Demo Abstract: Acoustic Ruler using Wireless Earbud

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ABSTRACT

In the paper, we demonstrate an application of the wireless earbud - an acoustic ruler. Approaches are proposed to improve the robustness of the design in the low signal-to-noise ratio environment. We also share our solution to several engineering challenges, which aims at facilitating the transformation of earbuds to into acoustic sensing research platforms without any hardware modification.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

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1 INTRODUCTION

Recently, wireless earbuds (e.g., AirPods and Galaxy Buds) are increasingly popular. With embedded microphones and various types of sensors, these small "earables" are expected to inspire a huge number of innovations in "earable computing"[2].

In the work, we demonstrate a simple but handy tool enabled by earbuds. Specifically, we build an acoustic ruler that provides ubiquitous range/size measurements without the need of carrying a real ruler. As Fig.1 shows, to measure an object, the smartphone is first placed on the one end of the object. Then the user removes one earbud from the ear and places it on the other end of the object. A ranging signal is transmitted from the built-in loudspeaker of the smartphone and recorded by the microphone of the connected earbud. The propagation delay of the signal is estimated and used to obtain the size of the objects.

Although acoustic ranging has been extensively studied in the literature, building a practical tool using *unmodified* wireless earbuds and smartphones requires us to address several technical as well as engineering challenges. For example, the microphone of most wireless earbuds only have strong response to sound under 10 KHz [1], which contains human speech, music and all kinds of background noise. Without a careful design, the ranging performance could suffer from low signal-to-noise ratio (SNR). To improve the robustness of the acoustic ruler, we provide two approaches that trade off a small amount of delay for the better ranging accuracy.

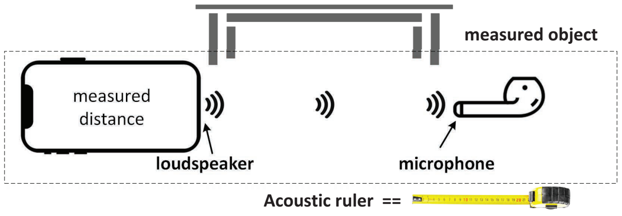

Figure 1: Acoustic Ruler using Earbud Ranging

The acoustic ruler app is developed on Android and evaluated with commercial wireless earbuds (e.g., Galaxy Buds). The results show < 5 mm measurement error within 1 meter and < 2 cm error within 5 meters.

2 SYSTEM DESIGN

2.1 Overview

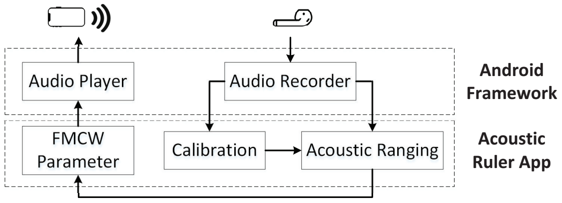

Figure 2: Overview

Fig.2 depicts the overview. The loudspeaker of smartphone plays frequency-modulated continuous-wave (FMCW) chirps that are recorded by the microphone of the earbud and sent back to the smartphone via Bluetooth. The recorded sound is analyzed to obtain the propagation delay which is used to estimate the distance between the smartphone and earbud. Section 2.2 introduces the configuration to enable acoustic sensing among the smartphone and earbud. Then, the calibration (e.g., clock synchronization) between the smartphone and earbud is addressed in Section 2.3. Finally, we introduce the ranging algorithm in Section 2.4, with the focus on improving the signal-to-noise ratio (SNR) for better robustness.

2.2 Platform Settings

The design requires playing audio through the smartphone's built-in loudspeaker while recording audio via the microphone of a connected earbud. This is non-trivial because when an earbud is connected, the audio is by default played through the speaker of earbud instead of the smartphone's built-in loudspeaker, making the ranging from smartphone to earbud infeasible.

Fortunately, we discovered that Android system defines several different output stream types (e.g., music, phone call, and ring) and

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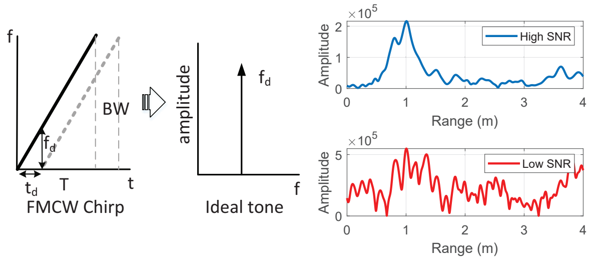
it allows the user to set the specific stream types that are routed to earbuds. Therefore, we can disable the earbuds for playing media audio (e.g., music) in the Android device setting while setting the steam type of the FMCW chirp audio to be "STREAM_MUSIC" in our App. This allows the FMCW chirps to be played by the built-in loudspeaker. Moreover, we enable the earbud to handle the phone calls so that microphone of the earbud is used as a recorder.

