TROY OLSSON

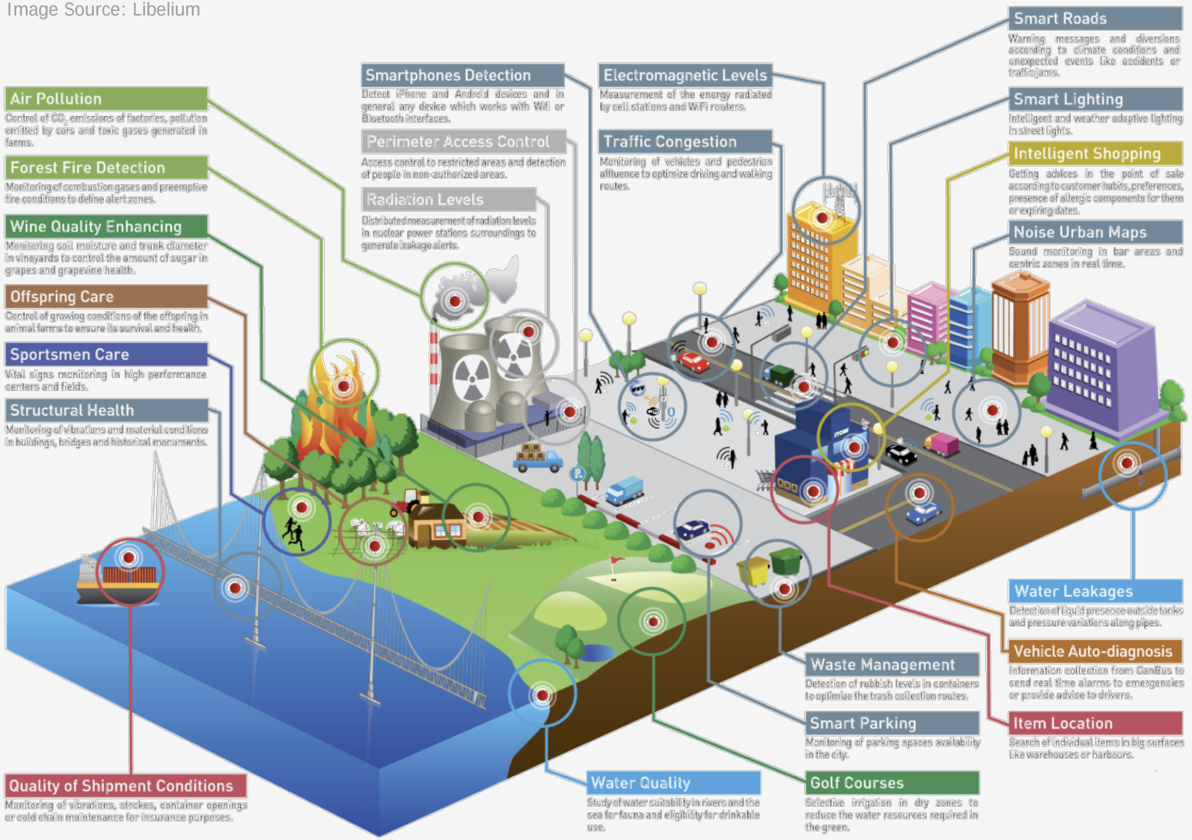
PROGRAM MANAGER

DARPA/MTO

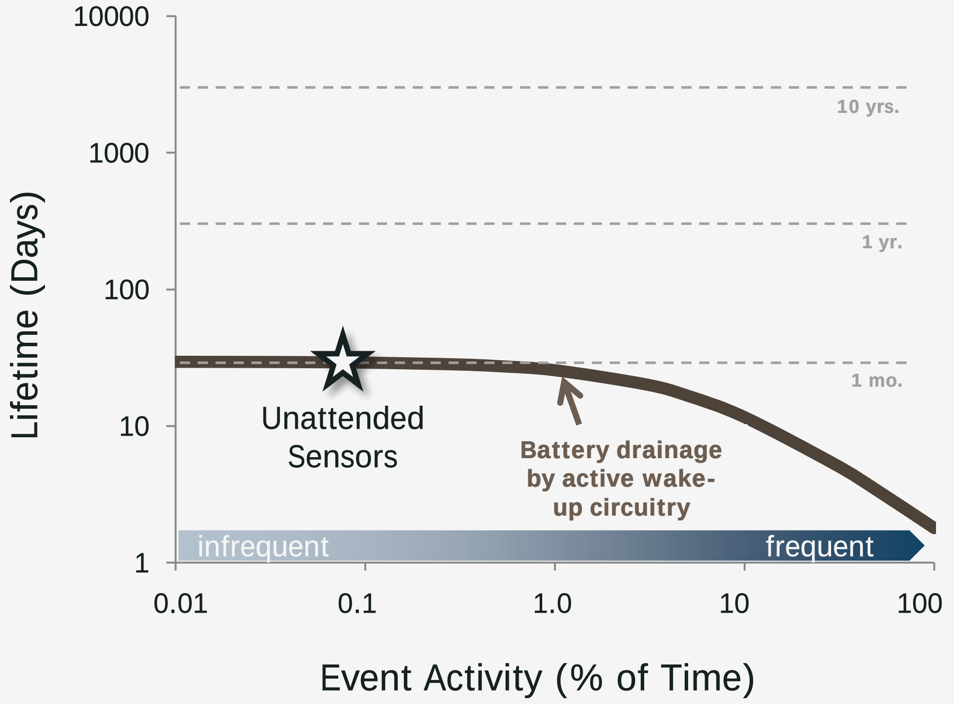
N-ZERO: NEAR-ZERO POWER SENSING

THE PROMISE OF THE INTERNET OF THINGS (IoT)

Image Source: Libelium



LIFETIME IS LIMITED BY ACTIVE WAKEUP CIRCUITRY



- 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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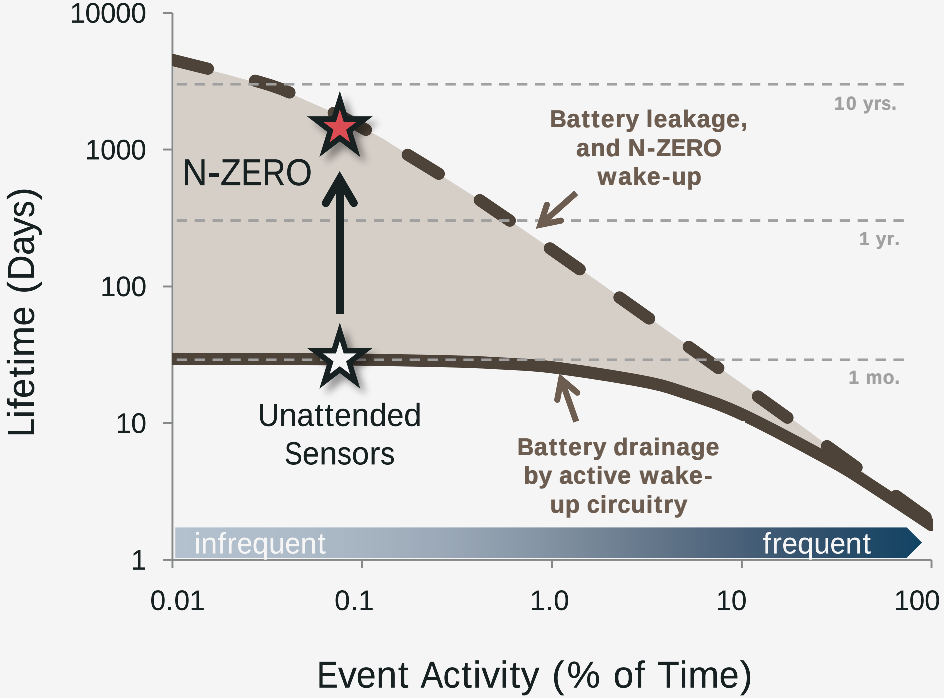

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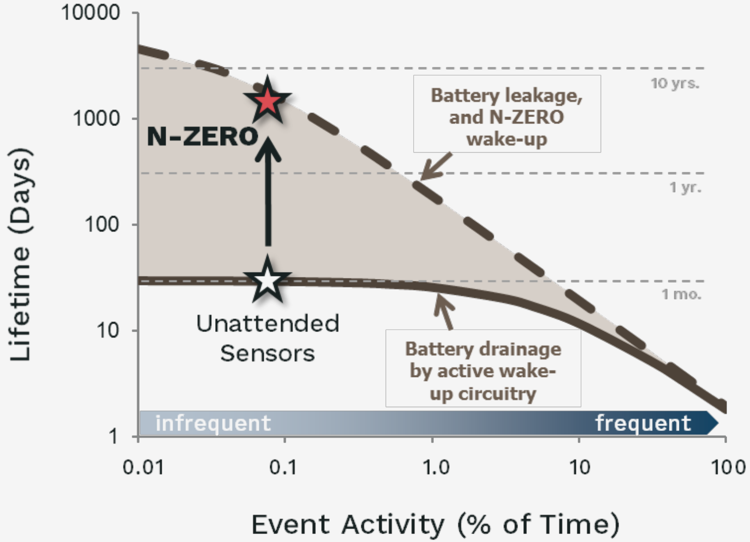
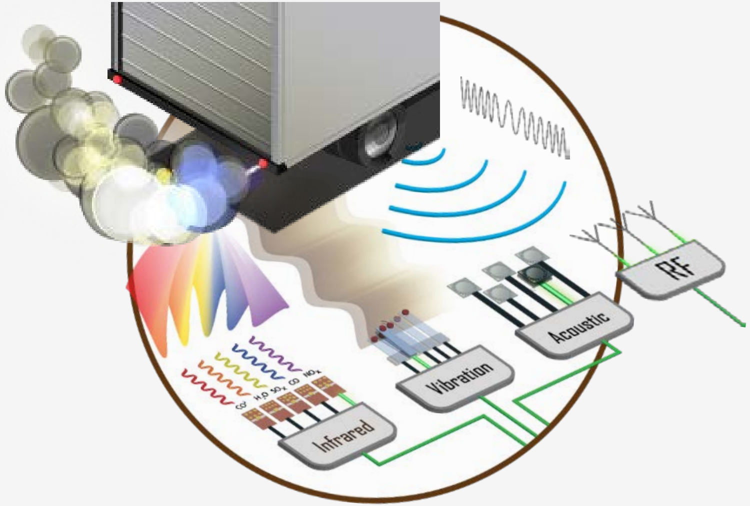
N-ZERO VISION: OFF BUT ALERT!

