6.1820/MAS.453: Mobile and Sensor Computing
aka IoT Systems

https://6mobile.github.io/

Lecture 11: Earables and Health

Slides adapted from Xiaoran Fan (Google), and Cecilia Mascolo (University of Cambridge)

Course Staff

Lecturers

Fadel Adib (fadel@mit.edu)

Tara Boroushaki (tarab@mit.edu)

TAs

Waleed Akbar (wakbar@mit.edu)

Jack Rademacher (jradema@mit.edu)

Announcements

1- Lab 3 due next Tuesday

2- Project Proposal Instructions out today

3- Finish forming teams

What are we learning today?

Health Sensing

1- What is PPG and How does it work?

2- How can you measure SPO2, breathing rate, and heart rate with PPG?

3- How do active noise canceling headphones work

3- How can you measure cardiac activities through earables?

This week in IoT

Health Care | Wearables

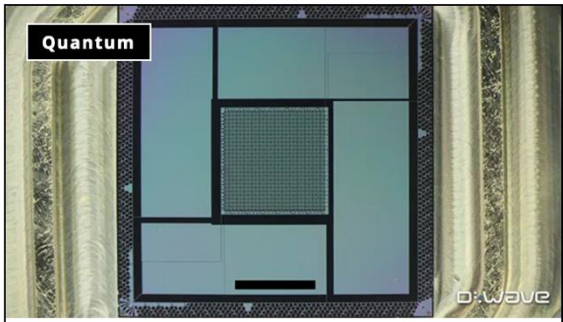
Health-Tracking Smart Lenses Featured at Mobile World Congress 2025

Five prototypes went straight from the laboratory to the show floor to highlight possible benefits

Graham Hope, Contributing Writer
March 7, 2025

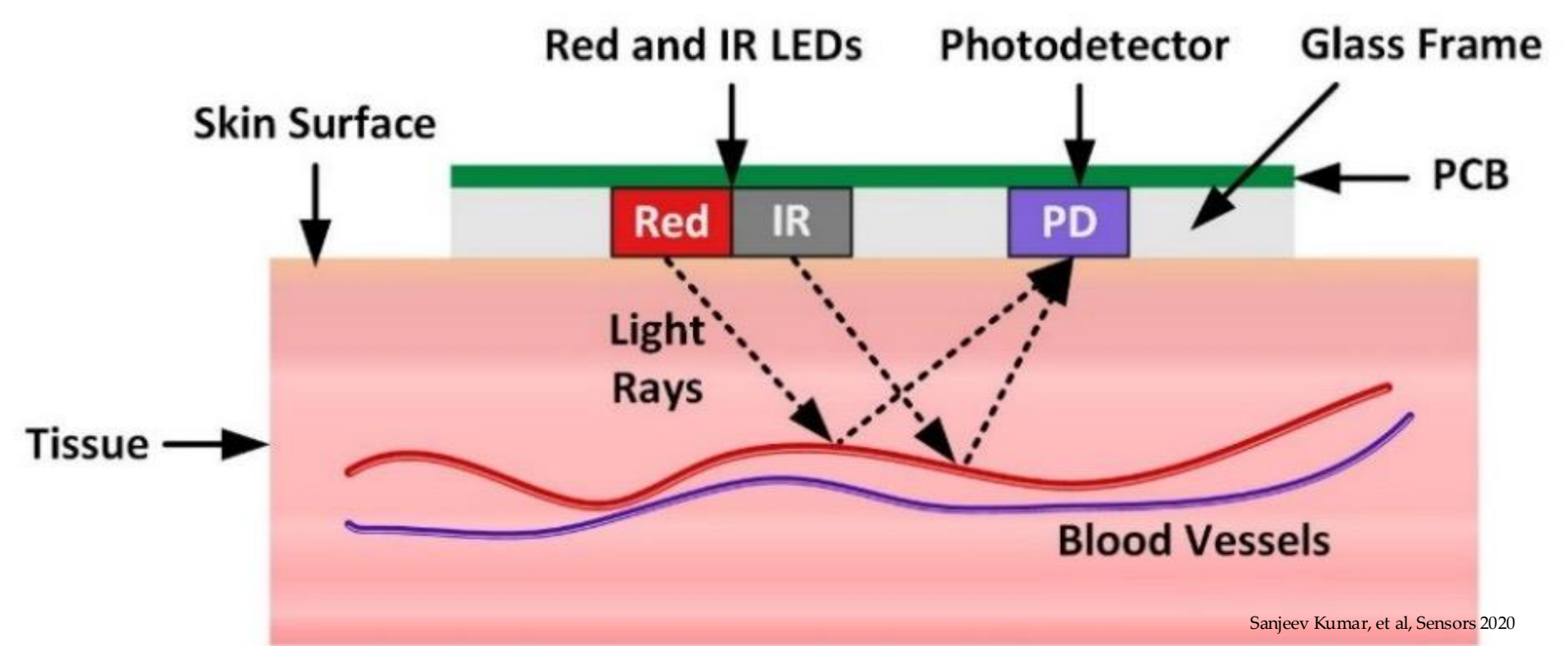
2 Min Read

Latest News



Wearable PPGs

How does a PPG (Photoplethysmography) sensor work?



Sanjeev Kumar, et al, Sensors 2020

Respiration Rate and PPG

- Respiratory rate (RR), the number of breaths taken in a minute, is used for diagnosis and prognosis in a range of clinical settings.

