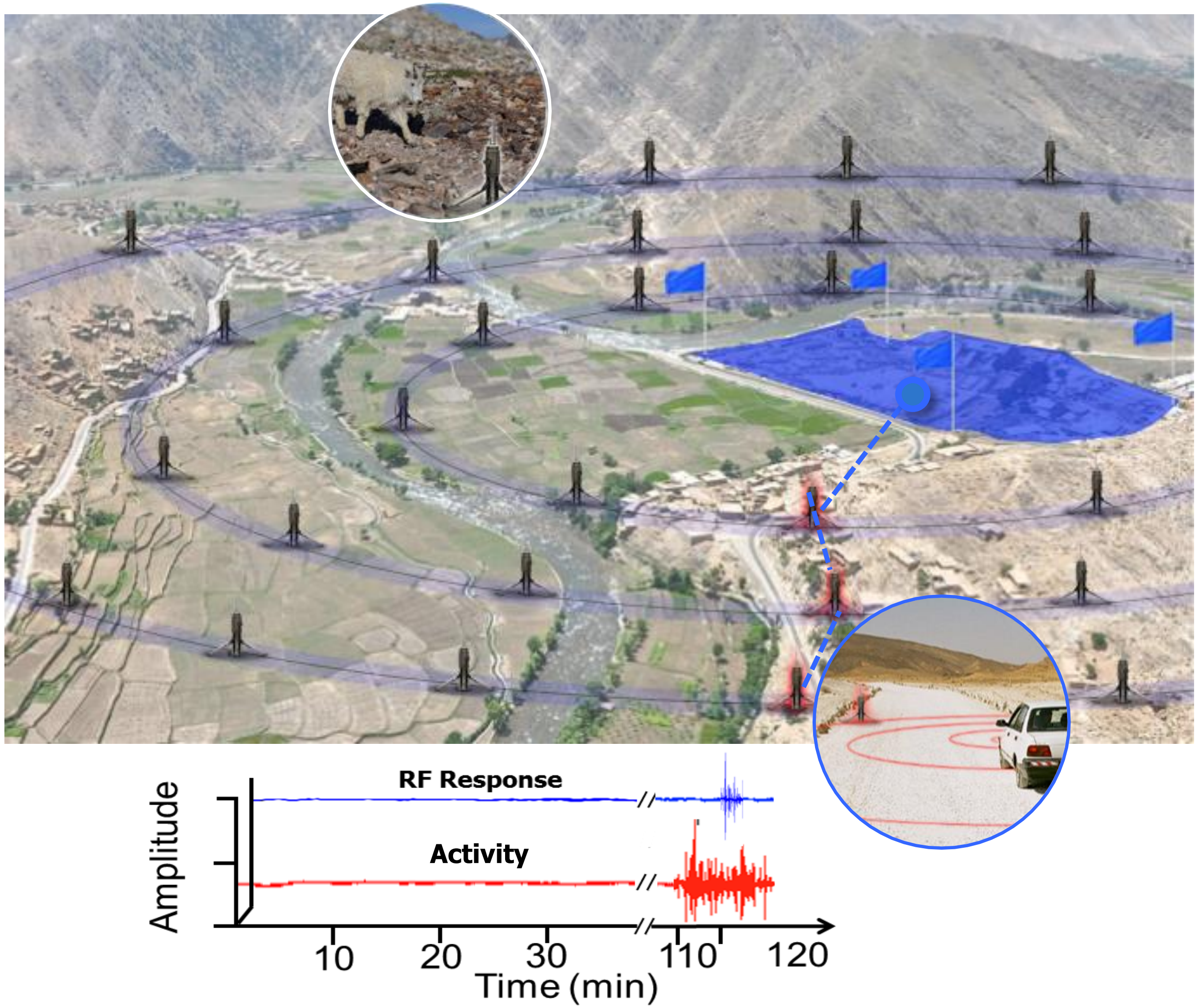
Near-Zero Power Radio Frequency Receivers

Troy Olsson, Ph.D.
Defense Advanced Research Projects Agency
Radoslav Bogoslovov, Ph.D.
ECS Federal
Christal Gordon, Ph.D.
Booz Allen Hamilton

IEEE RFID 2017
May 11, 2017

N-ZERO Vision: Persistent Sensing for the DoD



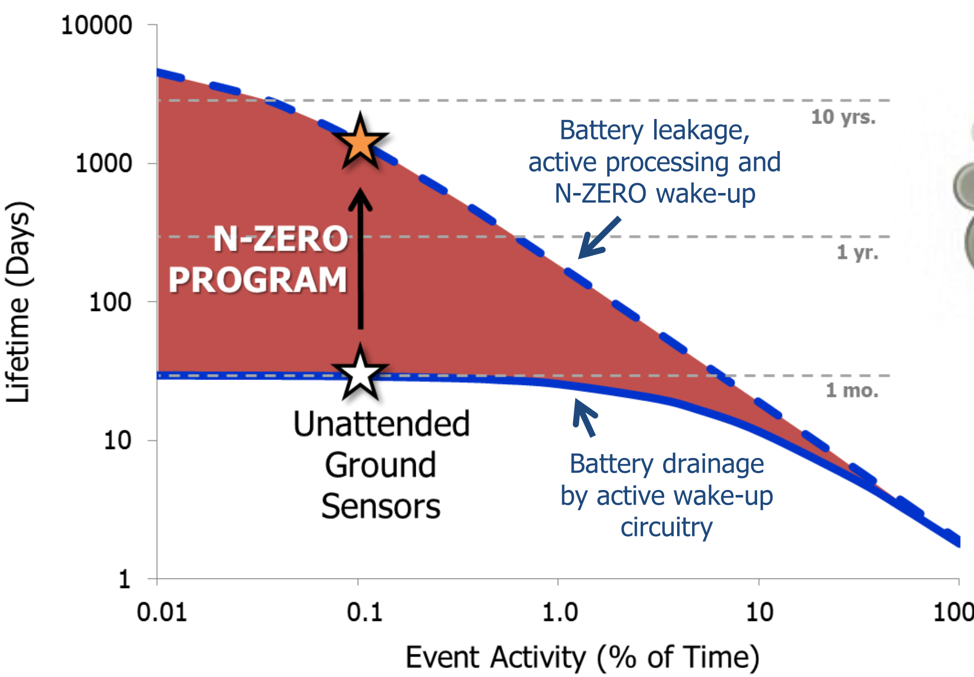
Geophone recording of activity followed by RF transmission

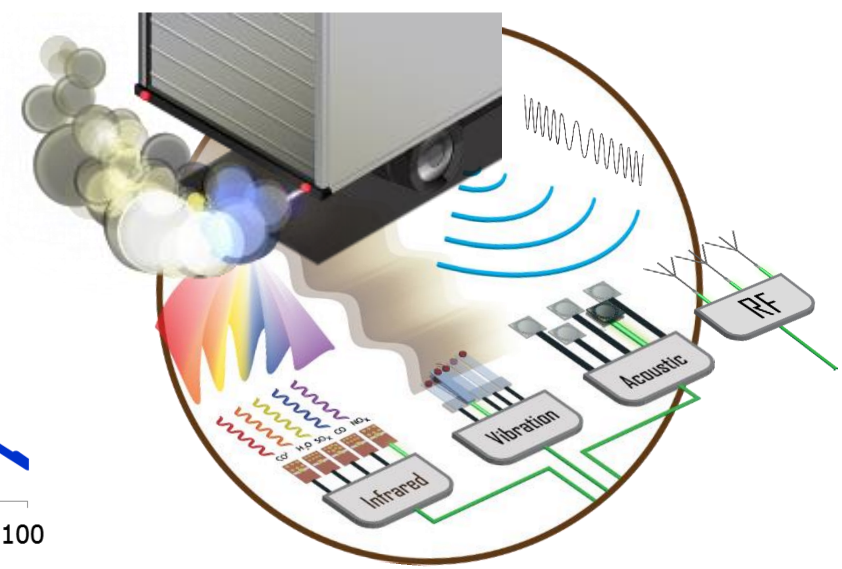
N-ZERO seeks to greatly extend mission capabilities and lifetime at reduced cost

N-ZERO Vision: OFF but ALERT!

N-ZERO passive sensor wake-up:

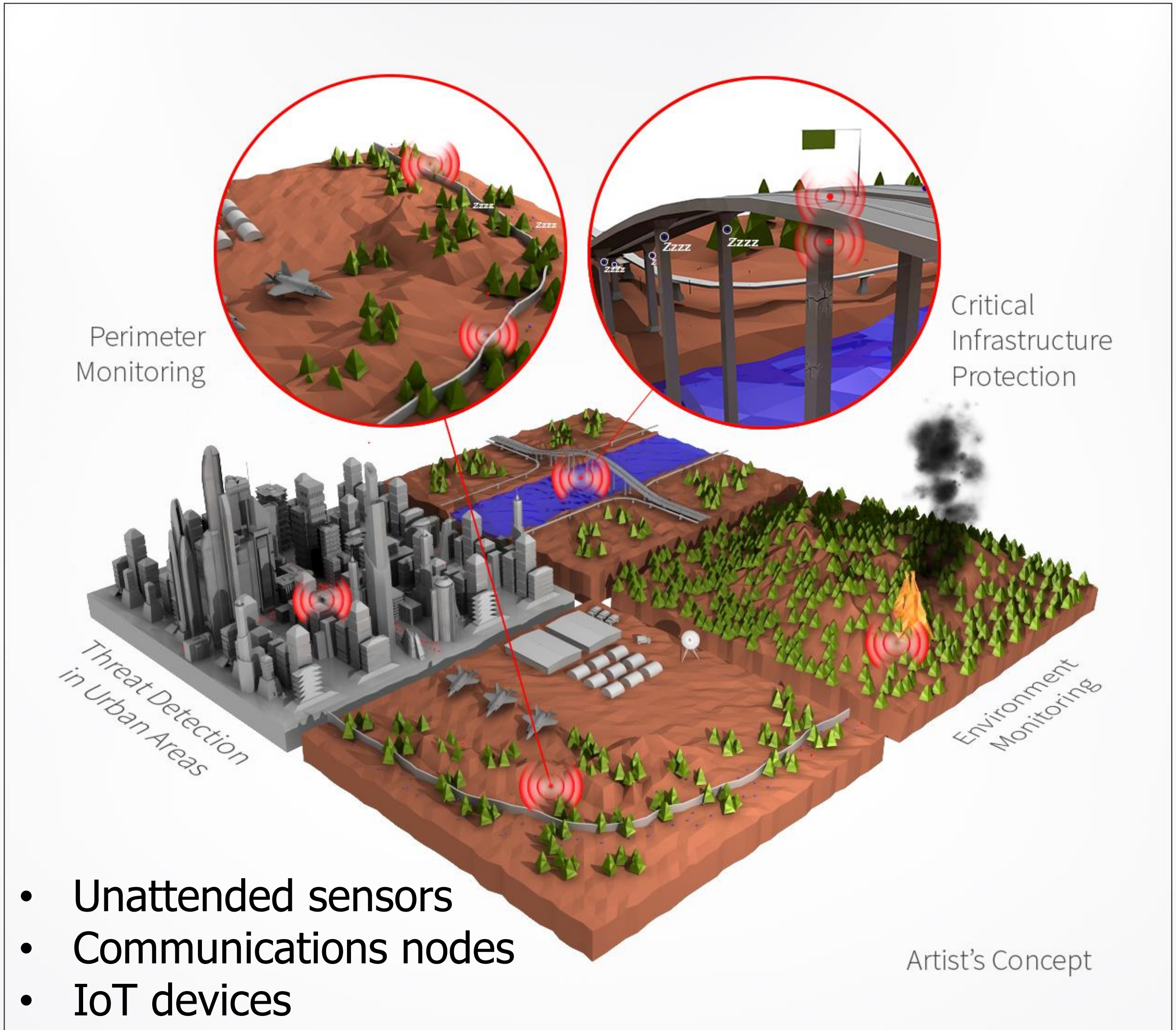
- Continuous operation and near-zero power processing
- Persistent sensing with greatly extended lifetime and reduced cost
- Multiple sensing modalities with sensor fusion





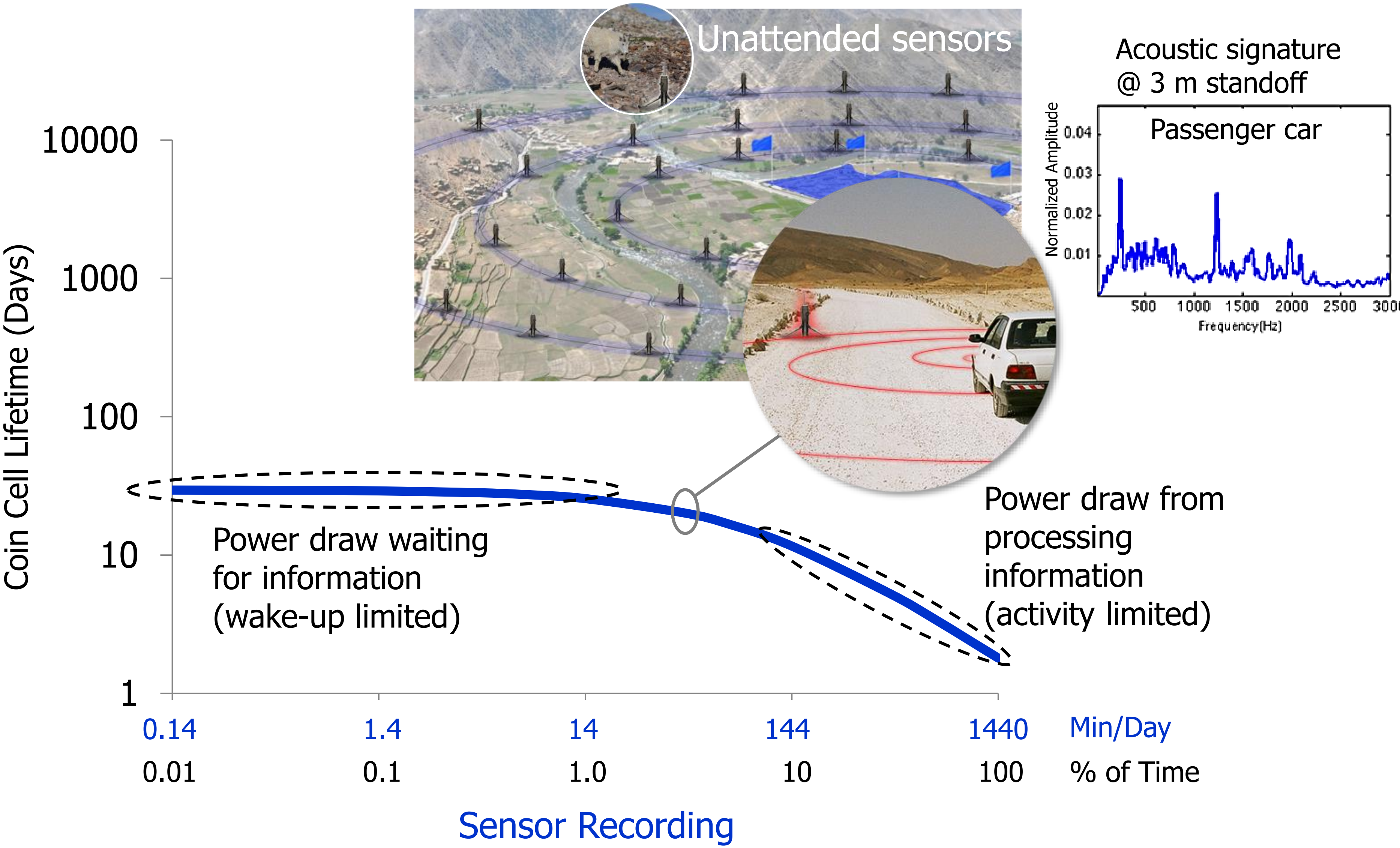
Devices are OFF (zero power consumption) yet continually ALERT!

