EnerHarv 2022

PSMA International Energy Harvesting Workshop • April 5-7, 2022 • Raleigh, NC, USA

Technical Sponsors: EnABLES, pels IEEE Power Electronics Society, CPSS

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Powering the IoT: An Energy Harvesting Perspective

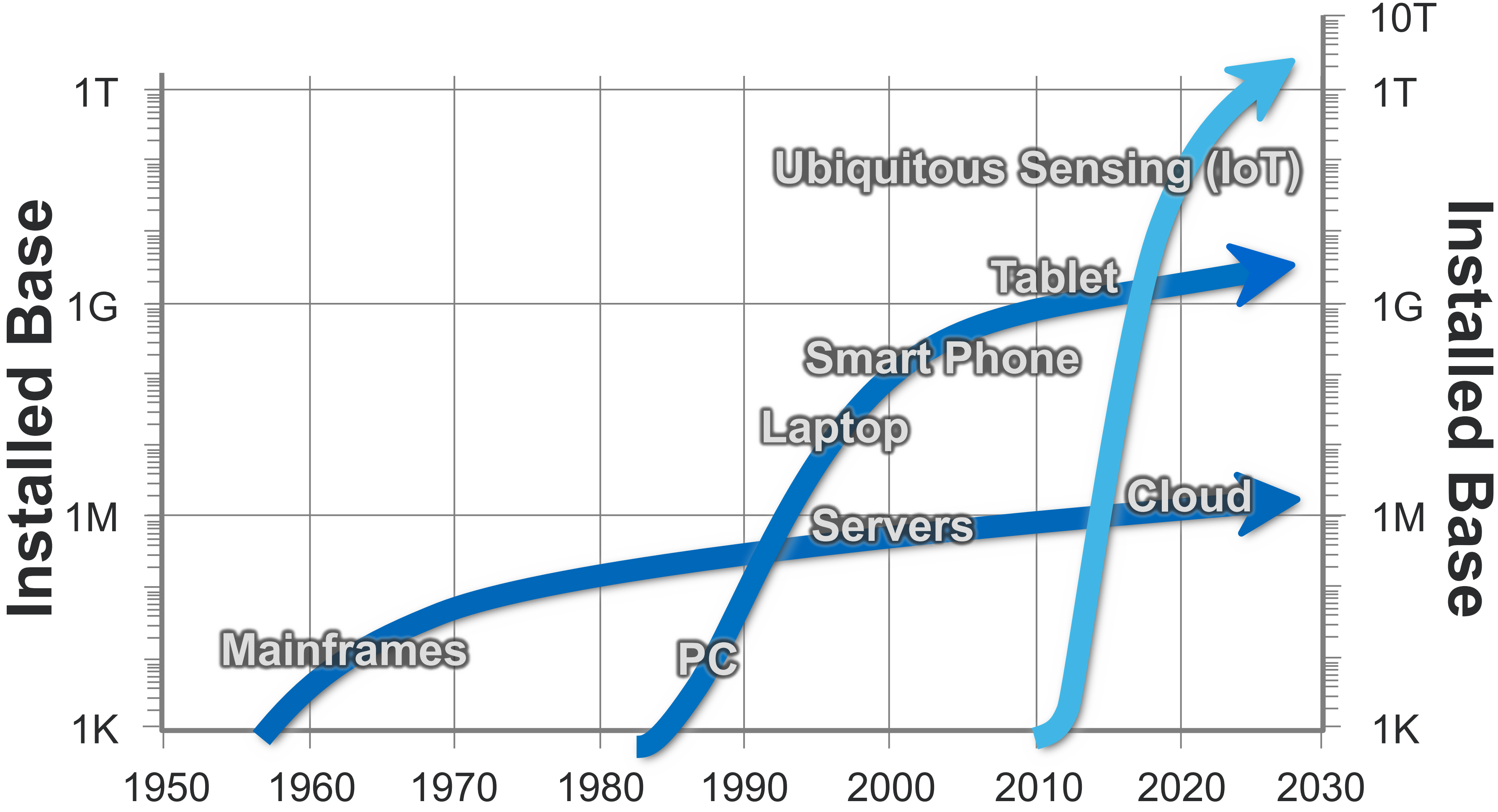
Baoxing Chen

ADI Fellow, IEEE Fellow

ANALOG DEVICES

AHEAD OF WHAT'S POSSIBLE™

IoT Riding the Third Wave of IT Revolution



The Connected World – Huge Opportunities for IoT

