PineBuds Pro+: Unlocking In-Ear Audio Sensing on Off-the-Shelf Wireless Earbuds

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Abstract

In-ear audio sensing with earbuds enables rich physiological and behavioral monitoring, but existing approaches often rely on custom prototypes or specialized platforms that are costly and difficult to reproduce. Commercial earbuds, despite their wide availability, remain largely inaccessible due to restricted firmware and lack of access to in-ear microphones. In this paper, we present PineBuds Pro+, a low-cost, fully wireless platform that enables in-ear audio sensing on off-the-shelf earbuds via firmware modification. By unlocking the feedback microphone in PineBuds Pro, our system allows developers to capture subtle in-ear acoustic signals using standard Bluetooth audio interfaces, without additional hardware or custom software. We demonstrate the feasibility of PineBuds+ across multiple sensing scenarios, including heartbeat, respiration, and daily activities. Our results highlight the potential of PineBuds+ to lower the barrier for in-ear sensing research, enabling accessible data collection and reproducible experimentation. We release our modified firmware at https://github.com/Qiangest/PineBuds-Pro-Plus/.

CCS Concepts

• **Human-centered computing** → *Ubiquitous and mobile computing design and evaluation methods.*

Keywords

Earable computing; Earable Sensing; Earbuds

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1 Introduction

In-ear audio sensing has emerged as a promising paradigm for capturing rich physiological and behavioral signals in everyday settings [9]. By leveraging microphones embedded inside the ear canal, prior work has demonstrated the ability to sense a wide range of signals, including respiration [7, 10, 11], heartbeats [4, 6], chewing and swallowing[16], gait and footsteps [8], as well as fine-grained interactions such as toothbrushing [17, 18] and finger movements [13, 19]. These capabilities enable diverse applications in mobile health, activity recognition, and human-computer interaction, positioning earable devices as a powerful platform for continuous, unobtrusive sensing.

Despite its promise, existing in-ear sensing research largely relies on either custom-built prototypes [5, 12] or specialized development platforms [15]. Such systems are often bulky, expensive, and require significant engineering effort to build and maintain. For example, OpenEarable 2.0 costs USD 2770 [2]. Moreover, differences in hardware design and sensing setups make it difficult to reproduce results or establish standardized benchmarks across studies. Meanwhile, although commercial earbuds are widely available and highly integrated, they remain largely inaccessible for sensing due to closed firmware and restricted access to internal microphones—particularly the feedback microphone used in active noise cancellation (ANC) systems [14].

To address this gap, we present PineBuds Pro+, a low-cost, fully wireless platform that enables in-ear audio sensing on off-the-shelf earbuds through firmware modification. Built upon low-cost PineBuds Pro (USD 69.99) [3], our system unlocks access to the internal feedback microphone by modifying the audio input pipeline, allowing it to be used as a sensing modality. Specifically, we reconfigure the microphone routing in the firmware to redirect the ANC feedback channel into the standard audio capture path, enabling recording through conventional Bluetooth interfaces without requiring custom applications or drivers. In addition, we introduce a lightweight workaround to support dual-channel data collection, enabling bilateral sensing without modifying the Bluetooth protocol stack.

To demonstrate the feasibility of our approach, we conduct exploratory experiments using the modified earbuds across a range of sensing scenarios, including heartbeat, respiration, footsteps, eating, toothbrushing, and finger interactions. Our results show that PineBuds Pro+ can reliably capture diverse in-ear signals using a low-cost, widely accessible device. More importantly, by requiring only firmware flashing and no hardware modification, PineBuds Pro+ lowers the barrier to entry for in-ear sensing research, paving

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(a) Device appearance **(b) Microphone placement**

Figure 1: The device appearance and microphone configuration of PineBuds Pro (adapted from [3]).

the way toward standardized, scalable, and community-driven research on earable sensing.

2 PineBuds Pro+ Design

2.1 Hardware and Audio Pipeline

PineBuds Pro+ is built upon PineBuds Pro [3], a commercially available, open-source earbud platform equipped with multiple microphones and a fully programmable firmware stack. As shown in Fig. 1, earbud integrates three microphones: a primary talk microphone (MIC5 / CH4), an ANC feedforward microphone (MIC1 / CH0), and an ANC feedback microphone located inside the ear canal (MIC3 / CH2). Among these, the feedback microphone is particularly well-positioned to capture subtle in-ear acoustic signals generated by physiological activities and daily interactions.