Smart Cities Applications

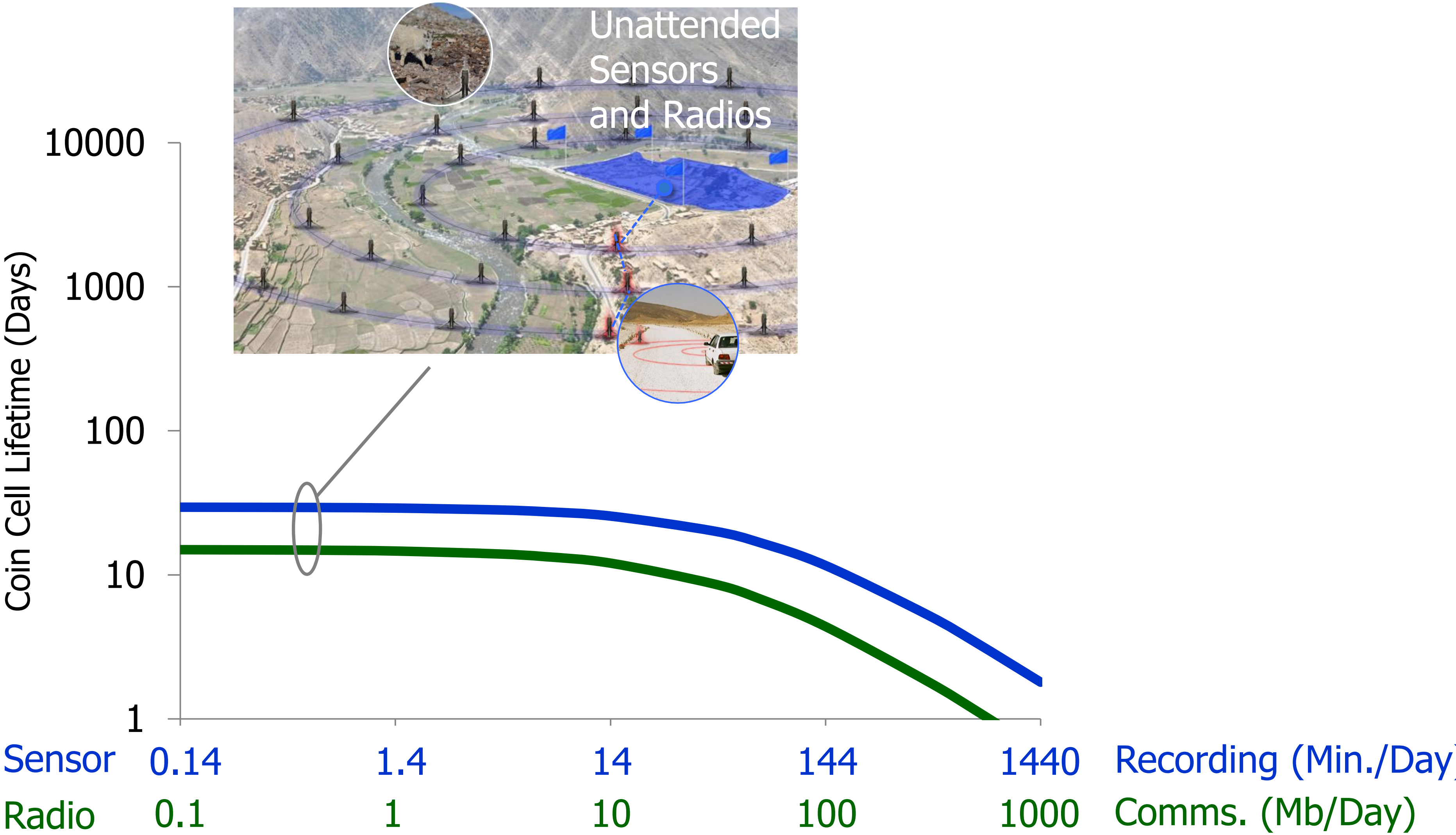


- Unattended sensors
- Communications nodes
- IoT devices

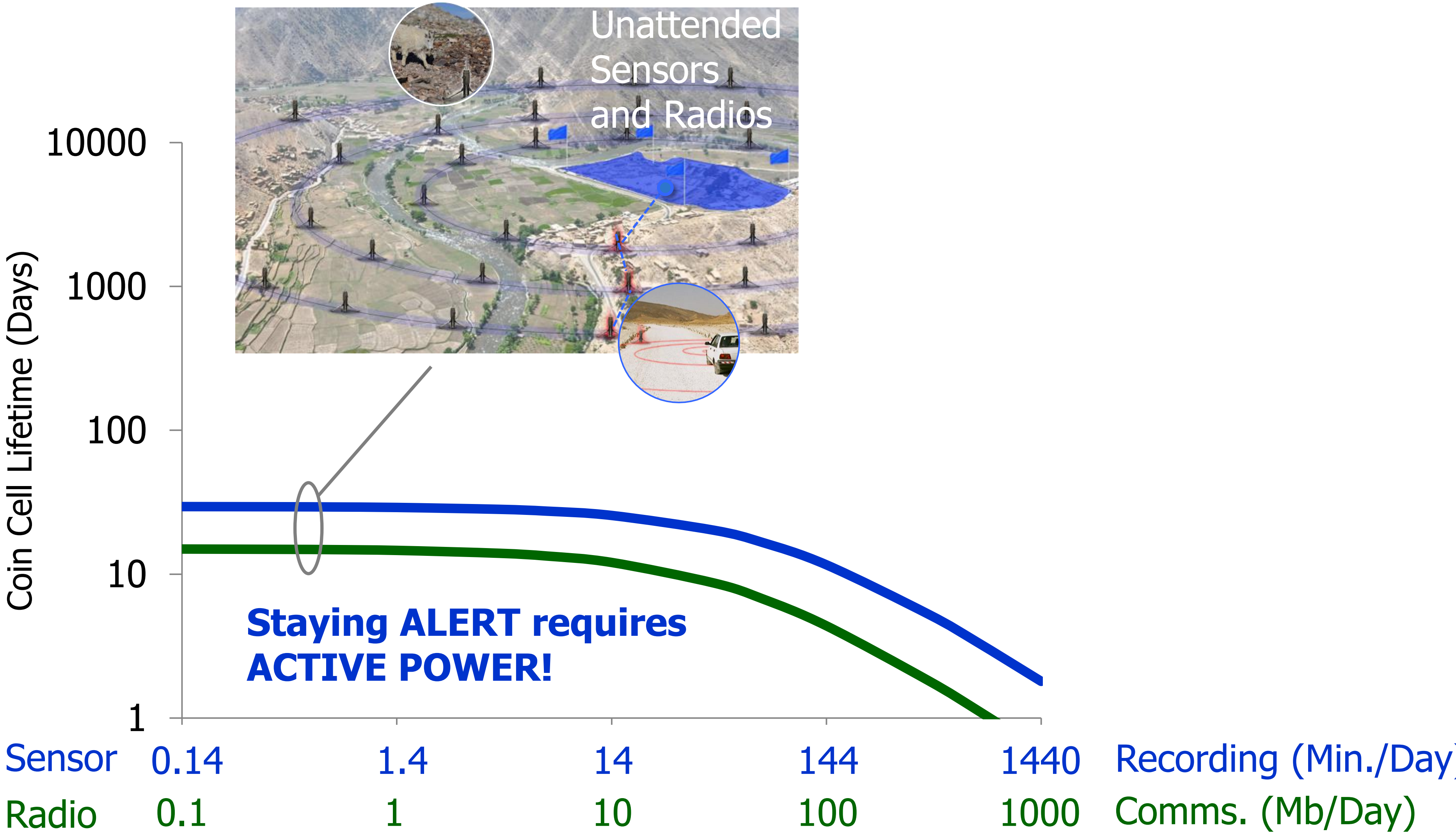
Current State-of-the-Art (SOA): Awaiting Activity Constrains Mission Life



Current SOA:
Awaiting Activity Constrains Mission Life

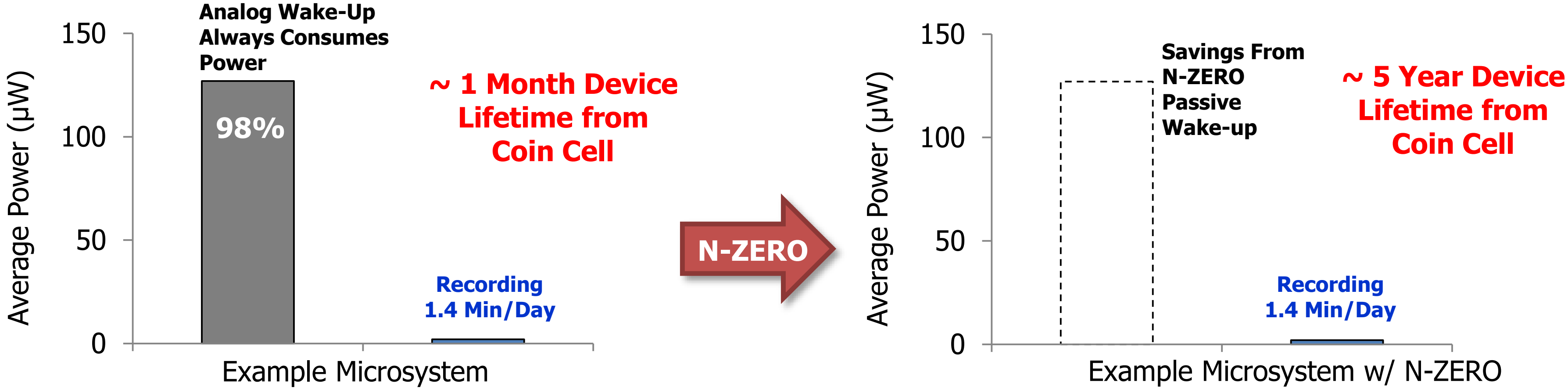


Current SOA:
Awaiting Activity Constrains Mission Life

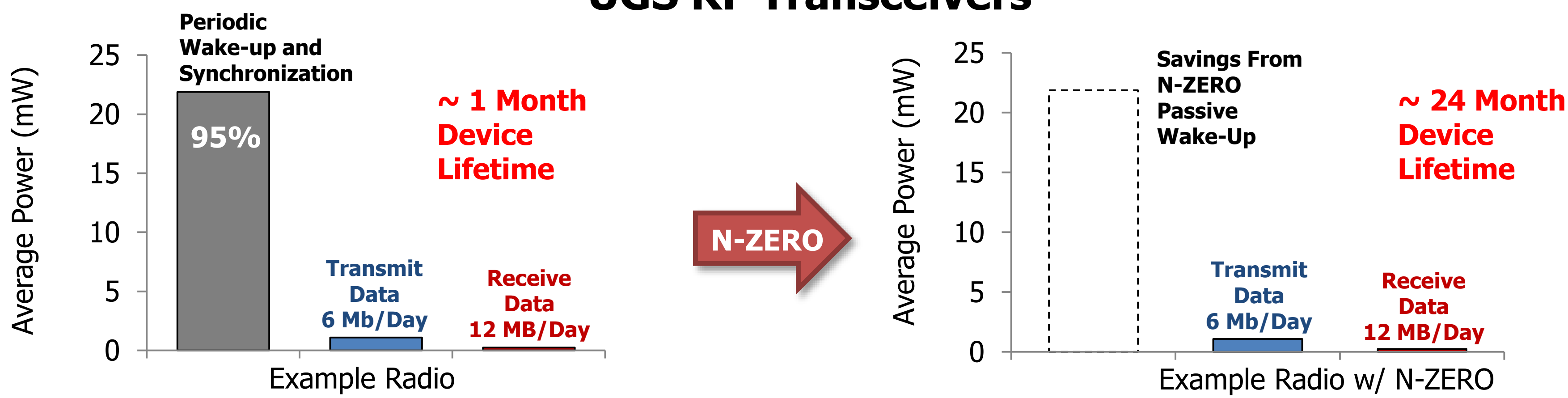


The N-ZERO Advantage

Unattended Ground Sensors



UGS RF Transceivers

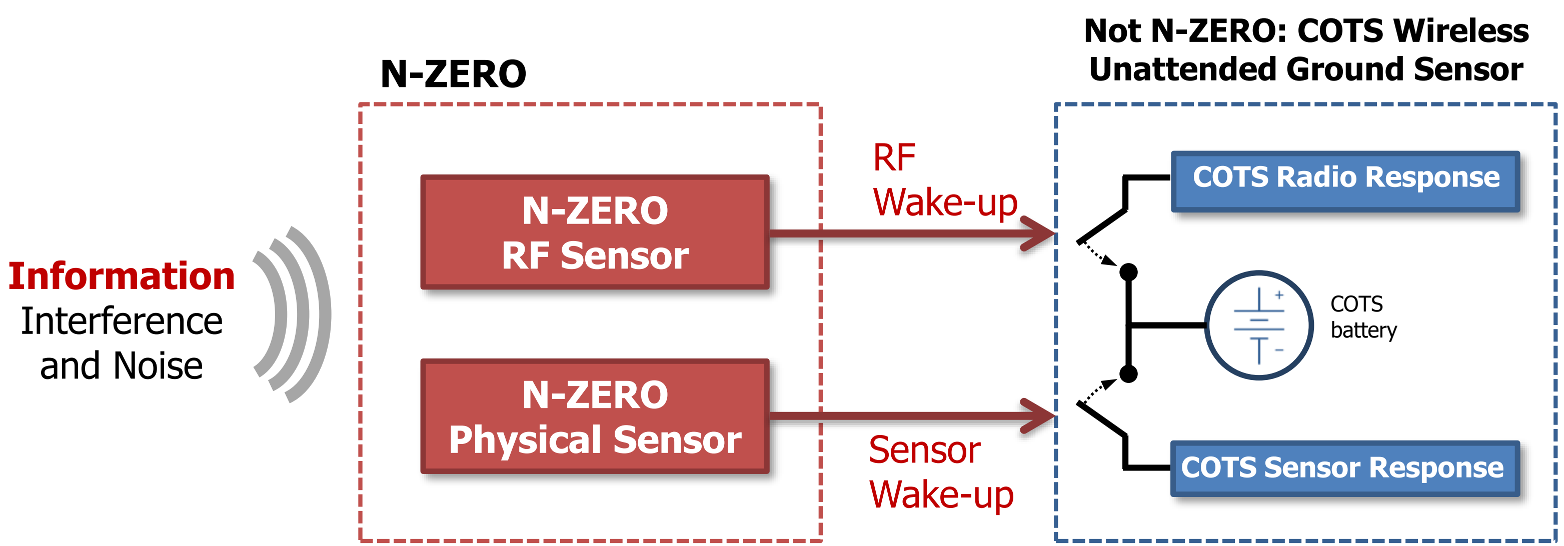


- Staying alert requires active power
- Wake-up and synchronization consume **> 95%** of battery life for sparse signals

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

N-ZERO 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



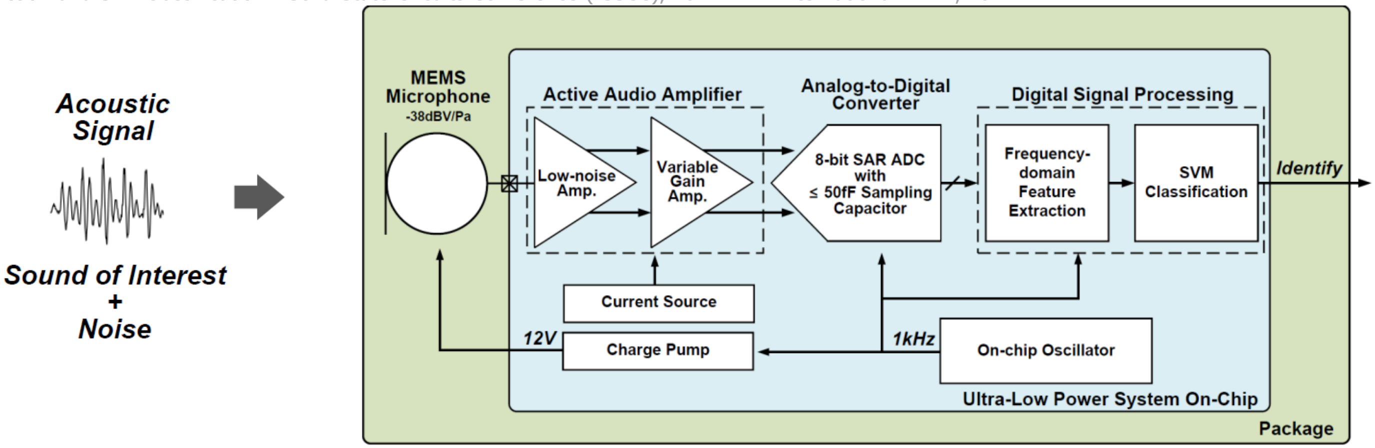
N-ZERO does not replace COTS functionality. N-ZERO will reduce COTS "on" time, thereby dramatically increasing the sensor's useful lifetime.