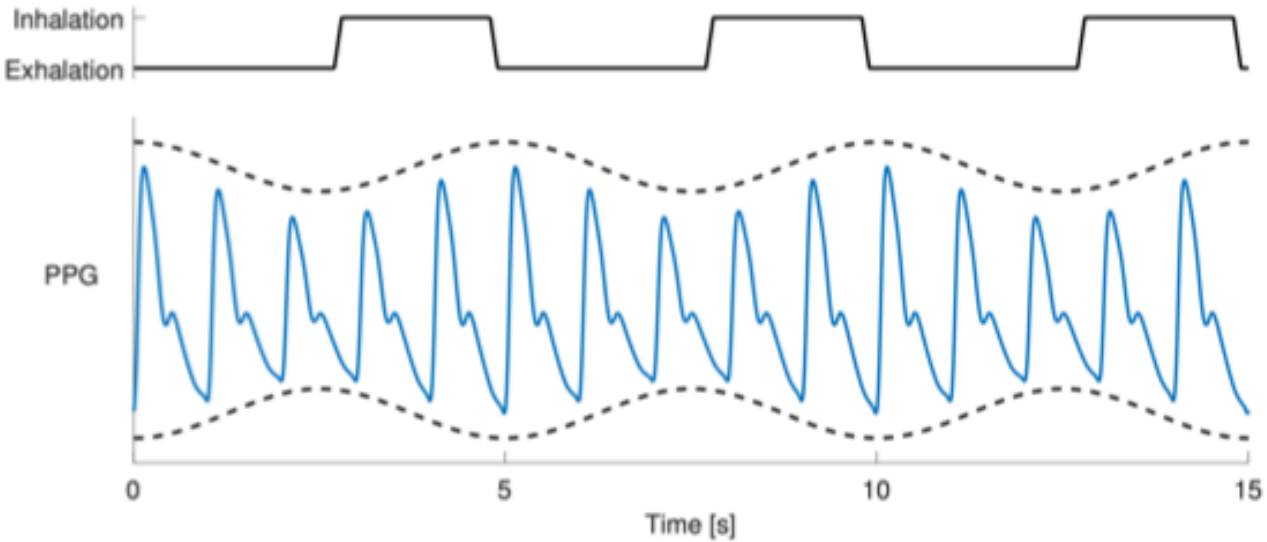
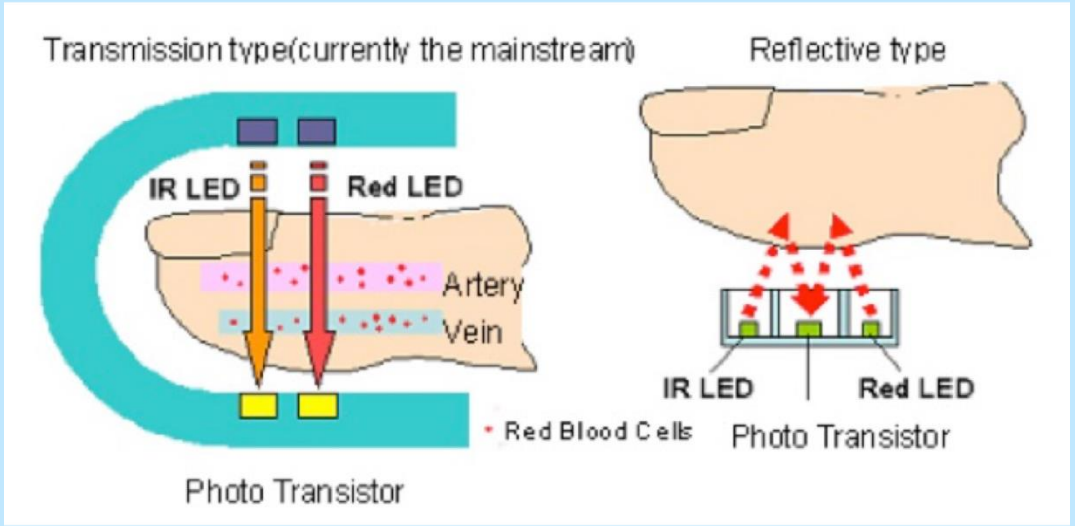


Figure from P. Charlton. Continuous Respiratory Rate Monitoring to Detect Clinical Deteriorations using Wearable Sensors. PhD Thesis. 2017.

The Oximeter at hospital



www.ee.columbia.edu/~kinget/EE6350_S14

Oxygen Saturation (SpO2)

- Oxygenated hemoglobin absorbs less red light emitted whereas deoxygenated hemoglobin absorbs less infrared light. Thus, the ratio between red and infrared light intensities measured by the PPG sensor can be used to estimate peripheral oxygen saturation (SpO2).

$$R = \frac{R_{red}}{R_{infrared}} = \frac{AC_{red}/DC_{red}}{AC_{infarared}/DC_{infrared}}$$

The PPG accuracy is impacted by motion and location of sensing

- Avoid sampling when accelerometer detects activity.
- Correlate accelerometer data to filter out motion artifacts.

News & views

Racism in science

Forum: Medical devices

Skin colour affects oxygen-sensor accuracy

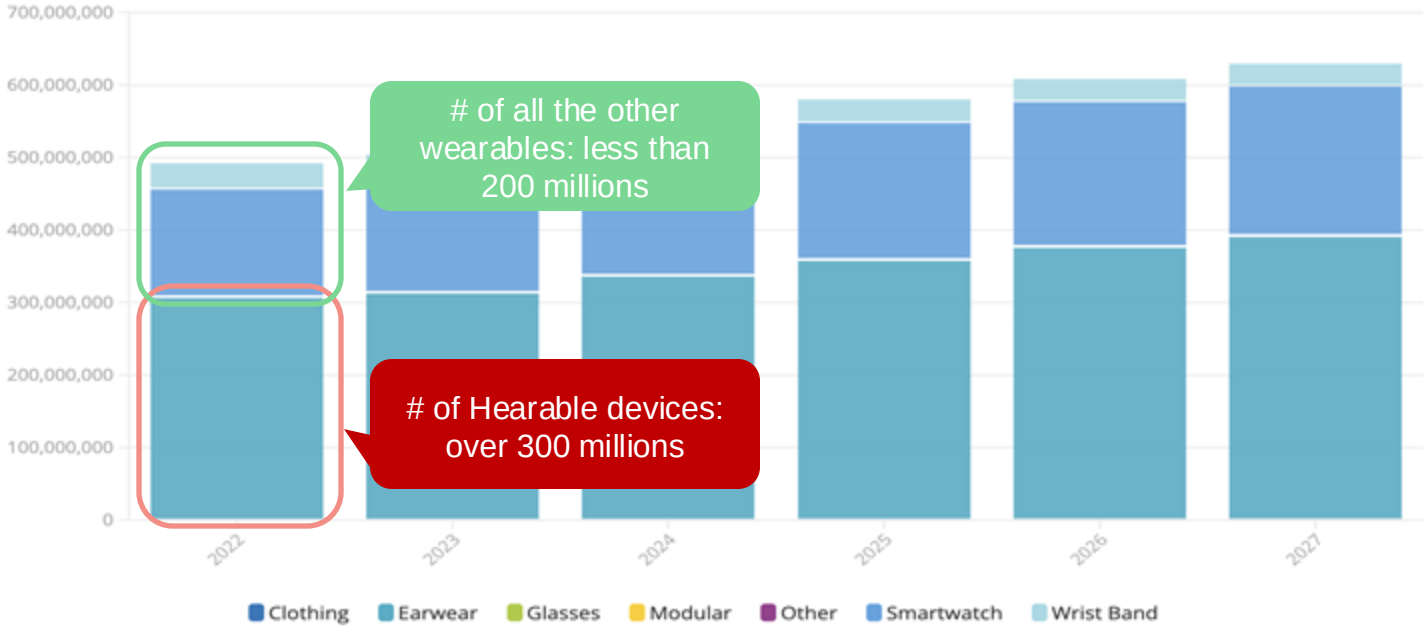
COVID-19 broadened the use of pulse oximeters for rapid blood-oxygen readings, but it also highlighted the fact that skin pigmentation alters measurements. Two groups of researchers analyse this issue, and its effects on people with dark skin.