In the default firmware configuration, only the talk microphone is exposed to the Bluetooth audio pipeline for voice capture, while the feedforward microphone is used to capture external ambient noise before it enters the ear canal and the feedback microphone is used to monitor the residual sound inside the ear canal for adaptive noise cancellation. Specifically, audio captured by the talk microphone is routed through the internal codec and transmitted via the Bluetooth Hands-Free Profile (HFP) as a single-channel audio stream. In contrast, the feedback microphone operates as part of the closed-loop ANC system and is not accessible to application-level recording.

2.2 Unlocking Feedback Microphone Recording

To enable in-ear audio sensing, we build upon the open-source firmware OpenPineBuds [1]. We modify the firmware to redirect the ANC feedback microphone into the standard audio capture path. Concretely, we reconfigure the microphone routing in the hardware abstraction layer, replacing the default talk microphone input with the feedback microphone in the main audio input path. This allows the feedback microphone signal to be captured using the existing Bluetooth audio streaming interface without modifying higher-level protocols.

This firmware-level modification requires no changes to the Bluetooth stack or host-side software. Once flashed, the earbuds can stream feedback microphone audio directly to commodity devices (e.g., smartphones or laptops) through standard recording interfaces. As a result, PineBuds Pro+ maintains full compatibility with existing operating systems and applications, enabling immediate deployment without custom drivers or dedicated mobile applications. Researchers can deploy PineBuds Pro+ by simply flashing the firmware onto off-the-shelf devices, significantly reducing the engineering effort required for in-ear sensing experiments.

2.3 Enabling Dual-Channel Sensing

Some in-ear sensing applications benefit from multi-channel recordings, for example, to capture signals from both ears or to analyze spatial or asymmetric patterns. However, standard Bluetooth audio protocols typically support only single-channel uplink from one device, limiting direct access to multi-channel data.

To address this limitation, PineBuds Pro+ adopts a lightweight and practical workaround that leverages the dual-device nature of true wireless stereo (TWS) earbuds. Instead of operating the two earbuds as a synchronized pair connected to a single host, we enable `freeman mode`, in which each earbud functions as an independent Bluetooth device. In this mode, each earbud can separately connect to a host device as an individual audio input, and stream its own feedback microphone signal. This effectively enables dual-channel data collection without modifying the underlying Bluetooth protocol stack and audio profiles.

In practice, signals captured by two host devices can be streamed in the background to a single endpoint, without imposing the burden of manually controlling multiple devices simultaneously. Although the two audio streams are not strictly hardware-synchronised, they can be aligned during post-processing, for example by introducing a short pilot acoustic signal as a synchronization reference. Experiments suggest that, in stable systems, streaming delays can be highly consistent with per-collection variantions within 0.01 seconds. This design therefore provides a simple yet effective solution for extending PineBuds Pro+ to multi-channel sensing scenarios.

3 Feasibility Demonstration

To evaluate the feasibility of PineBuds Pro+ for in-ear audio sensing, we conduct a set of exploratory experiments across diverse sensing scenarios. For each scenario, we collect representative audio signals using the modified earbuds and visualize short segments to illustrate the captured patterns.

3.1 Physiological Signals

We first examine physiological signals that are typically subtle and challenging to capture. Using PineBuds Pro+, we record in-ear audio during resting conditions. The captured signals (Fig. 2 (Top)) reveal periodic patterns corresponding to respiration cycles, with clear differences between inhalation and exhalation phases.

We further explore heartbeat-related signals by recording under quiet conditions. While the signal amplitude is relatively weak, we observe consistent low-frequency components aligned with cardiac activity (Fig. 2 (Bottom)). These results suggest that the feedback microphone is sufficiently sensitive to capture fine-grained physiological vibrations within the ear canal.