Outline

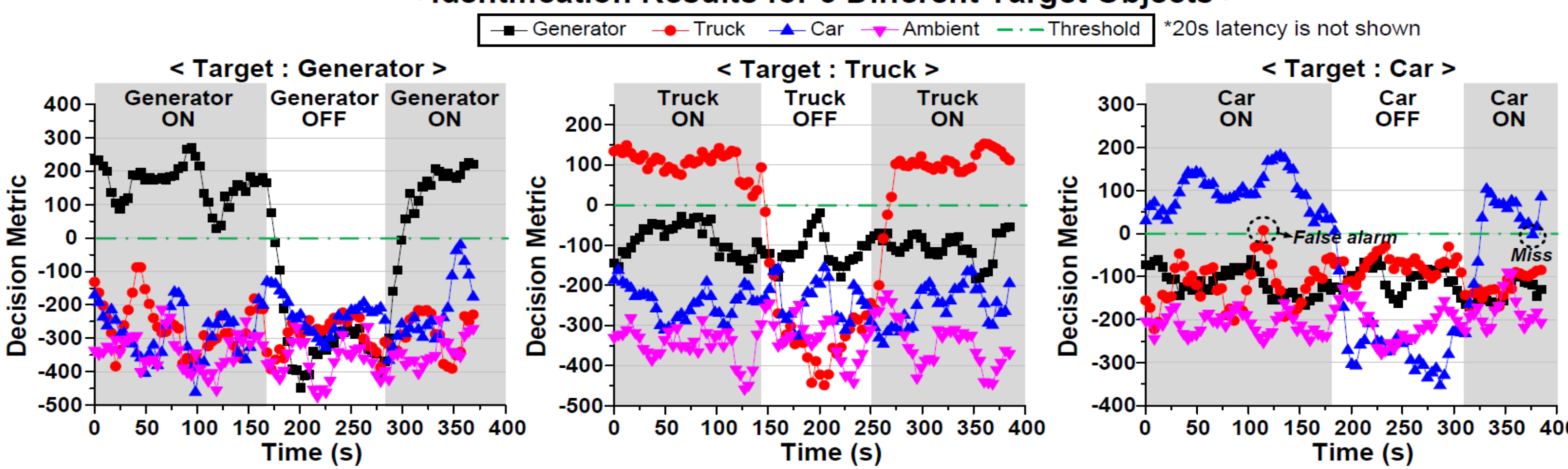
- Sensor Examples
  - Acoustic
  - Infrared
  - Chemical
- Near-Zero Power Receivers
  - Challenge
  - Architecture
  - Components
    - Transformers
    - Rectifiers
  - Receiver demonstrations
  - Measured performance vs. state-of-the-art

Acoustic Sensor Wake-up

S. Jeong, et al. "21.6 A 12nW always-on acoustic sensing and object recognition microsystem using frequency-domain feature extraction and SVM classification." Solid-State Circuits Conference (ISSCC), 2017 IEEE International. IEEE, 2017.



< Identification Results for 3 Different Target Objects >

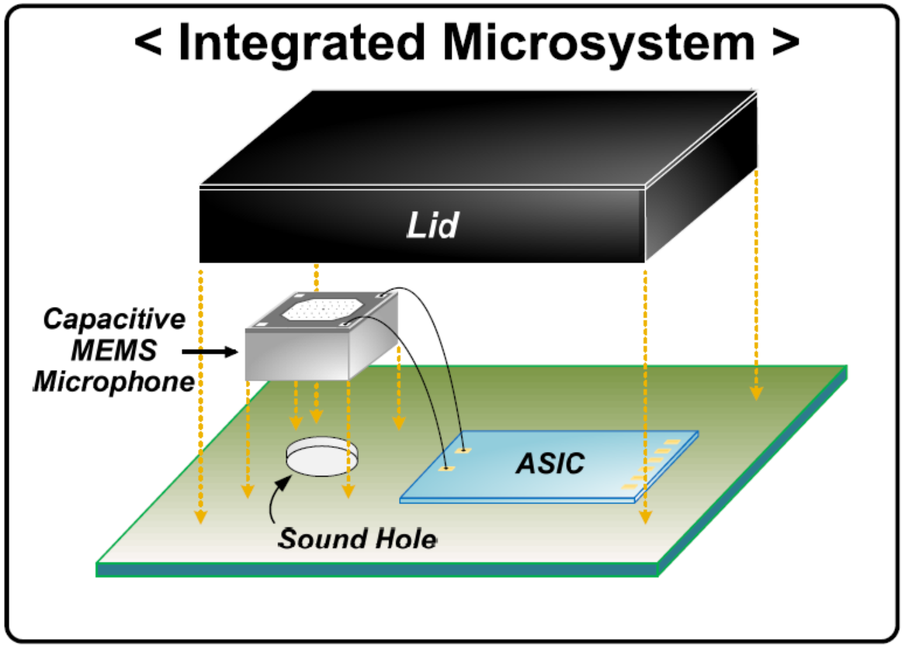


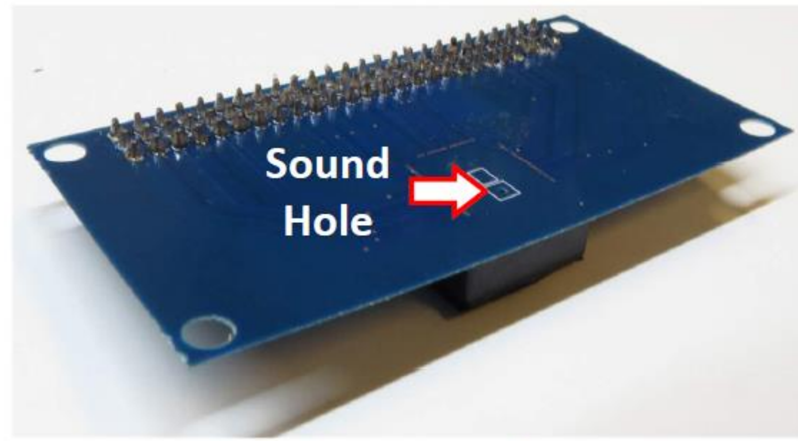
Target	Generator	Truck	Car
Detection Accuracy (N=512, K=8, m=5)	100% No false alarm	100% No false alarm	95% 1.5% false alarm (w/ Truck input)

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

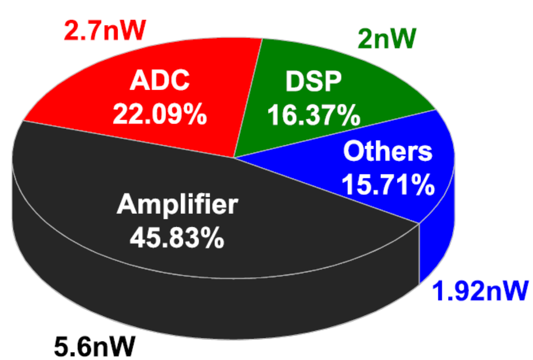
Programmable Microphone Wake-up

S. Jeong, et al. "21.6 A 12nW always-on acoustic sensing and object recognition microsystem using frequency-domain feature extraction and SVM classification." Solid-State Circuits Conference (ISSCC), 2017 IEEE International. IEEE, 2017.



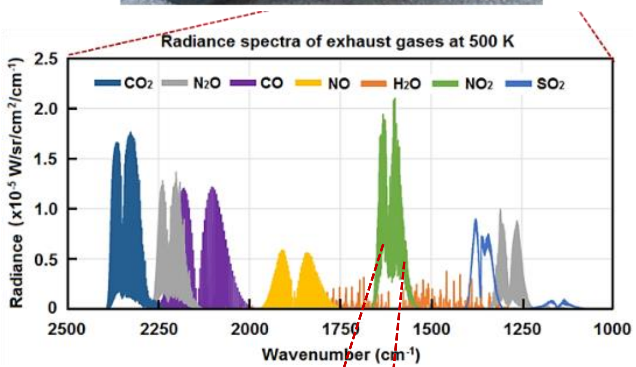


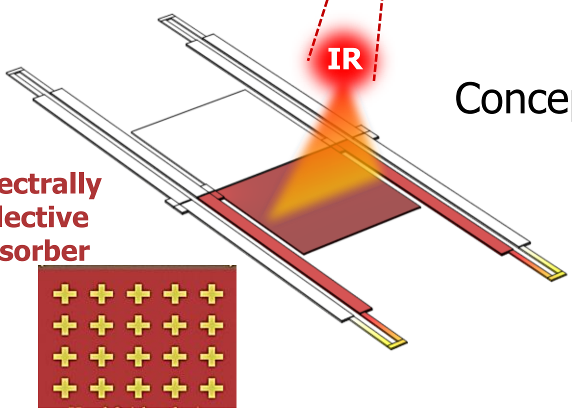
[Backside]



Zero Power IR Spectrum Sensor

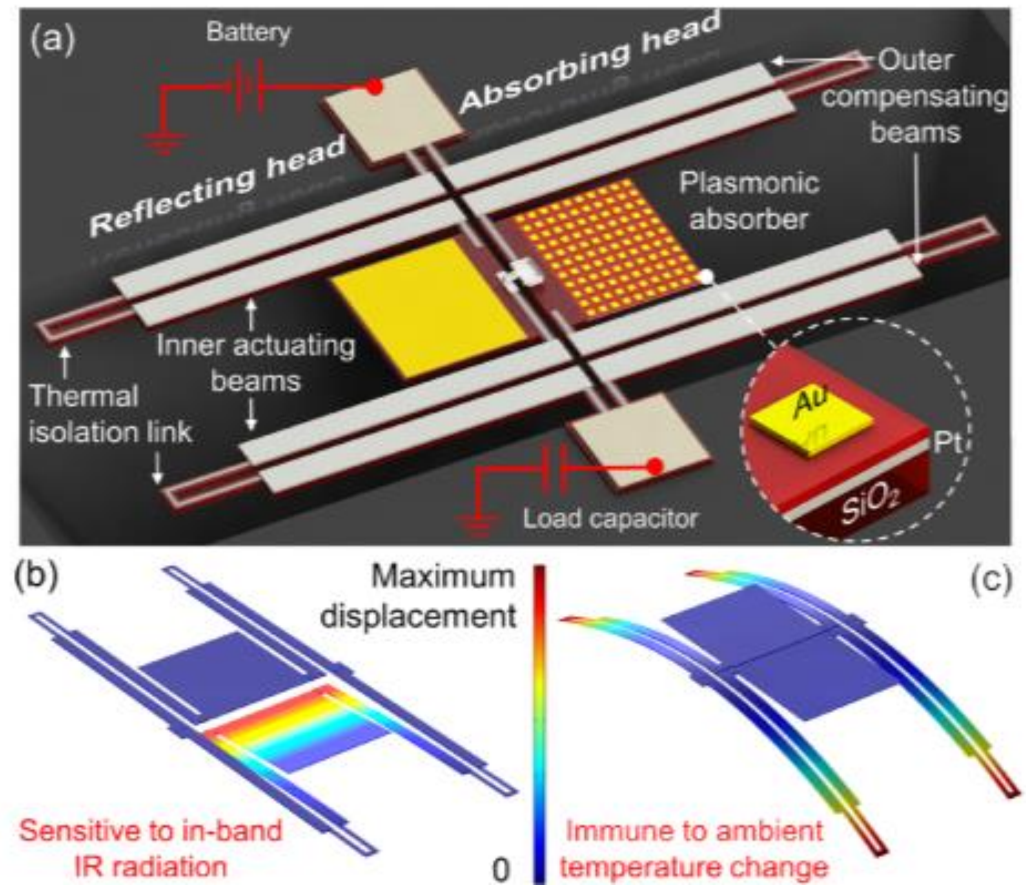
Qian, Zhenyun, et al. "Zero-power light-actuated micromechanical relay." Micro Electro Mechanical Systems (MEMS), 2017 IEEE 30th International Conference on. IEEE, 2017.





Concept

spectrally selective absorber

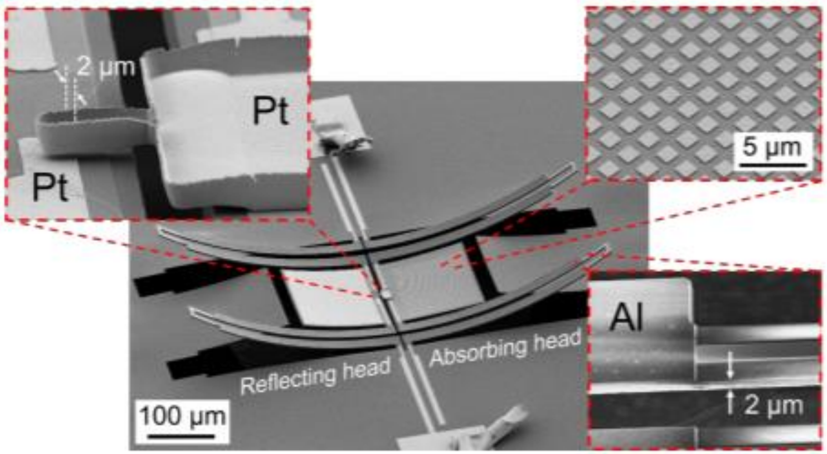


Operation Description

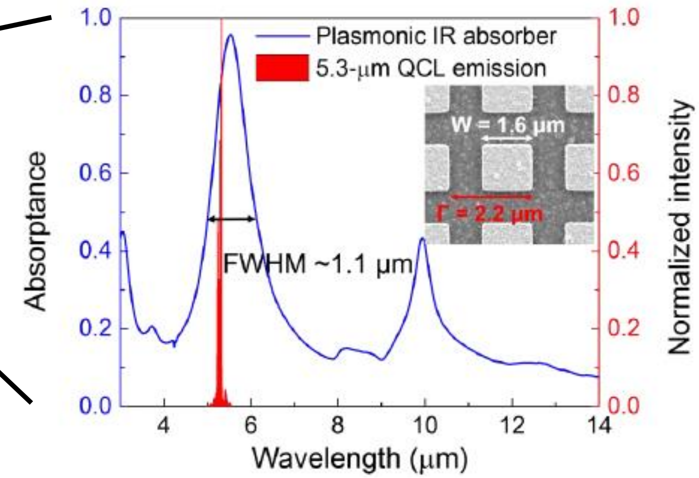
IR spectrometer with zero standby power

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.

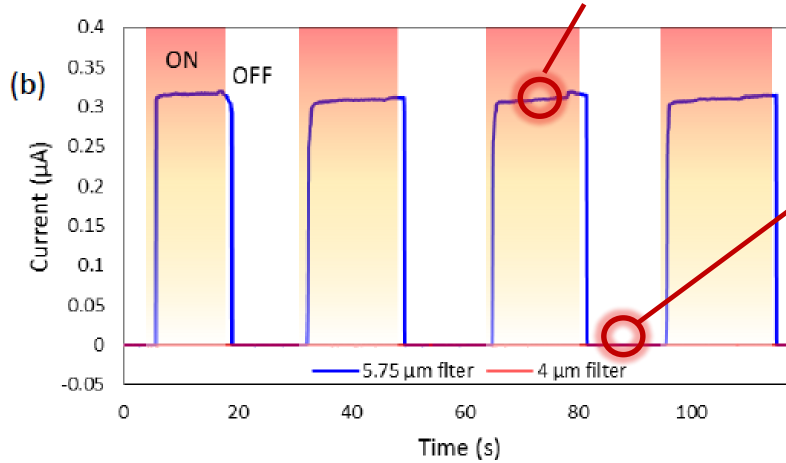


SEM Image



Plasmonic Absorber Response

Switch triggered by 6 µm IR



Rejects 4 µm IR

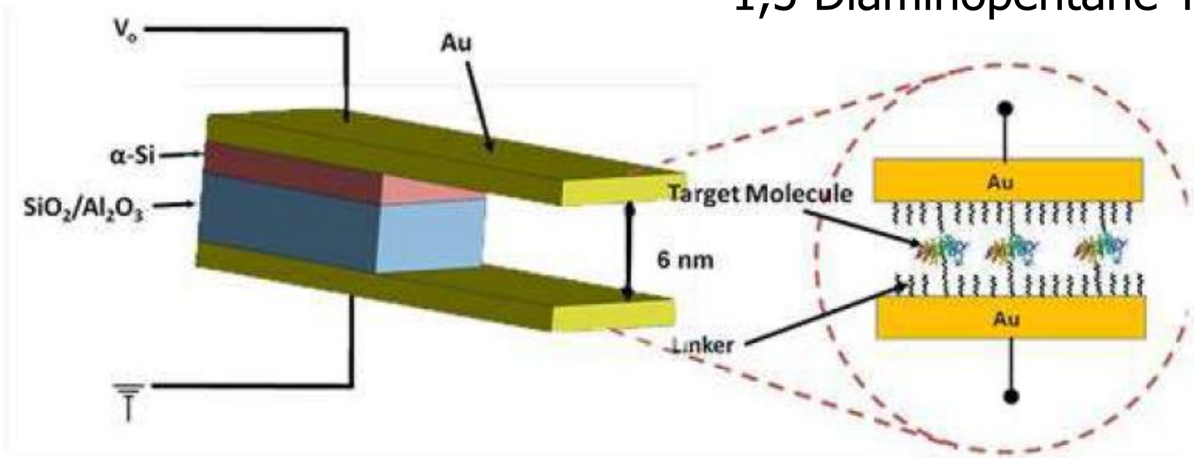
Measured Response

IR spectrometer with zero standby power

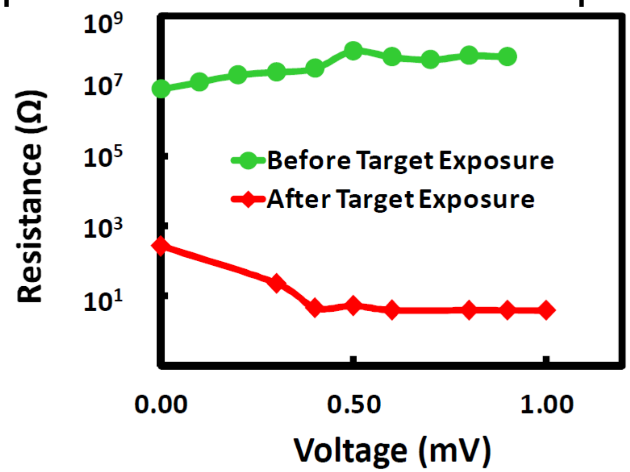
Chemical Percolation Wake-Up

Banerjee, A., et al. "Picowatt gas sensing and resistance switching in tunneling nano-gap electrodes." SENSORS, 2016 IEEE. IEEE, 2016.