Matthew D. Keller & Brandon Harrison-Smith
Pulse-oximetry errors affect patient outcomes

Since Sjoding and colleagues' report, several large retrospective studies have confirmed that darker-skinned people (those self-identifying as Black, Asian, Hispanic or a combination of these) are more likely than white people to experience occult hypoxaemia[2–5]. In one study of people with COVID-19, had equivalent arterial blood-gas values[3]. A more comprehensive analysis showed that, even when baseline health conditions are taken into account, people with occult hypoxaemia are prone to organ dysfunction and in-hospital mortality, and that Black people in this group have the worst organ dysfunction[5].

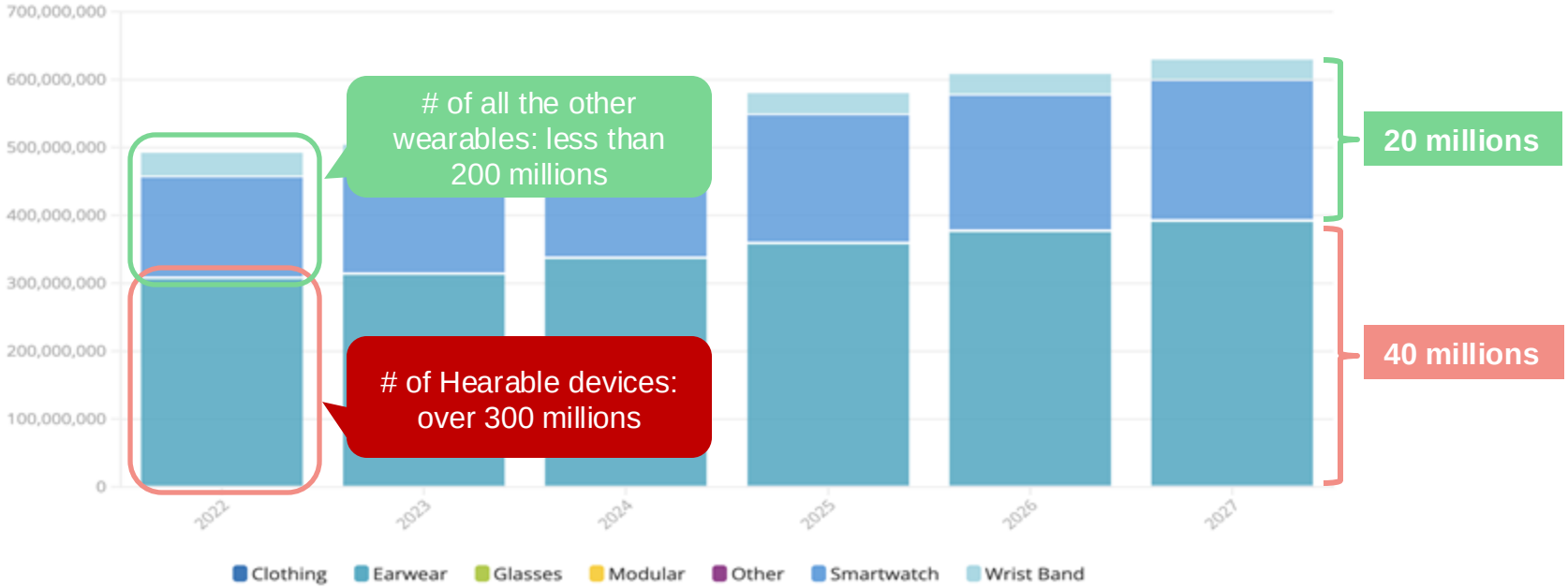
Although clinical reports of skin-colour bias in pulse oximetry were not widespread until the COVID-19 pandemic, evidence for this issue has been accumulating for decades[6,7]. A comparison reported in February found that pulse-oximeter readings from nine devices were consistently less accurate for darker-skinned people than for lighter-skinned people[8]. But the study also found that testing healthy individuals under carefully controlled laboratory conditions resulted in fewer cases of occult hypoxaemia than are measured in hospitals. In fact, none of the 491 people who were tested by the authors had readings consistent with occult hypoxaemia, whereas Sjoding and colleagues tallied 187 cases out of 3,527 measurements from a

The Surge of Hearable Devices



- Hearables are estimated to **double the shipment volume** than the sum of all other wearables in 2027

The Surge of Hearable Devices



- Hearables are estimated to **double the shipment volume** than the sum of all other wearables in 2027

Hearable Health Is Still An Uncharted Territory

- Manufactures like Apple, Samsung, and Google have nearly zero health features in their earbuds
    - Focus more on user experience, such as interactions, comfortableness, battery-life, etc.