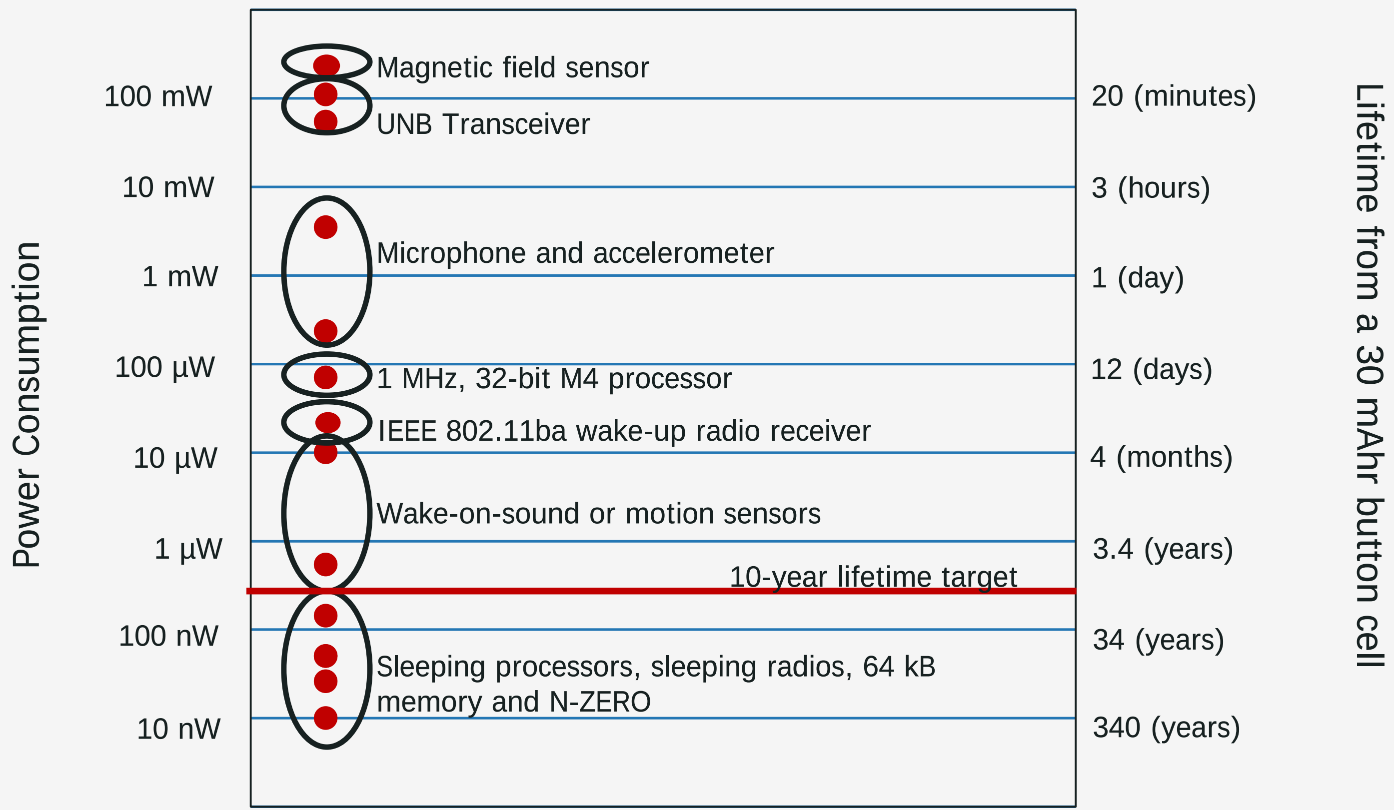




<u>N-ZERO passive sensor wake-up:</u>

- Continuous operation and near-zero power processing
- Persistent sensing with greatly extended lifetime and reduced cost

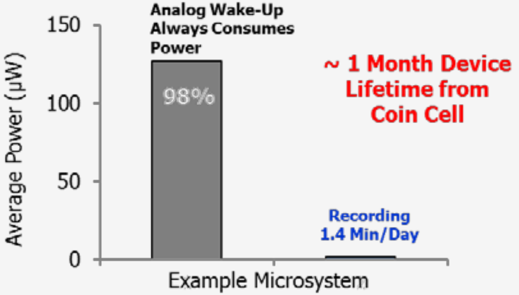
POWER CONSUMPTION AND LIFETIME OF UNATTENDED SENSOR SYSTEM COMPONENTS



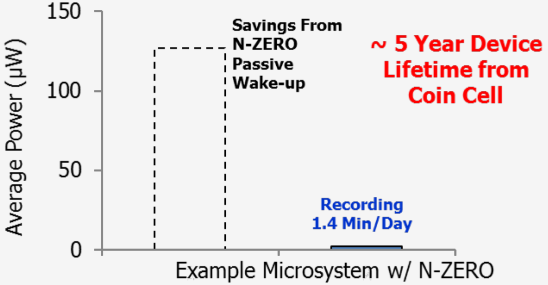
Source: http://theinstitute.ieee.org/resources/standards/ieee-wakeup-radio-standard-expected-to-boost-battery-life-of-iot-devices

THE N-ZERO ADVANTAGE

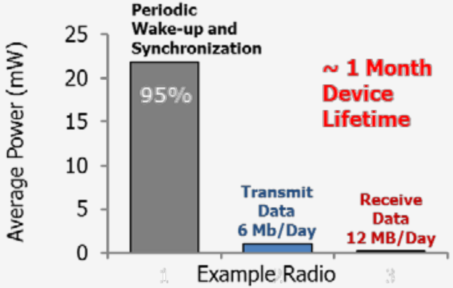
Unattended Ground Sensors



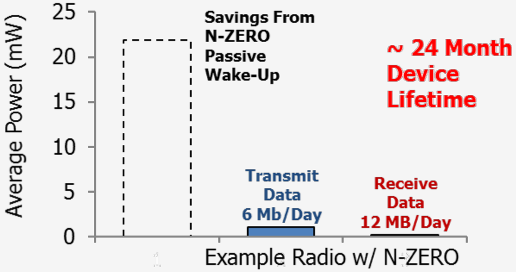
N-ZERO



UGS RF Transceivers



N-ZERO



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

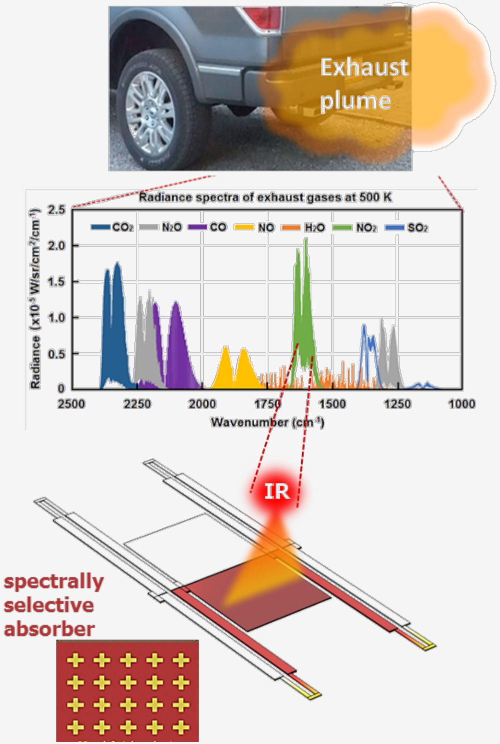
- OFF but constantly ALERT
- Wake-up and synchronization do not drain lifetime

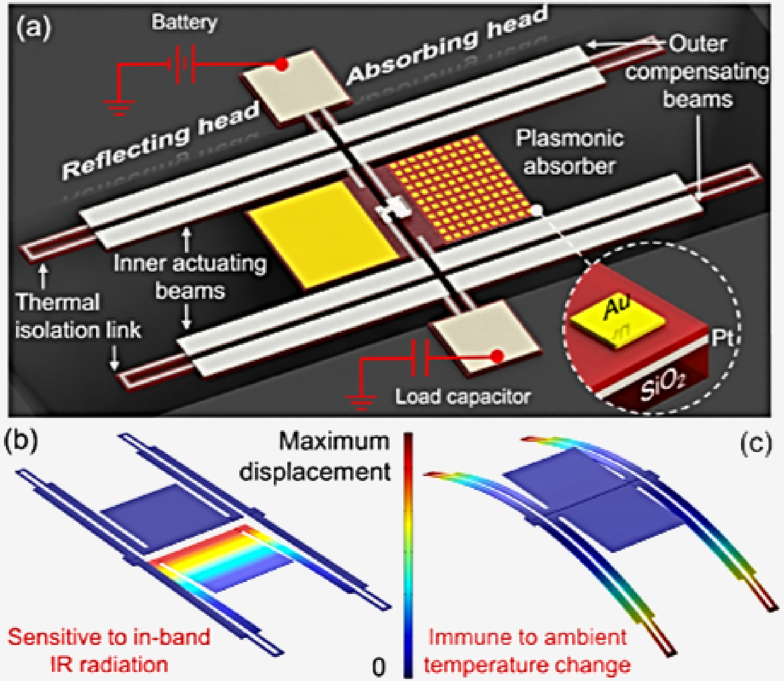
N-ZERO SENSOR PERFORMANCE

Sensor Type	Signature Detected > 95% POD	Interference w/ Specificity	Standby Power
Acoustic	Vehicle at 10 m	Urban	20 nW
Infrared	Wavelength-specific IR	Broadband thermal & other wavelengths	passive
Chemical	~1 ppm of 1,5-diaminopentane	Ambient and pentane	passive
RF	-80 dBm coded waveform	Urban	6 nW