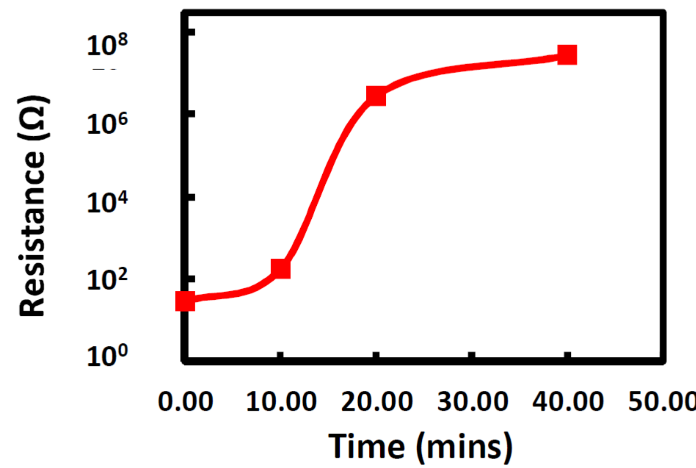
1,5 Diaminopentane Target



Expose sensor to chemical in petri dish



Remove sensor from chemical gas



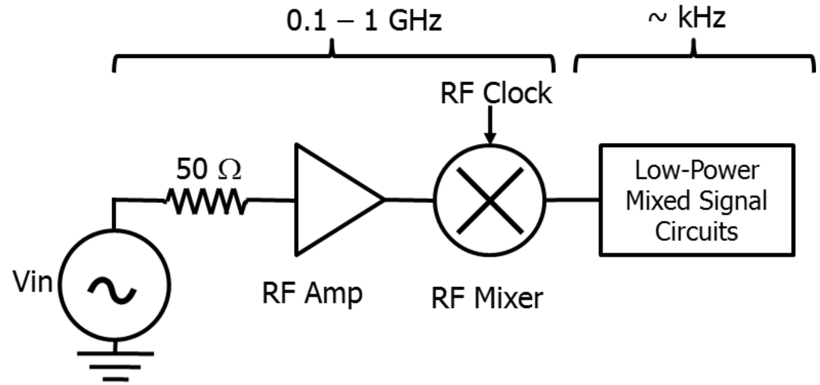
Passive detection of chemical warfare agents with zero power

TA-1A RF Microsystem Metrics

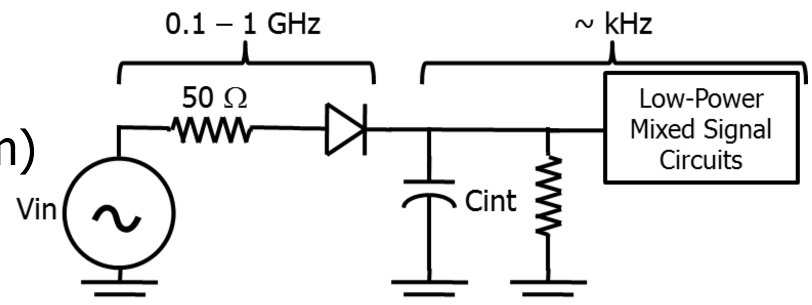
Metric	Phase I	Phase II	Phase III
RF level at sensor input	≤ -60 dBm	≤ -80 dBm	≤ -100 dBm
RF frequency limits	0.05-1 GHz	0.05-1 GHz	0.05-1 GHz
Received energy required for signature detection	≤ 30 pJ	≤ 300 fJ	≤ 3 fJ
Probability of detection	95%		
False alarm rate	< 1 per hour		
Environment	low interference background	high interference background	high interference background

The Challenge of Near-Zero Power RF Wake-Up

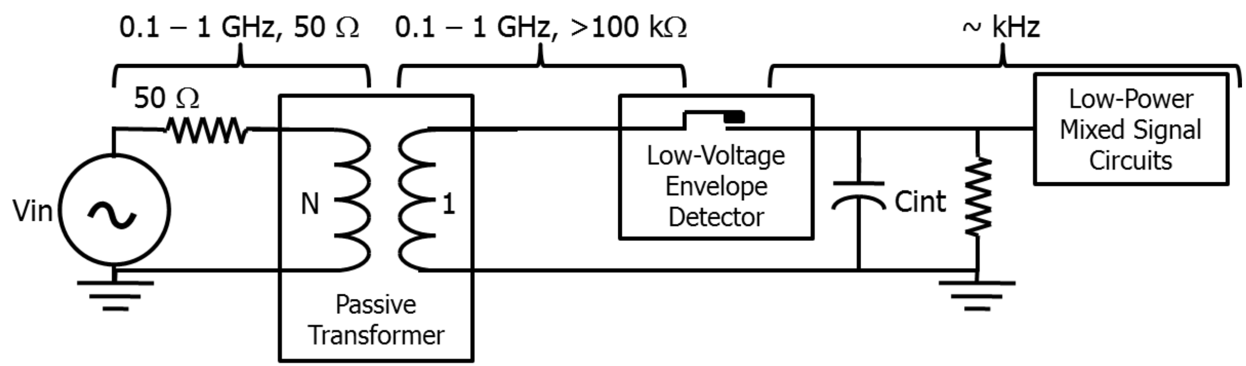
<u>Traditional Rx</u>
High Power (mW)



<u>Traditional Wake-Up</u>
Low Sensitivity (-30 dBm)

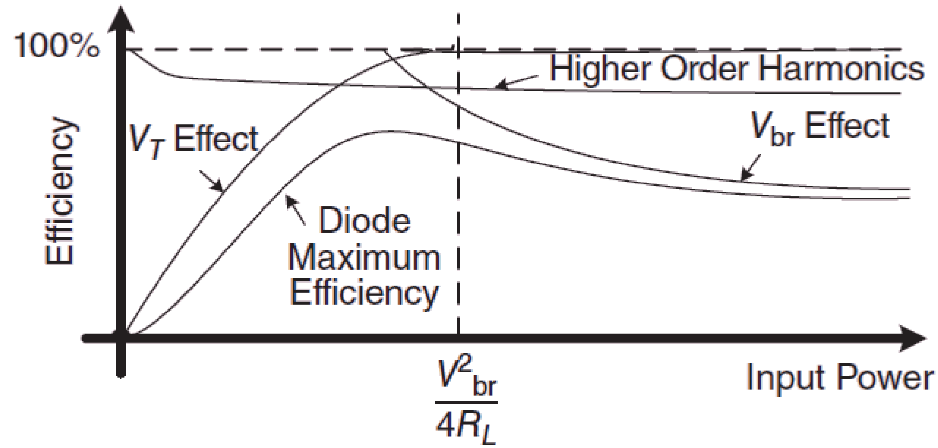


<u>N-ZERO Wake-Up</u>
< 10 nW
< -60 to -100 dBm



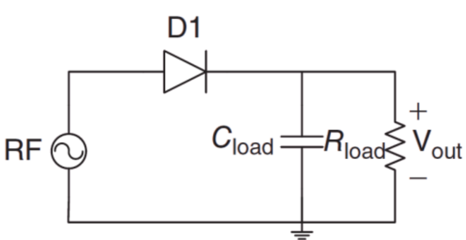
Rectifier Efficiency

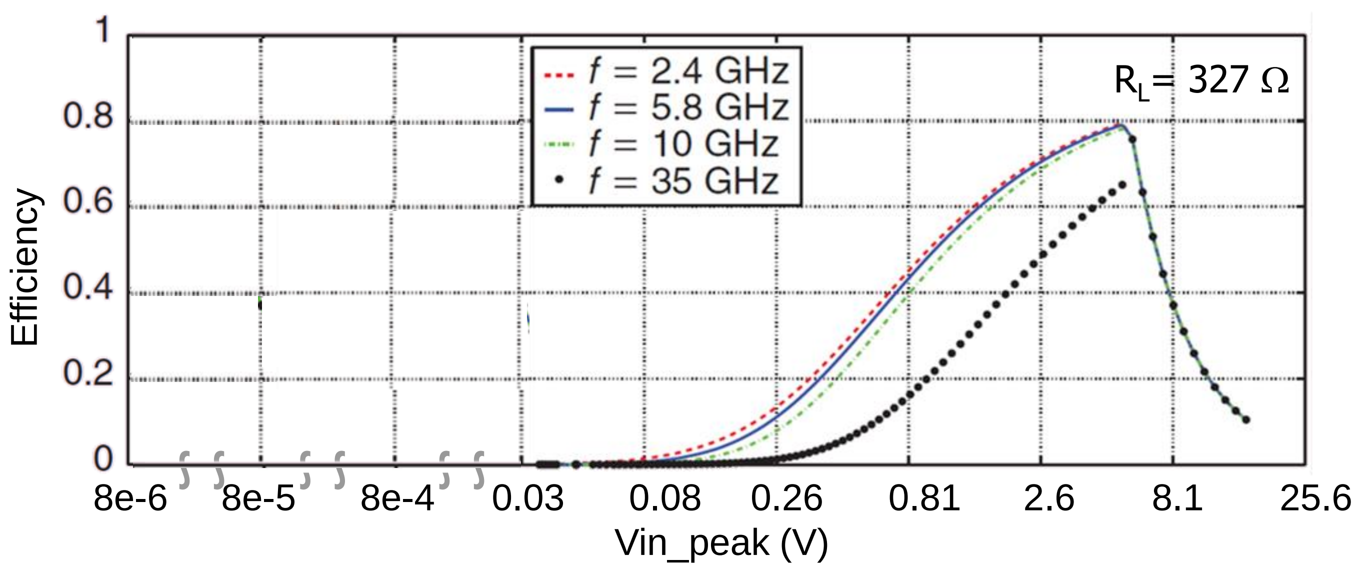
Efficiency Limited by V_T



Antenna (50 Ω) Referred Peak Voltage at Various Power Levels

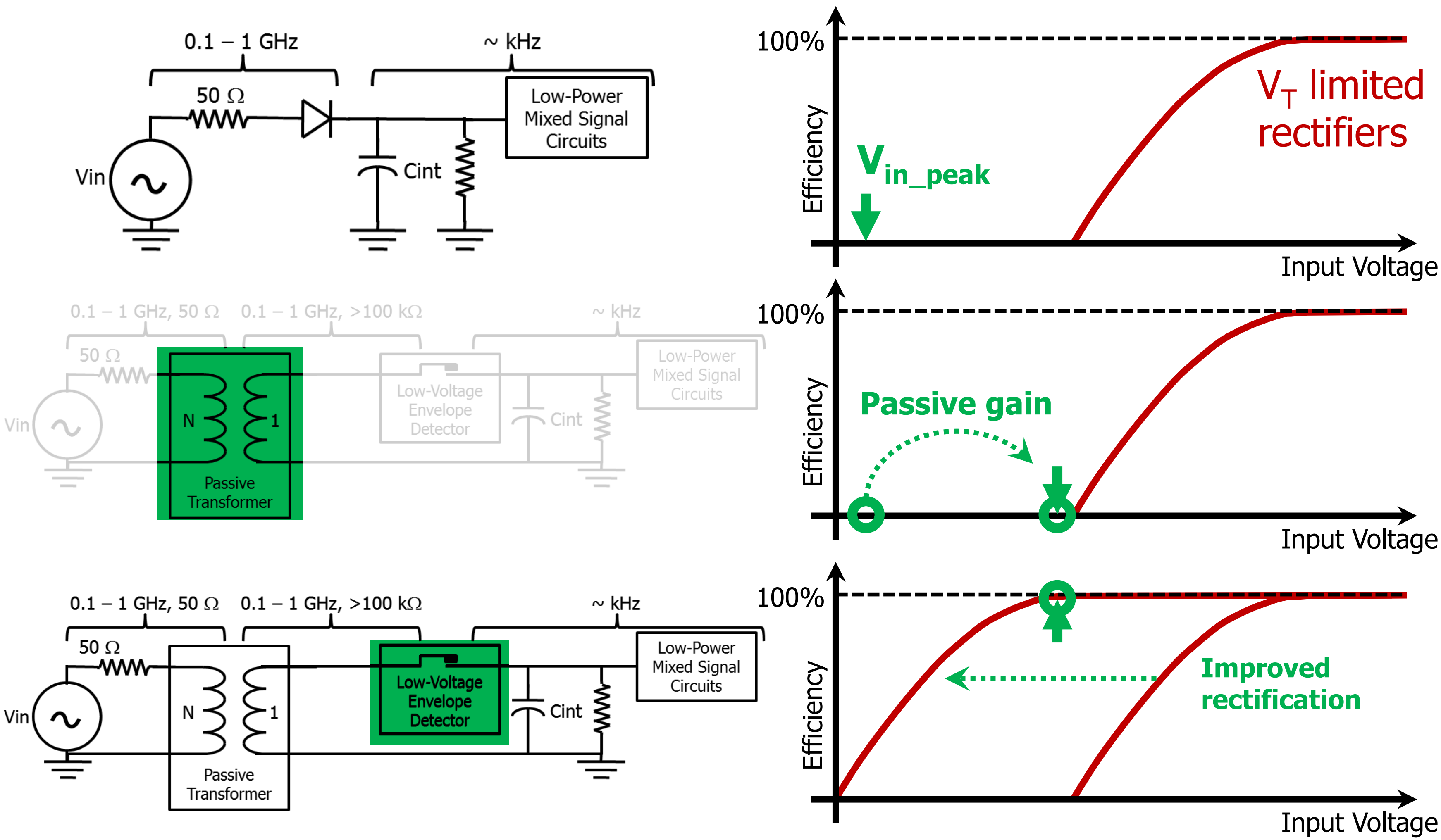
- -60 dBm = 316 μV
- -80 dBm = 31.6 μV
- -100 dBm = 3.16 μV



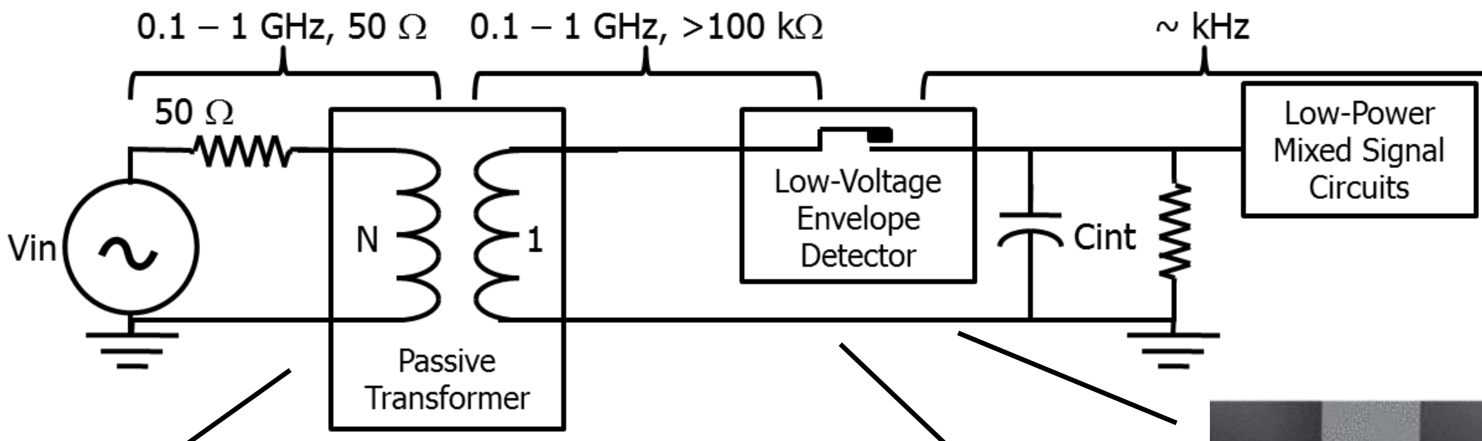


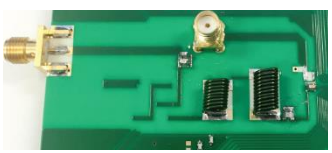
Valenta, C, et al. "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems." IEEE Microwave Magazine 15.4 (2014): 108-120.

