Near-Zero Power Radio Frequency Receivers

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N-ZERO Vision: Persistent Sensing for the DoD

N-ZERO seeks to greatly extend mission capabilities and lifetime at reduced cost

Geophone recording of activity followed by RF transmission
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
- Multiple sensing modalities with sensor fusion

Devices are OFF (zero power consumption) yet continually ALERT!

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Smart Cities Applications

- Unattended sensors
- Communications nodes
- IoT devices

Perimeter Monitoring

Critical Infrastructure Protection

Threat Detection in Urban Areas

Environment Monitoring

Artist’s Concept
Current State-of-the-Art (SOA): Awaiting Activity Constrains Mission Life

- Unattended sensors
- Power draw waiting for information (wake-up limited)
- Power draw from processing information (activity limited)

Acoustic signature @ 3 m standoff

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Current SOA: Awaiting Activity Constrains Mission Life

Unattended Sensors and Radios

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Staying ALERT requires ACTIVE POWER!

Current SOA: Awaiting Activity Constrains Mission Life

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The N-ZERO Advantage

Unattended Ground Sensors

- Analog Wake-Up Always Consumes Power
- Recording 1.4 Min/Day
- ~ 1 Month Device Lifetime from Coin Cell
- Savings From N-ZERO Passive Wake-up
- ~ 5 Year Device Lifetime from Coin Cell

- Analog Wake-Up Always Consumes Power
- Recording 1.4 Min/Day
- Example Microsystem
- Example Microsystem w/ N-ZERO

UGS RF Transceivers

- Periodic Wake-up and Synchronization
- Transmit Data 6 Mb/Day
- Receive Data 12 MB/Day
- ~ 1 Month Device Lifetime
- Example Radio
- Example Radio w/ N-ZERO

- Transmit Data 6 Mb/Day
- Receive Data 12 MB/Day
- ~ 24 Month Device Lifetime

- Savings From N-ZERO Passive Wake-Up

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

• Staying alert requires active power
• Wake-up and synchronization consume > 95% of battery life for sparse signals

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N-ZERO Concept

- **N-ZERO senses** the environment 100% of the time at near-zero power
- N-ZERO uses energy in the signals to perform **signal processing** to detect information while rejecting noise and interference
- **Detection** of an event triggers activation of the COTS module for further processing and follow-up action

**N-ZERO**

- **N-ZERO RF Sensor**
- **N-ZERO Physical Sensor**
- **RF Wake-up**
- **Sensor Wake-up**

**Not N-ZERO: COTS Wireless Unattended Ground Sensor**

- **COTS Radio Response**
- **COTS Sensor Response**
- **COTS battery**

**N-ZERO does not replace COTS functionality. N-ZERO will reduce COTS “on” time, thereby dramatically increasing the sensor’s useful lifetime.**

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Outline

- Sensor Examples
  - Acoustic
  - Infrared
  - Chemical

- Near-Zero Power Receivers
  - Challenge
  - Architecture
  - Components
    - Transformers
    - Rectifiers
  - Receiver demonstrations
  - Measured performance vs. state-of-the-art
Acoustic Sensor Wake-up


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Wake-up to generator and truck at > 5m with 12 nW of power consumption
Programmable Microphone Wake-up


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Zero Power IR Spectrum Sensor


Concept

Operation Description

IR spectrometer with zero standby power

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Zero Power IR Spectrum Sensor


SEM Image

Plasmonic Absorber Response

Switch triggered by 6 μm IR

Rejects 4 μm IR

IR spectrometer with zero standby power

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Passive detection of chemical warfare agents with zero power

**Chemical Percolation Wake-Up**

1,5 Diaminopentane Target

Exposure sensor to chemical in petri dish

Remove sensor from chemical gas

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<table>
<thead>
<tr>
<th>Metric</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF level at sensor input</td>
<td>≤ -60 dBm</td>
<td>≤ -80 dBm</td>
<td>≤ -100 dBm</td>
</tr>
<tr>
<td>RF frequency limits</td>
<td>0.05-1 GHz</td>
<td>0.05-1 GHz</td>
<td>0.05-1 GHz</td>
</tr>
<tr>
<td>Received energy required for signature detection</td>
<td>≤ 30 pJ</td>
<td>≤ 300 fJ</td>
<td>≤ 3 fJ</td>
</tr>
<tr>
<td>Probability of detection</td>
<td></td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>False alarm rate</td>
<td>&lt; 1 per hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>low interference background</td>
<td>high interference background</td>
<td>high interference background</td>
</tr>
</tbody>
</table>
The Challenge of Near-Zero Power RF Wake-Up

Traditional Rx
High Power (mW)

Traditional Wake-Up
Low Sensitivity (-30 dBm)

N-ZERO Wake-Up
< 10 nW
< -60 to -100 dBm
Efficiency Limited by $V_T$

Antenna (50 $\Omega$) Referred Peak Voltage at Various Power Levels
- -60 dBm = 316 $\mu$V
- -80 dBm = 31.6 $\mu$V
- -100 dBm = 3.16 $\mu$V

