1) tag localization with PnPLoc-TDoA (Section II-B); and (2) distance measurements for real-time anchor deployment (Section II-D).

D. Anchor Deployment

The geometry of the topology described by the anchors has significant implications for the localization accuracy obtained

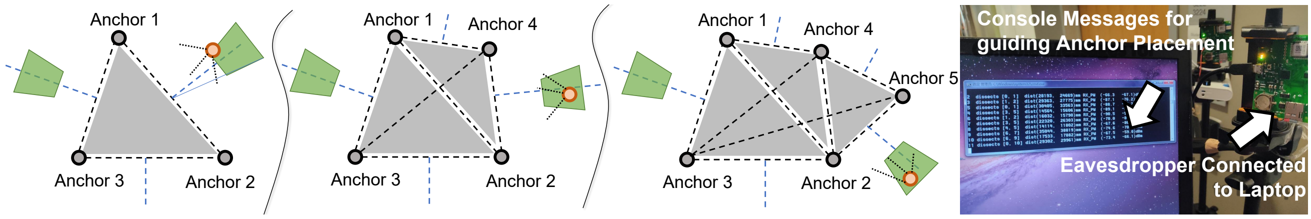

Fig. 6: Guidance for dynamic anchor deployment improves localization accuracy, while simplifying deployment.

by user devices due to a phenomenon called dilution of precision (DoP), where obliquely intersecting range-curves amplify small ranging errors into significantly larger localization errors. This effect is illustrated by simulation result in Fig. 7, where tag localization error changes under different anchor geometry. It is therefore important to deploy anchors intelligently. One extreme approach to finding the optimal anchor configuration is to solve an optimization problem offline prior to deployment, which minimizes the average tag localization error under coverage, connectivity, and practical constraints. However, this approach has several problems: (1) the optimization problem is non-convex due to real world constraints; (2) the actual constraint models, such as the path loss model of a particular building, are difficult to obtain, while simplified models can lead to non-optimal or infeasible configurations.

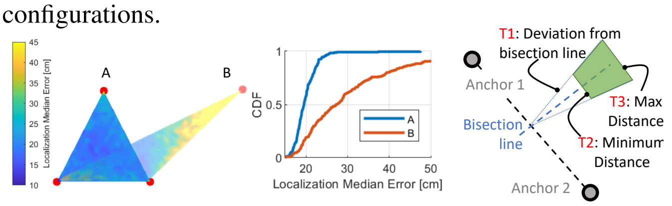

Fig. 7: The influence of anchor placement on tag localization. (a) Heatmap of Expected localization error inside the triangles. (b) CDF plot of the errors. (c) Next anchor placement strategy heuristic with thresholds.

Therefore, we propose an alternative heuristic approach to anchor deployment. With a human-in-the-loop, we plan to allow sequential deployment of anchors while ensuring a certain minimum signal strength from at least 3 of the previously deployed anchors. To reduce dilution of precision, our method utilizes the observation that anchors placed in geometrically regular shapes yield better localization accuracy [23] (see Fig. 7 (a)). However, ease of expansion of coverage, spanning irregular shaped large buildings, and variability of signal penetration at different parts of an indoor space prevent us from creating strictly regular shaped topologies. Additionally, deploying in real world will encounter issues around signal attenuation and inaccessible spaces. We therefore propose a strategy where a technician can dynamically determine a feasible region for deploying the next anchor. The core intuition is that placing the next anchor on the line bisecting two existing anchors creates an equilateral triangle which reduces DoP. PnPLoc allows a technician to walk around the indoor space and monitor how close they are to this imaginary bisecting line and to simultaneously monitor the obtained signal strength from other previously deployed anchors.

