Poster Abstract: Scaling Device-free Indoor Tracking based on Self Calibration

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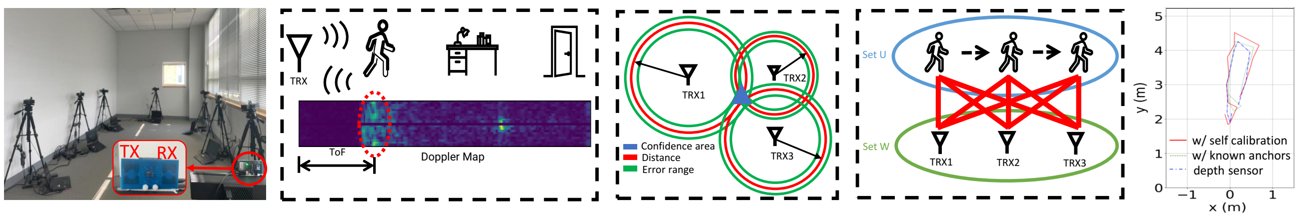

(a) Setup with distributed sensors (b) Distance Measurements (c) Localization (d) Self Calibration (e) Trajectories

Figure 1: The system overview of *SCALING* (Self-Calibrating Indoor Tracking). (a) It is a plug-and-play device-free indoor tracking system using distributed monostatic radars, each configured with a single pair of TX and RX. (b) Through range-Doppler profiles, the human subject can be detected for distance measurements in a cluttered environment. (c) Localization is based on multilateration combining simultaneous distance measurements from distributed nodes. (d) The self calibration of sensor placements eliminates the need of intensive manual calibration effort by optimizing the residual error of distance measurements to the person walking a trajectory based on a mass-spring model. (e) The estimated trajectories demonstrate that the tracking results with self calibration are comparable to those with known anchors, against the ground truth from depth sensors.

ABSTRACT

The democratization of indoor tracking systems lays the groundwork for a wide spectrum of smart home applications. While prior work on RF-based device-free localization/tracking have shown preferable features and promising results, they heavily relied on well-calibrated sensor placements, which require hours of intensive manual setup and respective expertise, making it prohibitively expensive to scale deployments to wide range (e.g., tens or hundreds of real homes). We propose *SCALING*, a plug-and-play indoor tracking system, of which the key enabler is a self calibrating algorithm that estimates the distributed sensor locations through their distance measurements to a person walking a trajectory, a trivial effort without taxing layman users physically or cognitively. We have experimentally evaluated *SCALING* via real world testbeds and shown an 80-percentile tracking accuracy of 40.5 cm, only 1% degradation compared to the classical multilateration with known sensor locations (anchors), which costs hours of intensive calibrating effort.

CCS CONCEPTS

• Applied computing → Health informatics; **• Human-centered computing → Ubiquitous and mobile computing systems and tools**.

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KEYWORDS

Radio Frequency (RF) Sensing; Self Calibration; Indoor Tracking; Device-free; Local Positioning System; Distributed Monostatic Radars

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1 INTRODUCTION

The democratization of indoor tracking systems enables continuous monitoring of the inhabitants' daily trajectories, and herein lays the groundwork for a wide spectrum of smart home applications. Two typical examples are: 1) smart home HVAC systems can dynamically adapt to users' current and potential trajectories/locations for better user experience and energy saving; 2) the duration and frequency of activities in certain functional spaces, such as the bathroom, can be extracted from daily trajectories as a new dimension of biometrics for health analytics (e.g., monitoring Alzheimer's, dementia based on behavior patterns).

Research in device-free schemes further pushes the limits of application scenarios, where users do not need to carry or wear any devices [4–6]. Various sensing modalities have been explored including vision, acoustic and structural vibration, however, they may incur privacy concerns, be susceptible to background noise, or require costly refurbishment for large coverage. While RF techniques have shown preferable features, they usually rely on well-calibrated sensor placements, which require hours of intensive manual setup and respective expertise to determine their 2D/3D coordinates, feasible only at small scale and by mostly researchers themselves. Scaling the deployments to tens or hundreds of real homes, however, would incur prohibitive manual efforts, and become infeasible for layman users.

In this paper, we present *SCALING*, a plug-and-play device-free indoor tracking system that a layman user can easily set up by walking a one-minute loop, suitable for large scale self installation [3]. The key enabler, self calibration of sensor placements, is achieved by optimizing the residual error between the measured distance through RF signal and the hypothesized distance (between the sensor location and the corresponding step location in a hypothesized configuration). The configuration of sensor locations with minimum residual errors of distance measurements is considered as calibrated sensor placements, and then combined with their respective distance measurements for indoor tracking using multilateration. Experimental results show that we can save hours of intensive calibrating effort from experts, yet achieving comparable indoor tracking performance at the cost of negligible (only 1%) degradation in accuracy.

