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

Nhat (Nick) Pham†‡, Tuan Dinh§‡, Zohreh Raghebi†‡, Taeho Kim†, Nam Bui†, Phuc Nguyen†★, Hoang Truong†, Farnoush Banaei-Kashani†‡, Ann Halbower‡‡, Thang Dinh§§, and Tam Vu†‡

†University of Colorado Boulder, ‡University of Oxford, §University of Wisconsin Madison, †‡University of Colorado Denver, ★University of Texas at Arlington, ††Children’s Hospital Colorado, §§Virginia Commonwealth University

ACM MobiSys’20, June 15-19, 2020
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 Billion
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

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

Camera:
- 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

- Challenges and our solutions to realize WAKE
- 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**

- **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 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.
Electrical model:

\[ V_o = G \ast V_s = \frac{A \ast V_s}{1 + (Z_{c1} + Z_{c2})\left(\frac{1}{R_i} + j\omega(C_w + C_i + (A - 1)C_p)\right)} \]  

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 \( Z_{01}, Z_{02} \) (~0) => eliminate the effect of \( C_w \).

- **Minimizing effect of \( Z_{c1} \) changes**: Minimize \( \gamma \) by using \( A=1 \), maximizing \( R_{i1} \), minimizing \( C_{i1}, C_{w1} \).
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)

- 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.

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

System Overview

Hardware
- Silicon earpieces
- Three-fold Cascaded Amplifying
- EEG/EOG/EMG, EDA Sensors

Firmware
- Adaptive gain control
- Oversampling & Averaging
- Contact Impedance Checking
- Bluetooth and SD card streaming

Sensor data stream
- Contact Impedance
- BTE EEG/EOG/EMG signals
- EDA signals

Signal Preprocessing
- Lead-Off Signal Removal
- DC removal
- Notch Filter
- Median and Outlier Filter

Signal Separation
- Cleaned overlapped EEG/EOG/EMG
- Frequency filtering
- Decomposition Analysis
- Cleaned EDA signals

Microsleep Detection
- Microsleep Feature Extraction
- Machine learning model
- Awake/Microsleep Classification

WAKE Wearable Device

Host Computer

Earpieces design

Sensing device
Evaluation #1 – Signal Sensitivity Validation

**Electrode placements**

<table>
<thead>
<tr>
<th></th>
<th>Ear1</th>
<th>Ear2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3-M2</td>
<td>0.35  (moderate)</td>
<td>0.44  (moderate)</td>
</tr>
<tr>
<td>C4-M1</td>
<td></td>
<td>0.44  (moderate)</td>
</tr>
<tr>
<td>O1-M2</td>
<td>0.28  (weak)</td>
<td>0.52  (moderate)</td>
</tr>
<tr>
<td>VEOG</td>
<td>0.47  (moderate)</td>
<td></td>
</tr>
<tr>
<td>HEOG</td>
<td></td>
<td>0.59  (strong)</td>
</tr>
<tr>
<td>Chin EMG</td>
<td>0.62  (strong)</td>
<td>0.76  (strong)</td>
</tr>
<tr>
<td>Left Wrist EDA</td>
<td>0.37  (moderate)</td>
<td></td>
</tr>
</tbody>
</table>
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

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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Precision</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leave-one-subject-out (Inter-subject)</td>
<td>0.76</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Test-set (75%/25%) (Intra-subject)</td>
<td>0.87</td>
<td>0.90</td>
<td>0.96</td>
</tr>
<tr>
<td>Leave-one-sample-out (Intra-subject)</td>
<td>0.88</td>
<td>0.89</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Evaluation #4 – Usability Analysis

❑ Power and Thermal:
  o **Active**: 241.5\( mW \), 9.2h (600 mAh battery); 37.4°C (avg.), 38.9°C (peak).
  o **Idle**: 51.60\( mW \), 43.1h (600 mAh battery); 31.6°C (avg.).

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

❑ User’s study:
  o 36 users who have used WAKE for 2 hours.

❑ WAKE and Eyeglasses study:
  o 8 people who wear WAKE and eyeglasses during their daily activities for 3-4 hours.
Conclusion

❑ Contributions of WAKE:

  o Devise a Three-fold Cascaded Amplifying (3CA) technique to mitigate motion and environmental noises.
  o 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.
  o Develop a hybrid classification model to detect users’ microsleep.
  o Evaluate the proposed system using our custom-built prototype on 19 subjects to show the feasibility for microsleep detection.

❑ Future work:

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