IoT makes the world better and safer

Powering IoT: Energy Harvesting (EH) Technologies

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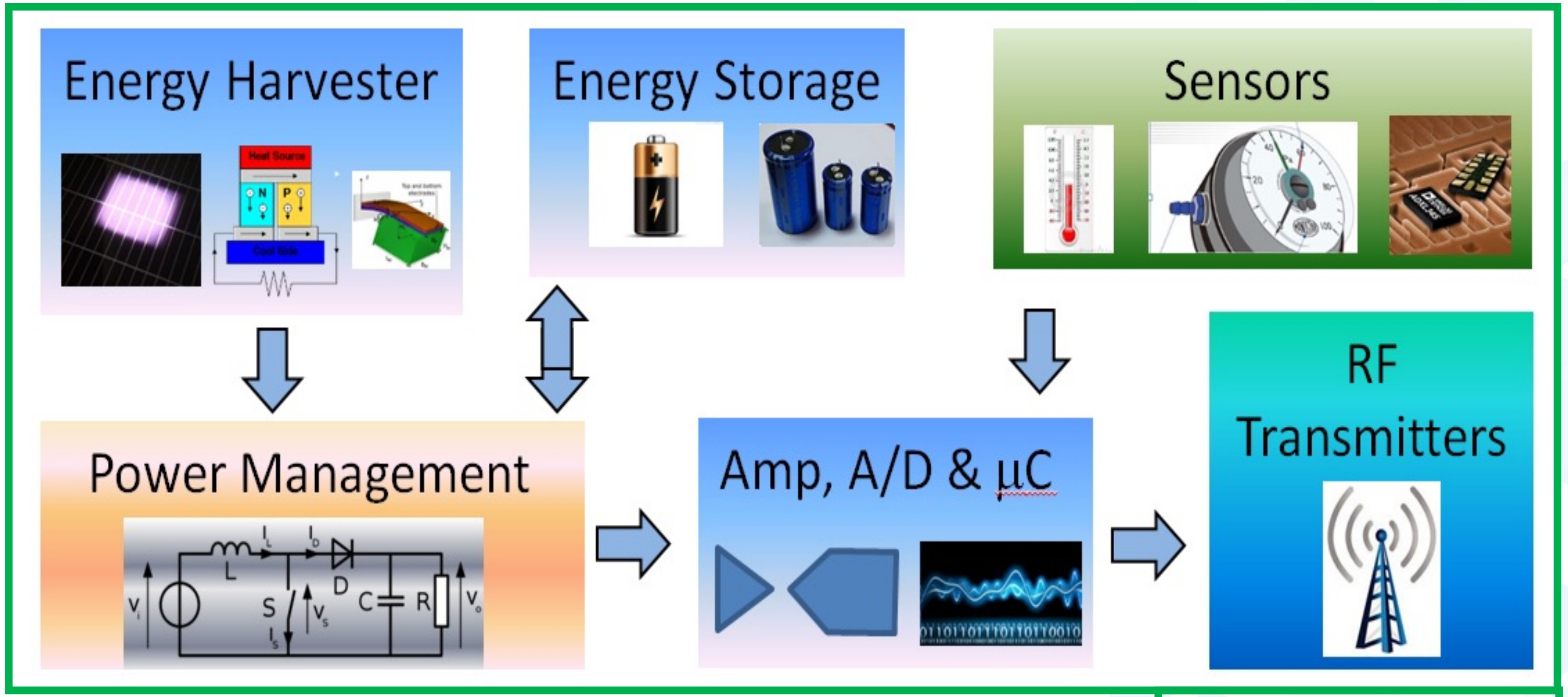

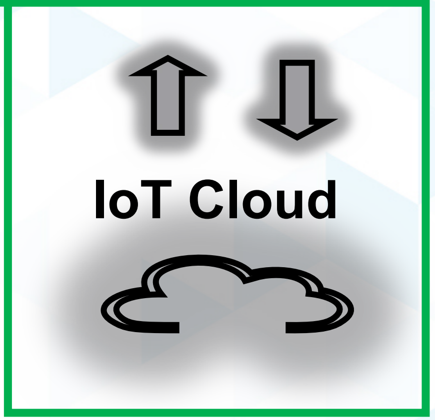

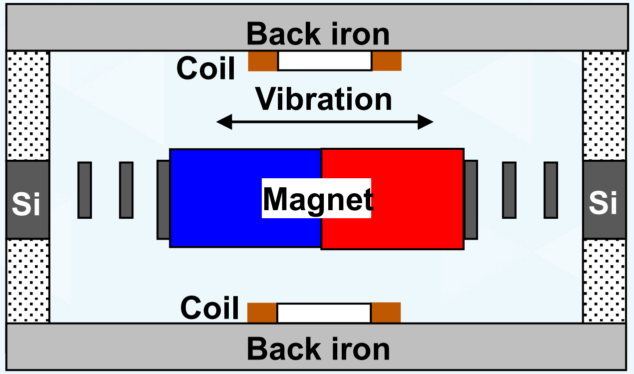

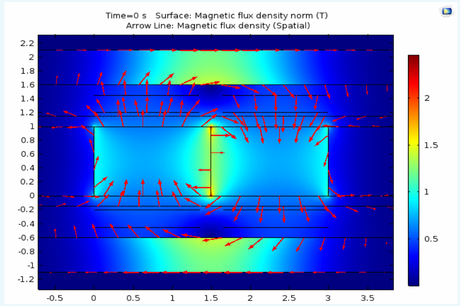

- Enable "Deploy & Forget" WSN
- Replaces or extend battery life
- Compact, Economic & <u>Reliable</u>
- <u>Easy to Use</u> & Integrated