RF Approaches


Passive Voltage Gain Approaches
New materials offer much larger figure of merit (FOM) and potential for higher voltage gain.

\[ K^2 = 19\% \]
\[ Q = 2200 \]
\[ \text{FOM} = 420! \]

High FOM Device Can Lead to New Levels of Passive Voltage Gain

Achievable Voltage Gain vs. Coupling$^2 \times$ Quality Factor (FOM = $K^2Q$)

- Demonstrated transformer gain
- Based on measured device FOM

- 1 GHz Si-MEMS
- AIN MEMS
- LiNbO$_3$ SAW
- 2014 LiNbO$_3$ MEMS

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High FOM µResonator

AIN cross-sectional Lamé-mode Resonators

\[ k_t^2 = 6.2\% \]

\[ Q_{\text{load}} = 1750 \]

\[ C_0 = 26.3 \text{ fF} \]

\[ R_m = 210 \Omega \]

FOM ~ 108!

High Gain Acoustic Transformer

FOM = 40
Voltage gain ~ 40 at 920 GHz


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MEMS Chirp Compressor

LC Transformer Filter


V\text{gain} = 17.9 \text{ V/V}
Antenna (50 Ω) referred peak voltage at various power levels
- -60 dBm = 316 μV
- -80 dBm = 31.6 μV
- -100 dBm = 3.16 μV
Low Voltage Rectifier Approaches
Micromechanical Switches as Efficient Rectifiers and Quantizers

- Displacement ~ $V^2$
- Very low thresholds achievable
- Steep subthreshold swing < 1mV/dec demonstrated
- Challenge is achieving small gaps and compliant structures for low threshold voltage

Micromechanical Rectifiers and Quantizers

300 µV threshold MEMS switch

Envelope Detector as a Rectifier

**Benefit:**
Active ED has high input impedance to support high RF gain

\[2^{\text{nd}}\text{ order } g_m \text{ non-linearity realizes the ED squaring-function}\]
Envelop Detector Implementation

Active-Inductor ED Bias

0.4V

V_B

Vantage ED bias improves SNR by 3dB & 25dB over diode load & resistor load, respectively


Benefit:
- high R_{out}
- high gain
- high SNR

Active-L ED bias improves SNR by 3dB & 25dB over diode load & resistor load, respectively
Why Low Voltage Rectifiers

Antenna (50 Ω) referred peak voltage at various power levels
- -60 dBm = 316 µV
- -80 dBm = 31.6 µV
- -100 dBm = 3.16 µV
Micromechanical Frequency-Selective N-ZERO Receiver

Demonstrated sensitivity: 
-62 dBm @ 20-kHz

All mechanical zero-power receiver

Zero Quiescent Power Low Frequency Mechanical Receiver, Transducers 2015

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N-ZERO VHF Wake-up Receiver

Lowest powered effort for N-ZERO wake-up receiver

RF Sensing - TA-1A

www.eecs.umich.edu/wics/low_power_radio_survey.html

Remote wake-up a circuit **without drawing stand-by power**

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### Current Results

<table>
<thead>
<tr>
<th></th>
<th>Phase I Goal</th>
<th>UCSD</th>
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</thead>
<tbody>
<tr>
<td>Power Consumption [nW]</td>
<td>≤10</td>
<td>4.5</td>
</tr>
<tr>
<td>Sensitivity [dBm]</td>
<td>≤-60</td>
<td>-69</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>50 - 1000</td>
<td>114</td>
</tr>
<tr>
<td>False Alarm Rates [#/hour]</td>
<td>≤1</td>
<td>0.64</td>
</tr>
<tr>
<td>Probability of Detection [%]</td>
<td>95</td>
<td>≥95</td>
</tr>
<tr>
<td>Transformer</td>
<td>Performer Defined</td>
<td>LC</td>
</tr>
<tr>
<td>Rectifier</td>
<td>Performer Defined</td>
<td>CMOS</td>
</tr>
</tbody>
</table>
N-ZERO Zero Power RF Wake-Up Impact

Networked sensors

~ 1 Month Device Lifetime

~ 24 Month Device Lifetime

N-ZERO RF wake-up greatly extends networked sensor lifetime

Transmission Data 6 MB/Day

Receive Data 12 MB/Day
Enabling Indefinite Operational Lifetimes

Temperature

Electronics/Actuators

Storage

Energy Scavenging Technologies

Thermoelectric ~90 uW/cm² (delta = 77-98 deg F)

Vibration ~100 uW/cm² (typ. inside a moving car)

Solar ~100 uW to 30 mW/cm² (office to direct sun)

N-ZERO – smart sensors and radios that can operate from harvested power

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Enabling Indefinite Operational Lifetimes

https://www.slideshare.net/Funk98/energy-harvesting-for-iot

[Image of solar power technology]

Solar power technology for small sensors and radios.
• Unattended sensors with unlimited lifetimes

• Expanded short range RFID with -70dBm sensitivity

• One trillion devices that do not require charging or battery changes
www.darpa.mil