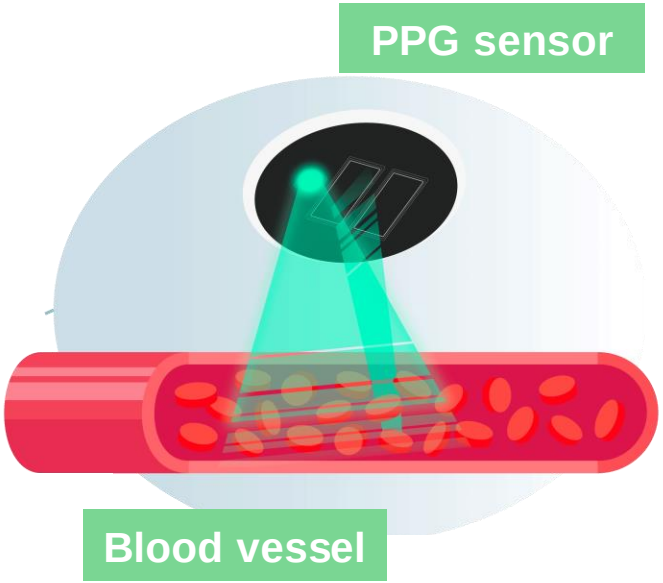
Is it possible to bring health features such as heart rate monitoring to hearable devices?

We focus on Active Noise Cancellation (ANC) Earbuds

How does an Active Noise Canceling headphone work?

An Overview of Existing Hearable Health Solutions

- **Active sensing using PPG sensors**

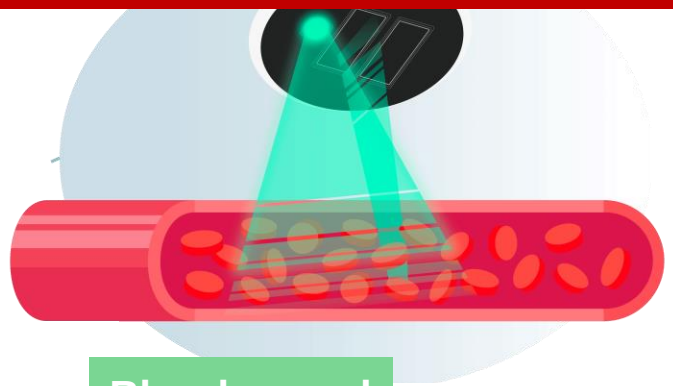


Soundcore Liberty 4 Earbuds are equipped with PPG sensors for heart rate tracking

An Overview of Existing Hearable Health Solutions

- **Active sensing using PPG sensors**

Drawback: high power consumption, sensitive to skin tones, complicate the hearable acoustic design



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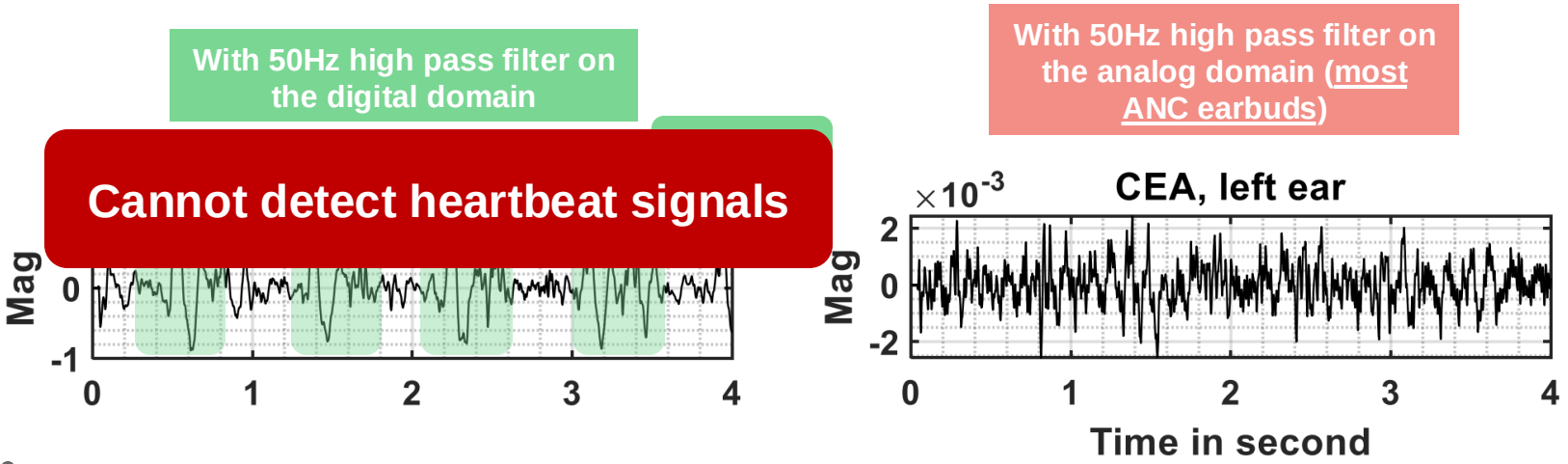
An Overview of Existing Hearable Health Solutions

- **Passive sensing using in-ear microphone**
  - **Rationale:** heartbeat vibrations propagate along the human body, arriving at the ear canal, which can be captured by an in-ear microphone
    - **Representative works**: [OESense, MobiSys'21], [hEARt, Percom'23], [EarAce, Ubicomp'23]

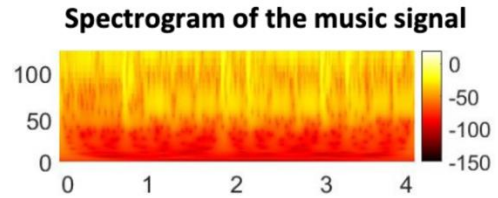
An Overview of Existing Hearable Health Solutions

- **Passive sensing using in-ear microphone**
  - **May not be a good solution to ANC earbuds:**
    - Sensitive to earbud sealing conditions;
    - The high-pass filter bult in the earbud's analog front-end would filter out low-frequency