2.3 Calibration

The smartphone and earbud use their own clocks. As a result, the clock drift over time could lead to severe cumulative distance measurement error. To eliminate the error, we introduce a calibration phase before the range measurement as shown in Fig.2. Specifically, the user is asked to place the earbud at zero distance from the loudspeaker of the smartphone. Ten FMCW chirps are collected and the distances are estimated using algorithm discussed in Section 2.4. The distance drift ratio is calculated under the static condition and will be used for compensation during the range measurement.



(a) FMCW Ranging (b) Performance: Low SNR vs. High SNR

Figure 3: FMCW Range: Impact of SNR

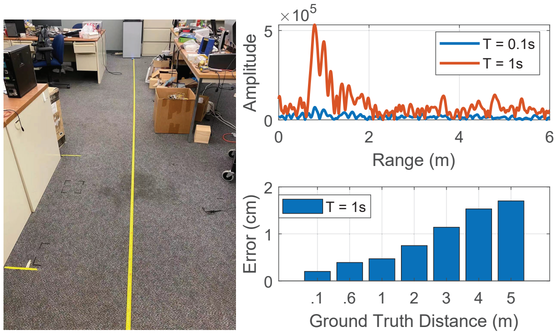
2.4 Acoustic Ranging

The range is estimated using the popular range FFT algorithm. For the sake of simplicity, we first assume zero noise. As Fig.3(a) plots, the received signal (dashed line) is a delayed version of the transmitted signal (solid line) by t_d. Mixing the received signal with the transmitted chirp produces a single tone at the intermediate frequency (i.e., f_d). f_d is estimated by discrete fourier transform (DFT) of the mixed signal and the peak in the amplitude-frequency plot is found. Finally, the range of the earbud is $d = t_d \times V_s = f_d \times \frac{T}{BW} \times V_s$. V_s is the speed of sound. T and BW are the duration and bandwidth of FMCW chirp. However, background noise could severely reduce the ranging accuracy. Specifically, most commercial wireless earphones are not able to receive sound signals of a frequency above 10 KHz [1]. Thus, we cannot apply the approach commonly adopted for the microphone of smartphone, i.e., using less noisy inaudible spectrum (> 16 KHz) and high-pass filtering to improve SNR. Fig.3(b) compares the amplitude-frequency plot of a 10 ms FWCM chirp under the moderate and strong white noise. Obviously, the peak frequency is not distinguishable when noise is strong. To enhance the robustness of the range estimation, we provide two simple but effective method:

Adjustable Chirp Duration: Increasing the chirp duration (i.e., T) improves the signal-to-noise ratios (SNR). Considering that the received signal is $X_r[n] = X_t[n] + \sigma[n]$. In the range FFT algorithm (mixing and FFT operation), the effective chirp signal ($X_t[n]$) is added up constructively, while the uncorrelated noise ($\sigma[n]$) cancels each other. Therefore, the longer chirp duration (i.e., more samples), the more total energy of the effective signal we have. Based on this insight, we dynamically adjust the chirp duration according to the SNR. Specifically, a SNR value is measured for each recorded FMCW chirp. When the SNR drops below a predefined threshold, we increase the chirp duration. Although this strategy inevitably increases the measurement time, we believe it is acceptable because distance measurements are delay-tolerant and most users are willing to tradeoff a small amount of latency for better accuracy. Also, when SNR is high, we dynamically decrease the chirp duration to improve the user experience.

Multi-Chirp Range Estimation: Instead of transmitting chirps with longer durations, we can also perform range estimation over multiple short chirps to improve SNR. In specific, when SNR is lower than the predefined threshold, we stack the range FFT results from multiple chirps into a matrix and perform a doppler FFT. Since the speed of the earbud does not change significantly during a short period of time, the effective signal in these chirps will add up constructively, leading to a more distinguishable peak.

3 DEMONSTRATION



(a) Evaluation Settings (b) Evaluation Results

Figure 4: Evaluation

We implement the acoustic ruler app on Android smartphone (e.g., pixel 3) and earbud (e.g., Galaxy Buds). In the virtual conference, we will demonstrate how to measure various distances with this app. To test the accuracy of our implementation, an evaluation is conducted in an office (Fig.4(a)). White noises are intentionally produced using a speaker to reduce SNR. As the upper part of Fig.4(b) shows, our method of adjusting chirp duration is effective. The range FFT of the increased duration (T = 1s) shows a significantly more distinguishable peak. The lower part of Fig.4(b) depicts that the app achieves mm-level accuracy within 2 meters. While the error increases moderately in larger distances due to lower SNR, it is bounded by 1.7 cm within 5 meters.

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