Bridging The Gap Between Harvester and IoT Load

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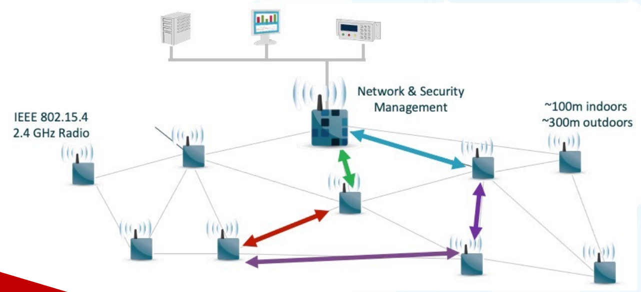
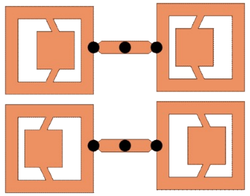
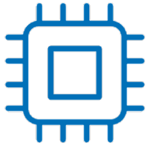
IoT Power Consumption

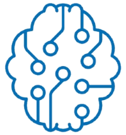




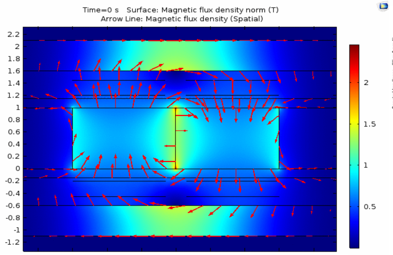
ULN/ULP Accelerometers



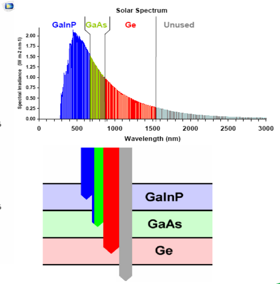
Ultra Low Power Microprocessors

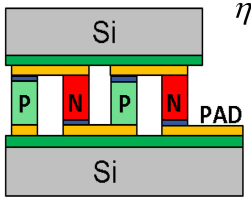


Neural Accelerator



$$P = \frac{m\zeta_e A^2}{4\omega(\zeta_e + \zeta_m)^2}$$

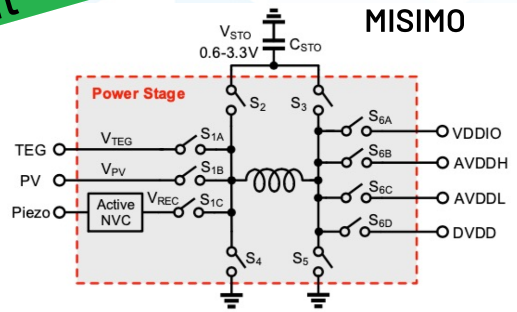




$$\eta_{\max} = \frac{\Delta T}{T_{hot}} \frac{\sqrt{1+Z\bar{T}} - 1}{\sqrt{1+Z\bar{T}} + \frac{T_{cold}}{T_{hot}}}$$

Harvest Power Output

$$P_{earth} = \frac{4\pi R_{sun}^{\ 2} \sigma T^4}{4\pi D_{sun-earth}^{\ 2}} \approx 1367(W/m^2)$$



***S. Li, et al, ISSCC 2022**

Sustainable IoT

ADI Chip-Scale Thermoelectric Generator (μTEG)

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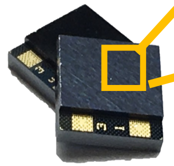
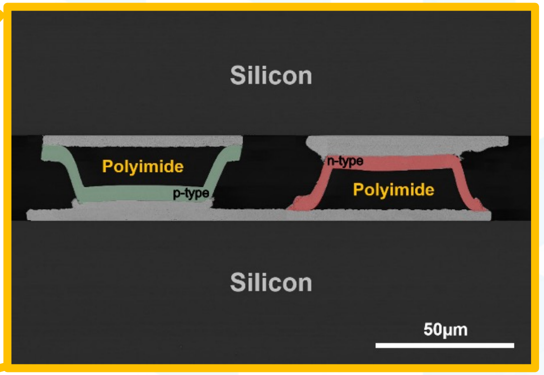
- **Leveraging ADI manufacturing and processing know-how to build high-performance, low-cost devices**
  - **Target: *400μW* from *ΔT=10°C***
- **Compared with typical bulk solutions:**