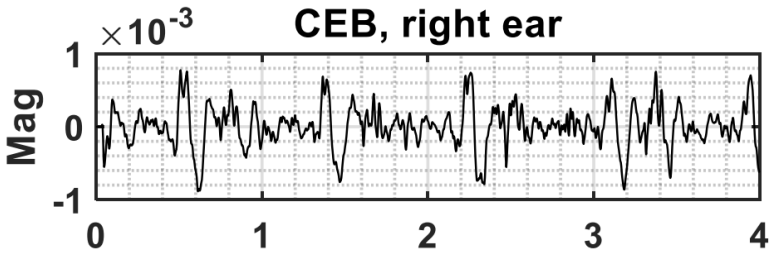


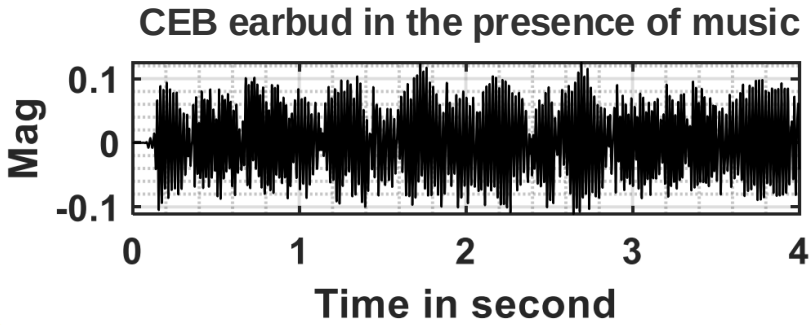
An Overview of Existing Hearable Health Solutions

- **Passive sensing using in-ear microphone**
  - **May not be a good solution to ANC earbuds:**
    - Sensitive to earbud sealing conditions;
    - The high-pass filter bult in the earbud's analog front-end would filter out low-frequency
    - Suffer from music interference, due to music harmonics



With 50Hz high pass filter on the digital domain

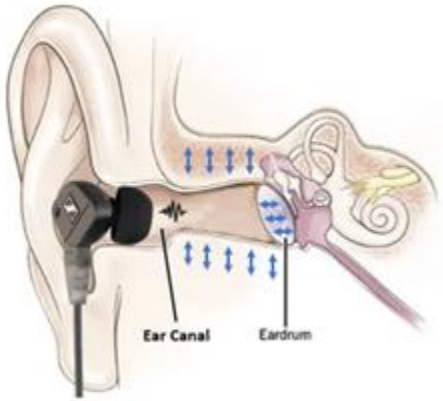


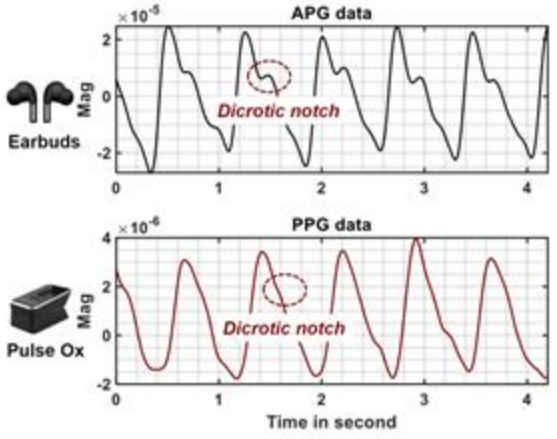


APG - A New Design Paradigm for Heart Rate Monitoring

- **Basic Principle:**
  - **Physiological observation**: the deformation of blood vessels → the tissues encircling the ear canal undergo a minor constriction → a subtle compression of the ear canal cavity

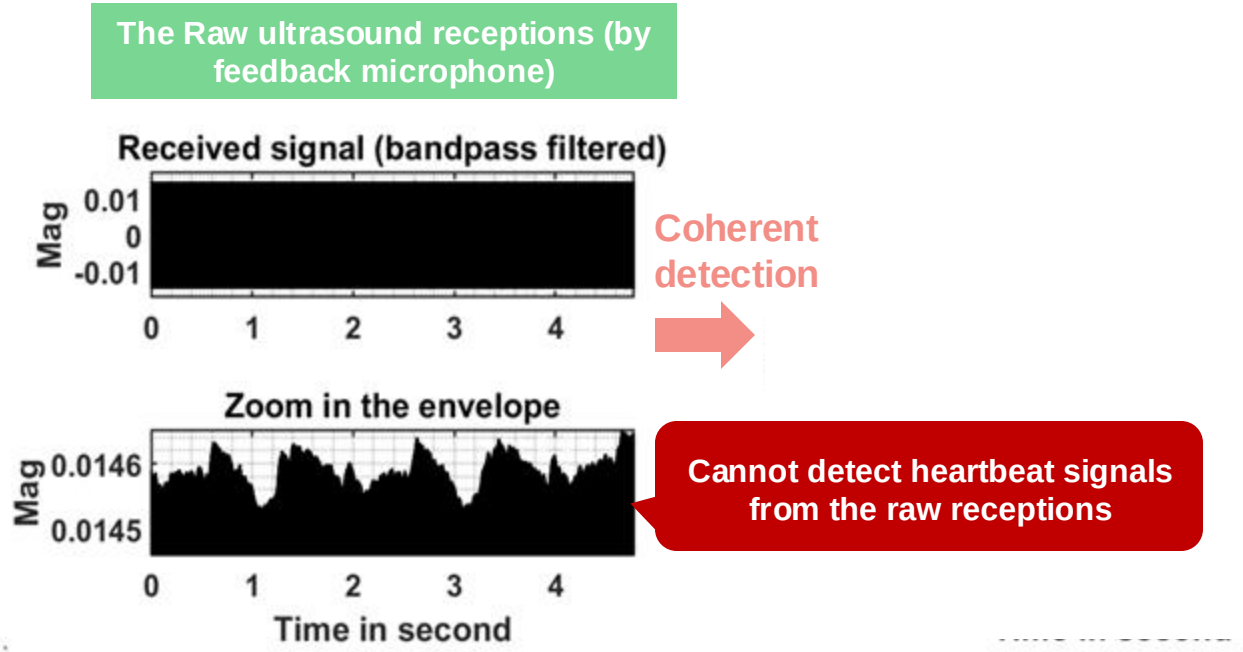
  - **Detect heart rate**: send a low intensity ultrasound probing signal using an ANC headphone's speakers and receives the echoes via the on-board feedback microphones.





