WAKE: A Behind-the-ear Wearable System for Microsleep Detection

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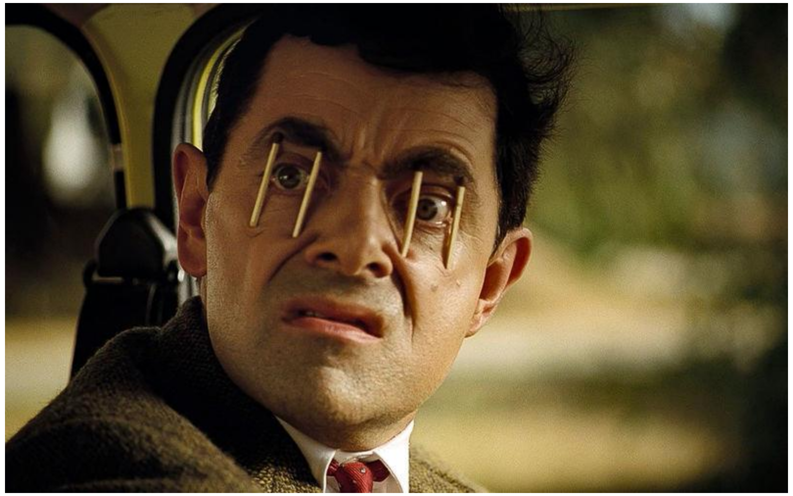
Microsleep detection problem

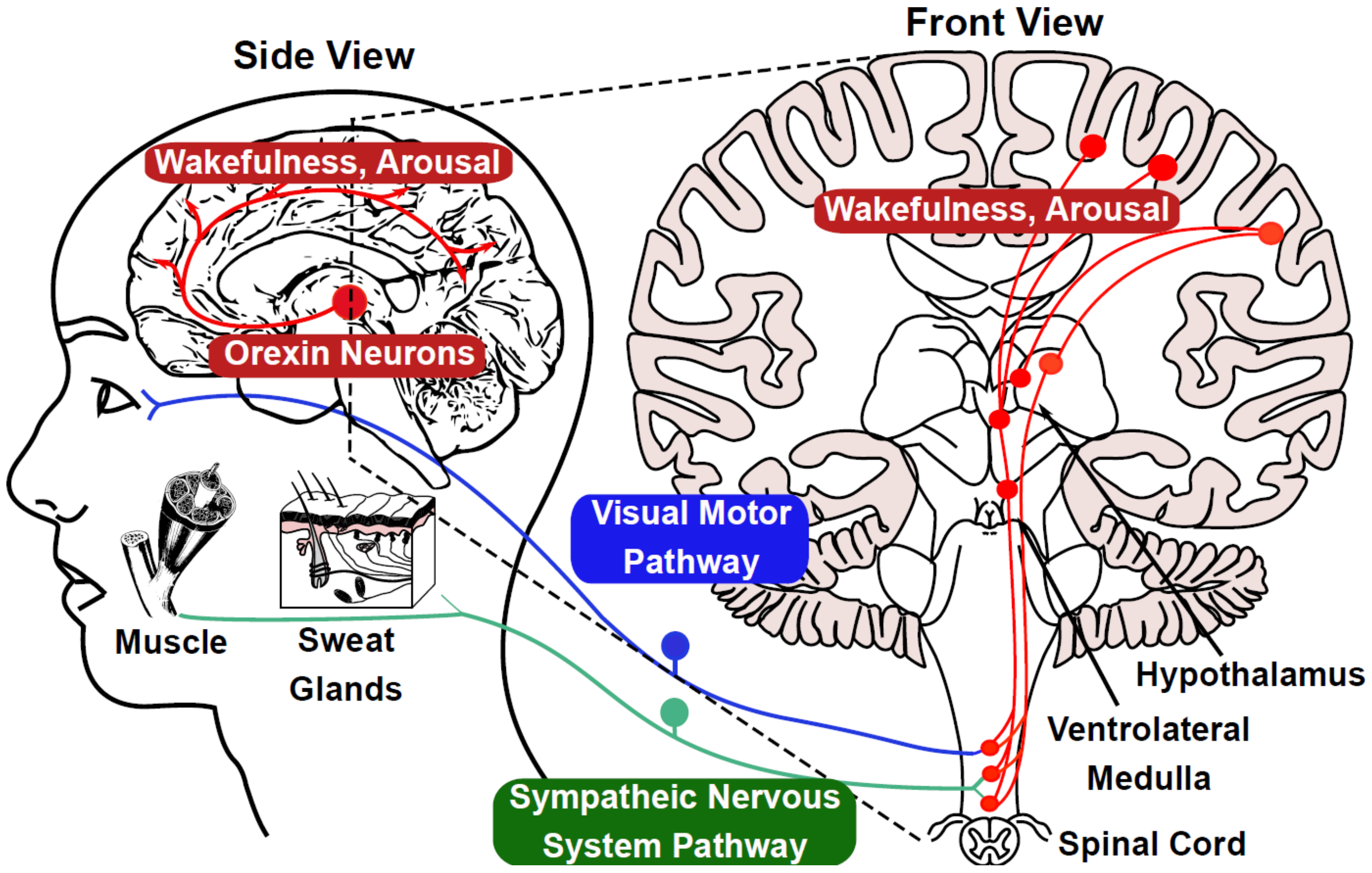
Microsleep can be costly and even deadly!



- ❑ **U.S.**: **65+ millions** people experiences Microsleep because of Sleep Deprivation, Narcolepsy, and Sleep Apnea.
- ❑ **3X** risk of vehicle accident
- ❑ **1.6X** risk of work accident

$411 Billions

What happens during a microsleep?



- ❑ **Cognitive States:**
  - The shift of brain waves from fast Alpha (awake, conscious) to slow Theta (sleep, unconscious) activities.
- ❑ **Behaviors:**
  - Slow rolling eyes, irregular eye blinks.
  - Relaxed facial muscle tone and reduced sweat glands' activity.

Keys to capture microsleeps!