Inherently, anchor placement strategy is governed by three thresholds of import: (T1) limiting how much deviation is permitted from the bisection line, (T2) setting a minimum distance from existing anchors, and (T3) setting a worst-case signal strength. All these parameters are measurable using previously deployed anchors, and are available to the technician for decision-making. Fig. 7 (c) pictorially shows how the feasible region (green) for the next anchor placement is determined based on the above thresholds (T1–T3). Of course, this approach raises the question: *How do we determine the values of these thresholds?* Choosing the actual values for each of these thresholds entails balancing a trade-off—stricter thresholds improve localization accuracy, but make finding the right-spot more difficult for the technician. We do not wish to prescribe the choice of thresholds and instead leave those to the technicians who can best judge the needs in a particular indoor space. Our real-time feedback mechanism constantly displays measured distance and signal-strength values—currently, text-based feedback is shown on a laptop connected to a UWB eavesdropper (see Fig. 6 (rightmost)). The technician carries this device during anchor deployment. As the network expands with more anchors, the number of feasible regions also increase enabling coverage for arbitrary shaped buildings (see Fig. 6).

Our treatment of the anchor deployment problem may be relegated to being just "engineering" and not being science. Sadly, that is true. However, given the vagaries of the wireless channel, the complexities of real built environments, and the requirement of simplifying deployment, we do not see a way around it.

E. Dynamic Anchor Selection

Despite careful anchor placement during deployment, the client's mobility introduces additional challenges in large indoor spaces. First, the ranging precision obtained by UWB is subject to accurate detection of the first arriving wireless signal at the receiver. The indoor environment, rich in multipath and non-line-of-sight (NLoS) conditions, can degrade the signal quality significantly, causing higher ranging errors. Second, DoP also affects the final localization error, which depends on the *geometry described by the anchors' locations* relative to the tag. DoP exists in GPS localization as well, which is overcome through a careful selection of participating satellites to obtain better localization accuracy.

In our proposed PnPLoc-TDoA, because different anchors alternate to initiate TWR (Section II-C), the tag overhears TWR messages from a changing set of anchors over time. This enables the tag to select the subset of anchors used to perform localization, that results in better accuracy. Therefore, we propose a two-stage anchor selection method: (1) filtering out received messages with low received power; (2) considering all subset of overheard anchors, choose the best subset measured by Geometric Dilution of Precision (GDoP) [29], [30]. We further reject any solutions whose GDoP is worse than a threshold value to eliminate poor anchor sets.

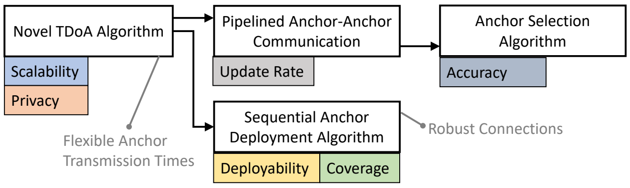

Fig. 8: Various modules of PnPLoc together satisfy all of our localization requirements.

Overall, our novel PnPLoc-TDoA algorithm, anchor placement strategy, and dynamic anchor-selection enables accurate localization in a large space without limits on number of tags it can help localize (see Fig. 8). We now describe our evaluation setup followed by our evaluation results.

III. IMPLEMENTATION

In our implementation both the tags and anchors run on Cortex M0 microcontrollers on Adafruit Feather M0s. The microcontroller governs the working of the UWB hardware and stores the computed timing and signal strength information. We use an existing UWB hardware module [31] based on Decawave DWM1000, which is interfaced with the Adafruit Feather M0. The UWB module uses $4\,GHz$ central frequency with $1\,GHz$ bandwidth, compliant with IEEE 802.15.4 [13]. Our current prototypes store all message timing information and signal strength information on an SDCard. This information is then processed in Matlab for easier evaluation of the various aspects of localization discussed in this work. We have also developed a special eavesdropper UWB device that captures all ongoing message exchanges and logs them to a laptop (see Fig. 6). This laptop aids in placement of anchors as described in Section II-D in real-time. We compare PnPLoc with One-way Wireless TDoA [16] by using the available code [32] installed on Decawave TREK1000 devices, thereby recreating the setup used by the authors of [16] for a fair comparison. Fig. 9(a) shows one of our indoor test-beds. Our custom hardware used is shown in Fig. 9 (b, c).