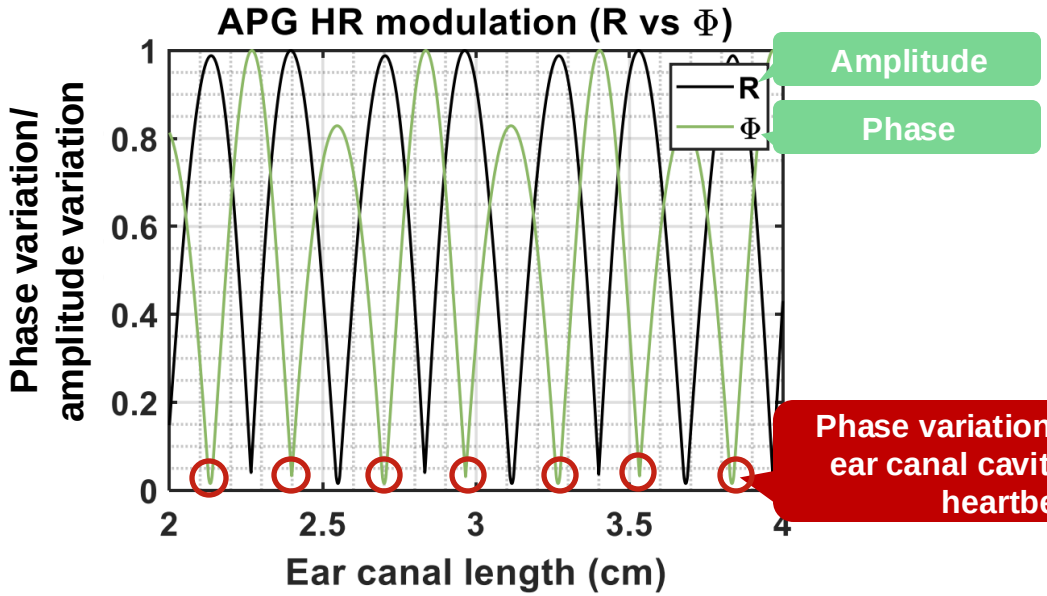
APG – How to Realize This Idea?

- **The alteration in volume within the ear canal due to heartbeat is subtle**



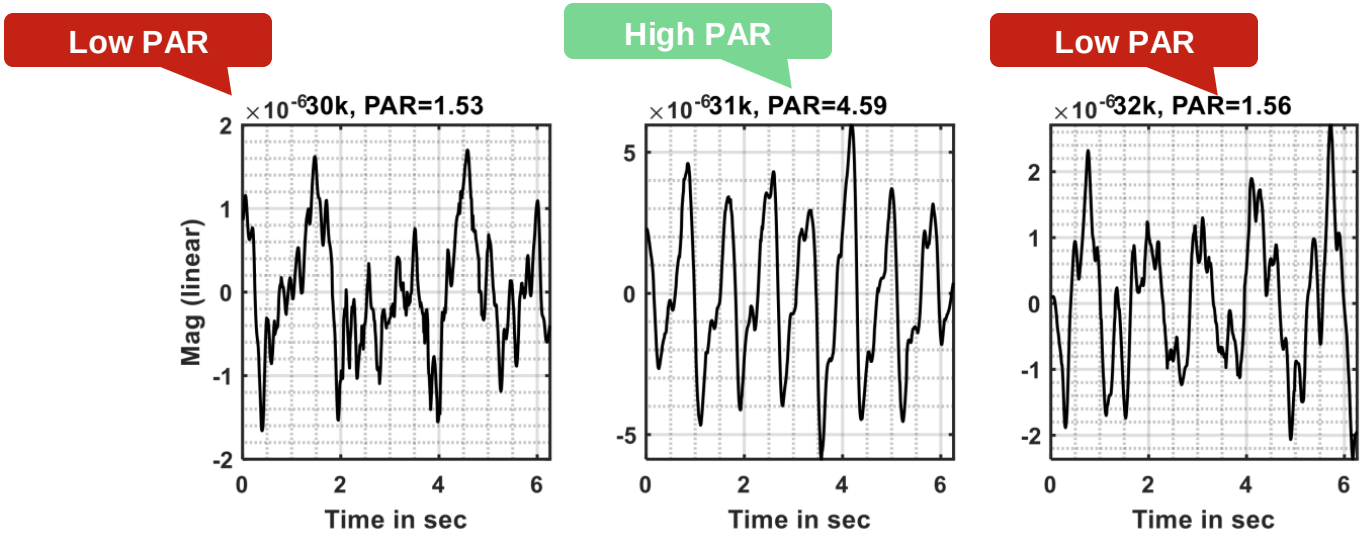
APG – How to Realize This Idea?

- **How to handle user diversity?**



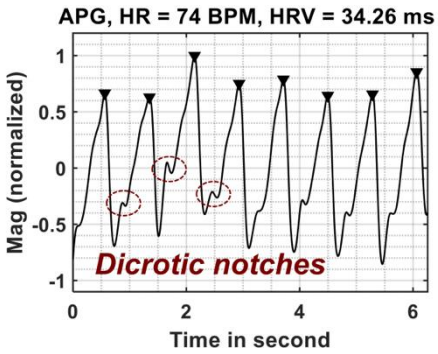
APG – How to Realize This Idea?

- **How to handle user diversity?**
  - **Solution:** Sending multiple APG signals at different frequency bands concurrently, using peak-to-average ratio to measure the quality of the detected heartbeat signal

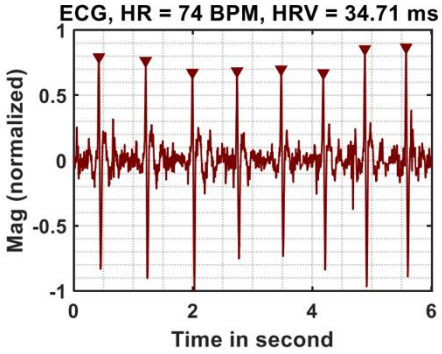


APG – How to Realize This Idea?