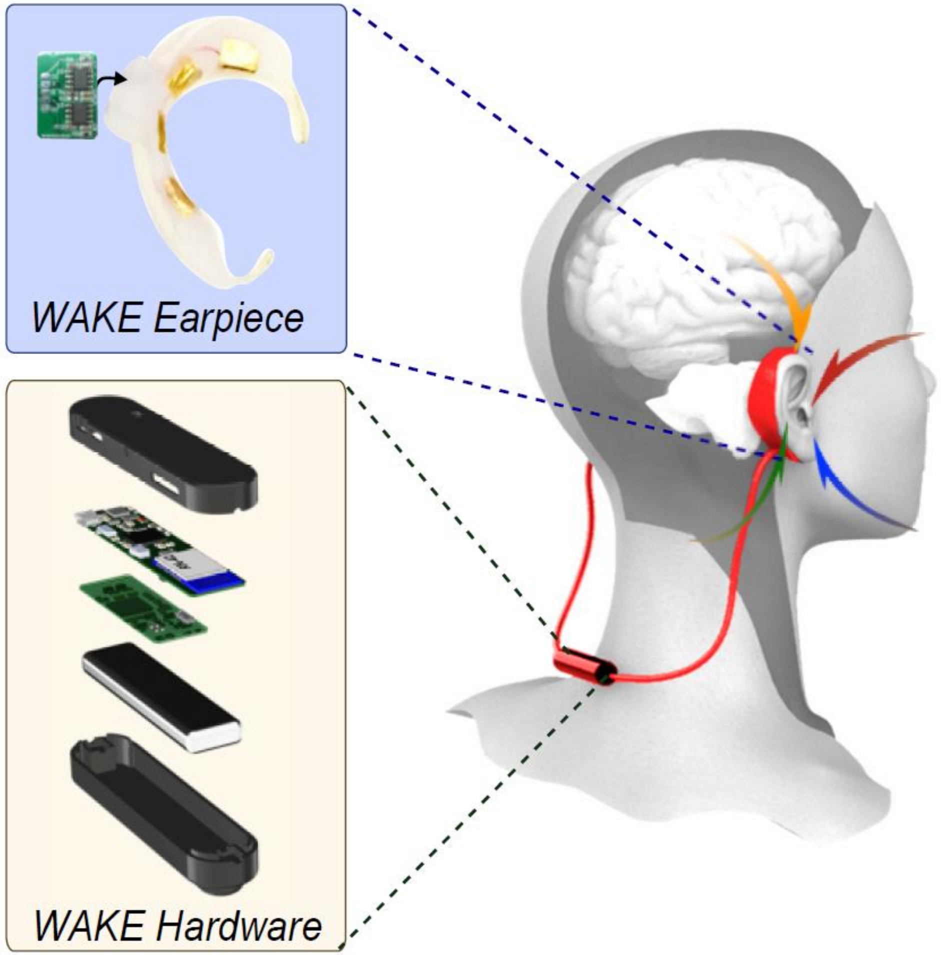
The need of a new solution

<u>Video-EEG + Maintenance of Wakefulness Test:</u>
- Medical 'gold-standard'
- Requires sleep expert and technicians
- High cost, can't be used daily
- Multiple sensors on the head and face.

<u>Camera:</u>
- Only captures behaviors
- Privacy concern
- Limited by lighting condition

A new (accurate, low cost, socially acceptable) solution is needed!

Our proposed Behind-the-ear wearable system



Able to capture key microsleep biomarkers

Compact, low cost, can be used daily

Socially acceptable

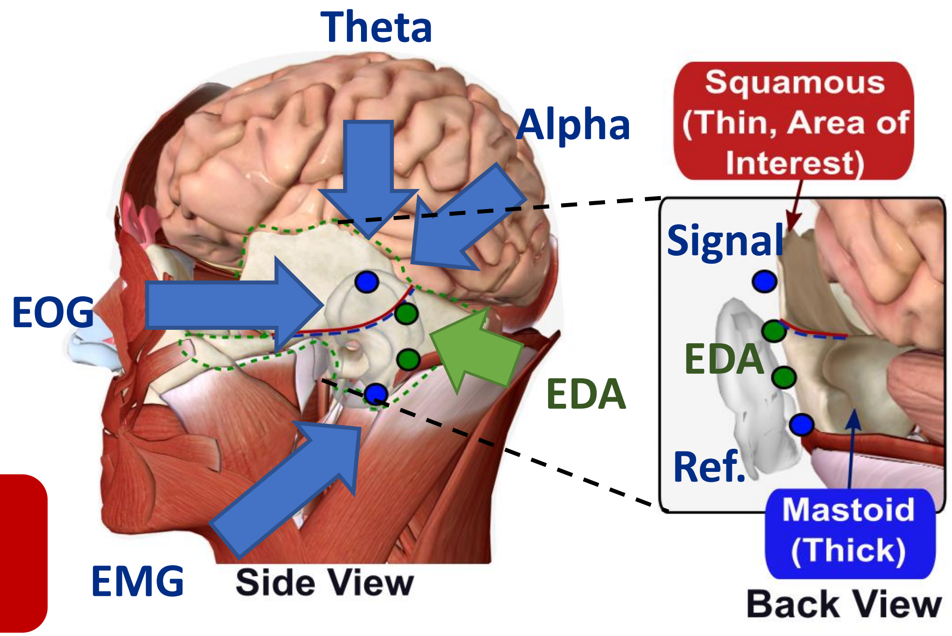
Roadmap

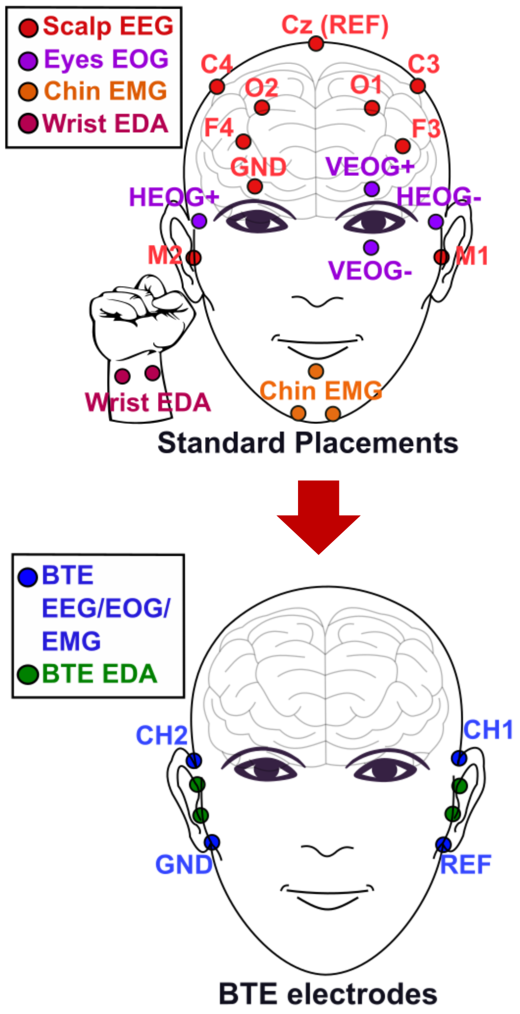
- ❑ <u>**Challenges and our solutions to realize WAKE**</u>
- ❑ **Implementation and Evaluations**
- ❑ **Conclusion**