vs



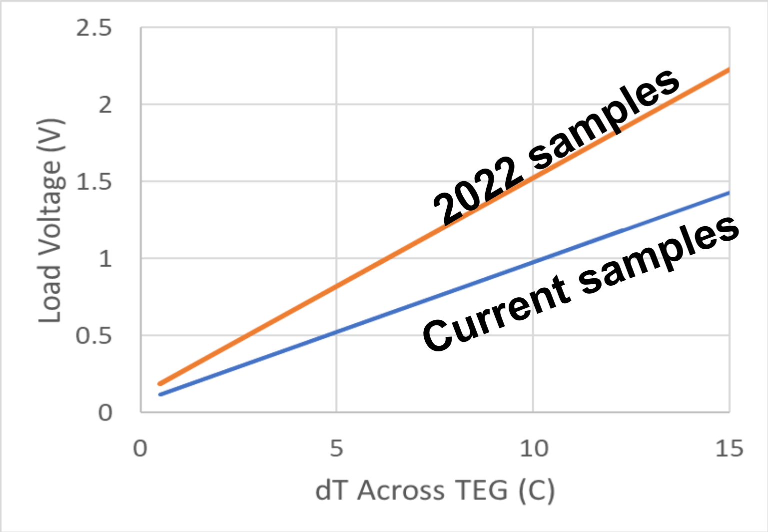


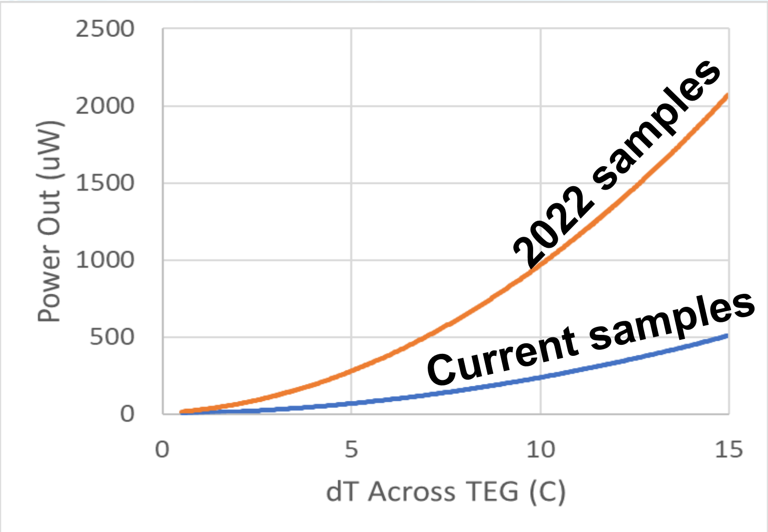
ANALOG DEVICES **TEG**

- *Based on novel device architecture*
- *TE materials (**Bi_2Te_3-based**) deposited along polyimide slope*
- *Long leg length, large thermal resistance*

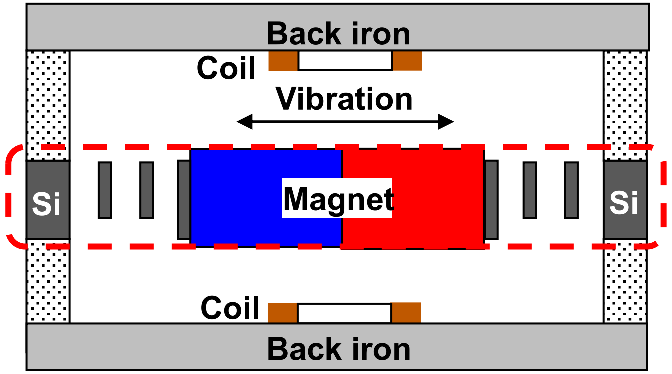
- **Small device area (*10mm²*)**
- **Higher output voltage:**
  - ***Maximize efficiency* of power management**
- **Higher thermal impedance:**
  - ***Optimize* ΔT captured**
  - ***Minimize* size of heat sink**
  - ***Maximize* power output**

