Towards Fine-grained Smartphone Localization via Low-complexity Anchors

Kaikai Liu, and Xiaolin Li
Scalable Software Systems Laboratory
University of Florida, Gainesville, FL 32611
kaikailiu@ufl.edu, andyli@ece.ufl.edu

ABSTRACT

To enable indoor location-based services (ILBS), there are several stringent requirements for an indoor localization system: highly accurate that can differentiate massive users' locations without site-survey; no additional hardware components or extensions on users' smartphones; scalable to massive concurrent users. In this paper, we propose a practical and accurate smartphone localization solution via low-complexity anchor nodes. Specifically, we design and implement a low-complexity anchor network with a coordination protocol to transmit modulated localization beacons using high-band acoustic signals, a realtime processing app in a smartphone, and a backend server for indoor contexts and location-based services. Our prototype shows high accurate localization accuracy via off-the-shelf smartphones. Such practical and accurate solution is expected to add real values to ILBS and our daily activities.

1. INTRODUCTION

From a methodology point of view, time-of-arrival (TOA) based ranging approaches tyically achieve better localization accuracy and robustness than fingerprinting-based [1] and other energy-based ranging approaches [2, 3]. Due to easy access to the existing infrastructure, fingerprinting-based and energy-based approaches are more popular than TOA. The TOA ranging accuracy directly depends on the bandwidth (B) and the transmission speed (c) of the operating signal with a simple relationship shown as ($\sim c/B$) [5]. Using Bluetooth, WiFi or Cellular signals, the achievable TOA ranging resolution is larger than 100 meters due to their relative narrow bandwidth (MHz level). This is why fine-grained location information is expensive to obtain in a smartphone. On the contrary, narrow band acoustic signal could achieve centimeter-level ranging accuracy due to its significant low transmission speed. Authors in [7] proposed distinct approaches to demonstrate the feasibility of using pervasive microphone sensors as a main or auxiliary way for location sensing. However, several major problems associated with the audible-band acoustic approach have not been conquered yet, i.e., the inherent sound interference in real environments, limited bandwidth and power of acoustic signal.

We propose an indoor localization system via low-complexity acoustic anchors. We make the acoustic beacons imperceptible to humans and improve detection sensitivity for better location coverage. Rather than simply using "Beep" signals and suffer from limited user capacity, we design the transmission waveform, wide-band modulation, anchor network synchronization via radio, and one-way acoustic synchronization and ranging schemes to enable passive sensing for multiple smartphone users. To reduce the randomness of radio arrival time during anchor network synchronization, we utilize real-time operating system and low-level hardware firmware programming to ensure timing accuracy. To handle the unknown arrival time of multiple mobile users in passive acoustic beacon sensing, we model the unknown time in location problem formulation and perform jointly estimation during computation. To improve the accuracy of ranging, we propose a fine-grained adaptive time-of-arrival (TOA) estimation approach that exploits the channel information of the beacon signal and signal-to-interference ratio. By combining all these techniques together, we implement the prototype system with anchor nodes and localization processing app in a smartphone, and make it work in realistic environment.

2. SYSTEM ARCHITECTURE

Leveraging our wireless anchor network prototype, our indoor localization system consists of an app in a smartphone that adopts the non-assisted passive mode to avoid random-access interference and multi-user division issues in the system. A plurality of sensor nodes as preconfigured anchor constellation to broadcast acoustic beacon. Because of the non-assisted passive mode of the system, the location system can be highly scalable to support hundreds of users simultaneously in a large indoor space, e.g., museums, job fairs, and shopping centers. Moreover, the position information can be calculated locally on a smartphone without reporting to the third-party servers, making it privacy-proof if desired.

To meet our long term objective, we design the low-complexity anchor node from scratch using the TI MSP430 microcontroller and CC2533 Zigbee chip. An app on a smartphone (e.g., an iOS or Android mobile device) is designed to perform signal detection, ranging, and localization (the localization step can be optionally offloaded to the server). The

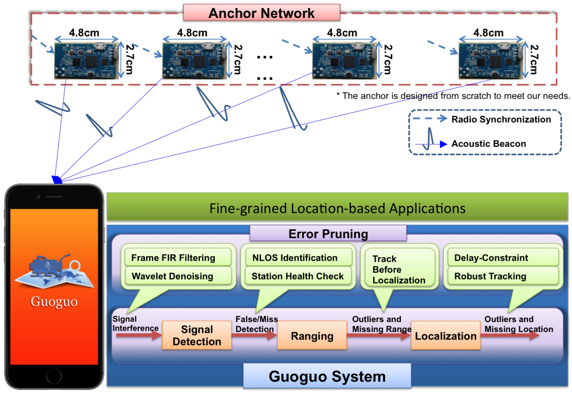

Figure 1: System Architecture.

architecture of the localization system is shown in Fig. 1.