Challenge #1: Where to place the sensors? (1/2)

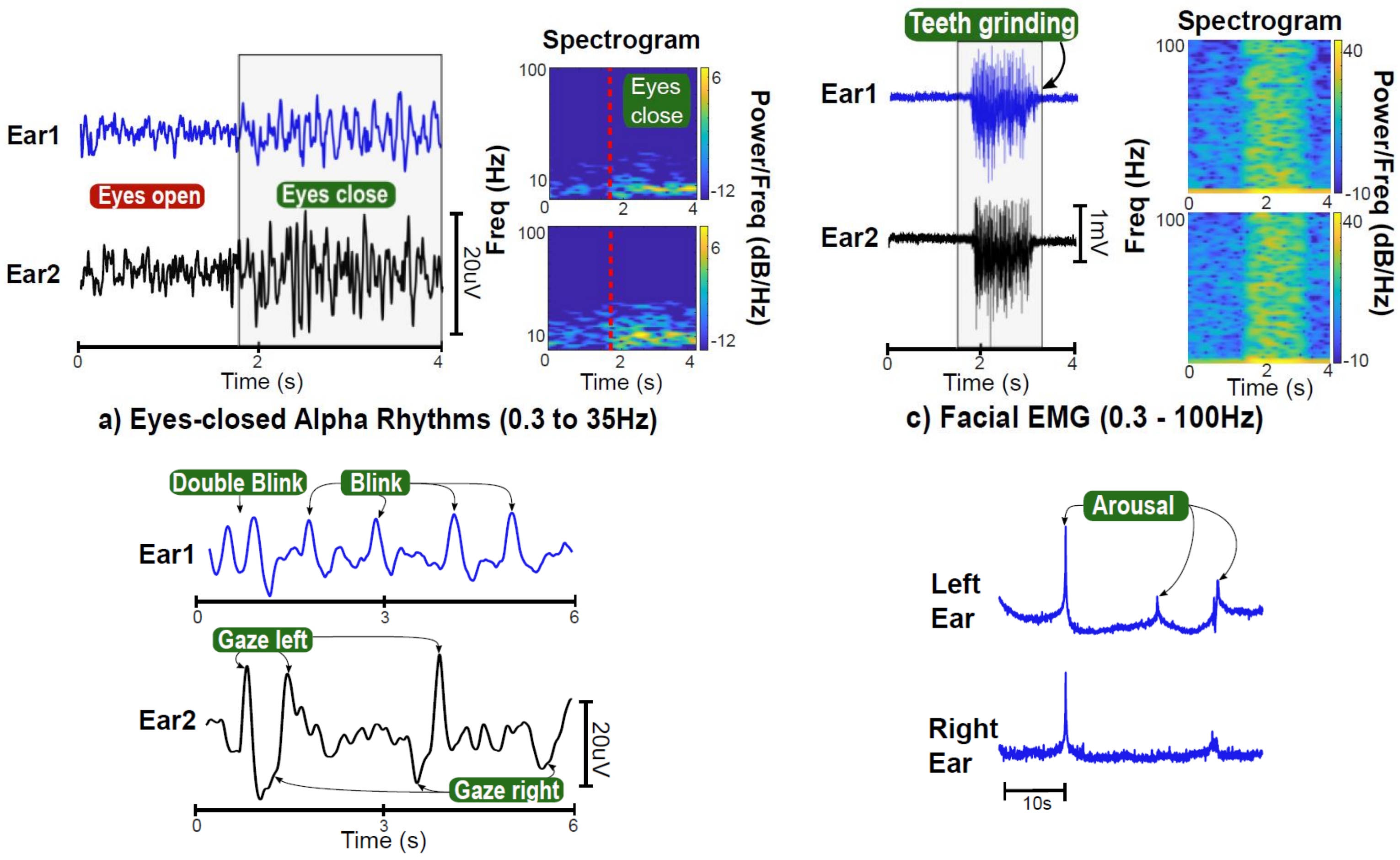
- **So that:**
  - **Wearability** and **sensing sensitivity** can be achieved.
  - **Minimal number of sensors** is desirable.

The ear is the intersection of microsleep biomarkers!





Challenge #1: Where to place the sensors? (2/2)
Feasibility confirmation



a) Eyes-closed Alpha Rhythms (0.3 to 35Hz)

b) Vertical and Horizontal EOG (0.3 - 10Hz)

c) Facial EMG (0.3 - 100Hz)

d) EDA (0.1-1.5Hz)

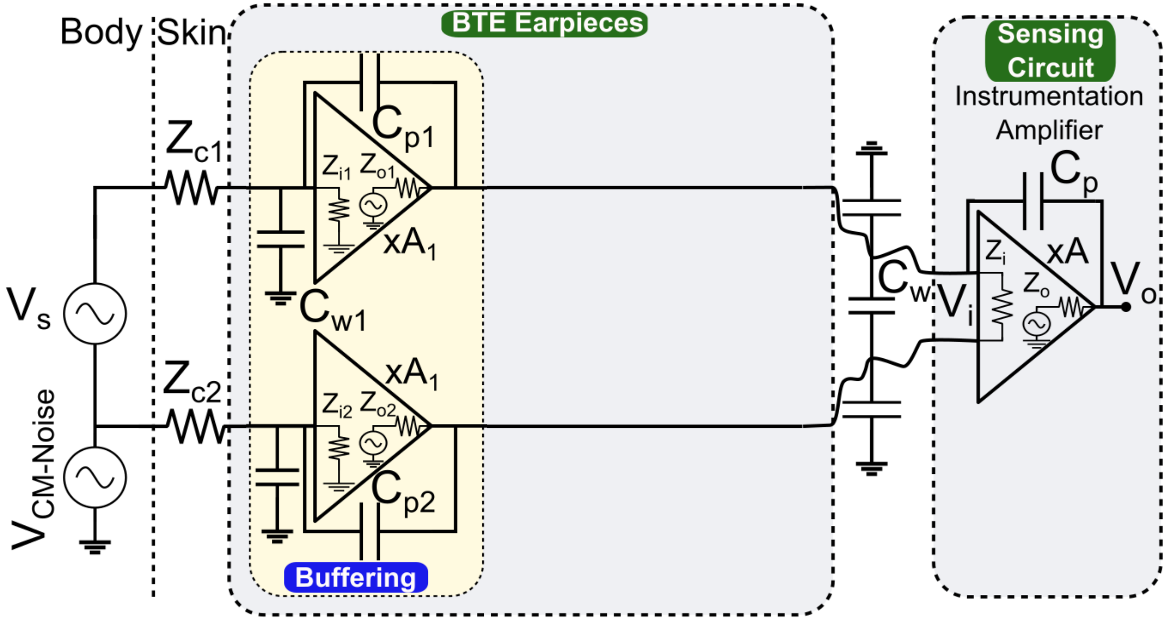
- **Unique characteristics/challenges** of the BTE signals?
  - **Low amplitude** of BTE EEG/EOG. (i.e. <50uV vs. 100-500uV)
  - **Overlap** frequency bands between BTE EEG/EOG and EMG with **a significant amplitude difference** (i.e. 1000x).