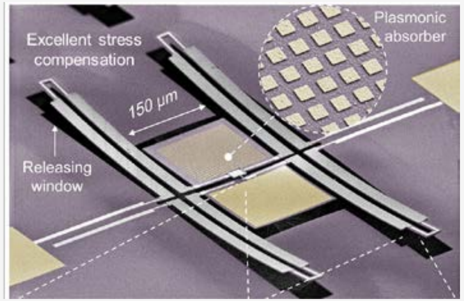
ZERO POWER IR SPECTRUM SENSOR

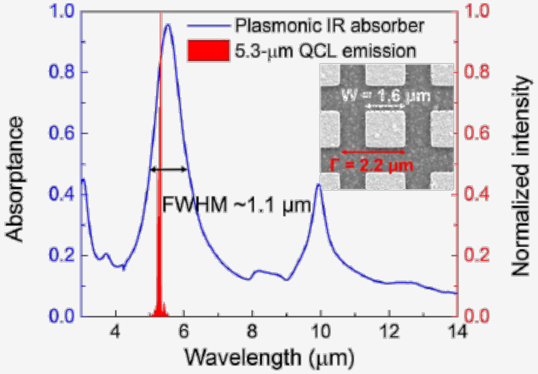
Qian, Zhenyun, et al. "Zero-power light-actuated micromechanical relay." Micro Electro Mechanical Systems (MEMS), 2017 IEEE 30th International Conference on. IEEE, 2017.

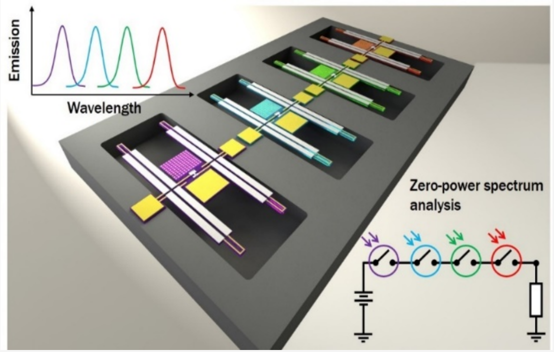




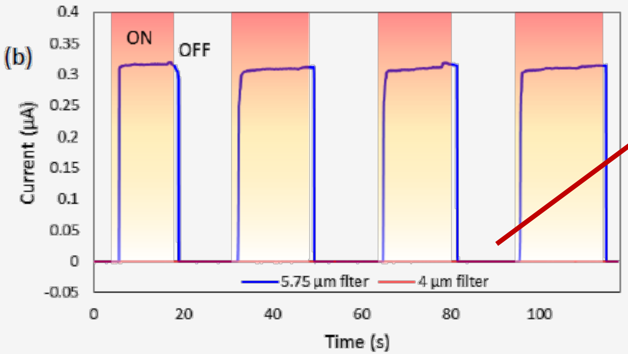
IR SENSING WITHOUT POWER







Switch triggered by 6 mm IR



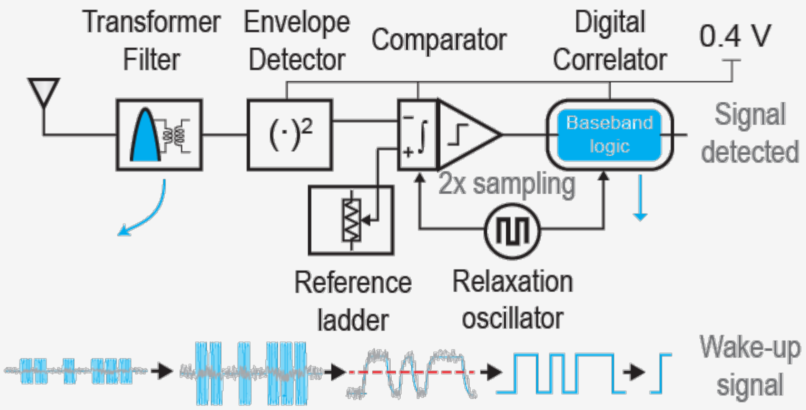
Rejects 4 mm IR

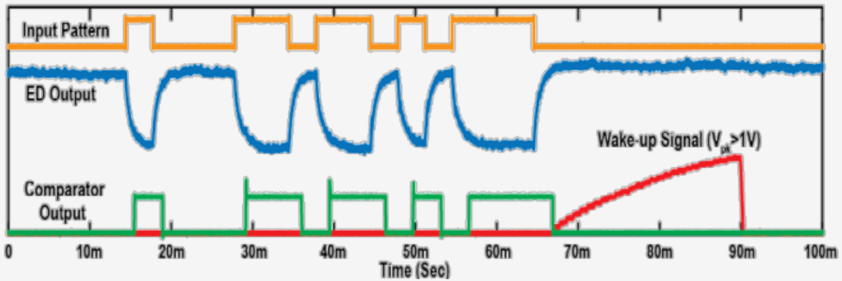
Measured Response

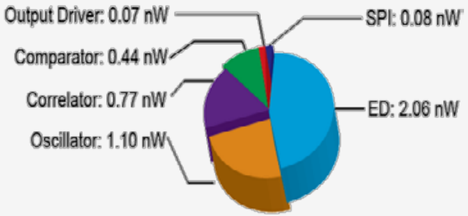
Z. Qian, S. Kang, V. Rajaram, C. Cassella, N. E. McGruer and M. Rinaldi., "Zero-power infrared digitizers based on plasmonically enhanced micromechanical photoswitches." *NATURE NANOTECHNOLOGY*, vol. 12, Oct. 2017.