- **How to handle user diversity?**
  - **Solution:** Sending multiple APG signals at different frequency bands concurrently, using peak-to-average ratio to measure the quality of the detected heartbeat signal
  - Once the optimal frequency is determined, we send APG signal on that specific frequency for a better signal quality



(a) final APG readings.

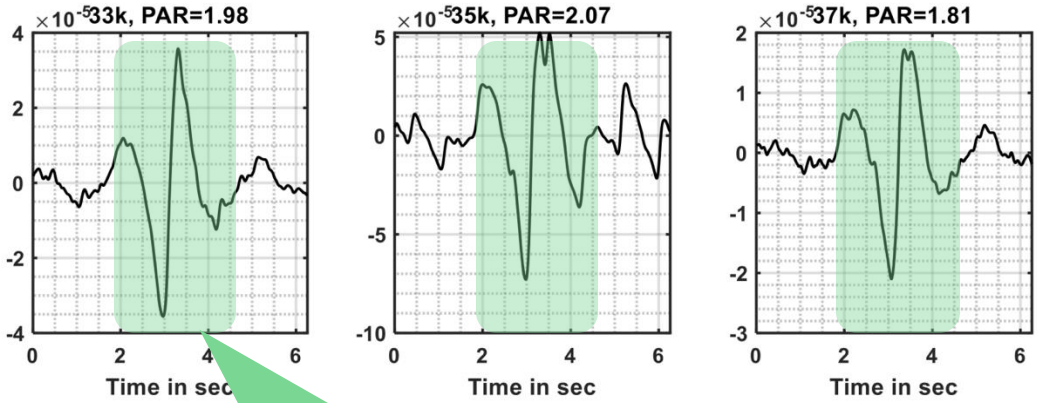


(b) ECG readings.

APG – How to Realize This Idea?

- **How to handle body motion artifacts?**
  - **Challenge:** body motion also squeezes ear canal; they are hundreds of magnitude stronger than the heartbeat signals

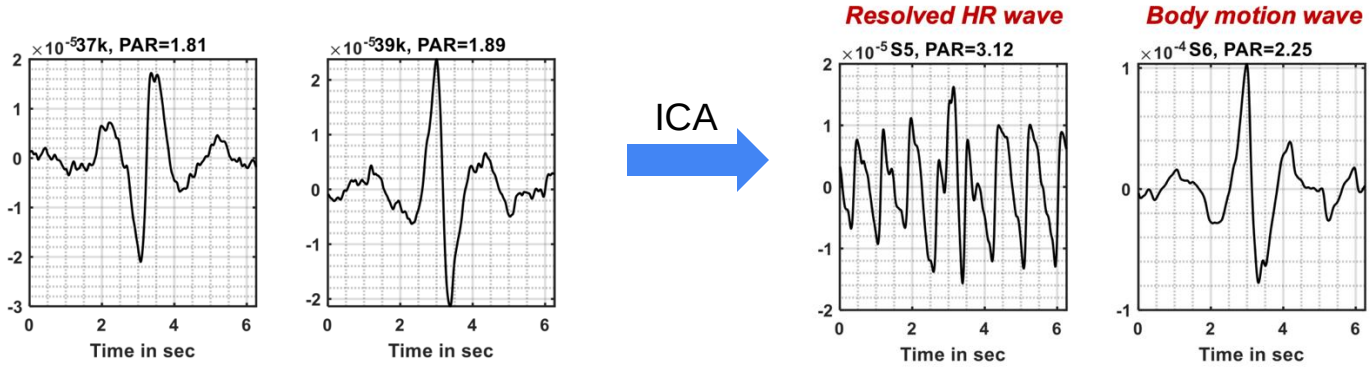
APG receptions on three different frequency bands (after coherent detection)

