TROY OLSSON
PROGRAM MANAGER
DARPA/MTO
N-ZERO:
NEAR-ZERO
POWER SENSING
THE PROMISE OF THE INTERNET OF THINGS (IoT)

Image Source: Libelium
LI FETIME IS LIMITED BY ACTIVE WAKEUP CI RCUITRY

- Sensor nodes must be deployed for long durations at low cost
- Energy consumption is extremely limited
- Data is continuously processed but rarely worthy of communication
- Sensing is often time critical, as the source may only briefly be in proximity of the sensor
- Communication of a sensing event is often time critical

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LIFETIME IS LIMITED BY ACTIVE WAKEUP CIRCUITRY

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N-ZERO VISION: OFF BUT ALERT!

N-ZERO passive sensor wake-up:
- Continuous operation and near-zero power processing
- Persistent sensing with greatly extended lifetime and reduced cost
<table>
<thead>
<tr>
<th>Power Consumption</th>
<th>Component Description</th>
<th>Lifetime from a 30 mAh button cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mW</td>
<td>Magnetic field sensor</td>
<td>20 (minutes)</td>
</tr>
<tr>
<td>10 mW</td>
<td>UNB Transceiver</td>
<td>3 (hours)</td>
</tr>
<tr>
<td>1 mW</td>
<td>Microphone and accelerometer</td>
<td>1 (day)</td>
</tr>
<tr>
<td>100 µW</td>
<td>1 MHz, 32-bit M4 processor</td>
<td>12 (days)</td>
</tr>
<tr>
<td>10 µW</td>
<td>IEEE 802.11ba wake-up radio receiver</td>
<td>4 (months)</td>
</tr>
<tr>
<td>1 µW</td>
<td>Wake-on-sound or motion sensors</td>
<td>3.4 (years)</td>
</tr>
<tr>
<td>100 nW</td>
<td>Sleeping processors, sleeping radios, 64 kB memory and N-ZERO</td>
<td>34 (years)</td>
</tr>
<tr>
<td>10 nW</td>
<td></td>
<td>340 (years)</td>
</tr>
</tbody>
</table>

THE N-ZERO ADVANTAGE

Unattended Ground Sensors

- Analog Wake-Up: Always Consumes Power
  - Recording: 1.4 Min/Day
  - Lifetime from Coin Cell: ~1 Month

UGS RF Transceivers

- Periodic Wake-up and Synchronization
  - Transmit Data: 6 Mb/Day
  - Receive Data: 12 Mb/Day
  - Average Power (mW): 95%

- N-ZERO

- OFF but constantly ALERT
- Wake-up and synchronization do not drain lifetime

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# N-ZERO SENSOR PERFORMANCE

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Signature Detected</th>
<th>Interference w/ Specificity</th>
<th>Standby Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic</td>
<td>Vehicle at 10 m</td>
<td>Urban</td>
<td>20 nW</td>
</tr>
<tr>
<td>Infrared</td>
<td>Wavelength-specific IR</td>
<td>Broadband thermal &amp; other wavelengths</td>
<td>passive</td>
</tr>
<tr>
<td>Chemical</td>
<td>~1 ppm of 1,5-diaminopentane</td>
<td>Ambient and pentane</td>
<td>passive</td>
</tr>
<tr>
<td>RF</td>
<td>-80 dBm coded waveform</td>
<td>Urban</td>
<td>6 nW</td>
</tr>
</tbody>
</table>
IR SENSING WITHOUT POWER

Switch triggered by 6 mm IR

Reacts 4 mm IR

ALWAYS-ON nW RECEIVER FOR NETWORKED IoT

N-ZERO HAS SIGNIFICANTLY ADVANCED LOW-POWER RF


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LOW-POWER PROCESSING

- ARM Cortex-M33 with DSP extensions
- Shutdown power: 10nW
- Active power: 10uW-2mW (0.1-50MHz)
- ROM capacity: 128kB
- RAM capacity: 16kB active + 4kB shutdown

How does the DoD use the technology?

Source: ARM
N-ZERO PERSISTENT SENSING OPPORTUNITIES

- New class of nW systems
- RF, acoustic, seismic, IR, and chemical modalities
- Orders-of-magnitude improvement in lifetime and battery size
- Persistent sensing without sleep-cycling
MICROSYSTEMS FOR THE IoT

Source: Dennis Sylvester, University of Michigan
ERI ELECTRONICS RESURGENCE INITIATIVE SUMMIT

2018 | SAN FRANCISCO, CA | JULY 23-25
DENNIS SYLVESTER
UNIVERSITY OF MICHIGAN
NEAR ZERO-POWER MACHINE LEARNING PROCESSORS FOR CONTINUOUS ACOUSTIC SENSING

Dennis Sylvester, David Blaauw, Hun Seok Kim
University of Michigan

THIS RESEARCH WAS DEVELOPED WITH FUNDING FROM THE DEFENSE ADVANCED RESEARCH PROJECTS AGENCY (DARPA).