Challenge #2: Motion and environmental noise (1/3)

Motion and environmental noise is a long-standing challenge!

- **Motion artifacts:**
  - **Micro-motions** of the sensing electrodes.
  - **Fluctuation (i.e. microphonic triboelectric effect)** of the signal wires.
- **Environmental noise:**
  - Noise coupled through the **human body** and **signal wires**.
  - Noise characteristic **varies across environments**.

Challenge #2: Motion and environmental noise (2/3)
Three-folds cascaded amplifying (3CA) – Motion artifacts



- **Electrical model:**

$$V_o = G * V_s = \frac{A * V_s}{1 + (Z_{c1} + Z_{c2})(\frac{1}{R_i} + jw(C_w + C_i + (A-1)C_p)} \quad (*)$$

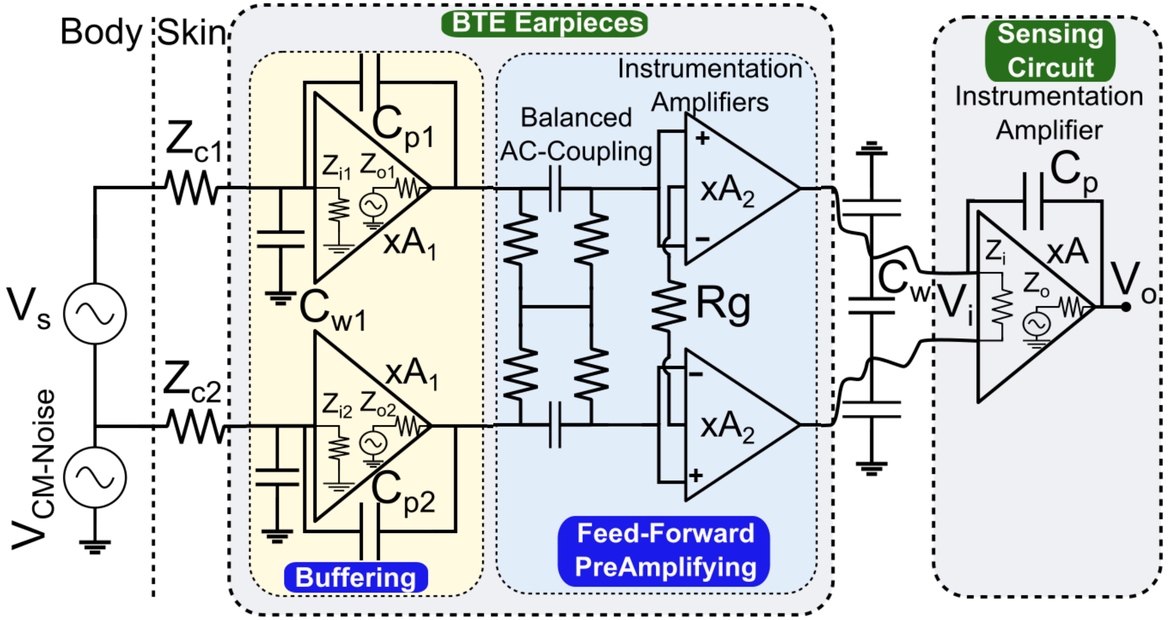
- Movement of the wires => changes in C_w
- Micro-motion of the electrode => changes in Z_{c1}, Z_{c2}

=> **Fluctuations** of the output signal.

- **Introduce Stage 1 - Unity-gain amplifying:**
  - **Z transformation:** transform Z_{c1}, Z_{c2} in (*) to Z_{o1}, Z_{o2} (~0) => eliminate the effect of C_w.
  - **Minimizing effect of Z_{c1} changes:** Minimize γ by using **A=1**, maximizing R_{i1}, minimizing C_{i1}, C_{w1}.

$$V_o = \frac{A_1 * V_s}{1 + Z_{c1}(\frac{1}{R_{i1}} + jw(C_{w1} + C_{i1} + (A-1)C_{p1})} = \frac{A_1 * V_s}{1 + Z_{c1}\gamma}$$

Challenge #2: Motion and environmental noise (3/3)
Three-folds cascaded amplifying (3CA) – Environmental noise

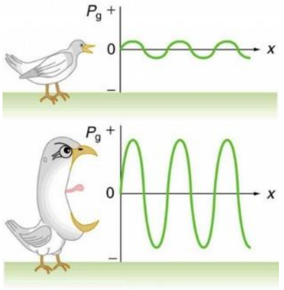


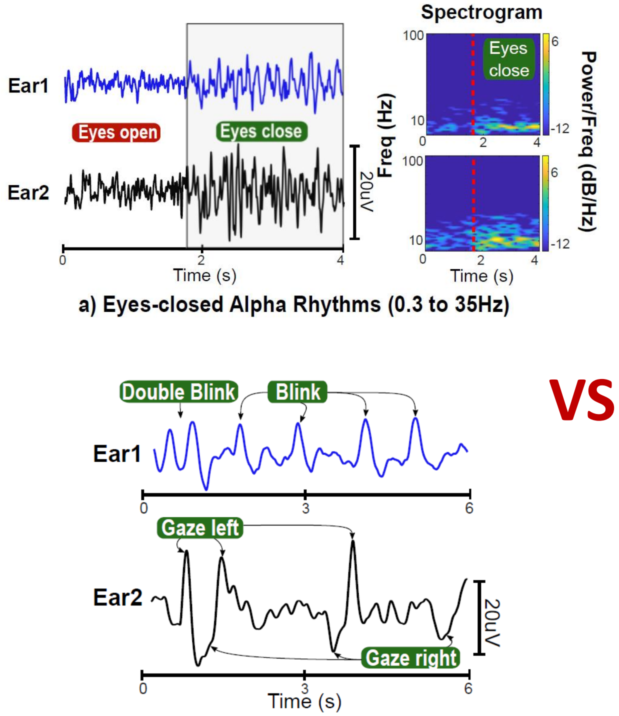
- **Introduce Stage 2 - Feed Forward Differential PreAmplifying (F2DP):**
  - **2 separate amplifying stages** minimize the effect of motion due to contact impedance.
  - **Feed-Forward Differential Amplifying** technique with dual instrumentation amplifiers:
    - Enhance Common-mode rejection ratio (CMRR).

