Poster Abstract: µ-BeepBeep: Low Energy Acoustic Ranging on Mobile Devices

Gurmanjeet S. Sidhu¹, Arundeep Kamboj¹, Prasant Misra², Salil Kanhere³, and Sanjay Jha³

¹ Indian Institute of Technology, Patna, India
² Swedish Institute of Computer Science, Stockholm, Sweden
³ University of New South Wales, Sydney, Australia
{g.sidhu,a.kamboj}@iitp.ac.in¹
prasant@sics.se²
{salilk,sanjay}@cse.unsw.edu.au³

Abstract. We present µ-BeepBeep: a low energy acoustic ranging service for mobile phones. µ-BeepBeep combines the efficacy of the basic BeepBeep ranging mechanism with a light-weight cross-correlation mechanism based on sparse approximation.

1 Introduction

Range (or proximity) information of high accuracy is a key enabling technology for many emerging applications in mobile sensing [1]. In retrospect, the development of this capability using commodity software and hardware (such as speakers, microphones, and wireless communication interfaces) is greatly beneficial as it can be readily used in commercial off-the-shelf (COTS) devices such as smart phones. The realization of this vision was pioneered by the BeepBeep [1] system. The key idea was to use the pairwise differential-time-of-arrival (DTOA) of acoustic signal between two devices to estimate their separation distance. The DTOA mechanism allows the local device clocks to run asynchronously and provides a mathematical way to compensate for the clock difference.

The ranging operation in BeepBeep involves three basic operations: (i) two-way sensing of audio signals, (iii) time-of-arrival (TOA) estimation, and (iii) TOA exchange between the two devices over a radio (WiFi) link to compute the distance. The TOA estimate is obtained by a matched filter that measures the time instance at which the reference signal (i.e., a locally stored copy of the original transmitted signal) yields the largest cross-correlation with the received signal. Although, cross-correlation is able to precisely recover timestamps, it is computation and power exhaustive due to greater resource requirements and longer execution time. Towards this end, we are motivated by our recent work [2] wherein an efficient implementation of cross-correlation (via sparse approximation) was demonstrated on resource constrained wireless sensor network platforms. Here, the key idea was to compress (rather than cross-correlate) the acoustic signal samples on the receiving device by efficient random projections.
and transfer them to a base-station (BS). The BS, then, estimates the range from the limited information by solving the $\ell_1$-minimization problem efficiently. While smart phones have good resources for implementing cross-correlation, their longer execution time leads to greater energy usage that affects the battery life that is limited on these devices.

In this preliminary work, we present $\mu$-BeepBeep: a low energy acoustic ranging service for mobile phones. $\mu$-BeepBeep combines the efficacy of acoustic waveforms, DTOA and sparse cross-correlation into a single ranging framework. Our preliminary results, using $\mu$-BeepBeep, shows $\approx 2.5$ times improvement in speed and similar ranging performance as BeepBeep.

2 System Architecture

Fig. 1 shows the system architecture of $\mu$-BeepBeep with only two mobile devices A and B. The basic ranging technique, similar to BeepBeep, is as follows. A two-way reception is performed where device A emits a signal at $t_{A0}$, which is recorded by itself at time $t_{A1}$ and device B at time $t_{B1}$. Similarly, the same tasks are performed when device B transmits the signal at $t_{B2}$, which is recorded by itself at $t_{B3}$ and device A at $t_{A3}$. Therefore, the received traces on each device should have two signals, one transmitted from the other device and one from itself.

The detection and post-processing mechanism is implemented in two-phases. In the following, we explain it for a single transmit-receive operation as the reverse mechanism is an exact replica of this scheme. Let $\mathbf{p} \in \mathbb{R}^{n_p}$ and $\mathbf{x} \in \mathbb{R}^{n_a}$ represent the transmitted and the received signal vectors, where $0 \leq n_p, n_a \leq \infty$ and $n_a \geq n_p$.