Current TEG Performance

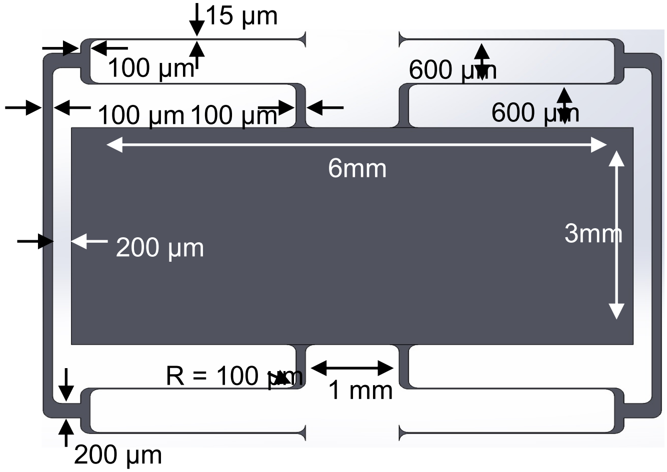




MEMS EM Vibrational Energy Harvester Prototype Achieved 165µW with 0.4g



EH cross-sectional view



Silicon structure

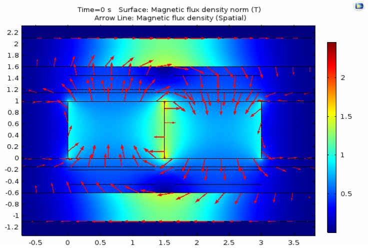
Mech. Domain

$$m\ddot{x} + c\dot{x} + kx + BLI = F\sin\omega t$$

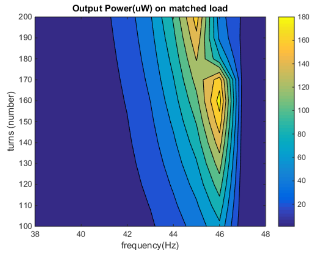
Elec. Domain

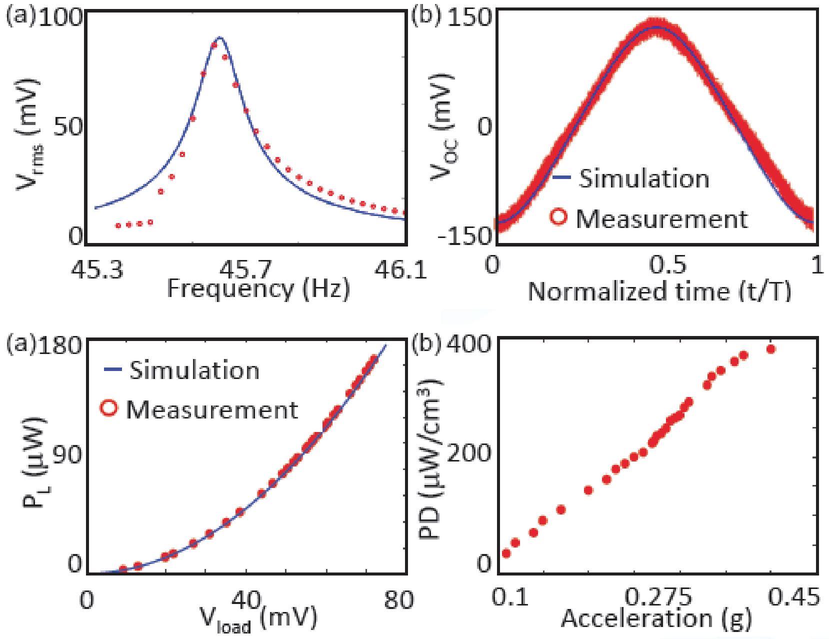
$$BL\dot{x} = I * (R_{coil} + R_{Load})$$

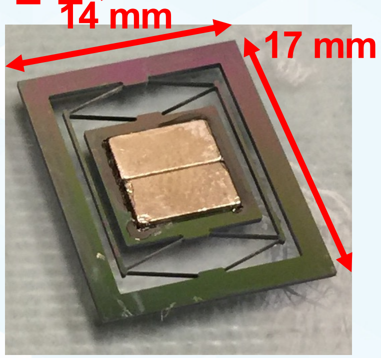
Silicon wafer



Simulated power (uW)

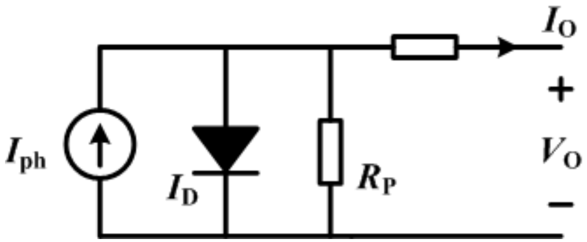


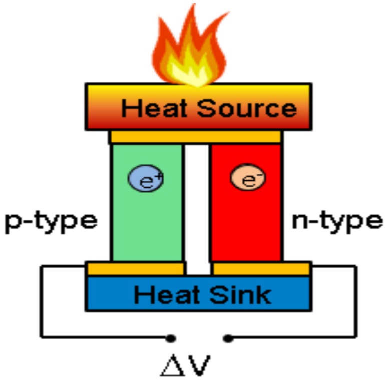


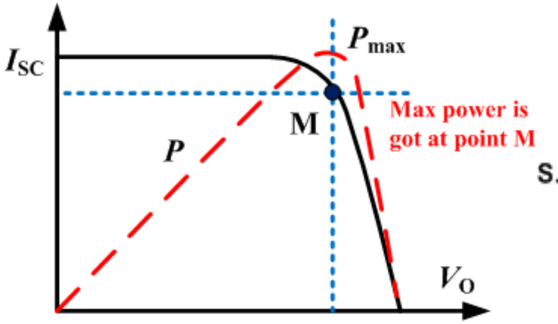


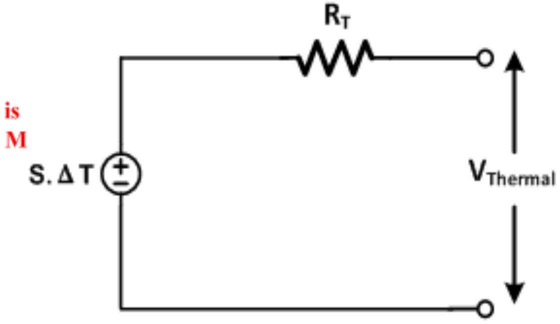
	Achieved	Target
Size	14 mm X17 mm	5 mm X 5 mm
Thickness	3.3mm	1 mm
Power	165 µW	100 µW
Freq.	45.7 Hz	~50 Hz
Bandwidth	±5%	±5%
Vib. amplitude	0.4g	0.05-1g