$$CMRR_{IA} = \frac{G_{DM}}{G_{CM}}; \quad CMRR_{F2DP} = \frac{G_{DM1} + G_{DM2}}{|G_{CM1} - G_{CM2}|}$$

    - Produce **amplified, fully differential** signals => robust again environmental noises.
  - **Balanced AC-coupling** topology: efficiently remove DC component while mitigating component mismatches issue.

Challenge #3: Overlap signal with a significant range (1/2)

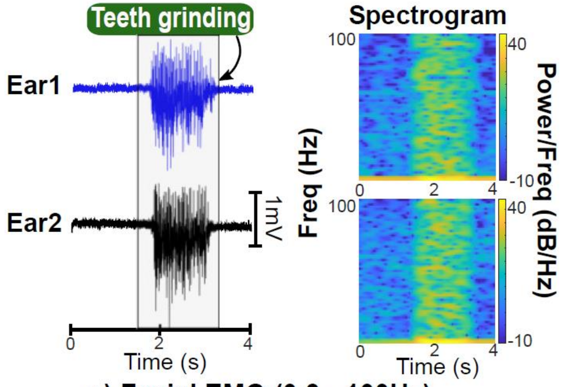




a) Eyes-closed Alpha Rhythms (0.3 to 35Hz)

b) Vertical and Horizontal EOG (0.3 - 10Hz)

VS.



c) Facial EMG (0.3 - 100Hz)

BTE EEG/EOG is overlap with EMG in a three-orders magnitude range!

❑ Using a fixed gain is not efficient!

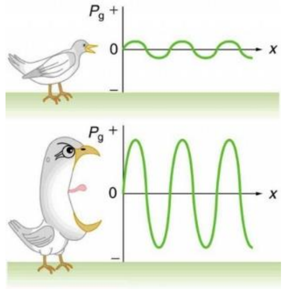
- High gain => saturate BTE EMG signal.
- Low gain => increase noise floor for weak BTE EEG/EOG signals.

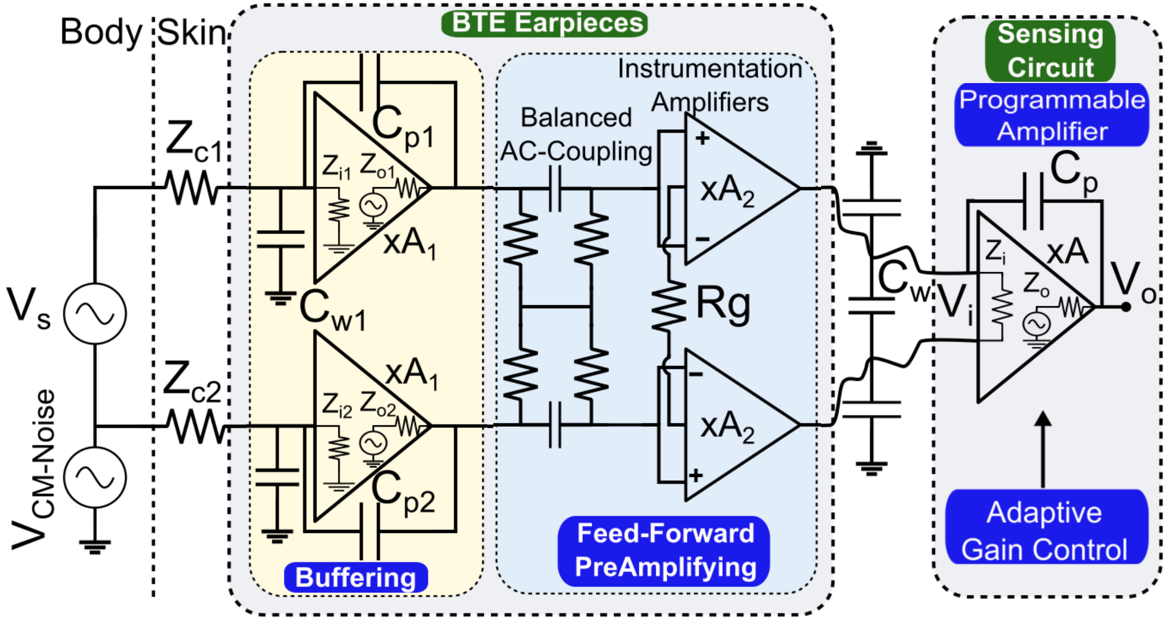
=> The amplifier gain needs to be changed on-the-fly.

❑ Observations on BTE signal patterns:

- Strong EMG events don’t happen frequently.
- EMG events can happen abruptly.
- EMG signal is stochastic and can vary significantly.

Challenge #3: Overlap signal with a significant range (1/2)
Adaptive Amplifying and Adaptive Gain Control





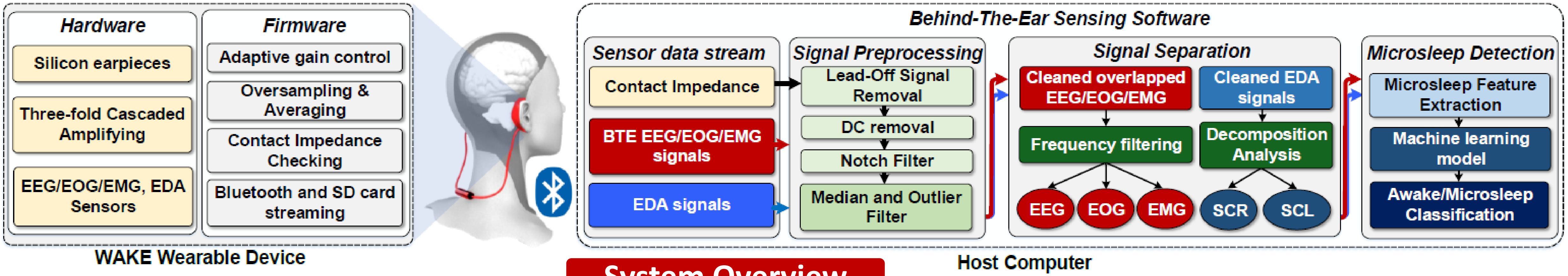
- **Introduce Stage 3 – Adaptive Amplifying with an Adaptive Gain Control algorithm:**
  - Initially, **keep the gain at maximum** for BTE EEG/EOG signal.
  - **React quickly to abrupt increases** from the initial state => capture an EMG event quickly.
  - **React slowly to abrupt decreases** while an EMG event is happening => avoid gain oscillation.