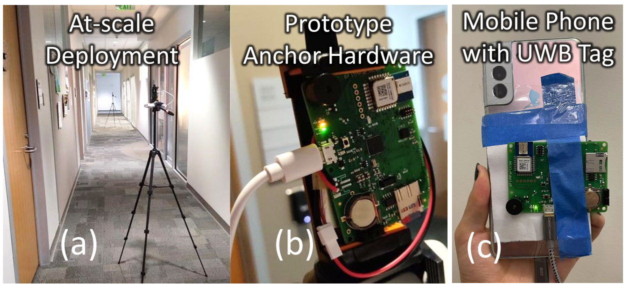

Fig. 9: PnPLoc implementation: (a) Sample anchors on tripod as part of at-scale experiments, (b) Our prototype anchor hardware platform, (c) The user device that consists of a mobile phone equipped with UWB tag.

IV. EVALUATION RESULTS

PnPLoc aims at creating a localization system that is inherently easy to deploy, scalable, and privacy preserving. While these attributes are a property of our system design, they are not straightforward to evaluate. Our evaluation setup attempts to show the promise enabled by PnPLoc by deploying the setup in three separate indoor spaces demonstrating the ease of deployment. We co-locate multiple tags in our mobile experiments to show that additional tags do not affect the obtained update rate or location accuracy.

A. At-scale Evaluations

Our final system has been deployed in three indoor settings—Area A ($695\,m^2$), Building L ($1208\,m^2$), and Building K ($2241\,m^2$), spanning a large indoor atrium and two buildings. All the experiments performed for at-scale evaluations were performed in buildings with normal day-to-day activity—other people were present in the building at the time of these experiments and were freely moving around, bringing our evaluations close to real-world use cases. Due to pandemic restrictions, the anchors were deployed in corridors and open spaces only, causing additional constraints on anchor deployment heuristic.

■ **Open Atrium Mobile Experiment:** Most existing TDoA UWB localization systems have been evaluated in small indoor areas, spanning a couple of rooms. To establish a similar baseline, we first evaluate PnPLoc in Atrium A and perform a head-to-head comparison[1] with One-way Wireless TDoA [16] (we implement it on similar hardware as the original work) using co-located anchors and identical walking path in Fig. 10. PnPLoc achieves 75% error of $28.9\,cm$, and 90% error of $44.0\,cm$. Atrium A covers a $24.5m \times 28.3m$ area, which is several times larger than the test area of many previous works. We observe that the accuracy of PnPLoc-TDoA and One-way Wireless TDoA is comparable, if we do not perform anchor selection. However, PnPLoc outperforms competition when anchor selection is enabled.

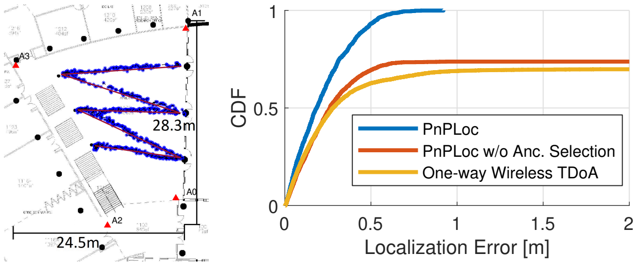

Fig. 10: Influence of anchor selection. (a) PnPLoc tag localization. (b) CDF comparison of PnPLoc, PnPLoc without anchor selection, and One-way Wireless TDoA.