Path to -100 dBm Sensitivity



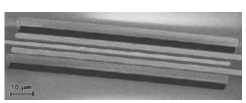
RF Approaches

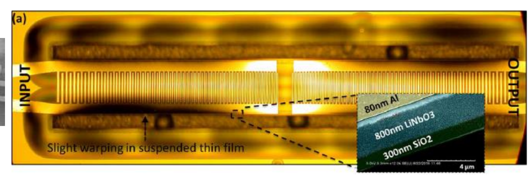




LC
UCSD

H. Jiang, et al. "24.5 A 4.5 nW wake-up radio with– 69dBm sensitivity." Solid-State Circuits Conference (ISSCC), 2017 IEEE International. IEEE, 2017. (Both UC San Diego images.)

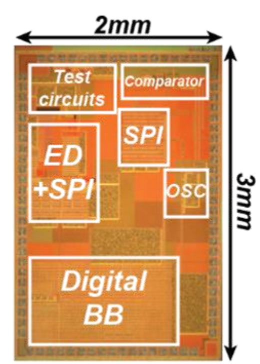




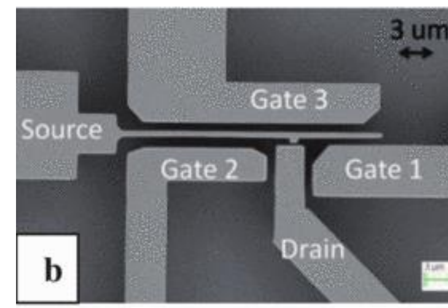
Piezo

Northeastern

UIUC



CMOS
UCSD



MEMS
Cornell

Amponsah, Kwame, et al. "Near-kT switching-energy lateral NEMS switch." Nano/Micro Engineered and Molecular Systems (NEMS), 2010 5th IEEE International Conference on. IEEE, 2010.

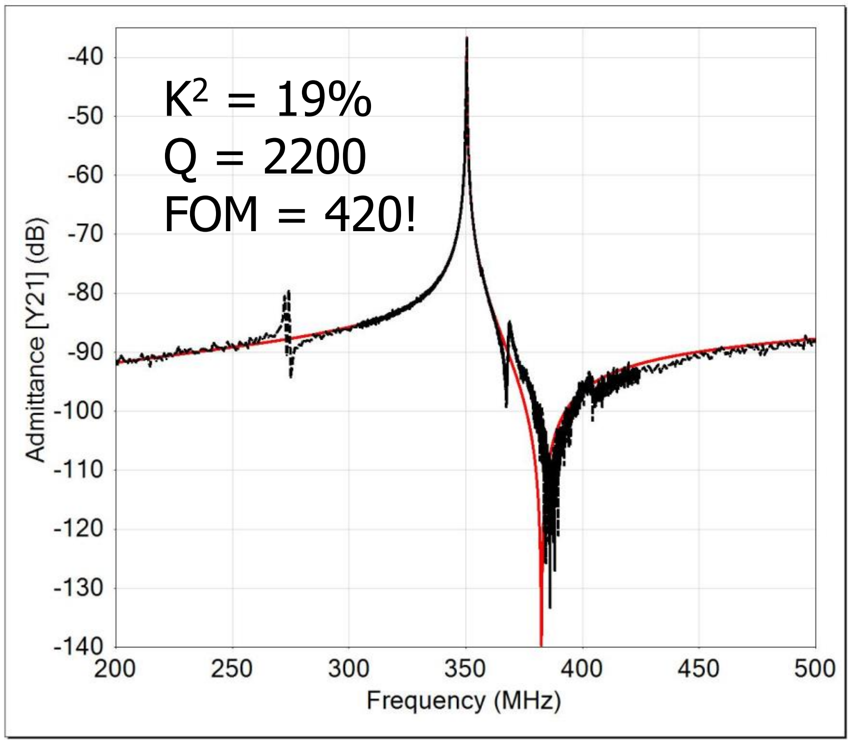
C. Cassella, et al. "Unprecedented Figure of Merit in Excess of 108 in 920 MHz Aluminum Nitride Cross-Sectional Lamé Mode Resonators Showing kt2 in Excess of 6.2%", Proceedings of the 2016 Solid-State Sensors, Actuators and Microsystems Workshop (Hilton Head 2016), Hilton Head Island, 5-9 June, 2016

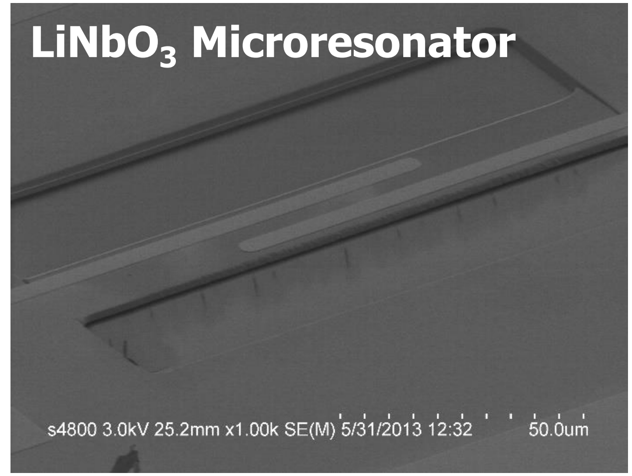
T. Manzaneque, et al. "An SH0 Lithium Niobate dispersive delay line for chirp compression-enabled low power radios", 2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS), Las Vegas, NV, 2017, pp. 155-158.

Passive Voltage Gain Approaches

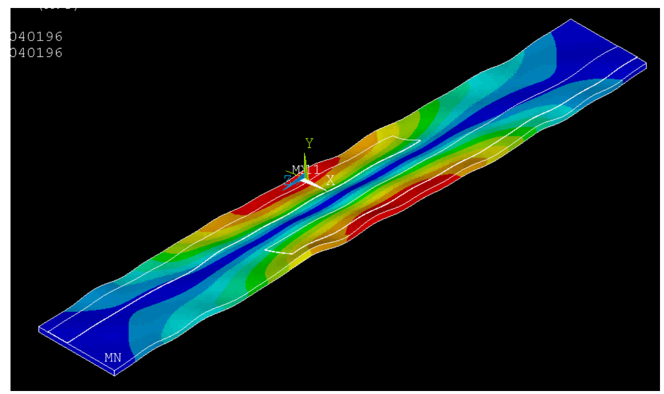
High FOM Micromechanical Resonators

New materials offer much larger figure of merit (FOM) and potential for higher voltage gain



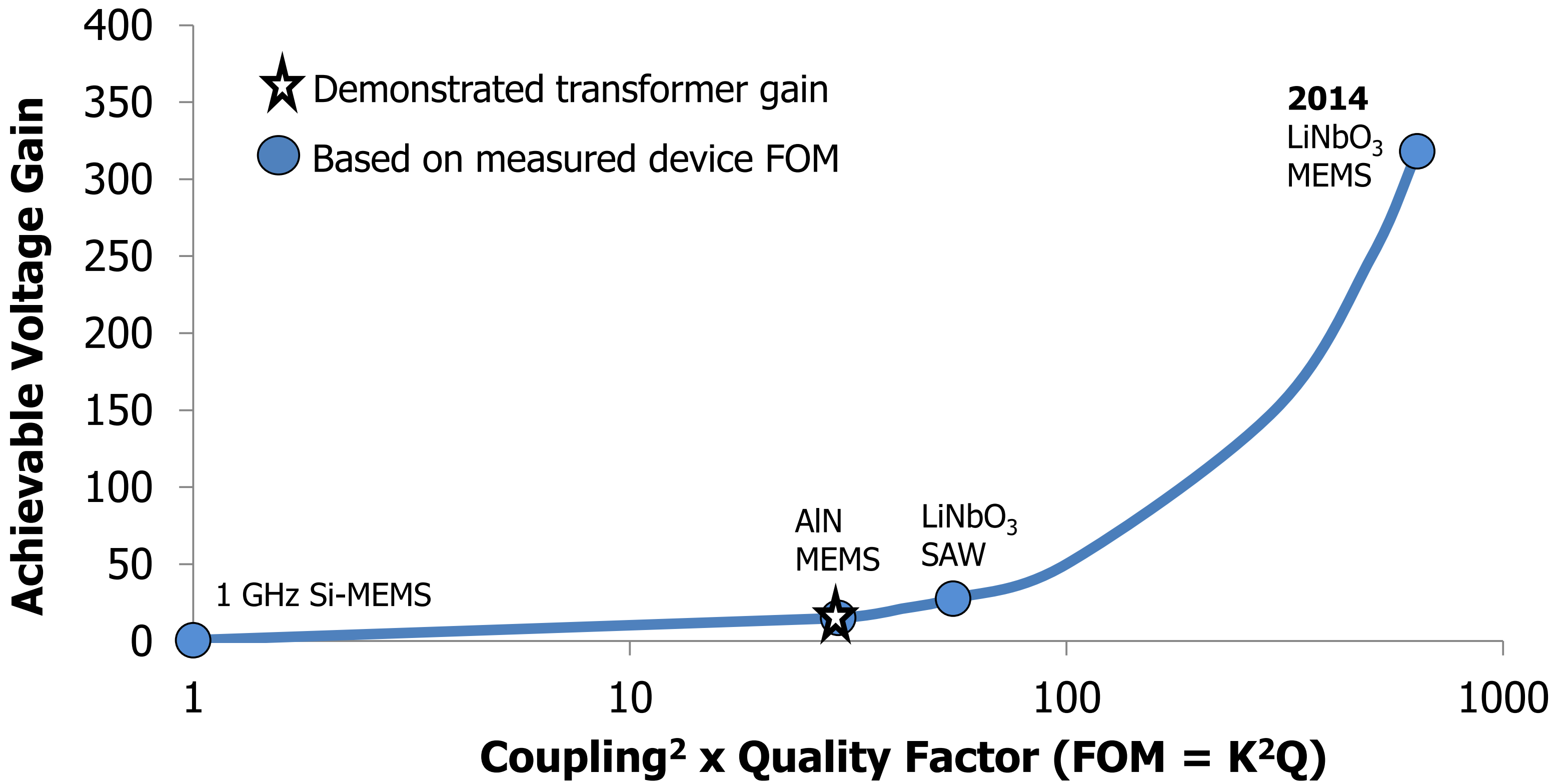


Shear horizontal Lamb wave (SH0)



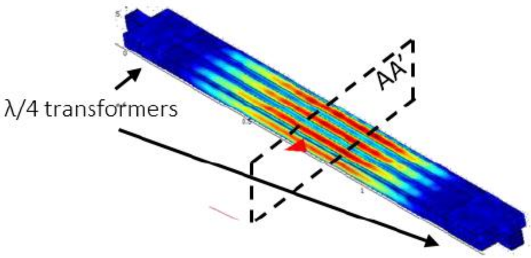
R. H. Olsson III, K. Hattar, M. S. Baker, M. Wiwi, J. Nguyen, C. Padilla, S. J. Homeijer, J. R. Wendt and T. A. Friedmann, "Lamb Wave Micromechanical Resonators Formed in Thin Plates of Lithium Niobate," *Solid-State Sensor, Actuator, and Microsystems Workshop,* pp. 281-284, June 2014.

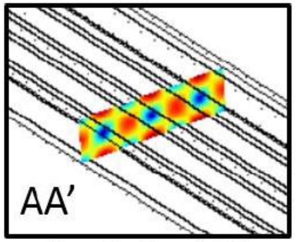
High FOM Device Can Lead to New Levels of Passive Voltage Gain



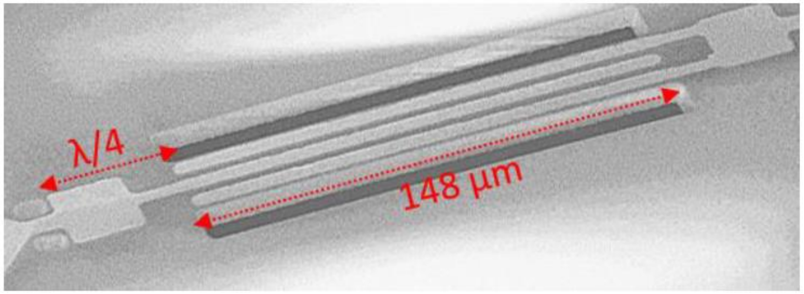
High FOM μResonator

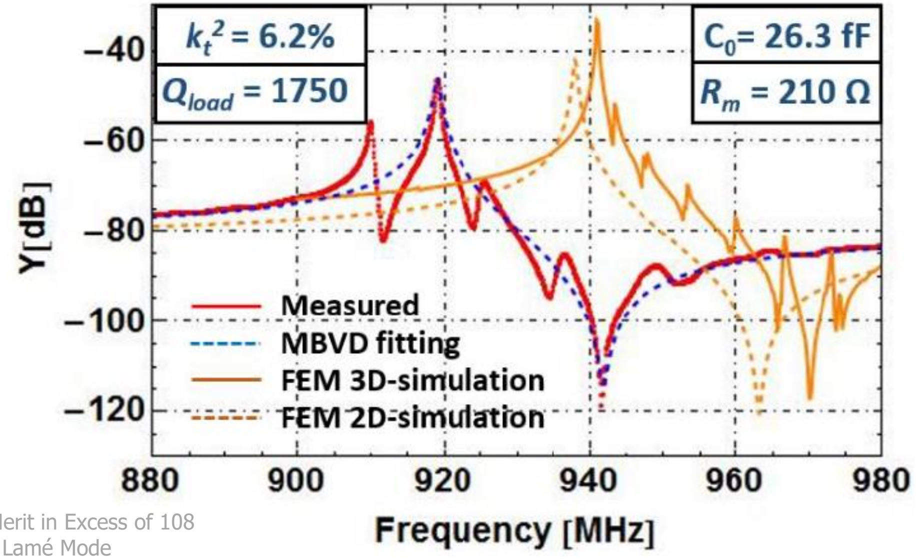
AlN cross-sectional Lame-mode Resonators





Cross-Sectional Cut

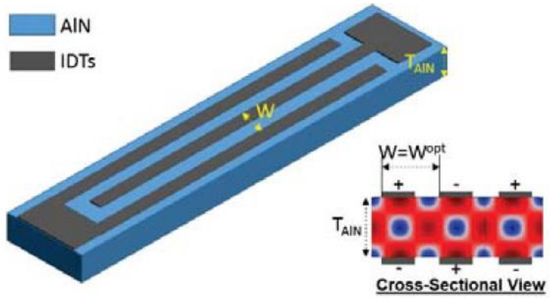


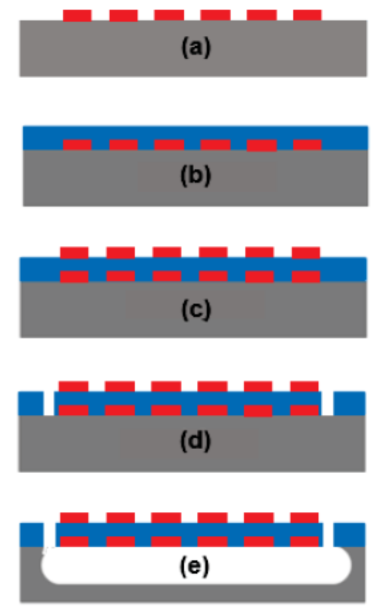


FOM ~ 108!