- **Square Law Detector vs. Peak Envelope Detector:**
  - Both can be used for AGC.
  - PED with dynamic windows is used because of low complexity.

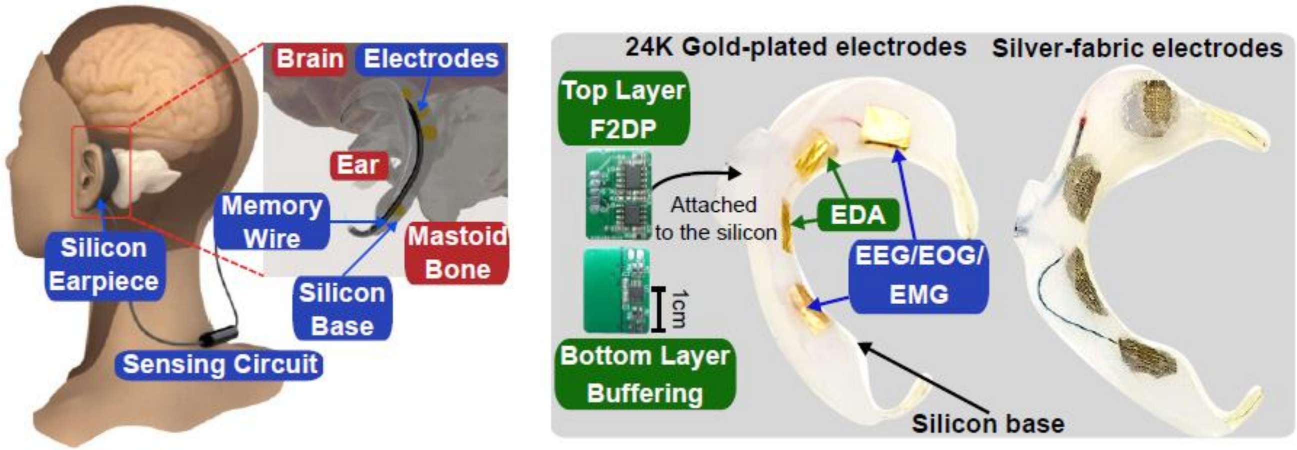
Roadmap

- ❑ **Challenges and our solutions to realize WAKE**
- ❑ **<u>Implementation and Evaluations</u>**
- ❑ **Conclusion**