3. LOCALIZATION PROCESS

3.1 Basic Procedures

Each sampling point of the received acoustic signal vector $\mathbf{r_j}$ can be modeled as

$$r_j(k) = \sqrt{\epsilon} p_j \cdot g(k - k_j) + n_j(k) + I_j(k), k = 1, \ldots, K \quad (1)$$

where ϵ is the transmitted pulse energy; p_j is the information bit; $K = T_s F_s$ is the total sampling points in one symbol duration; $n_j(k)$ and $I_j(k)$ are the noise and interference term.

Localization in a smartphone involves three key steps:

- **Signal Detection:** Detect the acoustic signal $g(k)$; Decode the $\hat{p}_j$ associated with the current symbol ($\hat{p}_j$ is the estimated version of p_j, with the vector term as $\hat{\mathbf{p}}$); Perform code matching with the pre-stored pseudocode sequence $\mathbf{p_m}$, obtain the station id m for the j-th symbol.
- **Ranging:** Estimate the sampling point of TOA path $\hat{k}_j$ for the j-th symbol as the pseudorange; Associate the TOA measurement $\hat{k}_j$ to the m-th anchor node and l-th index of the pseudocode $\mathbf{p_m}$; Convert $\hat{k}_j$ into the base symbol time ($j = 1$) and add it into the vector of TOA measurement $\mathbf{k}_m = [\hat{k}_j - jT_sF_s, \ldots]$.
- **Localization:** Using M pseudoranges $\hat{\mathbf{r}}_m = \mathbf{k}_m v_s / F_s$ and the preconfigured coordinates of anchor nodes $\mathbf{x}_m$ to estimate the position of the smartphone $\mathbf{y}$ by minimizing the quadric term of the remaining error $\varepsilon_m = ||\hat{\mathbf{r}}_m - (||\mathbf{y} - \mathbf{x}_m||_2 + \delta_r)||_2$, where δ_r is the unknown delay that compensates the difference between the pseudorange and real distance.

3.2 Optimization

Our previous work [6] illustrates the process of using acoustic signal for non-assisted passive localization, e.g., signal modulation and demodulation, one-way synchronization of the smartphone-anchor pair, radio synchronization for the anchor network, code-matching for anchor node identification, and TOA ranging and localization. Leveraging these works on basic signal modulation, synchronization, and TOA ranging and localization, this paper focuses on breaking the bottlenecks of audible-band acoustic localization under severe noise and interference. We propose a suite of error mitigation algorithms to improve the robustness of the whole system as shown in Fig. 1. Specifically, we perform preprocessing before signal detection, then apply cluster detection and spectrum matching to identify signal-like interference. During localization, we propose track-before-localization, delay-constraint semidefinite programming (DC-SDP), and outliers-robust filtering to smooth users' location traces for further robustness.

4. REFERENCES

[1] Y. Chen, D. Lymberopoulos, J. Liu, and B. Priyantha. Fm-based indoor localization. In *Proceedings of the 10th international conference on Mobile systems, applications, and services*, pages 169–182. ACM, 2012.

[2] I. Constandache, S. Gaonkar, M. Sayler, R. Choudhury, and L. Cox. Enloc: Energy-efficient localization for mobile phones. In *INFOCOM 2009, IEEE*, pages 2716–2720. IEEE, 2009.

[3] M. Kjærgaard, J. Langdal, T. Godsk, and T. Toftkjær. Entracked: energy-efficient robust position tracking for mobile devices. In *Proceedings of the 7th international conference on Mobile systems, applications, and services*, pages 221–234. ACM, 2009.

[4] P. Lazik and A. Rowe. Indoor pseudo-ranging of mobile devices using ultrasonic chirps. In *Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems*, pages 99–112. ACM, 2012.

[5] J. Lee and R. Scholtz. Ranging in a dense multipath environment using an UWB radio link. *IEEE Journal on Selected Areas in Communications*, 20(9):1677–1683, 2002.

[6] K. Liu, X. Liu, and X. Li. Guoguo: Enabling fine-grained indoor localization via smartphone. In *Proceedings of the 11th international conference on Mobile systems, applications, and services*. ACM, 2013.

[7] Z. Zhang, D. Chu, X. Chen, and T. Moscibroda. Swordfight: enabling a new class of phone-to-phone action games on commodity phones. In *Proceedings of the 10th international conference on Mobile systems, applications, and services*, pages 1–14. ACM, 2012.