■ **Large Building Mobile Experiments:**

Fig. 11 shows the localization accuracy for 3 co-located mobile tags walking through the corridors of Building L—a total length of $52.7\,meters$. The qualitative observation clearly outlines the path taken during the walk. Quantitative

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[1] While we would like to also compare with concurrent ranging techniques [19], the code is not available as of this writing.

calculations are performed by marking the approximate ground truth trajectory on the map and then finding the distance of each computed location from this trajectory. We observe a sub-meter overall accuracy at the $75^{th} percentile$ for all tags with average update rate of 2.5-3 Hz.

Building K (see Fig. 12), with walking length of approximately $141\,meters$, showed similar pattern with $75^{th} percentile$ localization error around $1\,m$, demonstrating the utility of PnPLoc. Notice Building K is a significantly larger space with over 30 rooms and a large open area, and the tag almost always experiences several NLoS links where the signal penetrates at least one wall. Some sections of the trajectory obtain low-signal strength from anchors and therefore the density of obtained location estimates is not uniform along the route. This observation is in line with the poor DoP observation for static experiments. The average update rate was above 1 Hz, similar to typical GPS update rates, for the entire trajectory after filtering out low-signal strength messages and those from poor DoP anchors.

Most existing schemes would not allow such a large area to be covered due to single-collision domain restriction in One-way Wireless TDoA [16], and dynamic range restrictions imposed by concurrent ranging schemes [20] respectively.

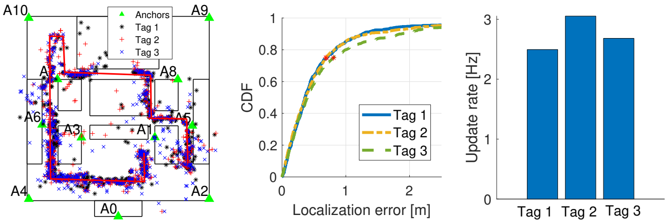

Fig. 11: Building L with 3 co-located mobile tags: (1) solution scatter plot; (2) localization error CDF; (3) update rate.

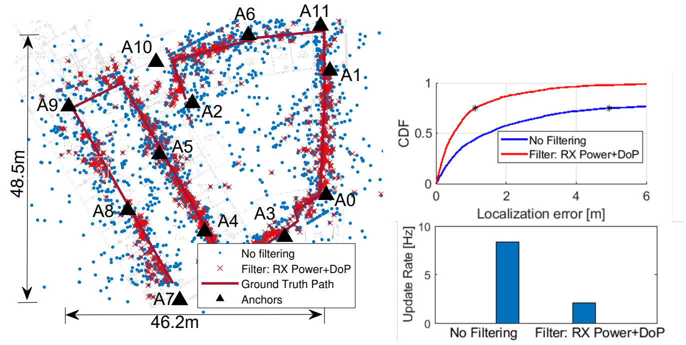

Fig. 12: Localization result of mobile tag in Building K: (a) scatter plot, (b) update rate and accuracy.

■ **Static Tag Experiments:** Fig. 14 and Fig. 13 show the localization accuracy obtained from a total of 23 different static locations in Building K and L. We have shown both the scatterplot as well as the error CDF to show visualizations of localization results and quantitative analysis. The average localization accuracy is $< 1\,m$ while the $75^{th} percentile$ accuracy is $\approx 2\,m$ for almost all static locations. For location $T12$ in Building K, the accuracy is lower due to the poor geometric DoP from the anchors it can reliably overhear. Note that dead-spots like these exist for all localization schemes, but the extent of localization error depends on the quality of the ranging scheme. Even a few centimeters of ranging error can translate to large localization errors in large scale setups.

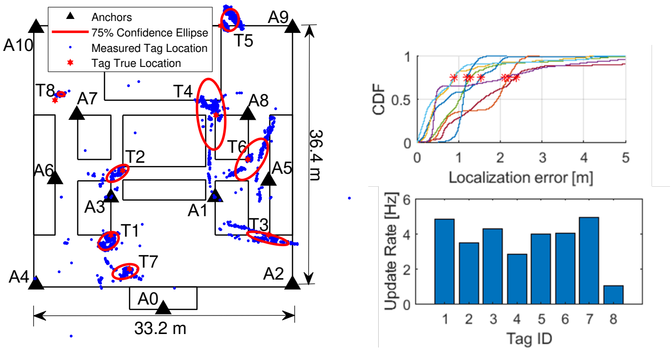

Fig. 13: Localization scatter plot, error CDF and update rate for 8 static tags in Building L ($1208m^2$ area).