Maximum Power Extraction from Energy Harvesters

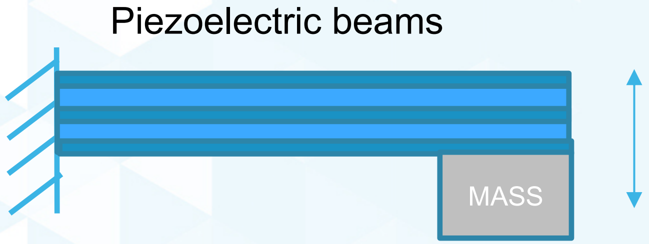


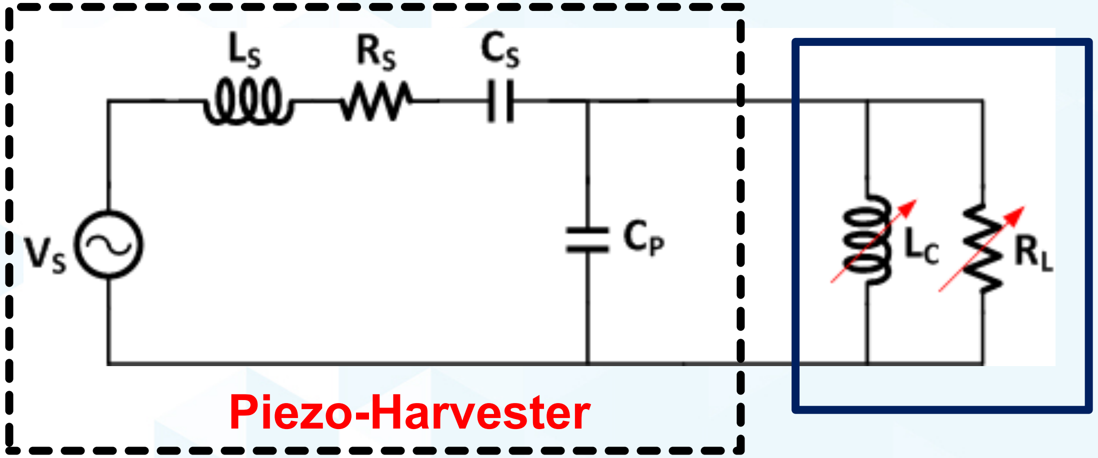






Thermoelectric Harvester





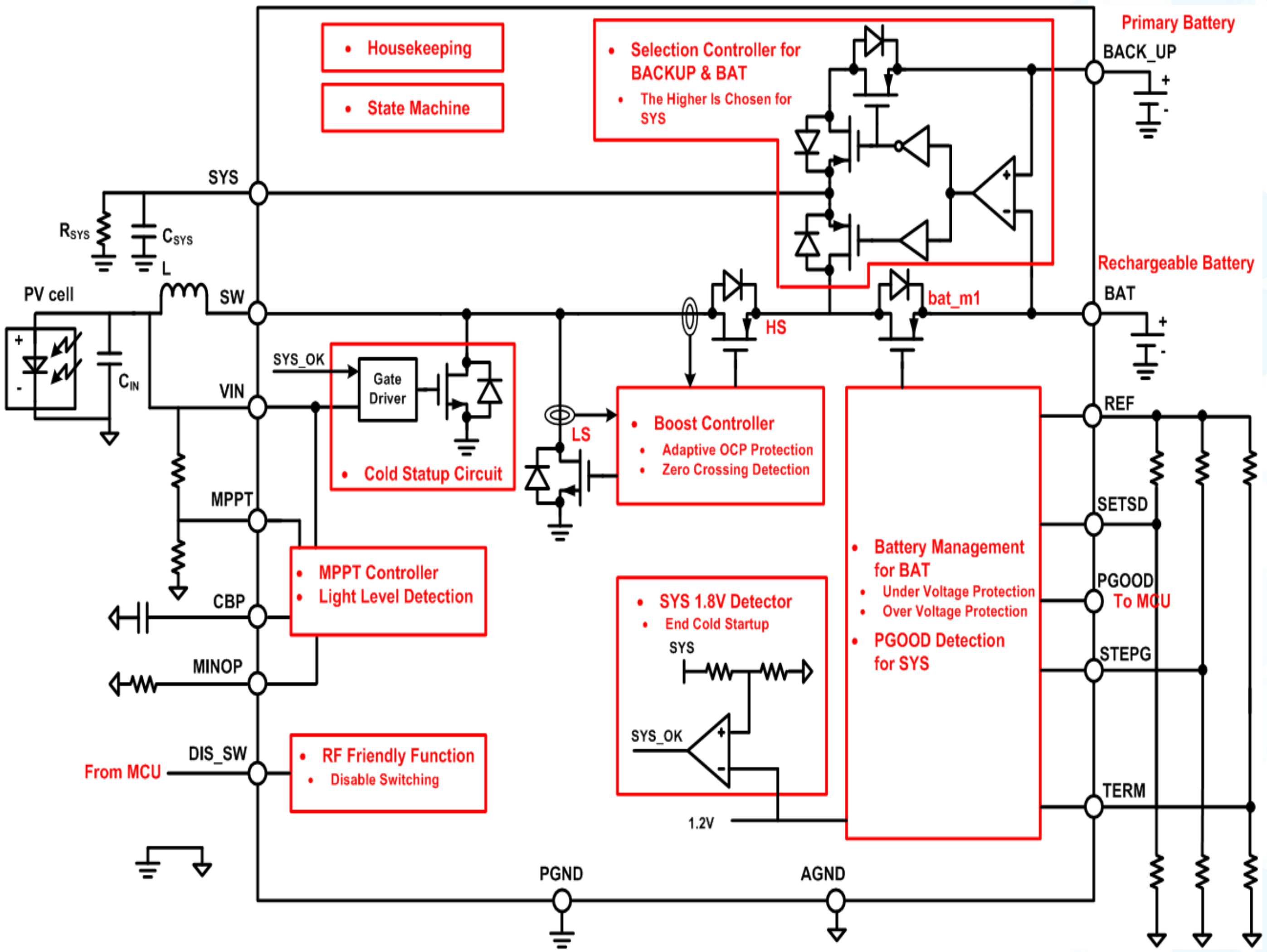
Electric Load

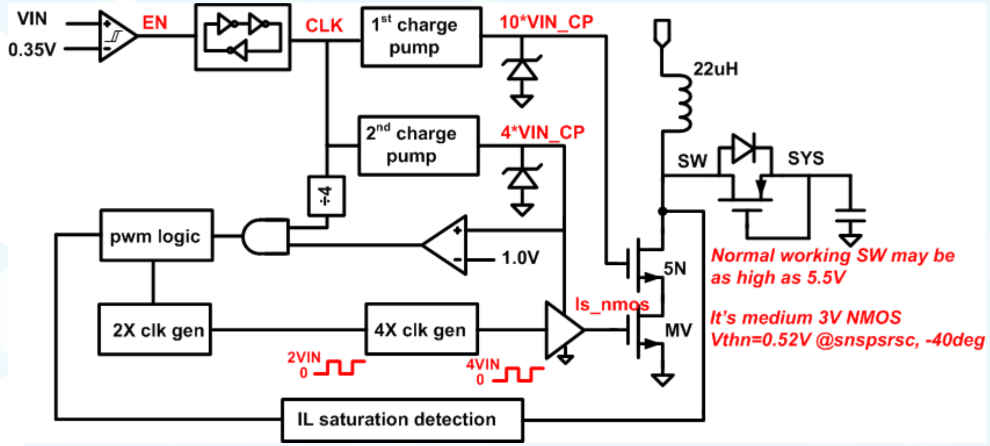
Maximum Power Point Tracking (MPPT)

Load Resistive Matching

Complex Conjugate Matching

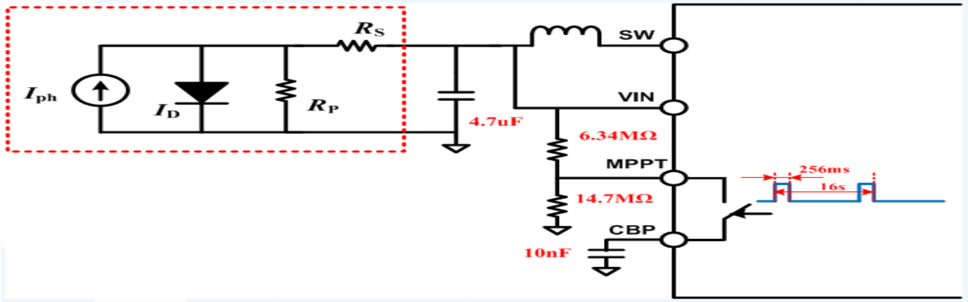
EH Boost Converter with MPPT (ADP5090)





Startup Circuit

- 5V cascode to protect 3V MV switch
- 1st charge pump not loaded down by GD oscillator



OCV Sense Implementation (FOC=0.8)