THE VIEWS, OPINIONS AND/OR FINDINGS EXPRESSED ARE THOSE OF THE AUTHOR AND SHOULD NOT BE INTERPRETED AS REPRESENTING THE OFFICIAL VIEWS OR POLICIES OF THE DEPARTMENT OF DEFENSE OR THE U.S. GOVERNMENT.
PROPOSED SYSTEM OVERVIEW

- ~10nW acoustic sensing and object recognition microsystem
- Initial targets: generator, car, truck
- Later targets: voice activity, keywords
SIGNAL PROPERTIES EXPLOITED FOR NEAR ZERO POWER DSP

Concentrated within a relatively narrow bandwidth (<500Hz)

Sparse in frequency domain → Full FFT/DFT unnecessary

Allows a 1kHz clock for all active components

Stationary in time domain → Sequential feature extraction

Generator

Truck

Car

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FEATURE EXTRACTION

- DFT performed **only** on the **discrete tones of interest (ToI)**

\[
\begin{align*}
X[0] & = \begin{bmatrix} 1 & 1 & 1 & \ldots & 1 \end{bmatrix} \\
X[1] & = \begin{bmatrix} 1 & W & W^2 & \ldots & W^{N-1} \end{bmatrix} \\
X[2] & = \begin{bmatrix} 1 & W^2 & W^4 & \ldots & W^{2(N-1)} \end{bmatrix} \\
X[3] & = \begin{bmatrix} 1 & W^3 & W^6 & \ldots & W^{3(N-1)} \end{bmatrix} \\
& \vdots \\
X[N-2] & = \begin{bmatrix} 1 & W^{N-2} & W^{2(N-2)} & \ldots & W^{(N-2)(N-2)} \end{bmatrix} \\
X[N-1] & = \begin{bmatrix} 1 & W^{N-1} & W^{2(N-1)} & \ldots & W^{(N-1)(N-1)} \end{bmatrix}
\end{align*}
\]

\[
W = e^{j2\pi n/N}
\]

\[
\begin{align*}
x[0] & \quad x[1] \\
& \vdots \\
x[n-2] & \quad x[n-1]
\end{align*}
\]
PROPOSED FEATURE EXTRACTION METHOD

- DFT performed **only** on the discrete tones of interest (ToI)
- **Serialized** tone-by-tone computation

Diagram:

- Vertical axis labeled $V_{\text{sig}}$
- Horizontal axis labeled Time
- N ADC output samples
- Distribution Statement "A" Approved for Public Release, Distribution Unlimited
• DFT performed **only** on the **discrete tones of interest (ToI)**
• **Serialized** tone-by-tone computation
PROPOSED FEATURE EXTRACTION METHOD

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- **Serialized** tone-by-tone computation (‘tone’ signal is complex valued)
PROGRAMMABLE, NEAR-ZERO POWER DSP ARCHITECTURE

Support vector machine (SVM)
Multi-layer fully connected NN
Piecewise-linear non-linear functions
N-ZERO TARGET CLASSIFICATION

- Targets: generator, small car, truck
- 32x1 ToI DFT feature input vector $\rightarrow$ 5 input frames combined to 160x1 input vector
- Weights quantized to 8-bit
- Fully connected NN with 2 layers, softmax output, moving average post-processing
- Programmable processor: other NN configurations possible
### Fixed-Point Performance Matrix

<table>
<thead>
<tr>
<th>Data Target</th>
<th>Generator</th>
<th>Car</th>
<th>Truck</th>
<th>Quiet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>99.47%</td>
<td>0%</td>
<td>0.53%</td>
<td>0%</td>
</tr>
<tr>
<td>Car</td>
<td>0.66%</td>
<td>95.33%</td>
<td>0.71%</td>
<td>3.30%</td>
</tr>
<tr>
<td>Truck</td>
<td>0.13%</td>
<td>0.41%</td>
<td>95.64%</td>
<td>3.82%</td>
</tr>
</tbody>
</table>

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**ENVIRONMENT-SPECIFIC TRAINING**

Trained without wind data, Tested with wind

<table>
<thead>
<tr>
<th>Data</th>
<th>Target</th>
<th>Generator</th>
<th>Truck</th>
<th>Car</th>
<th>Quiet+ Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>99.75%</td>
<td>0.0%</td>
<td>0.13%</td>
<td>0.06%</td>
<td></td>
</tr>
<tr>
<td>Truck</td>
<td>0.0%</td>
<td>96.35%</td>
<td>0.39%</td>
<td>6.35%</td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.18%</td>
<td>0.69%</td>
<td>96.59%</td>
<td>8.81%</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing probability of detection vs. power ratio wind/target (dB)](image-url)

*Distribution Statement “A” Approved for Public Release, Distribution Unlimited*
Trained with wind data, Tested with unseen wind

<table>
<thead>
<tr>
<th>Target</th>
<th>Generator</th>
<th>Truck</th>
<th>Car</th>
<th>Quiet + Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>99.63%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.04%</td>
</tr>
<tr>
<td>Truck</td>
<td>0.0%</td>
<td>97.02%</td>
<td>1.08%</td>
<td>2.75%</td>
</tr>
<tr>
<td>Car</td>
<td>0.09%</td>
<td>0.32%</td>
<td>95.57%</td>
<td>3.35%</td>
</tr>
</tbody>
</table>

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PHASE 2 HARDWARE TESTING

- Testing condition emulates 5m distance
A MORE COMPLETE AUDIO MICROSYSTEM

- Overall system size
  - 6×5×4 mm³

- Features
  - Real-time audio acquisition with low power compression
    - 15-38 mins of recording on 1 charge, 4.7uW avg power
  - 8Mb Flash storage
  - Solar energy harvesting
  - Wireless link
  - General purpose \( \mu \)-processor
A POSSIBLE PATHWAY

- Self-sustaining autonomous audio detection/recognition microsystem incl. moderate range RF (~50m)

Miniaturize N-Zero trigger

Wake up powerful DNN-based audio recording & analysis microsystem

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SUMMARY

- Ultra-low power audio detection possible, in mm-scale form factors
  - Unobtrusive, long lifetime
- Applications in surveillance/monitoring, as well as non-military spaces
  - Truly smart user interfaces for next generation IoT devices
- Combines advances in fully integrated DNNs, ULP analog/mixed-signal circuits
- Commercialization of mm-scale systems being pursued via Cubewoks
- Always-on voice control in ULP IoT being pursued via Ambiq Micro
- DNN in edge devices being pursued via Mythic