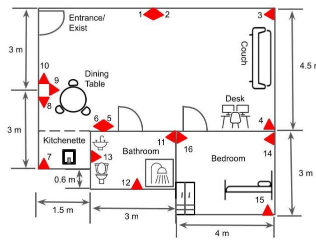


Figure 2: The floor plan indicates distributed sensor placements in a cluttered home environment.

2 SYSTEM DESIGN AND IMPLEMENTATION

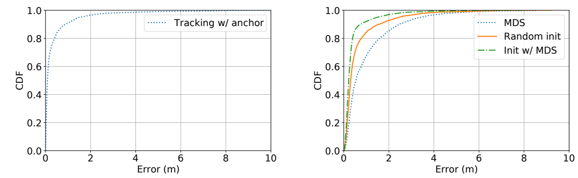
Figure 1 shows the overall framework of *SCALING*. The key enabler of *SCALING* is a self calibration algorithm which formulates the problem in a bipartite graph and leverage its rigidity to obtain the uniqueness of geometrical topology of sensor locations. It estimates sensor locations by finding the configuration with minimum stress in a virtual mass-spring model [3], based purely on distance measurements between the hypothesized sensor locations and step locations in walking trajectories. Upon the convergence of self calibrating process, we use the estimated sensor locations as pseudo anchors for multilateration. In addition, we adapted MDS to provide the self calibrating process with a reliable initial coordinate assignment with a similar geometrical topology to the ground truth, such that the mass-spring model can easily converge at a global minimum rather than a local minimum.

SCALING is designed without loss of generality because it works with minimum requirements on RF sensors (i.e., only capable of distance measurements) and is compatible and extensible with more advanced RF devices (e.g., those able to measure angles of arrival (AoA) or node-to-node pairwise distances).

We implement a prototype of *SCALING* with commercial-off-the-shelf (COTS) UWB sensors, each of which is a monostatic radar, configured with a single pair of transmitter (TX) and receiver (RX). Sensing data (e.g., distance measurements) from distributed sensor nodes have been synchronized through the Network Time Protocol (NTP) and forwarded to a central server for further computation (e.g., self calibration and localization/tracking).

3 EVALUATION

We evaluated *SCALING* by conducting indoor tracking experiments in real-world testbeds, shown in Figure 2. We invited volunteers with no expertise in calibrating sensor placements for data collection, during which they walked freely in the monitoring space to emulate the natural indoor trajectories as users will be performing in a real world scenario. We used the co-located depth sensor (Kinect v2) for ground truth. For the evaluation purpose, we transformed the estimated relative sensor locations from the self calibrating process in a local coordinate system to align with the global coordinate system through Procrustes analysis [1] (with a composition of translation, rotation, and reflection). As shown in Figure 3(b), tracking based on the proposed self calibrating method combined with the adapted MDS [2] for initial coordinate assignments achieves 80-percentile tracking accuracy of 40.5 cm, outperforms the adapted MDS as a baseline by 1.6m. Such results imply that our system can save hours of intensive manual calibration efforts at the cost of negligible (1%) degradation in tracking performance compared to tracking using well calibrated anchors (of known sensor locations) shown in Figure 3(a).



(a) Tracking with anchors (of known sensor locations).

(b) Tracking w/o anchors, but w/ estimated sensor locations from different self calibration approaches.

Figure 3: Evaluation of tracking performance in CDF. (a) w/ anchors; (b) SCALING (init w/ MDS) improves on random initial coordinate assignment, and outperforms MDS as a baseline for self calibration.

4 CONCLUSION AND FUTURE WORK

In this work, we present *SCALING*, a plug-and-play device-free indoor tracking system using distributed RF sensors that a layman user can easily set up by one-minute walking based on a self calibration algorithm, which saves hours of intensive manual efforts and technical expertise at the cost of negligible degradation in the end-to-end performance. We believe *SCALING* paves the way for democratization of indoor tracking system, facilitating broad smart home applications. In the future, we plan to apply *SCALING* to spaces (e.g., houses, rooms) of different layouts, cohabiting scenarios, where there exist multiple users to understand its limitations. Further, we plan to collect more diverse data in real life scenarios for health analytics with long-term daily indoor trajectories.

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