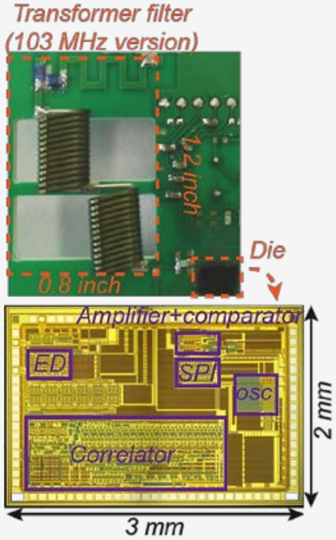
ALWAYS-ON nW RECEIVER FOR NETWORKED IoT

H. Jiang, et al. "A 4.5 nW wake-up radio with– 69dBm sensitivity." *IEEE Solid-State Circuits Conference (ISSCC)*, 2017.



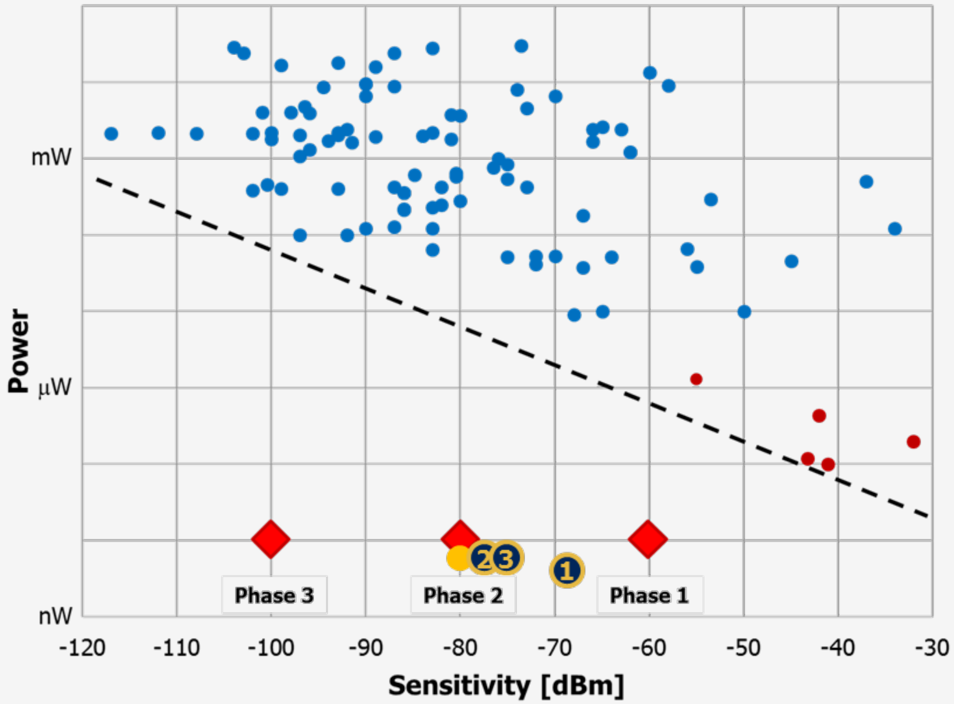






N-ZERO HAS SIGNIFICANTLY ADVANCED LOW-POWER RF

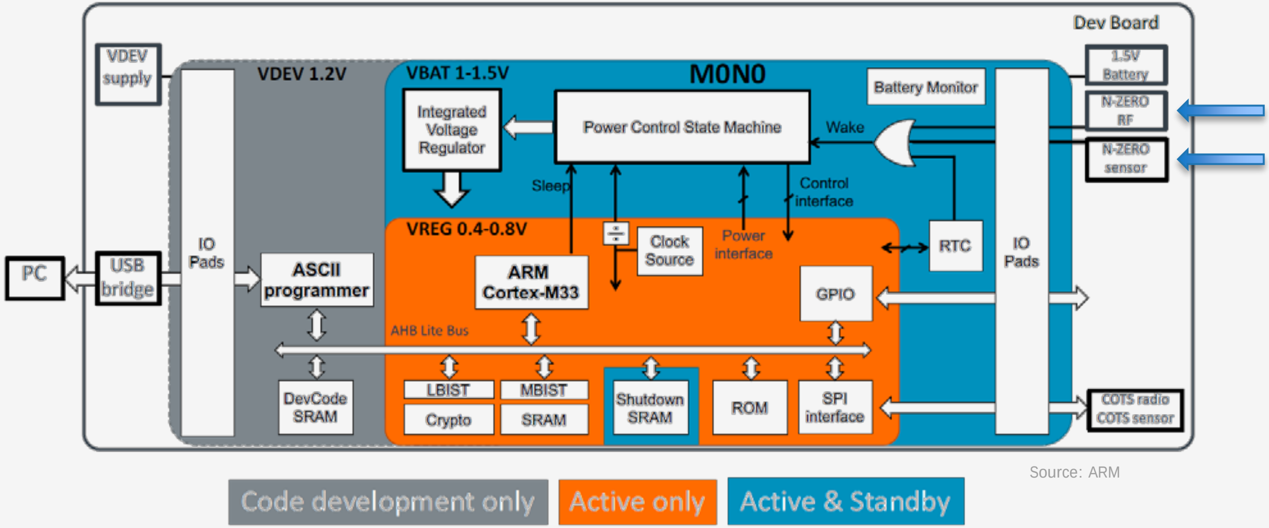
David D. Wentzloff, "Low Power Radio Survey," [Online].
www.eecs.umich.edu/wics/low_power_radio_survey.html



1 H. Jiang, et al. "A 4.5 nW wake-up radio with– 69dBm sensitivity." *IEEE Solid-State Circuits Conference (ISSCC)*, 2017.

2 3 J. Moody et al., "A −76dBm 7.4nW wakeup radio with automatic offset compensation," *2018 IEEE International Solid - State Circuits Conference - (ISSCC)*, San Francisco, CA, 2018, pp. 452-454..

LOW-POWER PROCESSING



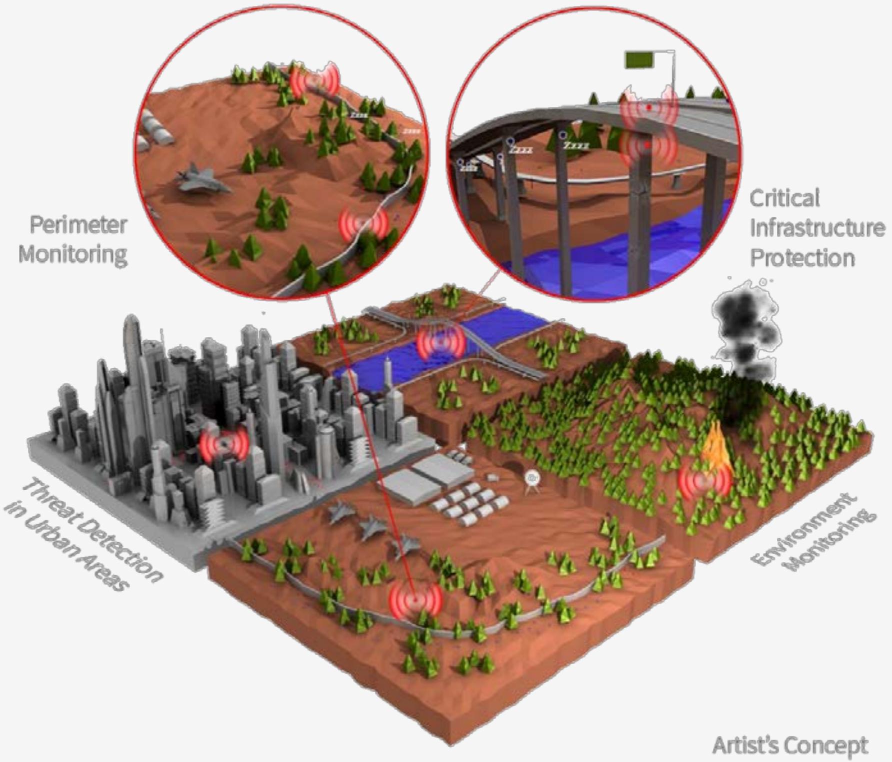
N-ZERO wakeup sensors

Source: ARM

- 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

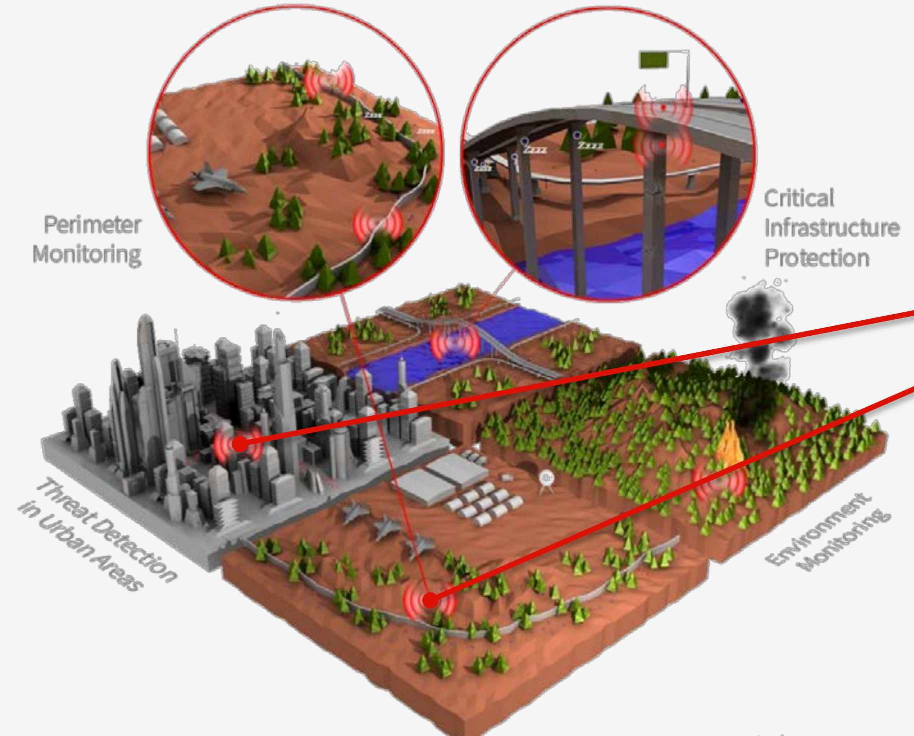
How does the DoD use the technology?

N-ZERO PERSISTENT SENSING OPPORTUNITIES

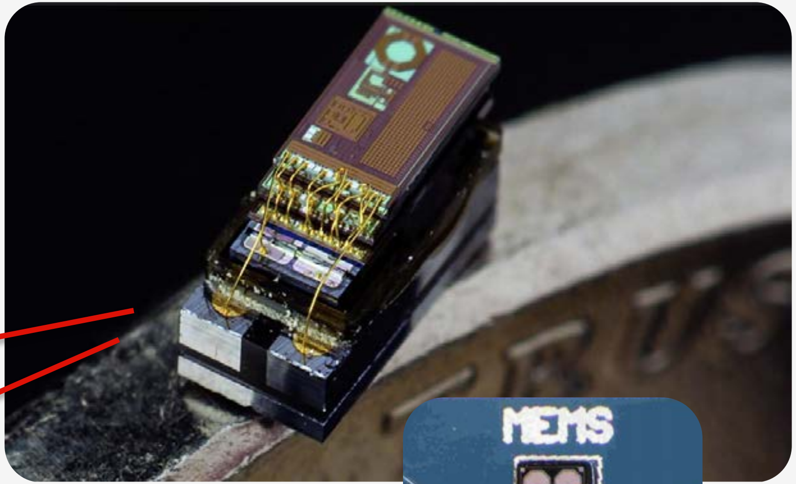


- New class of nW systems
- RF, acoustic, seismic, IR, and chemical modalities
- Orders-of-magnitude improvement in lifetime and battery size
- Persistent sensing without sleep-cycling

MICROSYSTEMS FOR THE IoT



Artist's Concept



Source: Dennis Sylvester, University of Michigan

ERI ELECTRONICS RESURGENCE INITIATIVE

SUMMIT

2018 | SAN FRANCISCO, CA | JULY 23-25

DENNIS SYLVESTER

UNIVERSITY OF MICHIGAN

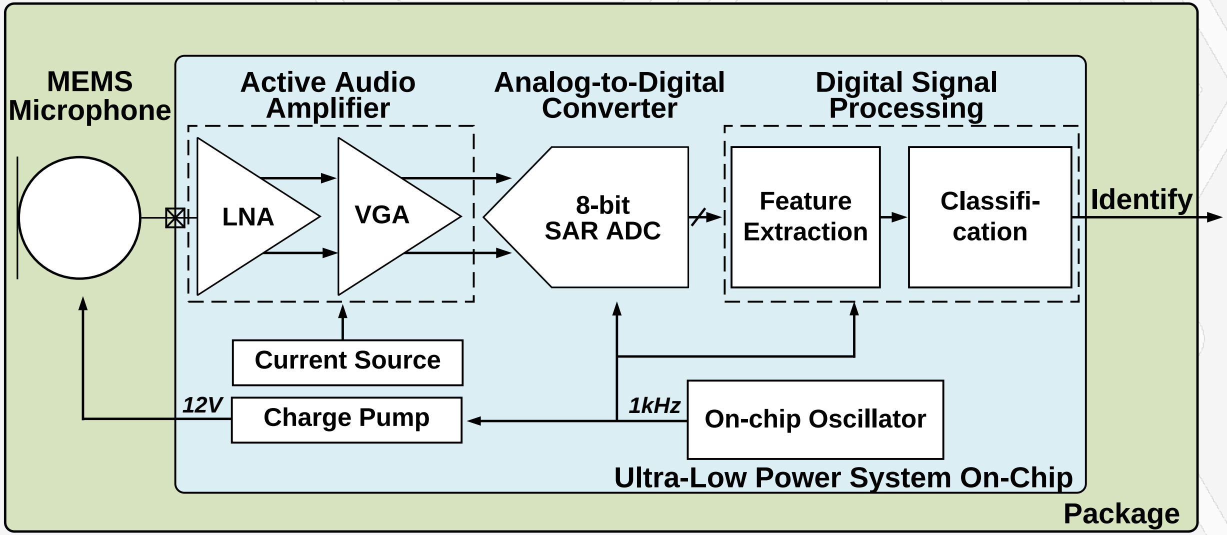
NEAR ZERO-POWER MACHINE LEARNING PROCESSORS FOR CONTINUOUS ACOUSTIC SENSING

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

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

PROPOSED SYSTEM OVERVIEW

- ~10nW acoustic sensing and object recognition microsystem
- Initial targets: generator, car, truck
- Later targets: voice activity, keywords