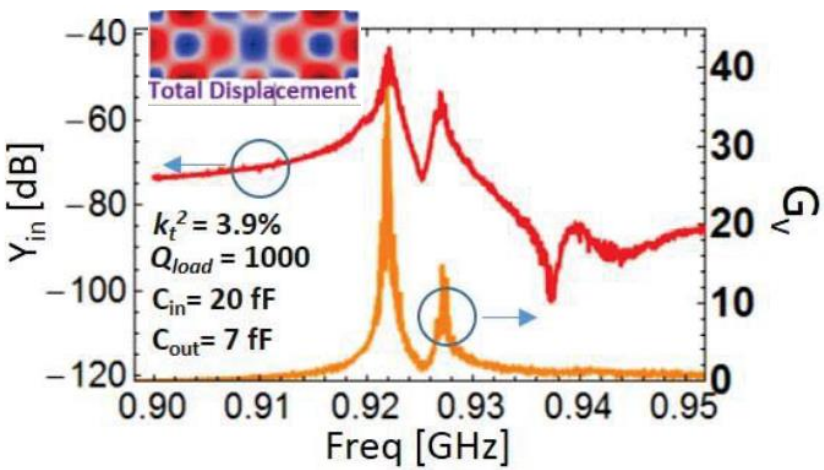
C. Cassella, et al. "Unprecedented Figure of Merit in Excess of 108 in 920 MHz Aluminum Nitride Cross-Sectional Lamé Mode Resonators Showing kt2 in Excess of 6.2%", Proceedings of the 2016 Solid-State Sensors, Actuators and Microsystems Workshop (Hilton Head 2016), Hilton Head Island, 5-9 June, 2016

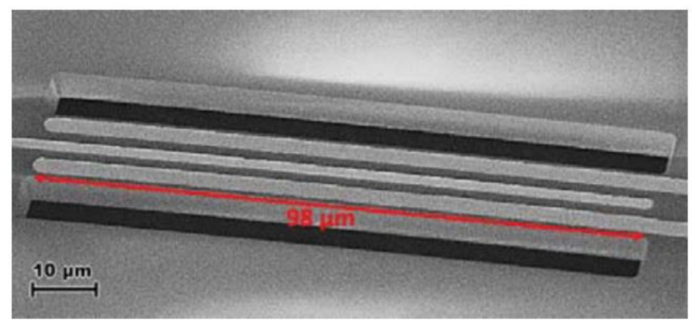
High Gain Acoustic Transformer





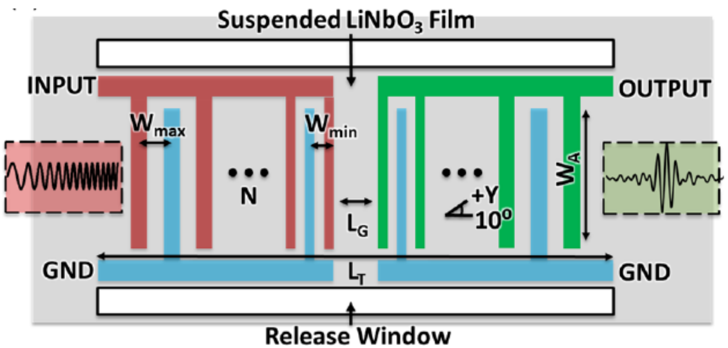
FOM = 40
Voltage gain ~ 40 at 920 GHz

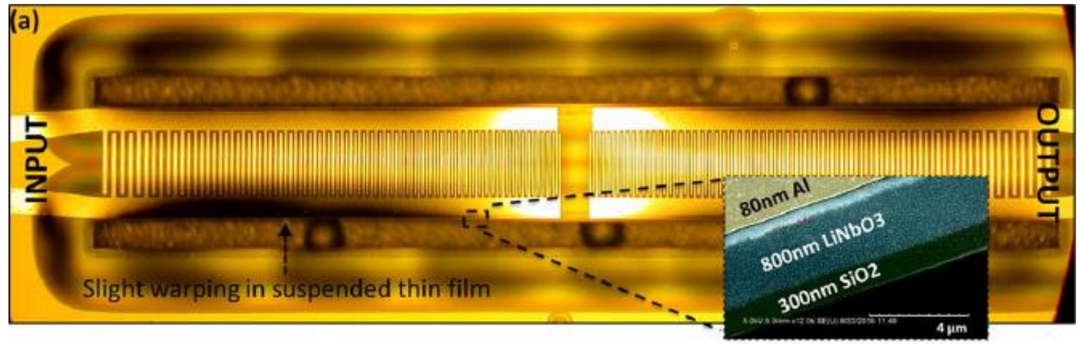


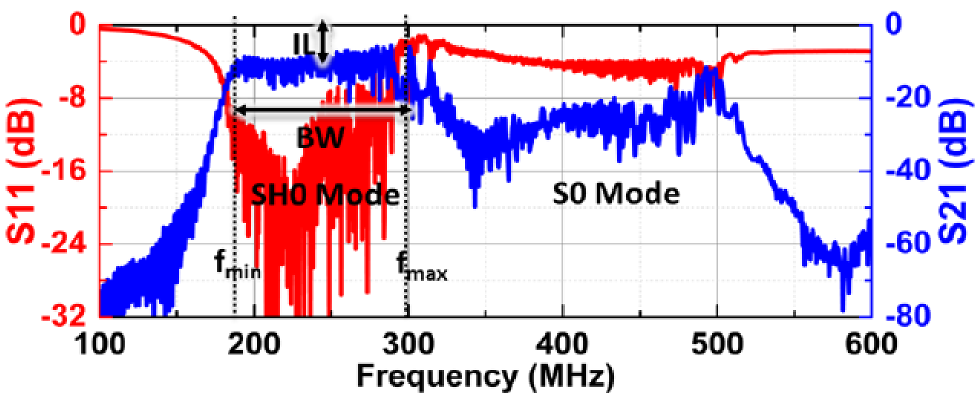


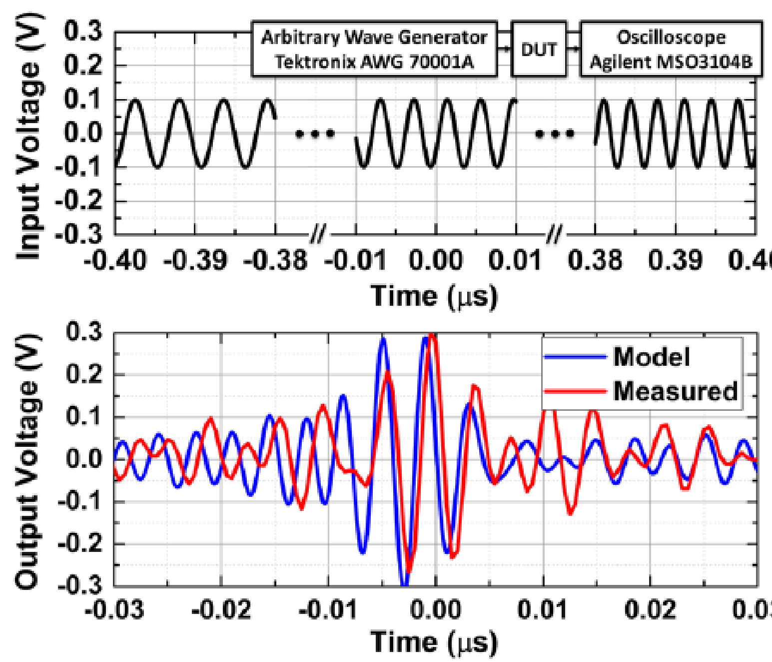
C. Cassella, et al. "Unprecedented Figure of Merit in Excess of 108 in 920 MHz Aluminum Nitride Cross-Sectional Lamé Mode Resonators Showing kt2 in Excess of 6.2%", Proceedings of the 2016 Solid-State Sensors, Actuators and Microsystems Workshop (Hilton Head 2016), Hilton Head Island, 5-9 June, 2016

MEMS Chirp Compressor





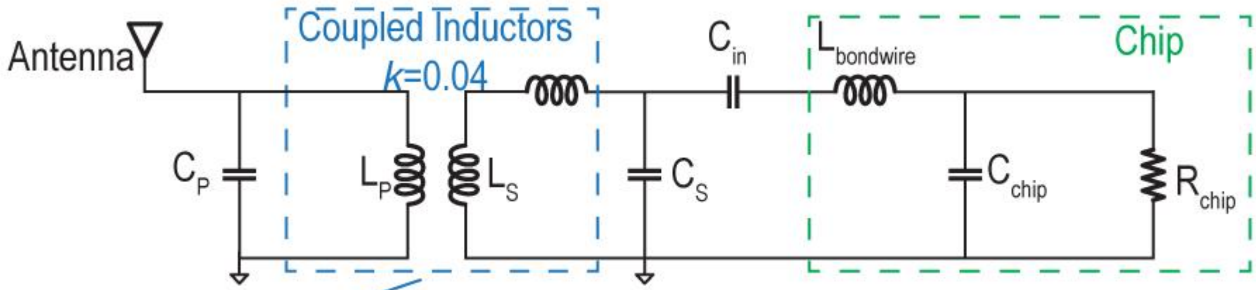




T. Manzaneque, et al. "An SH0 Lithium Niobate dispersive delay line for chirp compression-enabled low power radios", 2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS), Las Vegas, NV, 2017, pp. 155-158.

LC Transformer Filter

H. Jiang, et al. "24.5 A 4.5 nW wake-up radio with– 69dBm sensitivity." Solid-State Circuits Conference (ISSCC), 2017 IEEE International. IEEE, 2017.



L_P: **Distributed**
+
L_S: **Lumped+Distributed**
Realize large *L* with well-controlled *k*

3-D Model of Transformer Filter

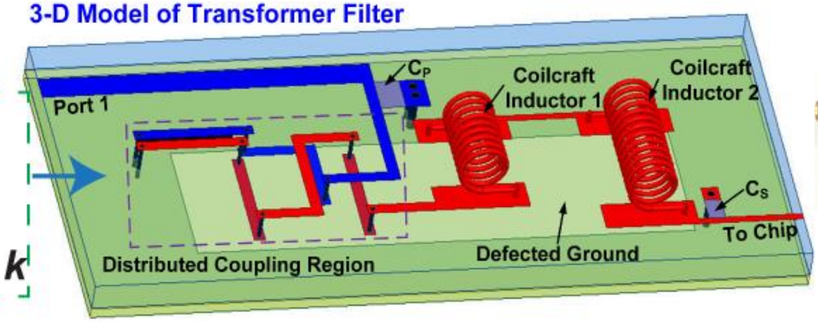
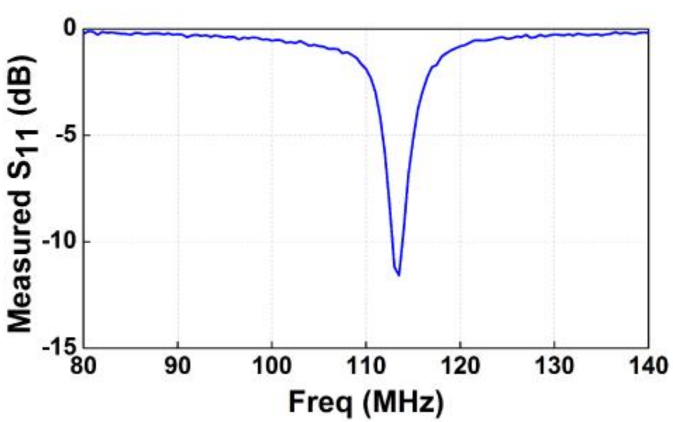
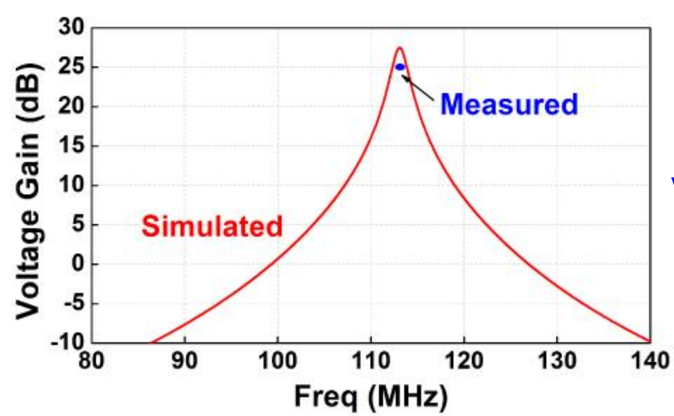


Photo of Transformer Filter



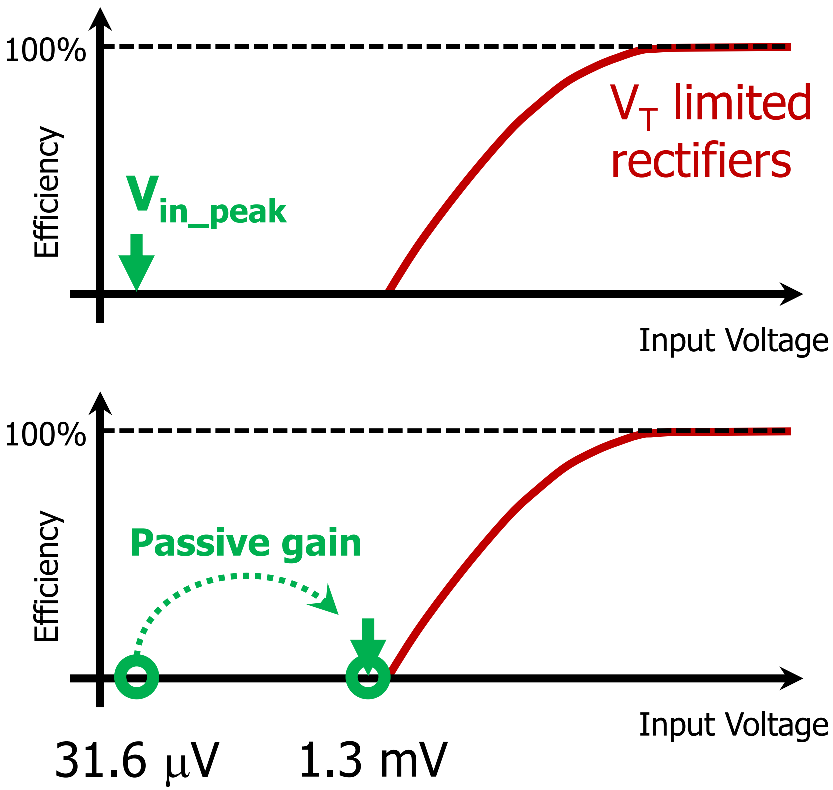


V_{gain} = 17.9 V/V

Why Voltage Gain Matters

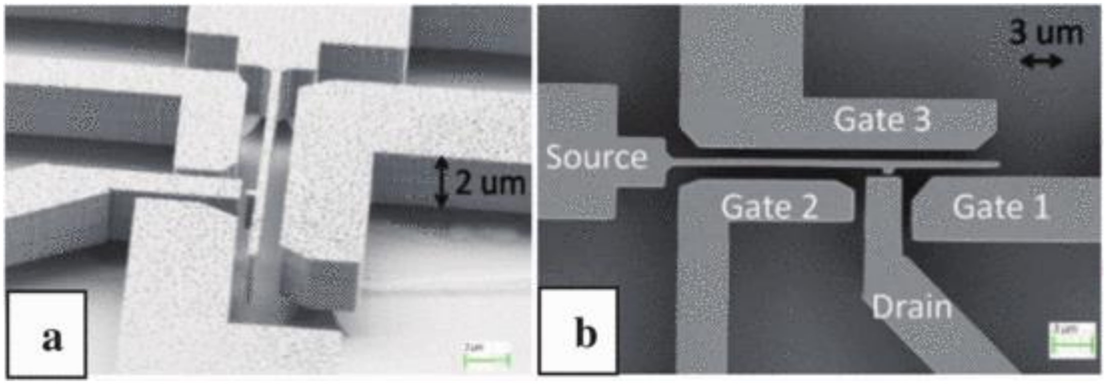
Antenna (50 Ω) referred peak voltage at various power levels

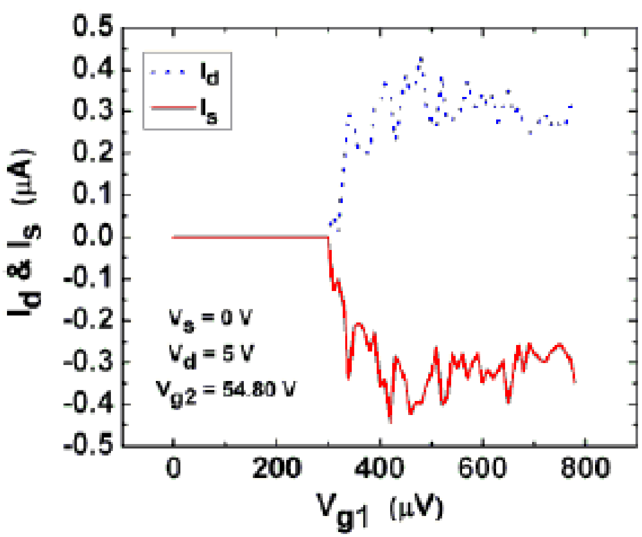
- -60 dBm = 316 μV
- **-80 dBm = 31.6 μV**
- -100 dBm = 3.16 μV