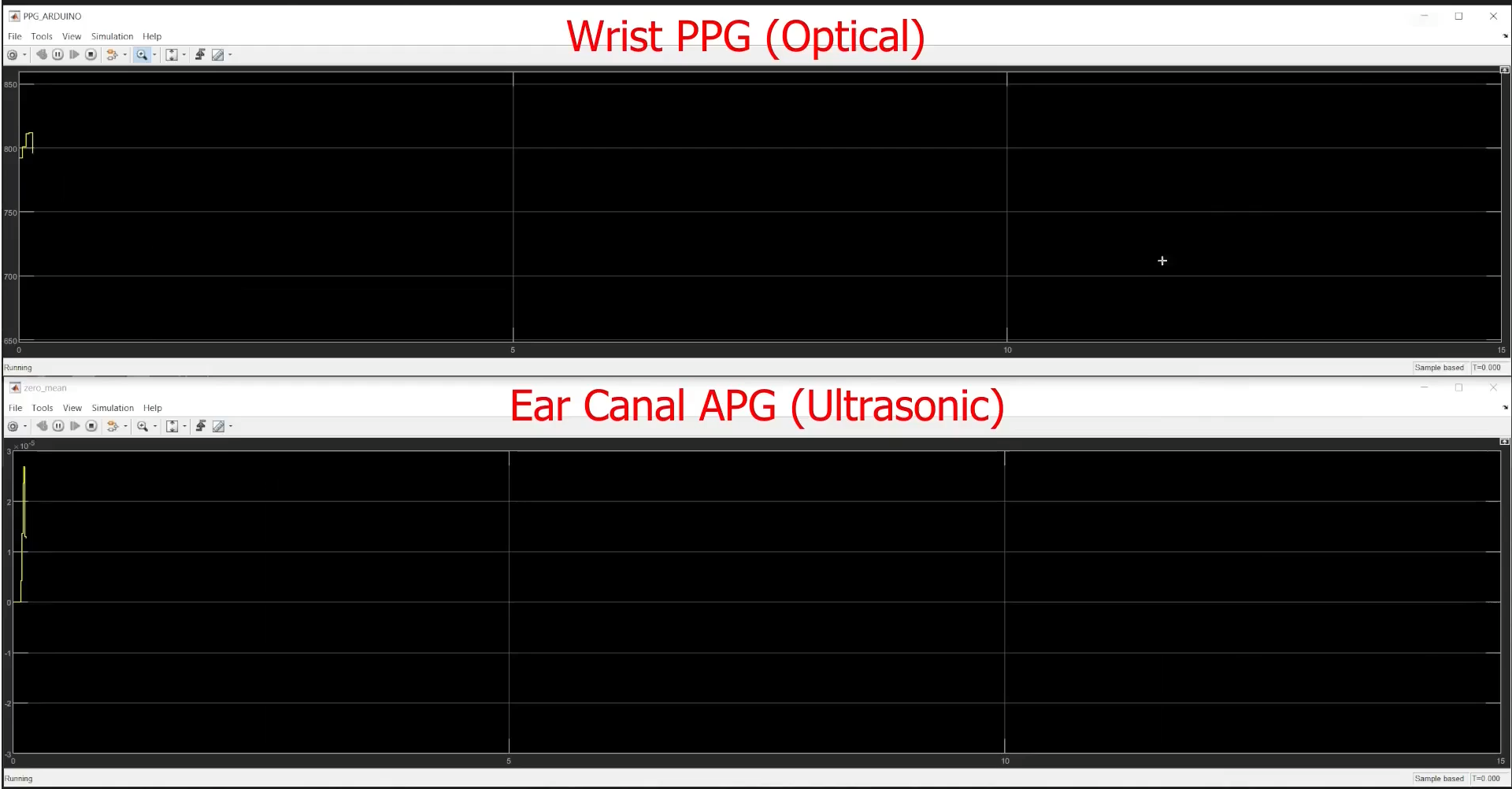


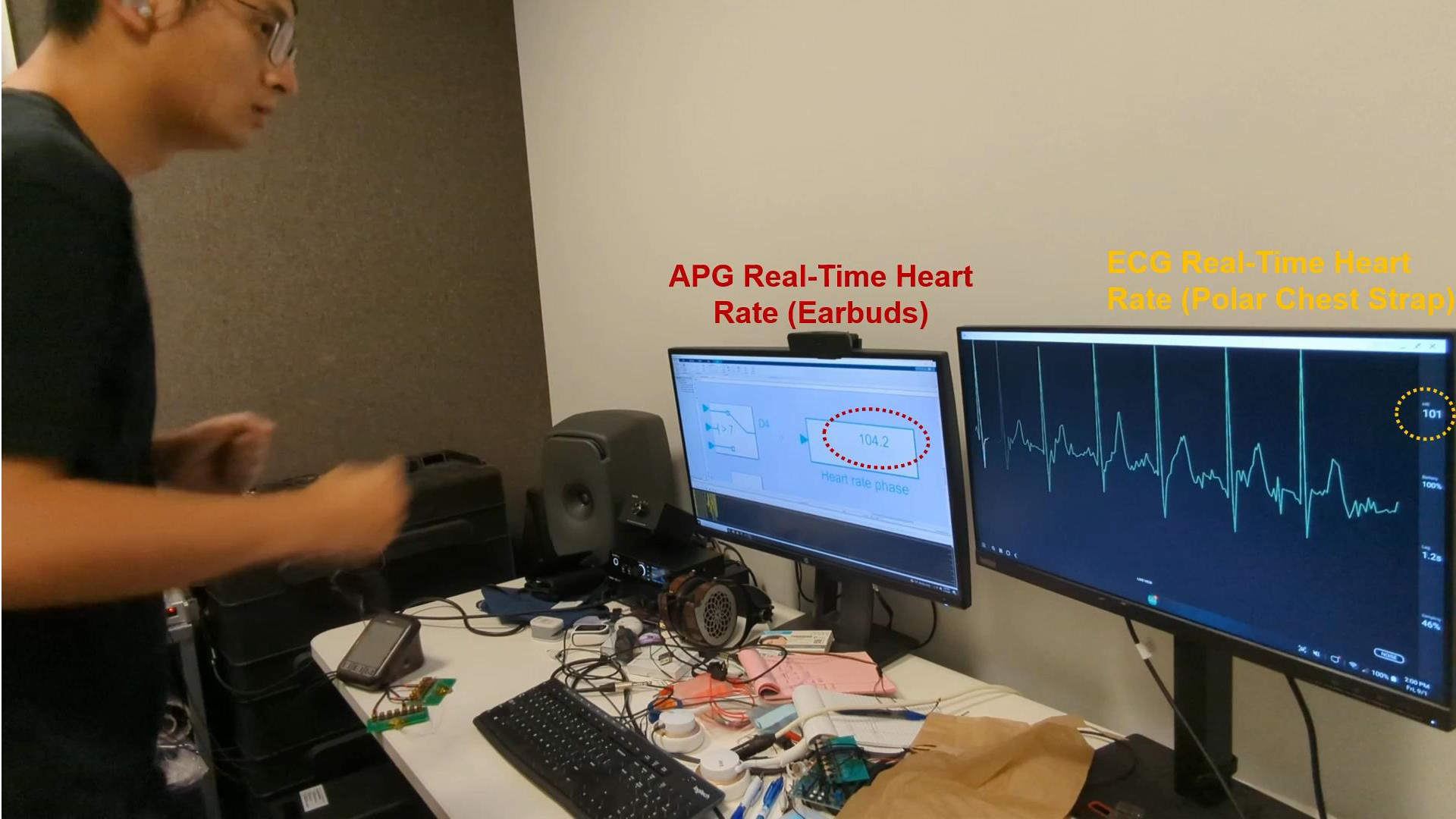
Head motions dominate

APG – How to Realize This Idea?

- **How to handle body motion artifacts?**
  - **Challenge:** body motion also squeezes ear canal; they are hundreds of magnitude stronger than the heartbeat signals
  - **Solution:** model it as a **blind source separation (BSS)** problem
  - **Opportunity**: the frequency bands of probing signals are statistically decorrelated due to the channel frequency diversity






APG Real-Time Heart Rate (Earbuds)
ECG Real-Time Heart Rate (Polar Chest Strap)
104.2
Heart rate phase
101

What did we cover today?

Health Sensing

1- What is PPG and How does it work?

2- How can you measure SPO2, breathing rate, and heart rate with PPG?

3- How do active noise canceling headphones work

3- How can you measure cardiac activities through earables?

TODO:

1- Lab 3 due next Tuesday

2- Project Proposal Instructions out today

3- Finish forming teams