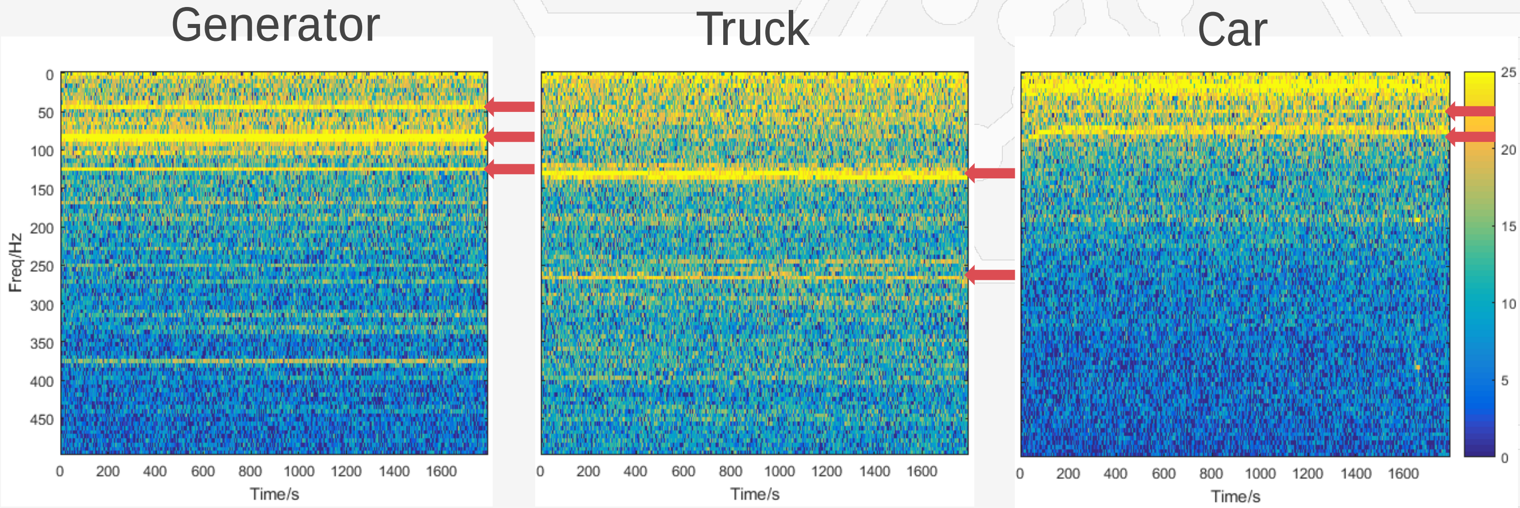
SIGNAL PROPERTIES EXPLOITED FOR NEAR ZERO POWER DSP

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



FEATURE EXTRACTION

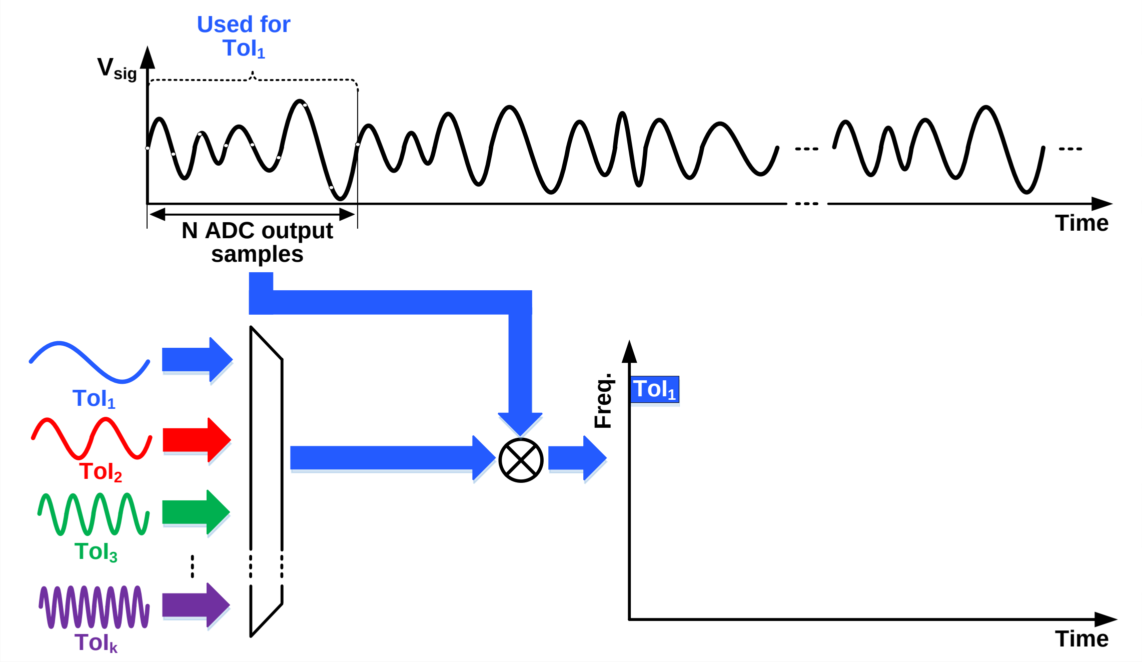
- DFT performed **only** on the **discrete tones of interest (ToI)**

$$
\begin{pmatrix} X[0] \\ X[1] \\ X[2] \\ X[3] \\ \vdots \\ X[N-2] \\ X[N-1] \end{pmatrix}
=
\begin{pmatrix}
1 & 1 & 1 & \cdots & 1 \\
1 & W & W^{2} & \cdots & W^{N-1} \\
1 & W^{2} & W^{4} & \cdots & W^{2(N-1)} \\
1 & W^{3} & W^{6} & \cdots & W^{3(N-1)} \\
\vdots & & & & \vdots \\
1 & W^{N-2} & W^{2(N-2)} & \cdots & W^{(N-2)(N-2)} \\
1 & W^{N-1} & W^{2(N-1)} & \cdots & W^{(N-1)(N-1)}
\end{pmatrix}
\times
\begin{pmatrix} x[0] \\ x[1] \\ x[2] \\ \\ \vdots \\ x[n-2] \\ x[n-1] \end{pmatrix}
$$

$$W = e^{-j2\pi/N}$$

PROPOSED FEATURE EXTRACTION METHOD

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



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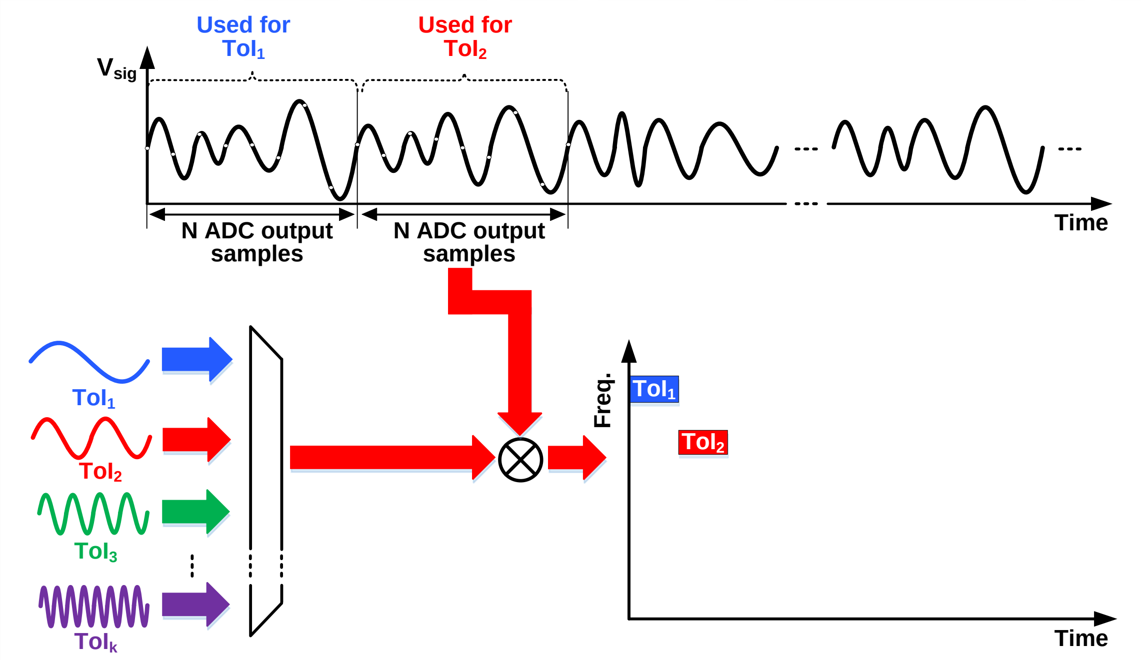