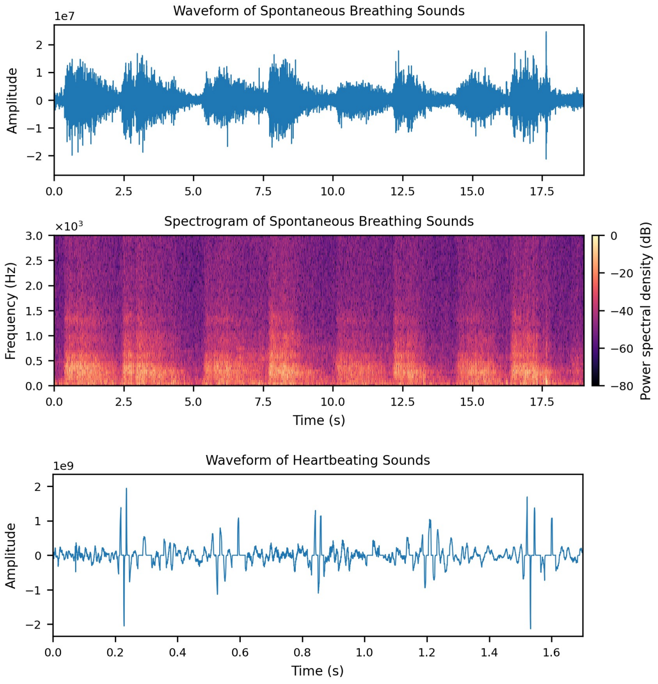

Figure 2: Top: Waveform and spectrogram of captured spontaneous breathing sounds. Bottom: Waveform of captured heart sounds with clear peaks.

3.2 Daily Activities

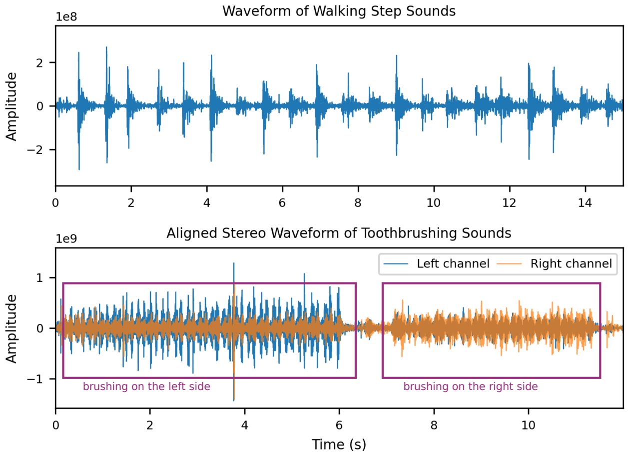

Figure 3: Top: Waveform of captured walking step sounds. Bottom: Stereo waveform of toothbrushing sounds at different locations.

Next, we evaluate PineBuds Pro+ in common daily activities. During walking (Fig. 3 (Top)), the recorded signals exhibit rhythmic patterns corresponding to footsteps, reflecting the transmission of body vibrations to the ear canal. During toothbrushing (Fig. 3 (Bottom)), the recorded signals exhibit continuous, high-frequency components with characteristic temporal variations corresponding to brushing motions.

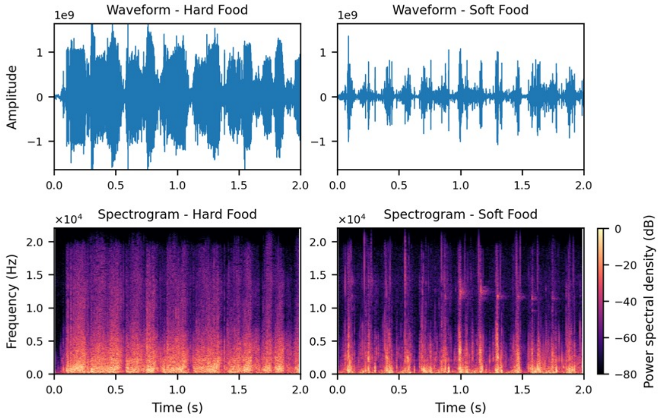

Figure 4: Waveforms and spectrograms of consuming hard (Left) and soft (Right) foods.