**Compression:** At each device, the dimensions of $\mathbf{x} \in \mathbb{R}^{n_a}$ are significantly reduced by multiplying it with a random sensing matrix $\Phi \in \mathbb{R}^{m \times n_a}$ resulting in the measurement vector $\mathbf{y} \in \mathbb{R}^{m}$ ($m \ll n_a$) as:

$$\mathbf{y} = \Phi \mathbf{x}$$

(1)
$m$ is related to $n_a$ by the compression factor $\alpha$ given as: $m = \alpha n_a$ where $\alpha \in [0, 1]$. $\Phi$ is a binary sensing matrix with its entries identically and independently (i.i.d.) sampled from a symmetric Bernoulli distribution. The $m$ samples of $y$ are transferred to the BS using the File Transfer Protocol (FTP) service.

**Reconstruction and Detection:** The BS requires the a-priori knowledge of the seed that generates $\Phi$ and the correlation dictionary $\Psi$. $\Psi \in \mathbb{R}^{n_a \times (2n_a - 1)}$ is the positive and negative time shifted Hankel matrix of $p$. The importance of $\Psi$ arises from the fact that it provides the representation basis where $x$ can be sparsely depicted by $s \in \mathbb{R}^{(2n_a - 1)}$ as:

$$x = \Psi s$$

The recovery mechanism at the BS reconstructs the sparse correlation coefficient vector $s$ by solving the following $\ell^1$- minimization problem for a given tolerance $\epsilon$:

$$(\ell^1_1): \hat{s}_1 = \arg \min_s \|s\|_{\ell^1}, \text{ s.t.: } \|\Phi \Psi s - y\|_2 \leq \epsilon$$

### 3 Preliminary Results

We implemented the $\mu$-BeepBeep ranging system on Google Nexus, a COTS smart phone. The device was running Android version 4.0. It featured a 1.2 GHz dual-core ARM Cortex-A9 processor, 1 GB RAM and a wide range of sensors and communication interfaces. Within the scope of this project, we only used the speakers, microphones and WiFi radio of the device.

The study was conducted in a quiet and large lecture theatre of dimension $[25 \times 15 \times 20]$ m (representative of an indoor, low multipath environment). Device A was fixed while the device B was moved along the direct line-of-sight (LOS) in a controlled manner. The correct ground truth was established using a measuring tape and markers. The speed of sound used in distance calculation was according to the model: $c_{\text{air}} = 331.3 + 0.6 \theta$ ($\theta$: air temperature in °C). For every setting at a different distance, the experiments were repeated 50 times.

![Fig. 2. Ranging performance in a spacious indoor environment.](image-url)
Table 1. Performance Analysis

<table>
<thead>
<tr>
<th>Operation</th>
<th>BeepBeep</th>
<th>µ-BeepBeep</th>
<th>Time (s)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Functionality Algorithm:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-correlation (Frequency domain)</td>
<td>4.75</td>
<td>-</td>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td>Compression (Time domain)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[2] Data:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-device exchange (WiFi)</td>
<td>0.05</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer to BS (WiFi)</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.8</td>
<td>1.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 shows the respective results for BeepBeep and µ-BeepBeep in this test environment. Both the systems achieved a maximum ranging distance of 8 m. µ-BeepBeep recorded almost similar performance as BeepBeep for [1 – 4] m. Thereafter, its performance deteriorated for distance measurements from [5 – 8] m, which was still within 2 cm of the respective measurement error reported by BeepBeep. These lower accuracy measurements of µ-BeepBeep were due to the decrease in signal sparsity (an important factor for efficient reconstruction) with lower signal-to-noise ratio (SNR) of the received signals [2]. Table 1 shows the overall time taken for completing the ranging process. The statistics suggest that µ-BeepBeep is more than 2.5 times faster than BeepBeep. This improvement in execution speed translates to lower energy consumption for µ-BeepBeep.

4 Conclusion and Future Work

In this work, we have presented some preliminary results from our project on low energy acoustic ranging for mobile devices. Although the results are encouraging, there remains a vast scope for future work and improvement.

– Developing a frequency domain implementation of compression by random ensembles, which could potentially improve the execution speed.
– Performance testing of µ-BeepBeep in indoor high multipath and outdoor environments.

5 Acknowledgment

This research was supported by the Australian Research Council’s Discovery Projects funding scheme (Grant No. DP110104344).

References