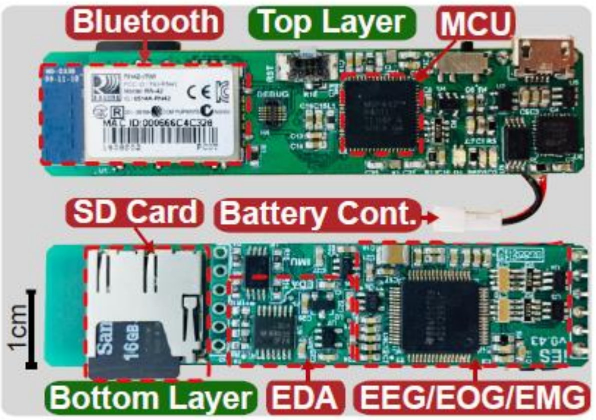
Implementation



System Overview

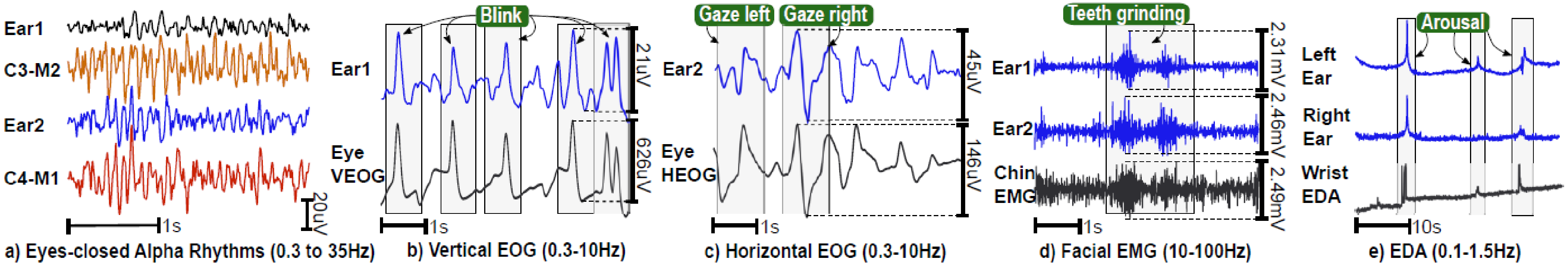


Earpieces design



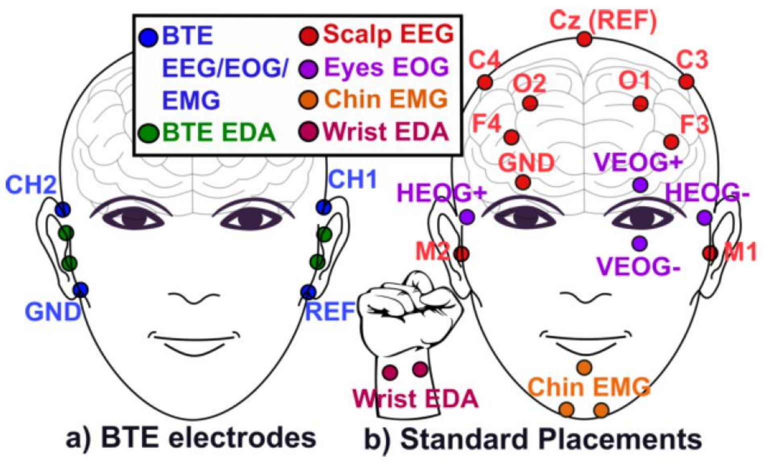
Sensing device

Evaluation #1 – Signal Sensitivity Validation



BTE vs. Ground-truth signals

Electrode placements

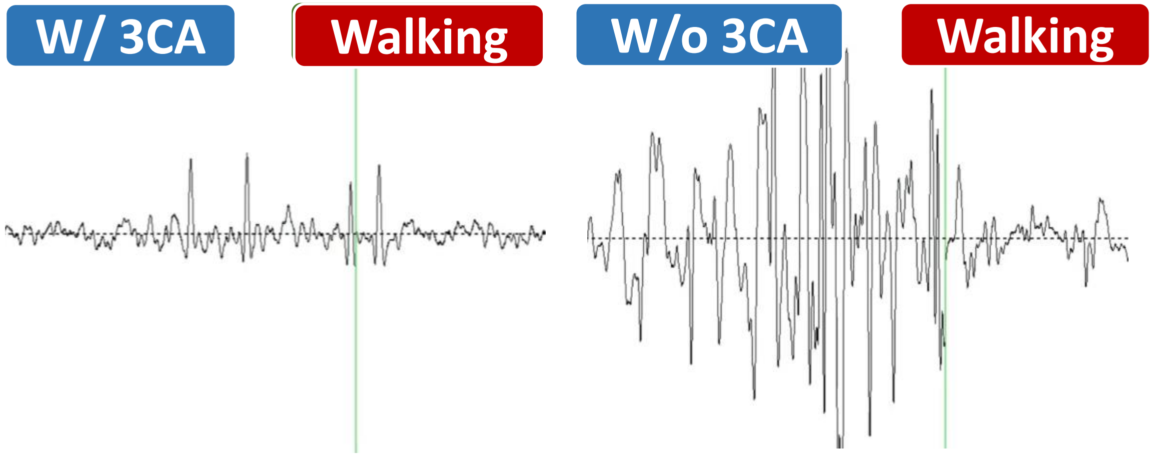


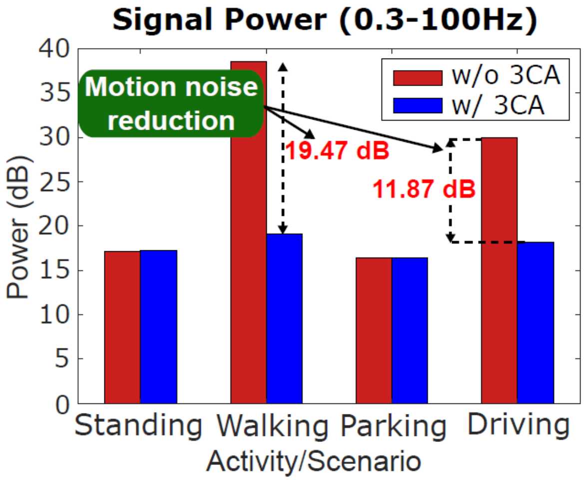
Normalized Cross Correlation

	Ear1	Ear2
C3-M2	0.35 (moderate)	
C4-M1		0.44 (moderate)
O1-M2	0.28 (weak)	
O2-M1		0.52 (moderate)
VEOG	0.47 (moderate)	
HEOG		0.59 (strong)
Chin EMG	0.62 (strong)	0.76 (strong)
Left Wrist EDA	0.37 (moderate)	

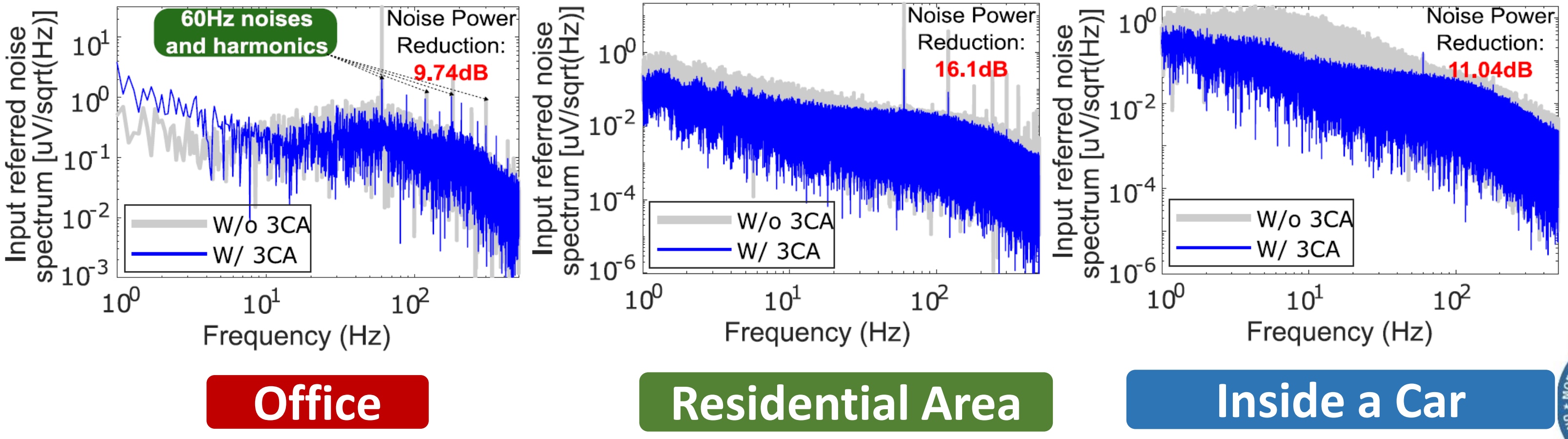
Evaluation #2 – Motion and Environmental Noise Suppression

- **Motion artifact evaluations:**
  - Standing vs. Walking.
  - Parking (w/ a running engine) vs. Driving.
  - Durations: 40-60 minutes