We also collect data during eating (Fig. 4). The in-ear audio signals show distinct temporal structures associated with chewing. We observe different acoustic characteristics when consuming hard versus soft foods, with each producing noticeably different patterns in the waveform and spectrogram. Compared to physiological signals, these eating-related sounds are stronger and more structured, making them easier to distinguish.

3.3 Interaction Signals

Finally, we demonstrate the ability of PineBuds Pro+ to capture fine-grained interaction signals.

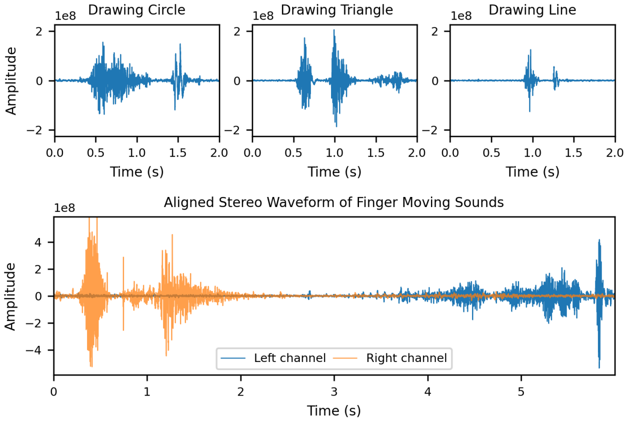

Figure 5: Top: Waveforms of the sounds made by a finger drawing different shapes near the ears. Bottom: Stereo waveform of the sounds made by a finger moving from the right ear, across the face, to the left ear.

We examine finger interactions such as sliding or drawing shapes on the face. These actions produce short, transient signals that are clearly distinguishable in the recorded audio (Fig. 5 (Top)), highlighting the potential of PineBuds Pro+ to capture subtle user interactions beyond passive sensing. We further investigate the fine-grained spatial information contained in the stereo signals by moving a finger across the face from the right ear to the left ear. The resulting signals (Fig. 5 (Bottom)) demonstrate that gradual spatial shifts can also be captured.

4 Limitation and Future Work

While PineBuds Pro+ demonstrates the feasibility of enabling in-ear audio sensing on off-the-shelf earbuds, several limitations remain.

First, the physical design of PineBuds Pro is not optimized for sensing. Compared to tightly sealed, custom-fit earable devices, the earbuds provide limited sound-proof capability and occlusion within the ear canal. This may reduce the strength and consistency of captured in-ear signals, particularly for subtle physiological measurements [9]. Future work could explore improved fitting strategies or hardware adaptations to enhance signal quality and robustness.

Second, our current design repurposes the ANC feedback microphone for sensing, which disables its original role in the noise cancellation pipeline. As a result, active noise cancellation is not available during data collection. Enabling simultaneous sensing and ANC, or designing mechanisms to dynamically switch between modes, remains an open challenge for future exploration [5].

Third, although our dual-device approach enables multi-channel data collection, the two audio streams are not hardware-synchronized. TWS protocols such as IBRT provide inter-ear synchronization for playback and control, but they do not offer sample-level alignment or synchronized audio capture. While simple alignment methods (e.g., pilot signals) can mitigate this issue during post-processing, more robust synchronization mechanisms would be beneficial for applications requiring precise temporal consistency.

Looking forward, we envision PineBuds Pro+ as a step toward more accessible and standardized in-ear sensing research. Future work could build upon this platform to develop robust sensing pipelines, explore cross-user generalization, and establish shared datasets and benchmarks, ultimately advancing the development of scalable and real-world earable sensing systems.

5 Conclusion

In this paper, we presented PineBuds Pro+, a low-cost and fully wireless platform that enables in-ear audio sensing on off-the-shelf earbuds through firmware modification. By unlocking access to the internal feedback microphone, our approach allows developers to capture in-ear acoustic signals and enables dual-channel recording using standard Bluetooth interfaces without requiring custom hardware or specialized software. Through a set of feasibility demonstrations, we showed that PineBuds Pro+ can capture a diverse range of physiological, activity, and interaction-related signals. We hope this work can serve as a foundation for future research toward scalable, standardized, and community-driven earable sensing systems.

Acknowledgments

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