Low Voltage Rectifier Approaches

Micromechanical Switches as Efficient Rectifiers and Quantizers





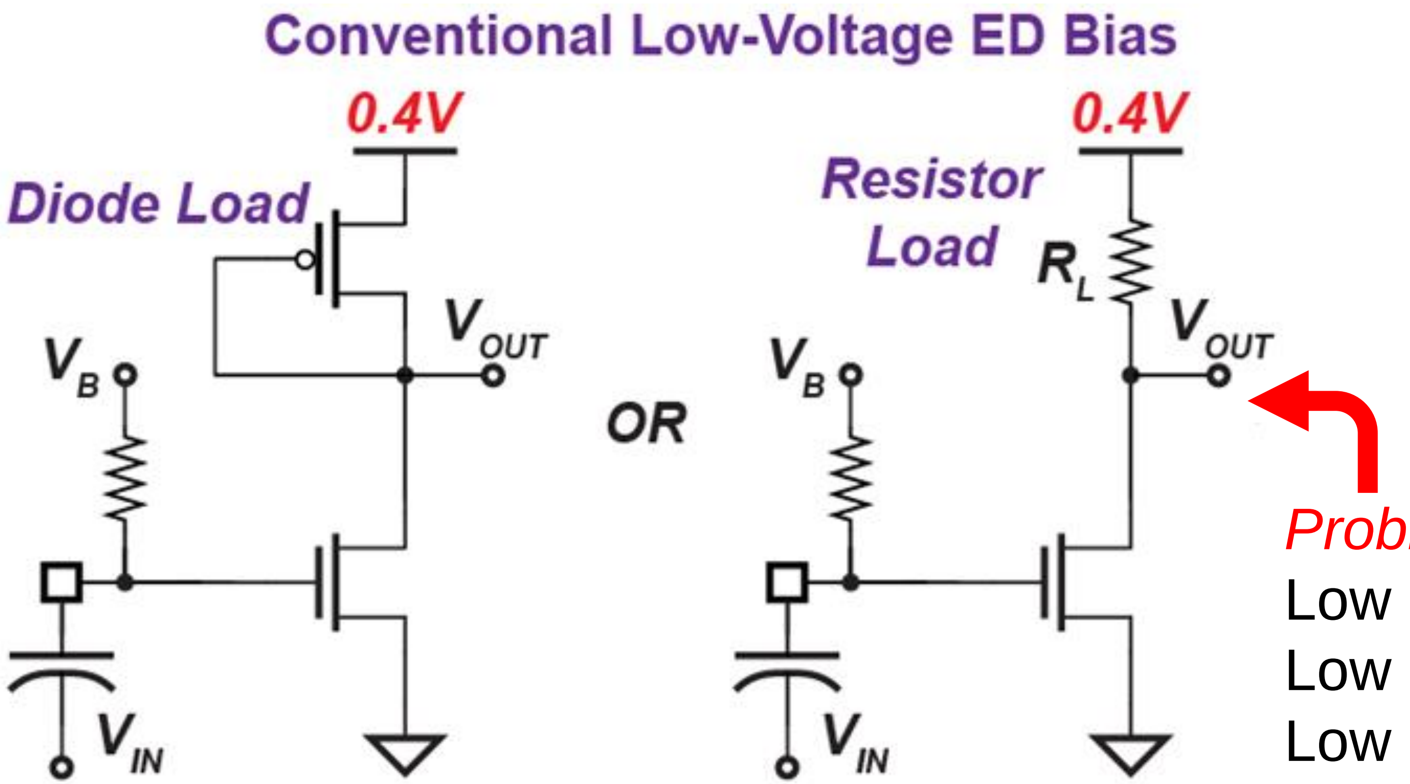
300 μV threshold MEMS switch

<u>Micromechanical Rectifiers and Quantizers</u>

- 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

Amponsah, Kwame, et al. "Near-kT switching-energy lateral NEMS switch." Nano/Micro Engineered and Molecular Systems (NEMS), 2010 5th IEEE International Conference on. IEEE, 2010.

Envelope Detector as a Rectifier



Problem:
Low R_{out}
Low gain
Low SNR

Benefit:

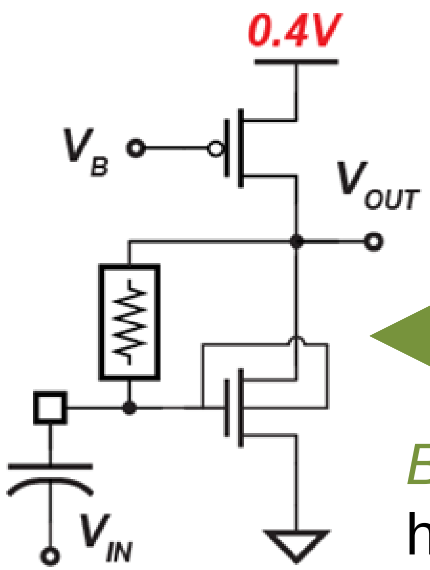
Active ED has high input impedance to support high RF gain

2nd order g_m non-linearity realizes the ED squaring-function

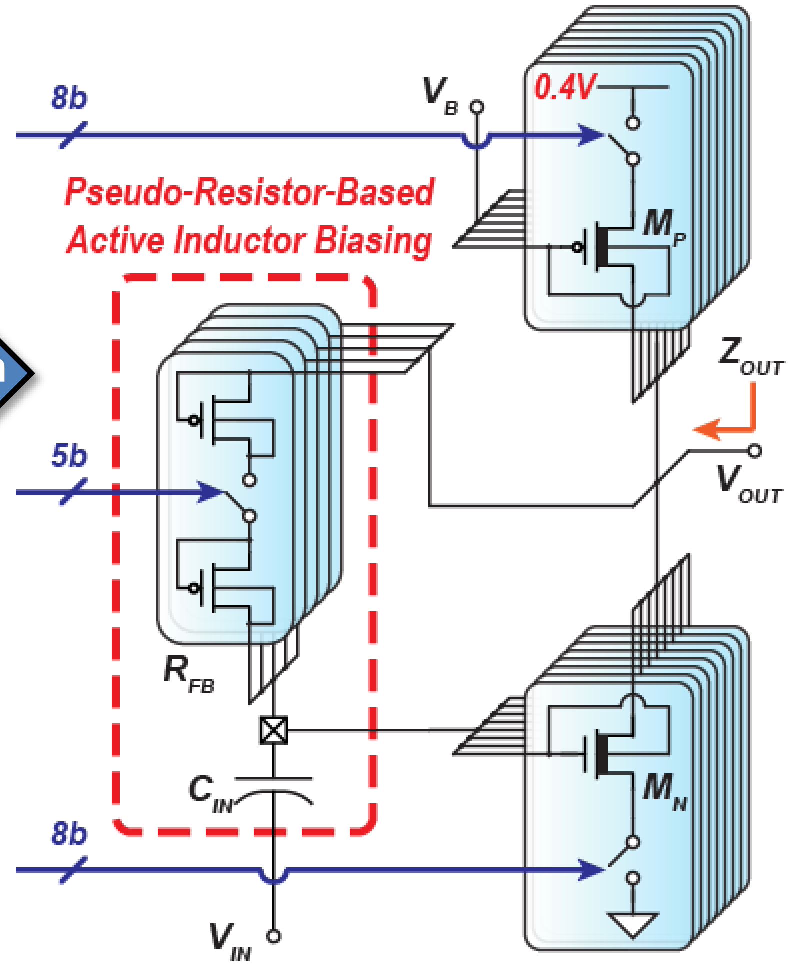
H. Jiang, et al. "24.5 A 4.5 nW wake-up radio with– 69dBm sensitivity." Solid-State Circuits Conference (ISSCC), 2017 IEEE International. IEEE, 2017.

Envelope Detector Implementation

Active-Inductor ED Bias



Implementation



Benefit:

high R_{out}

high gain

high SNR

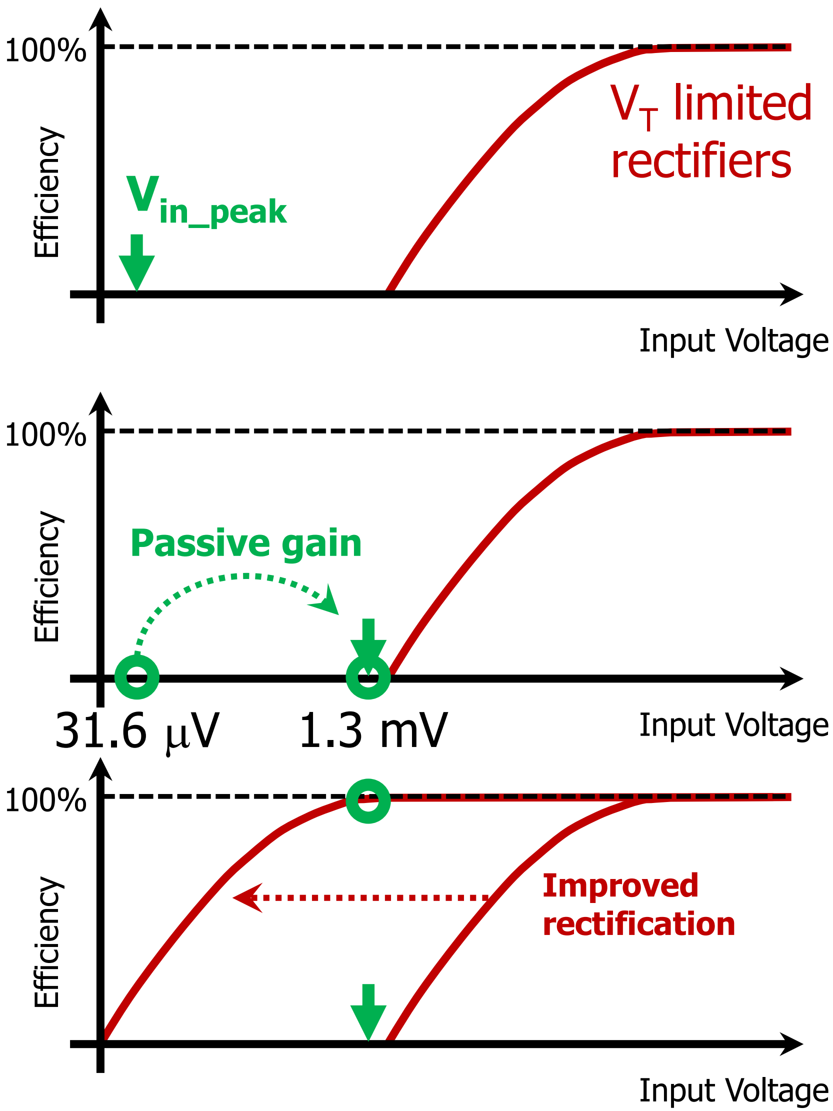
H. Jiang, et al. "24.5 A 4.5 nW wake-up radio with– 69dBm sensitivity." Solid-State Circuits Conference (ISSCC), 2017 IEEE International. IEEE, 2017.

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

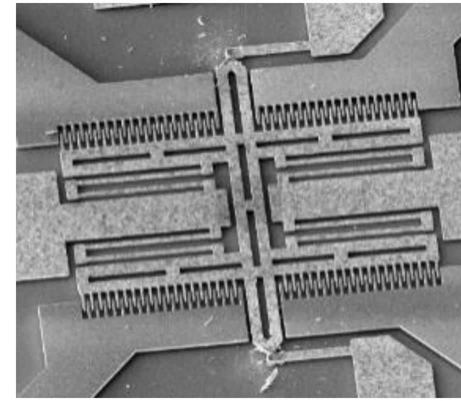
Why Low Voltage Rectifiers

Antenna (50 Ω) referred peak voltage at various power levels

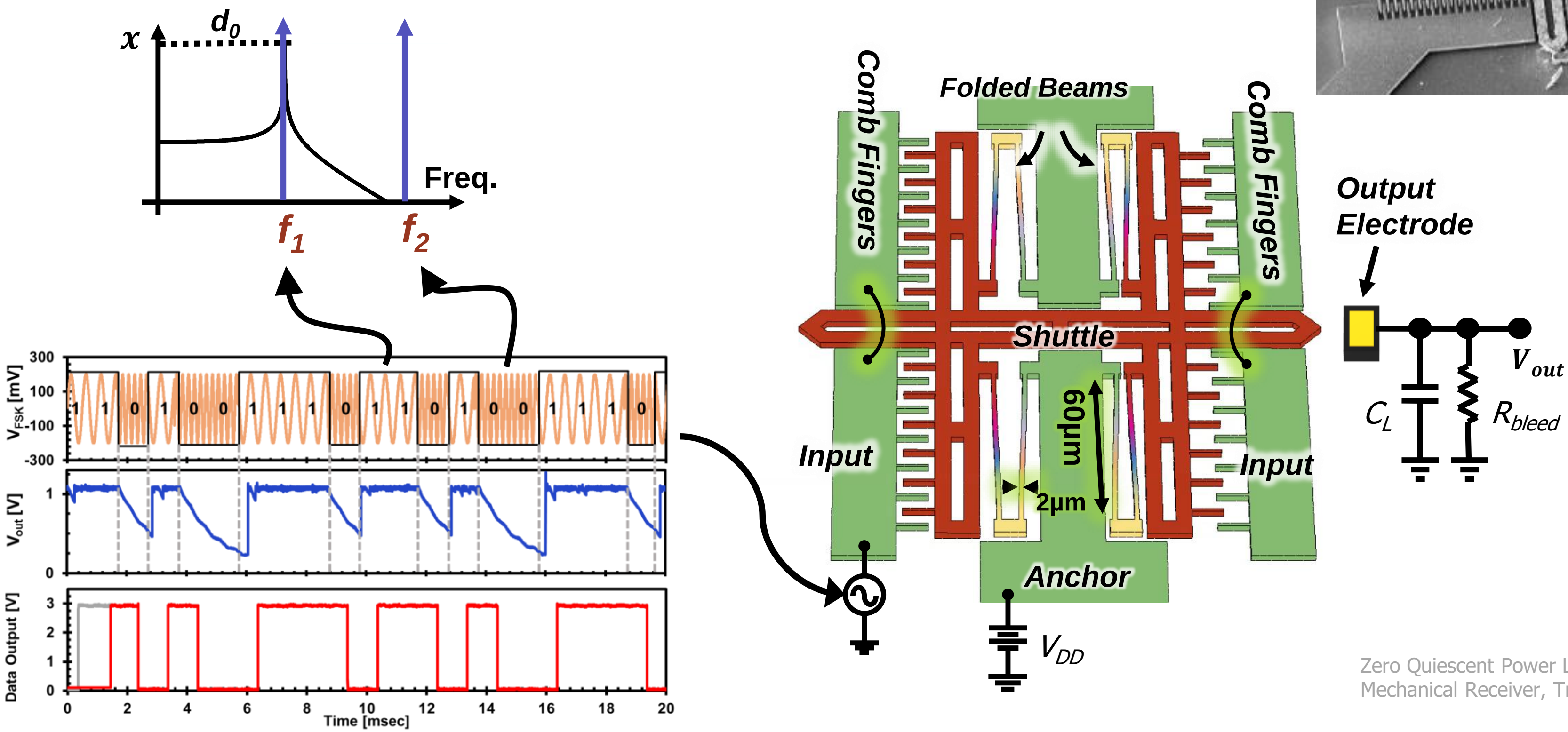
- -60 dBm = 316 μV
- **-80 dBm = 31.6 μV**
- -100 dBm = 3.16 μV



Micromechanical Frequency-Selective N-ZERO Receiver



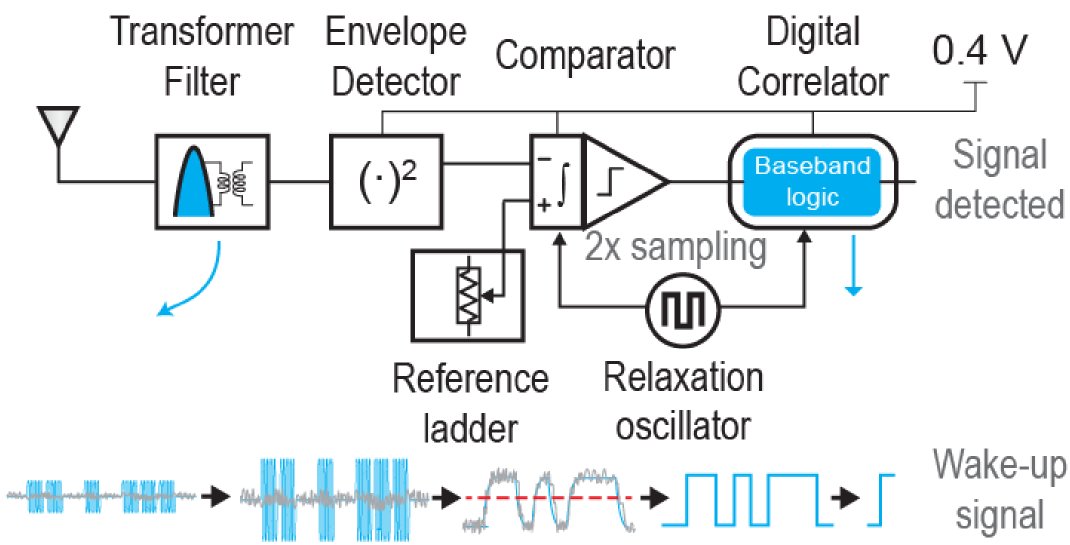
Demonstrated sensitivity:
-62 dBm @ 20-kHz