PROPOSED FEATURE EXTRACTION METHOD

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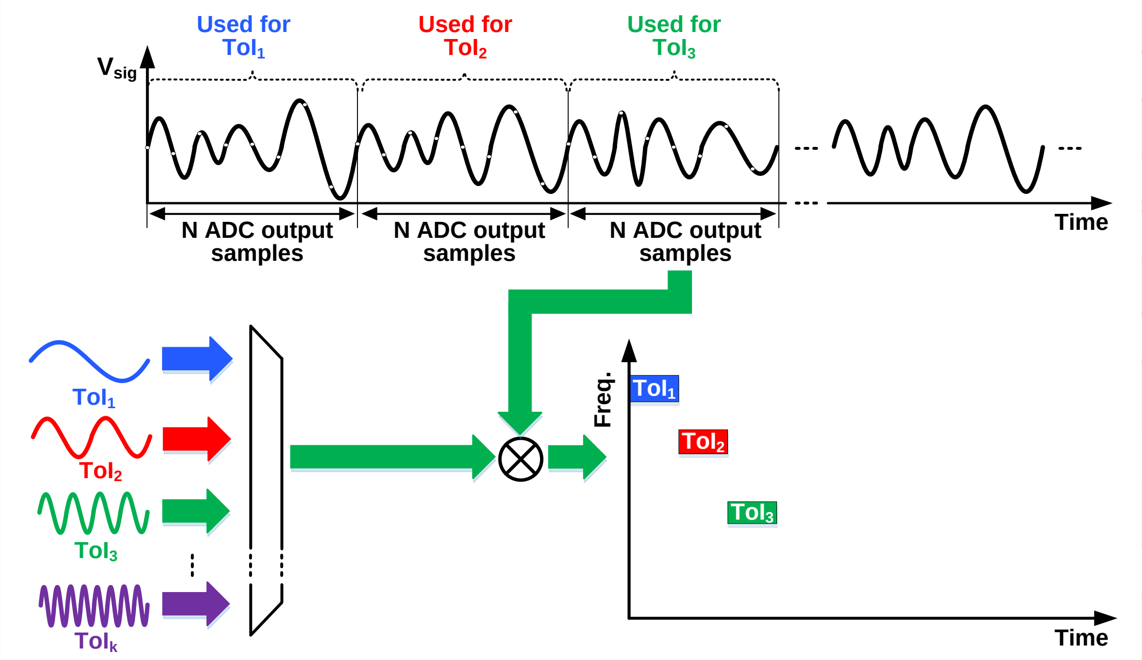

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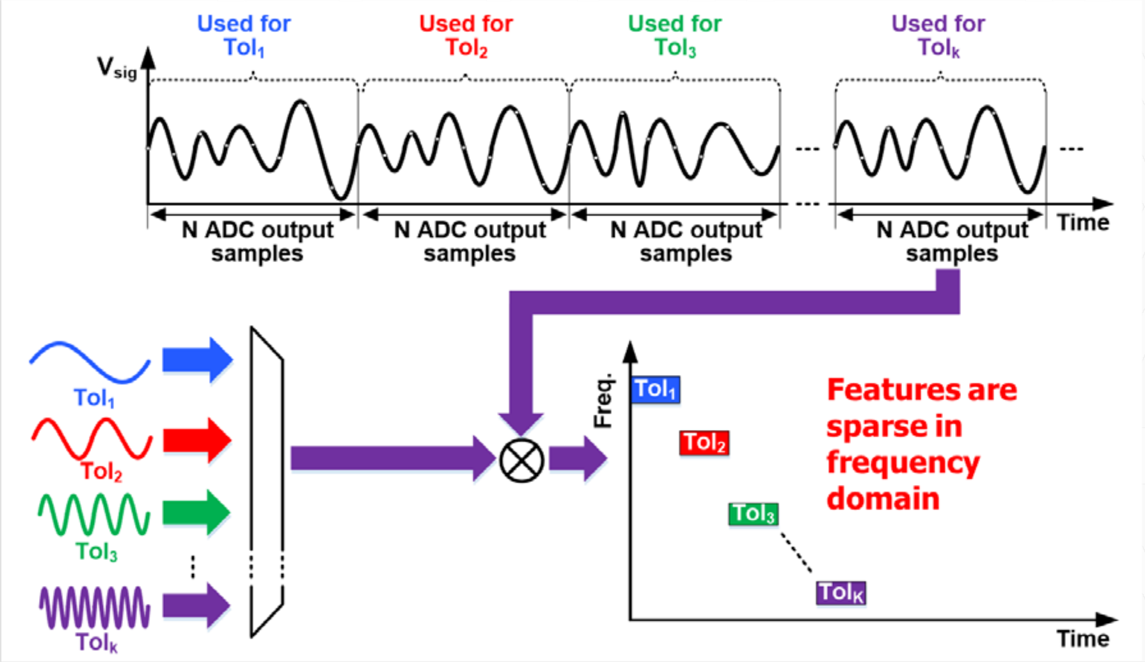

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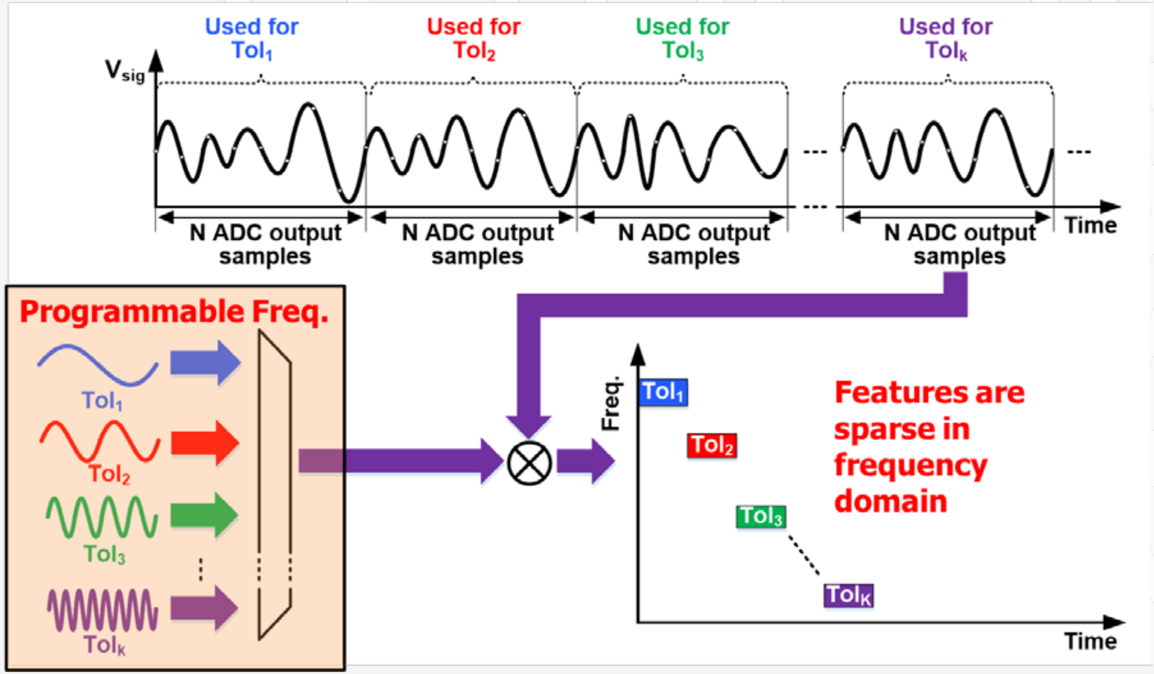
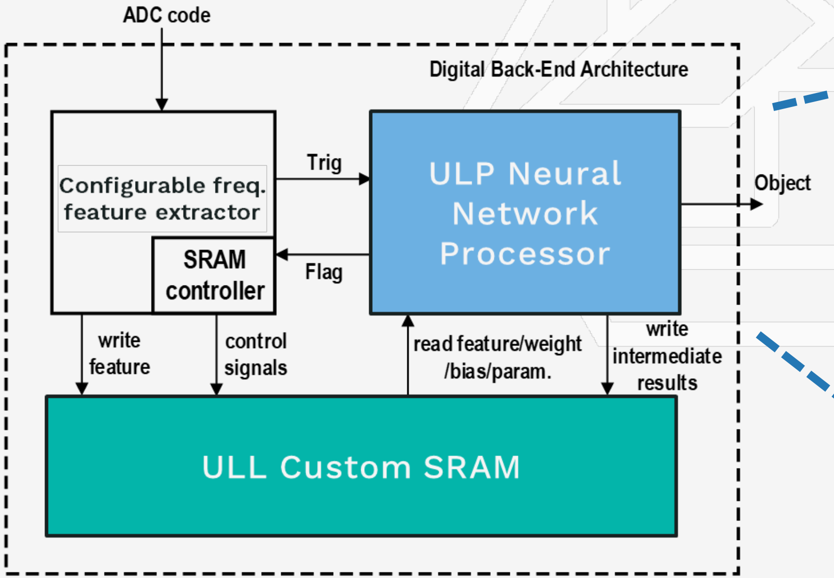
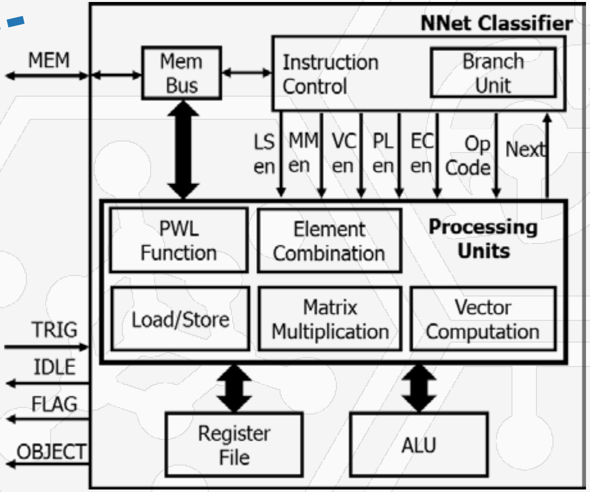
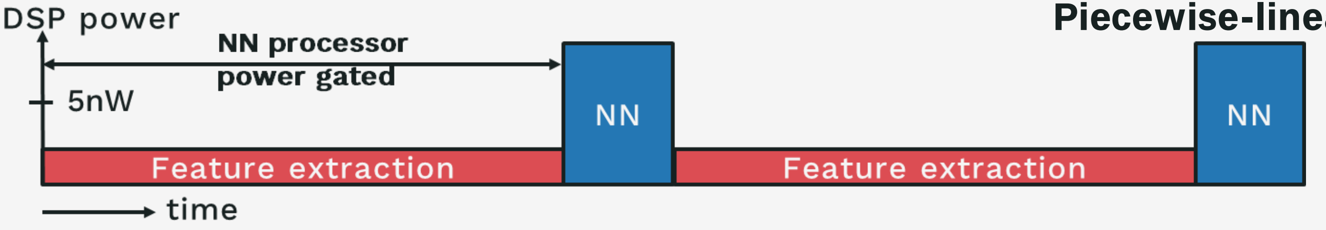