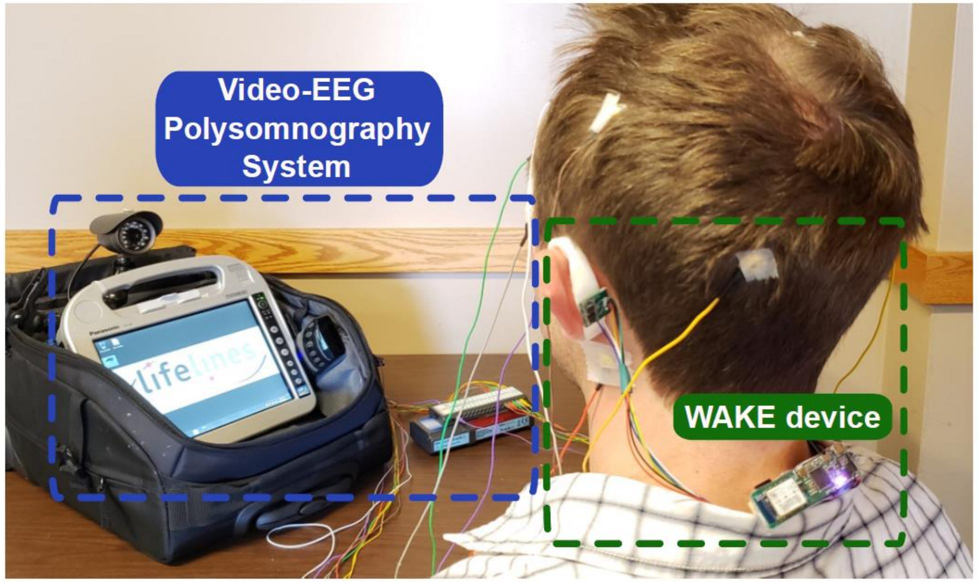




- **Environmental noise evaluations:**
  - 3 different environments: Office, Residential area, and Inside a car.
  - Durations: 60 minutes



Evaluation #3 – Microsleep Detection Performance



Experiment Setup

❑ Demographic:

- 19 subjects.
- Healthy: 9, Sleep deprivation: 9, Narcolepsy: 1.
- Experiment duration: maximum 2h.
- **Ground-truth:** Video-PSG system with 2 sleep experts.

❑ Classification model:

- 35,558 awake and 8,845 microsleep data points.
- Epoch size: 5s, 80% overlap (i.e. slide every 1s).
- Durations: maximum 2 hours/each subject.
- **Hybrid model** of **a hierarchical classifier** (Random Forest, Adaboost, SVM) and **EMG-event-based heuristic rule**.

Classification Performance

Experiment	Precision	Sensitivity	Specificity
Leave-one-subject-out (Inter-subject)	0.76	0.85	0.85
Test-set (75%/25%) (Intra-subject)	0.87	0.9	0.96
Leave-one-sample-out (Intra-subject)	0.88	0.89	0.96

Evaluation #4 – Usability Analysis

❑ Power and Thermal:

- **Active:** 241.5mW, 9.2h (600 mAh battery); 37.4°C (avg.), 38.9°C (peak).
- **Idle:** 51.60mW, 43.1h (600 mAh battery); 31.6°C (avg.).

❑ Cost:

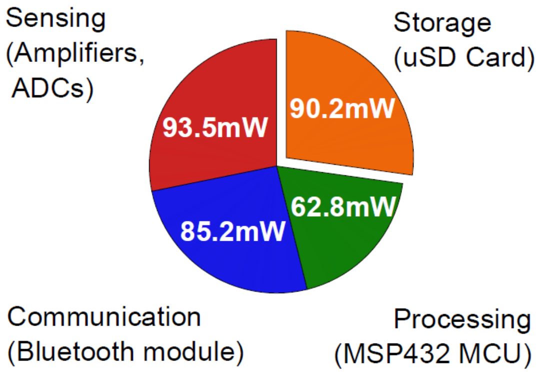
- Total component cost: <$150.
- Video-PSG: >$20,000.

❑ User's study:

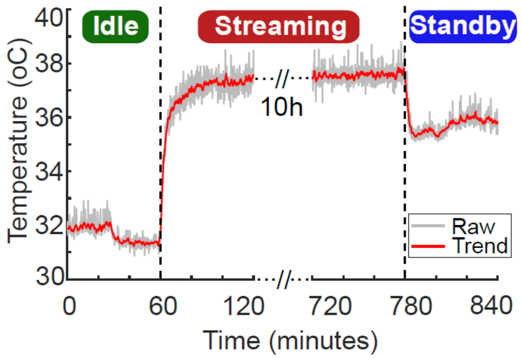
- 36 users who have used WAKE for 2 hours.

❑ WAKE and Eyeglasses study:

- 8 people who wear WAKE and eyeglasses during their daily activities for 3-4 hours.

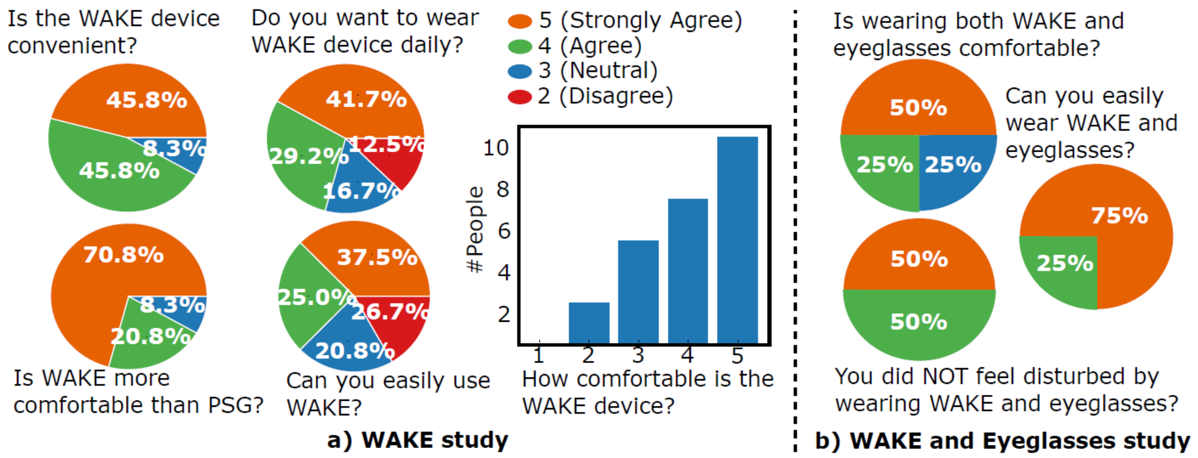


Active Power Usage



Thermal Profiling

User's study



Conclusion

- **Contributions of WAKE:**
  - Devise a **Three-fold Cascaded Amplifying (3CA)** technique to mitigate motion and environmental noises.
  - Identify a **minimal number of areas behind human ears** so that a **wearable, compact, and socially acceptable device** can be designed to capture multiple microsleep biomarkers.
  - Develop **a hybrid classification model** detect users' microsleep.
  - **Evaluate the proposed system** using our custom-built prototype on 19 subjects to show the feasibility for microsleep detection.

- **Future work:**
  - In-the wild microsleep detection evaluation.
  - Optimizing WAKE device such as: employing dry electrode, better mechanism of keeping the electrode contact, etc.
  - Exploring the effect of other human artifacts such as the impact of sweat condition, hydration, etc.