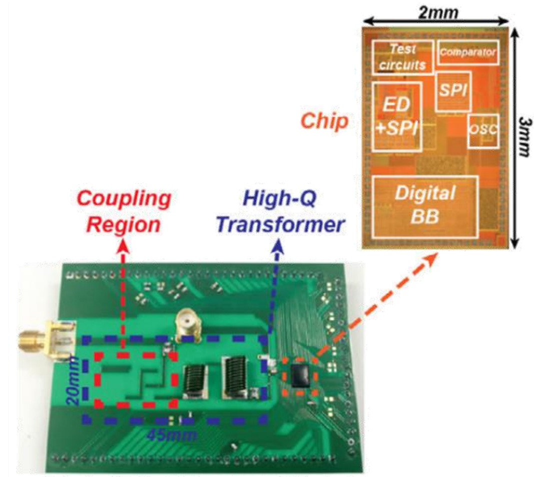


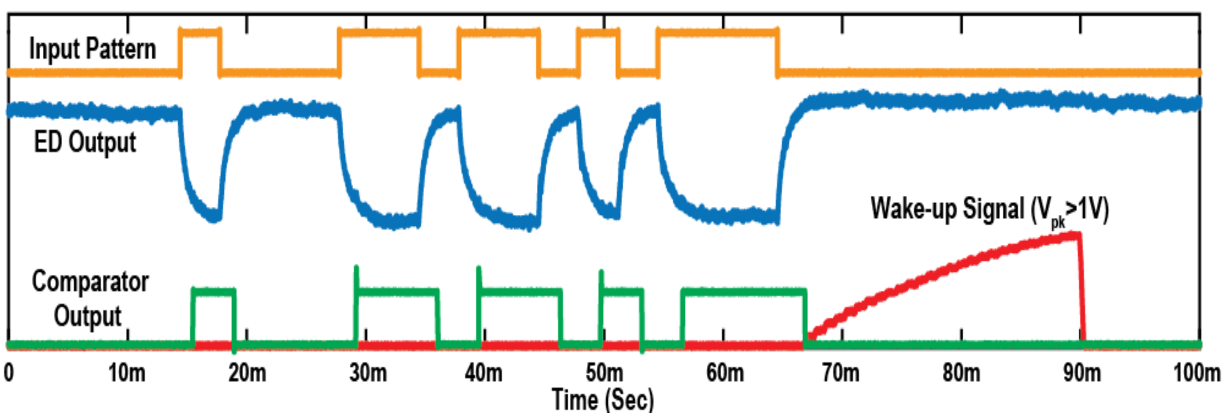
Zero Quiescent Power Low Frequency Mechanical Receiver, Transducers 2015

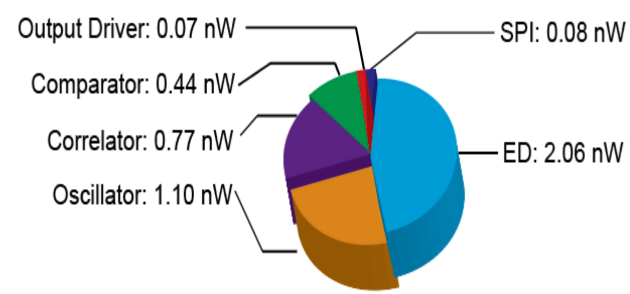
All mechanical zero-power receiver

N-ZERO VHF Wake-up Receiver







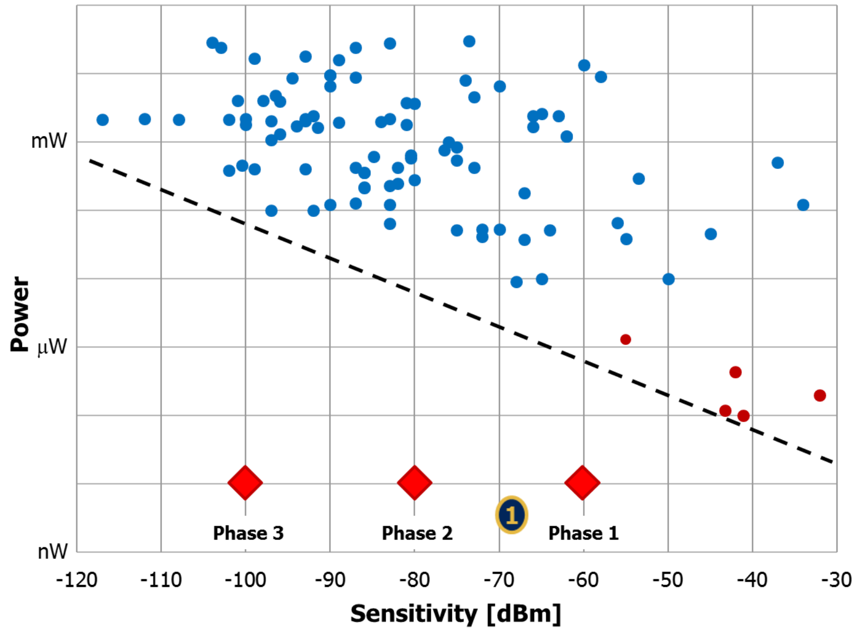


H. Jiang, et al. "24.5 A 4.5 nW wake-up radio with– 69dBm sensitivity." Solid-State Circuits Conference (ISSCC), 2017 IEEE International. IEEE, 2017.

Lowest powered effort for N-ZERO wake-up receiver

RF Sensing - TA-1A

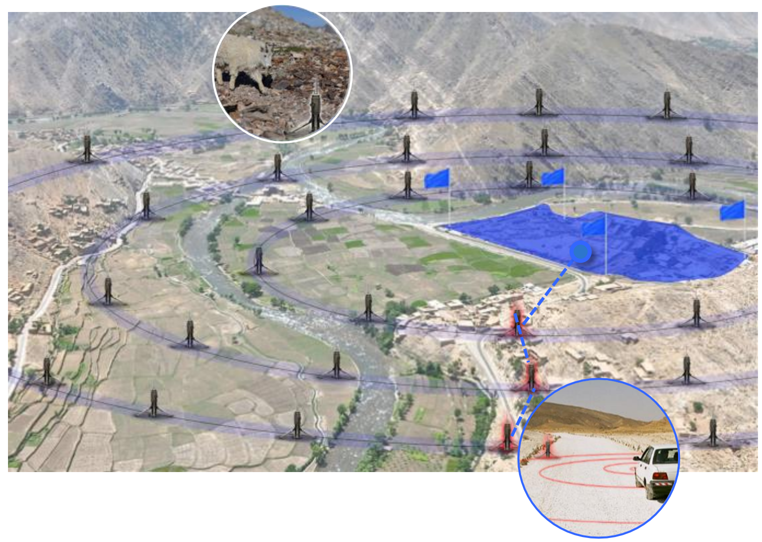
David D. Wentzloff, "Low Power Radio Survey," [Online]. www.eecs.umich.edu/wics/low_power_radio_survey.html

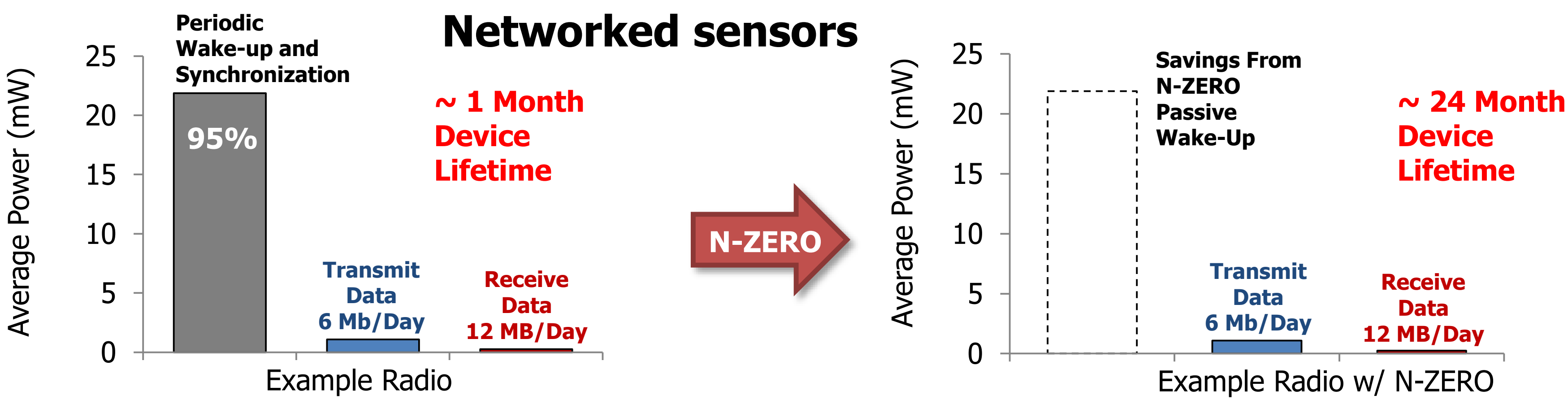


Current Results	Phase I Goal	UCSD (1)
Power Consumption [nW]	≤10	4.5
Sensitivity [dBm]	≤-60	-69
Frequency [MHz]	50 - 1000	114
False Alarm Rates [#/hour]	≤1	0.64
Probability of Detection [%]	95	≥95
Transformer	Performer Defined	LC
Rectifier	Performer Defined	CMOS

Remotely wake-up a circuit without drawing stand-by power

N-ZERO Zero Power RF Wake-Up Impact

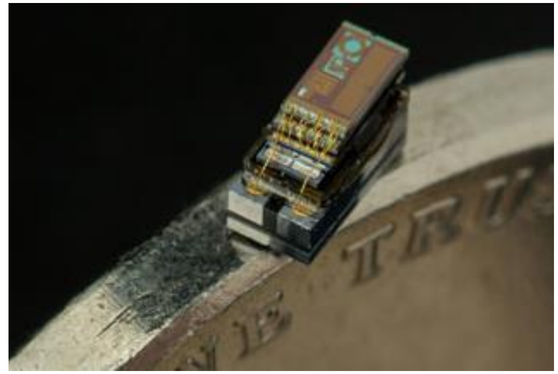




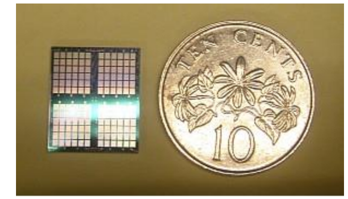
N-ZERO RF wake-up greatly extends networked sensor lifetime

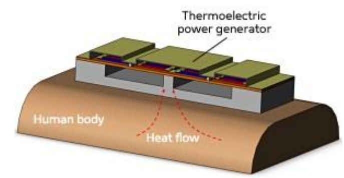
Enabling Indefinite Operational Lifetimes

https://www.eecs.umich.edu/eecs/about/articles/2015/Worlds-Smallest-Computer-Michigan-Micro-Mote.html



Electronics/Actuators





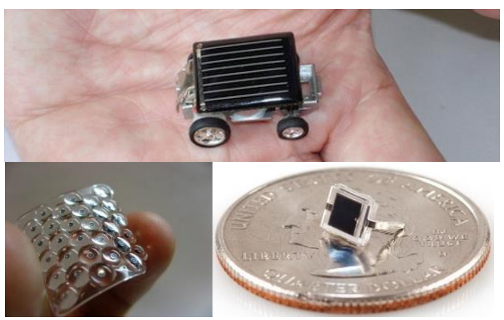
https://www.research.a-star.edu.sg/research/6218/the-power-of-heat

Storage

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

Energy Scavenging Technologies

http://inhabitat.com/worlds-smallest-solar-car-select-solar-mini/solar-car-solar-power-car-smallest-solar-car-small-car-tiny-car-gift-gadget-solar-gadget-solar-gift-techie-gift-geek-gift/

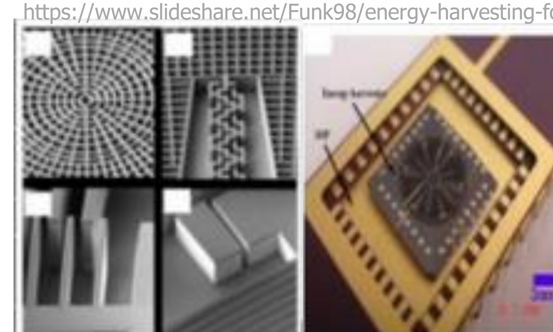


Sandia National Labs

sparkfun.com/products/9541

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

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

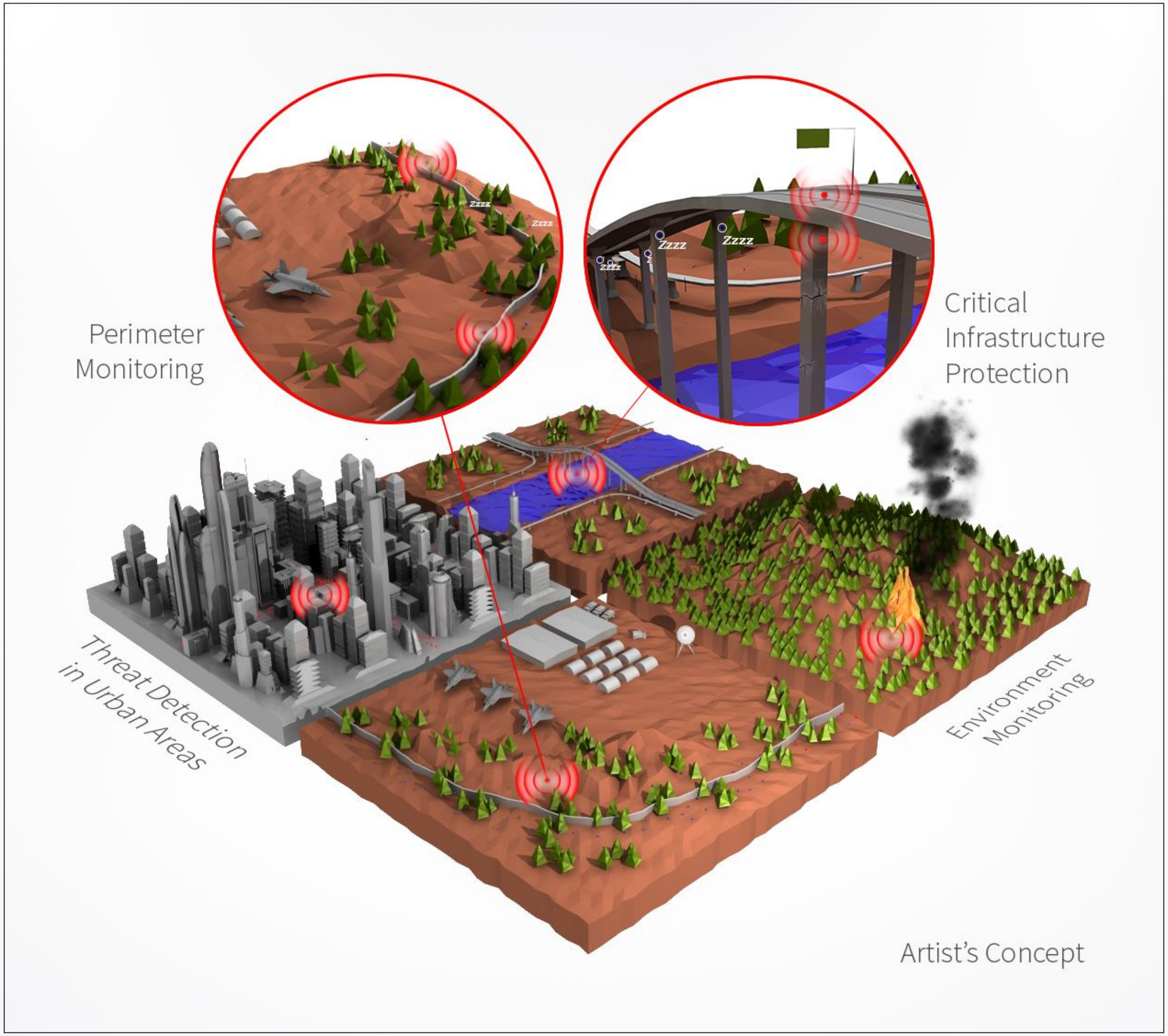


Vibration~100 uW/cm²
(typ. inside a moving car)

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

Smart Cities Applications

- 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