PROGRAMMABLE, NEAR-ZERO POWER DSP ARCHITECTURE





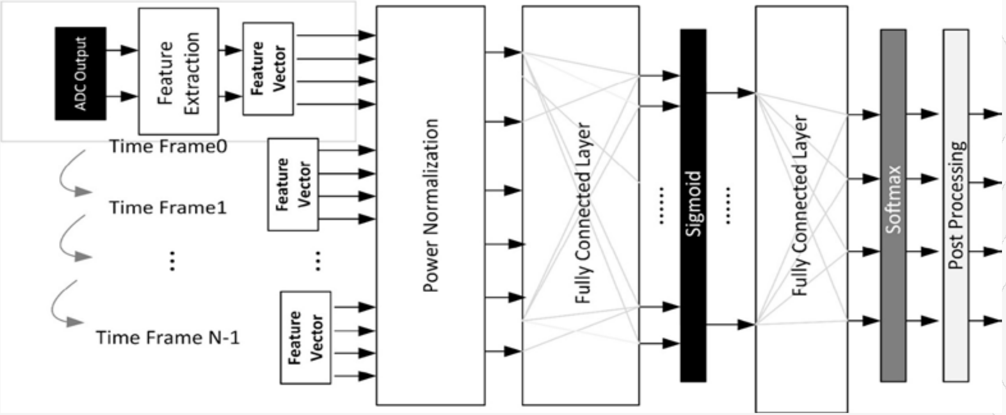
Support vector machine (SVM)
Multi-layer fully connected NN
Piecewise-linear non-linear functions

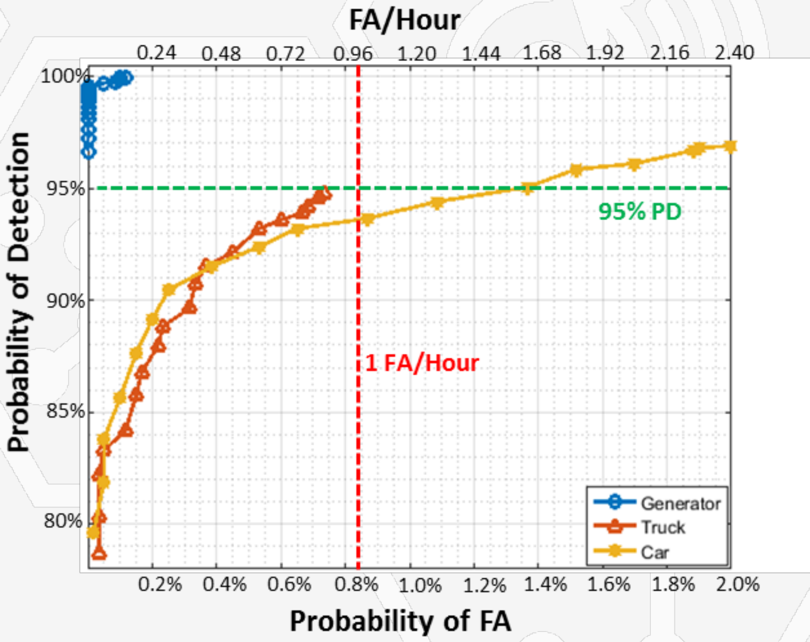


N-ZERO TARGET CLASSIFICATION

- Targets: generator, small car, truck
- 32x1 ToI DFT feature input vector → 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

N-ZERO TARGET CLASSIFICATION





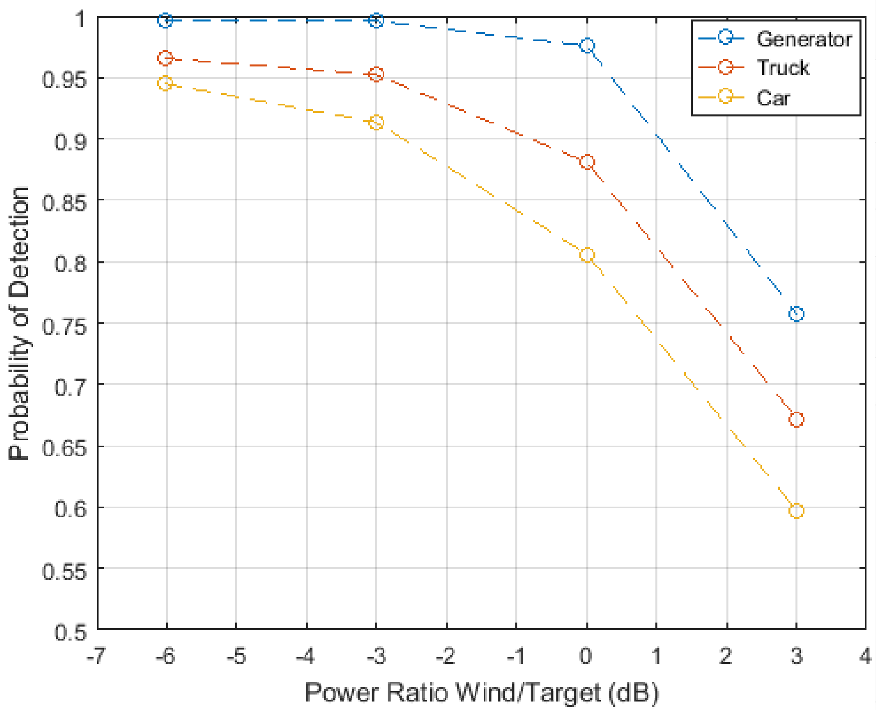
FIXED-POINT PERFORMANCE MATRIX

Data / Target	Generator	Car	Truck	Quiet
Generator	99.47%	0%	0.53%	0%
Car	0.66%	95.33%	0.71%	3.30%
Truck	0.13%	0.41%	95.64%	3.82%

ENVIRONMENT-SPECIFIC TRAINING

Trained without wind data,
Tested with wind

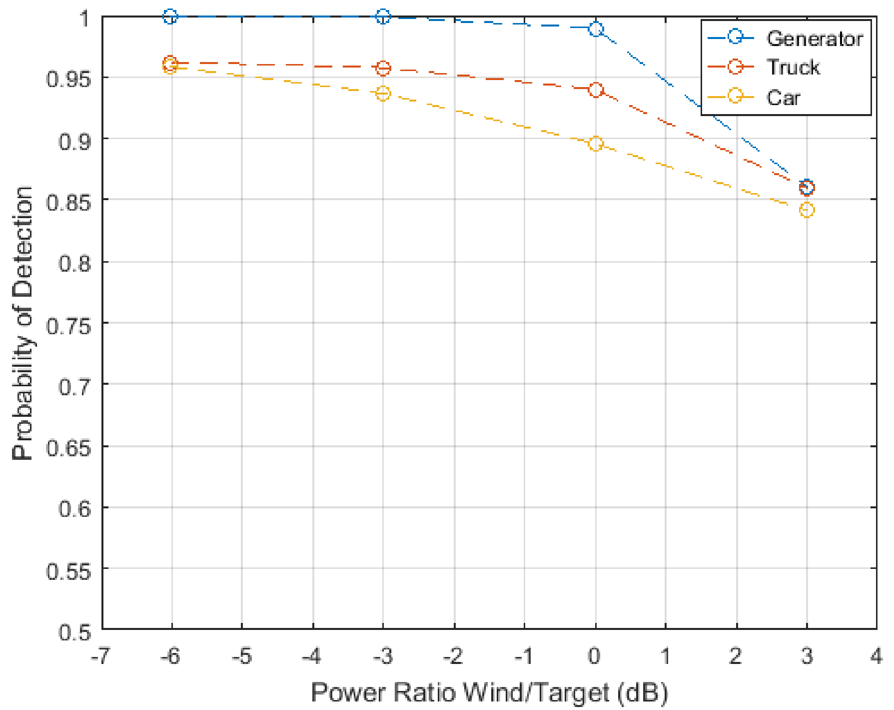
Target \ Data	Generator	Truck	Car	Quiet + Wind
Generator	99.75 %	0.0 %	0.13 %	0.06 %
Truck	0.0 %	96.35 %	0.39 %	6.35 %
Car	0.18 %	0.69 %	96.59 %	8.81 %