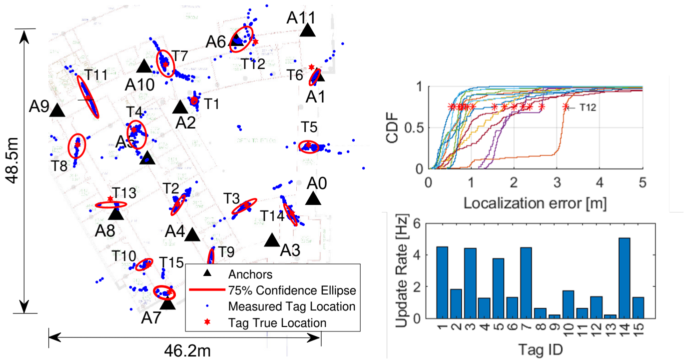

Fig. 14: Localization scatter plot, error CDF and update rate for 15 static tags in Building K ($2241m^2$ area).

Table I helps put our overall results in perspective when compared with other state-of-art wireless TDoA systems.

System	75% error	90% error	Test area
PnPLoc	28.9 cm 69cm 110cm	44.0 cm 125cm 251cm	A 695 m^2 (1304 samples) L $1208m^2$ (2329 samples) K $2241m^2$ (1139 samples)
SnapLoc [19]	55.8-74 cm	NA	31.36-60.5 m^2
CHORUS [20]	~80 cm	~100 cm	42.0-83.2m^2
TALLA [33]	69 cm	89 cm	1875 m^2

TABLE I: Comparison of localization error between PnPLoc and other state-of-art wireless localization solutions.

B. *Micro-benchmarks*

We now highlight the utility of the anchor deployment and anchor selection, with smaller, more controlled setups with limited human activity and disturbances.

1) Is anchor placement important?: Suppose 3 anchors, A1-A3 (Fig. 15(a)), have been already deployed. Now the question is: where to place the fourth anchor? Two candidate locations are compared in Fig. 15(a): location A is on the bisecting line of edge A1-A3, while location B is not. Fig. 15(b) shows that five arbitrarily placed tags in the vicinity obtain better localization precision for Location A, demonstrating the benefit of PnPLoc's anchor deployment. Note that the anchor deployment strategy was followed in all the previous large scale experiments, which showed high localization accuracy.

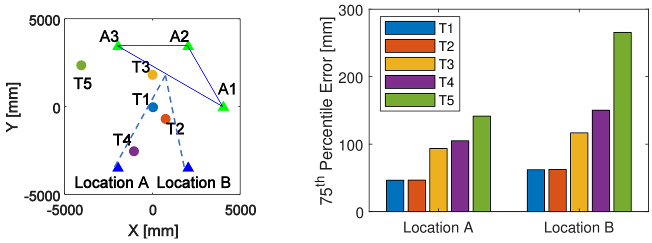

Fig. 15: Anchor Deployment: Localization error reduction

2) Is anchor selection important?: The open-atrium mobile experiment (Fig. 12) demonstrates the benefit of anchor selection. Dynamic anchor selection allows seamless transitions into new regions without sacrificing localization precision.

V. CONCLUDING REMARKS

PnPLoc represents an end-to-end UWB localization solution that supports large scale deployment of UWB anchors and localization of an unlimited number of client devices. Our novel TDoA protocol makes deployment easier, and improves localization accuracy. We are hopeful that by setting ease of deployment as one of the goals of this work, we have paved the way to accelerated adoption of UWB indoor localization.

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