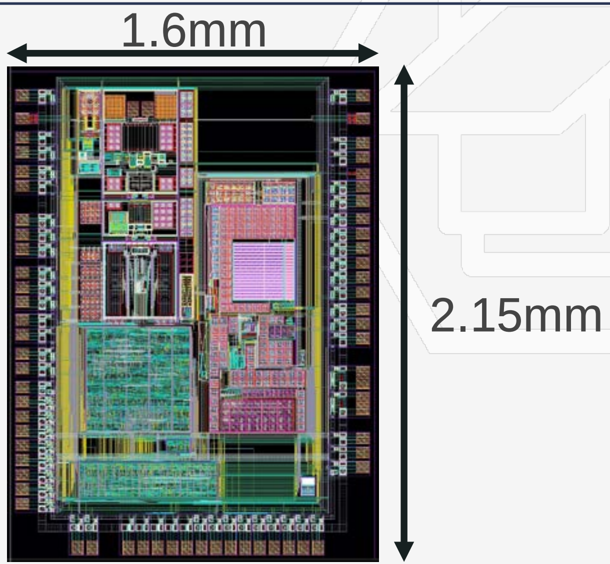
ENVIRONMENT-SPECIFIC TRAINING

Trained with wind data,
Tested with unseen wind

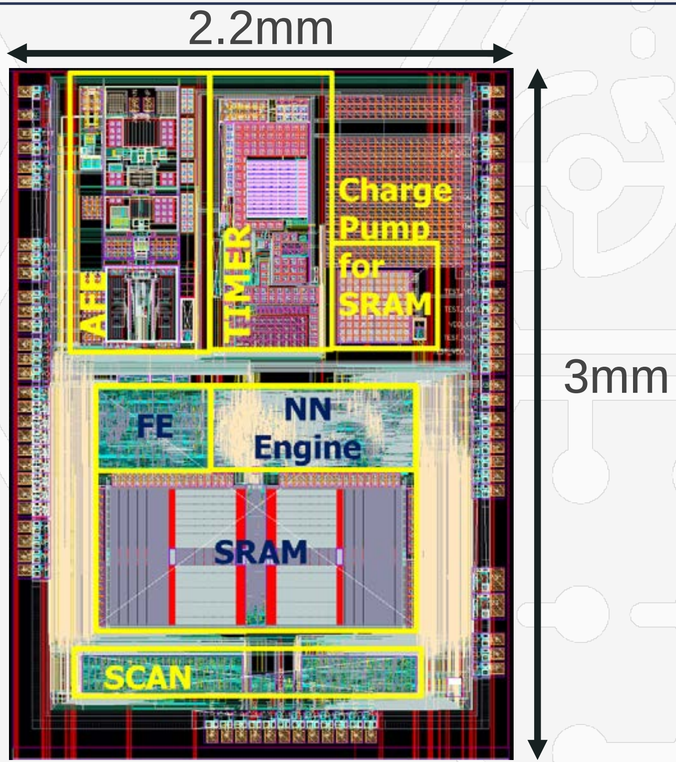
Target \ Data	Generator	Truck	Car	Quiet + Wind
Generator	99.63%	0.0%	0.0%	0.04%
Truck	0.0%	97.02%	1.08%	2.75%
Car	0.09%	0.32%	95.57%	3.35%



N-ZERO V2 DIE PHOTO



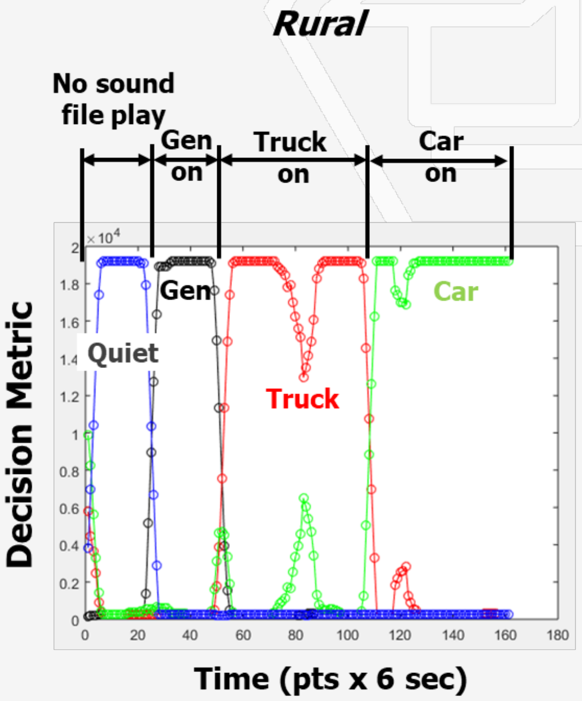
<V1 Chip>

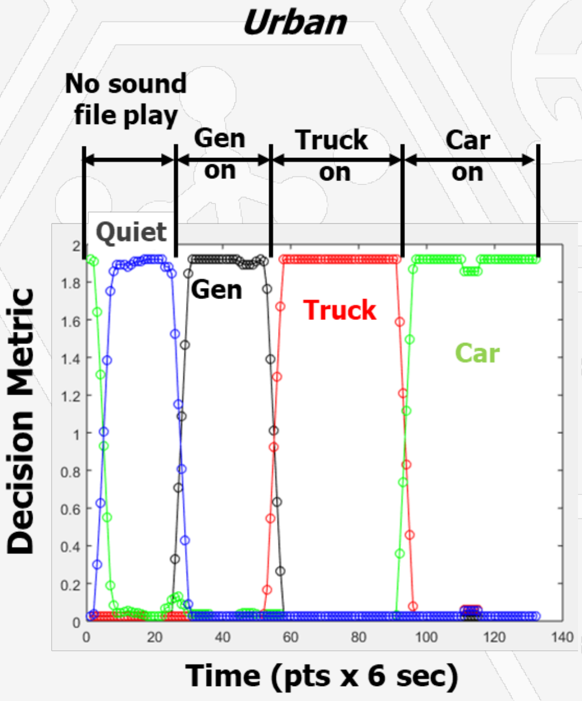


<V2 Chip>

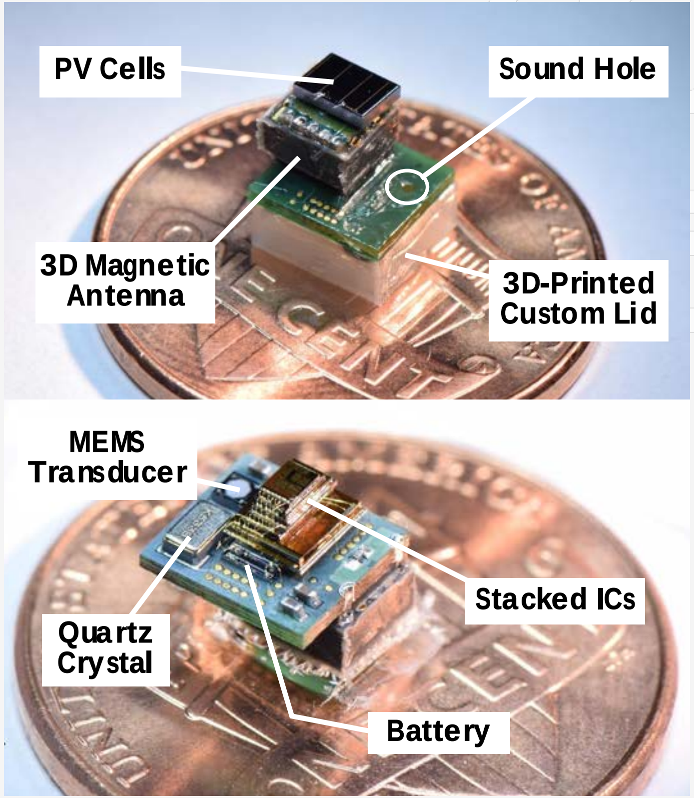
PHASE 2 HARDWARE TESTING

- Testing condition emulates 5m distance



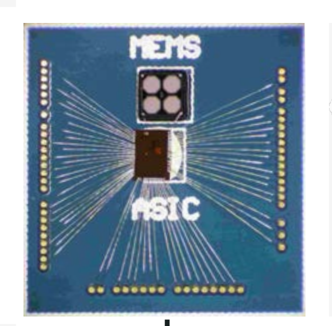


A MORE COMPLETE AUDIO MICROSYSTEM

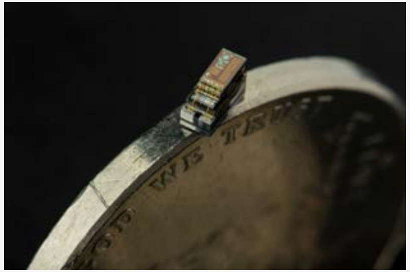


- Overall system size
  - 6×5×4 mm^3
- Features
  - Real-time audio acquisition with low power compression
    - 15-38 mins of recording on 1 charge, 4.7uW avg power
  - 8Mb Flash storage
  - Solar energy harvesting
  - Wireless link
  - General purpose µ-processor

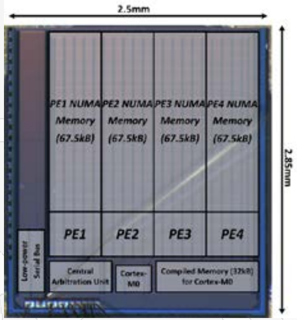
A POSSIBLE PATHWAY

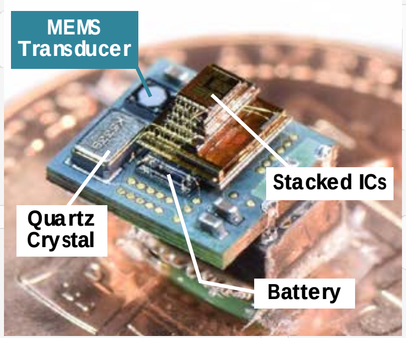


Miniaturize N-Zero trigger



Wake up powerful DNN-based audio recording & analysis microsystem





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

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 Cubeworks
- Always-on voice control in ULP IoT being pursued via Ambiq Micro
- DNN in edge devices being pursued via Mythic

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