Chip-Scale Supercapacitor

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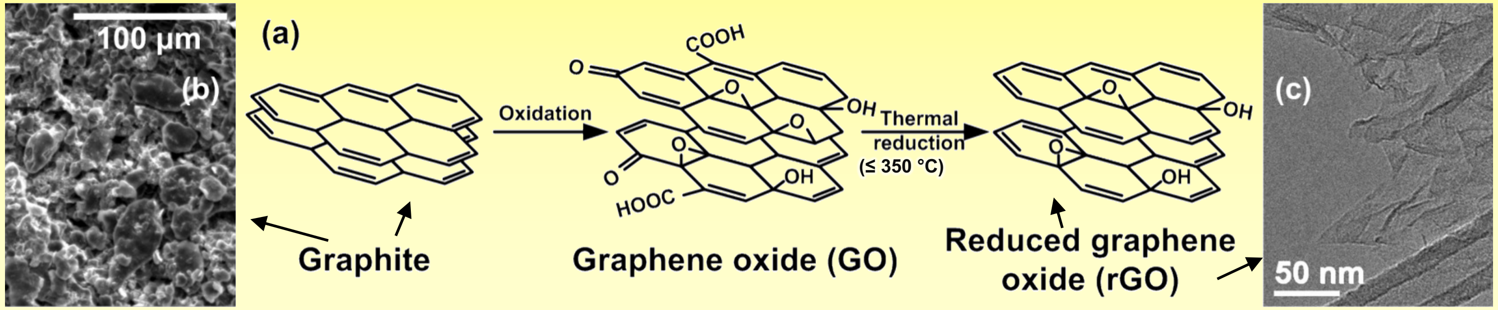
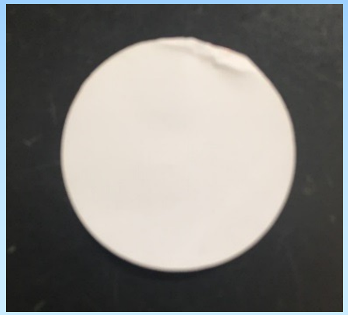
Graphene-Based Electrode

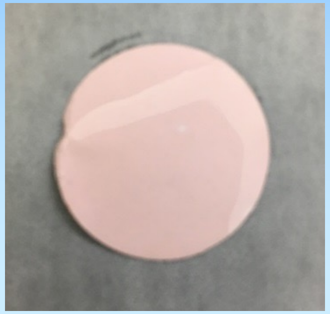


Dual-Functional Electrolyte

(1) Polymer + (2) nanopowders as the mechanical separator between electrodes.



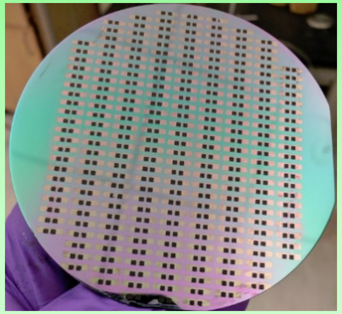
Spin-coating
→
ionic liquid

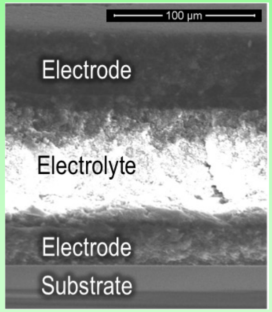


Plus (3) ionic liquid (nonflammable) to form ionic conduction medium, with high conductivity and safety.

Wafer-Level Fabrication

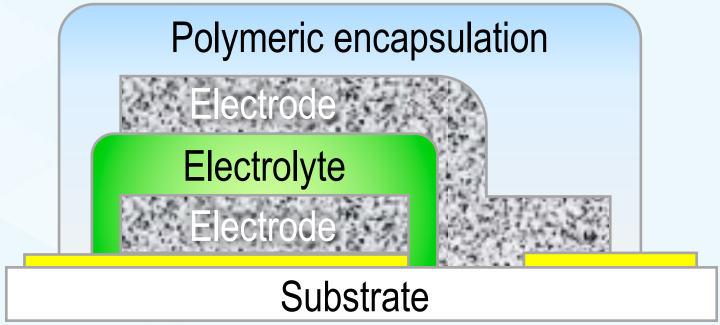
Screen printing system





Chip-scale prototype

Target Spec	
Size	5 mm X 5 mm
Thickness	0.1 mm
Nominal voltage	2.7 V
ESR	1 Ω
Capacitance	25 mF
Energy density	2 mWh/cm^3
Power density	146 W/cm^3
Cycle life	> 100k
Leakage current	1 µA/F



Sensing Technologies at ADI – Inertial MEMS

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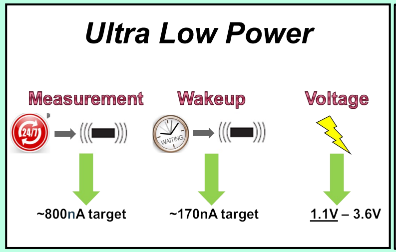
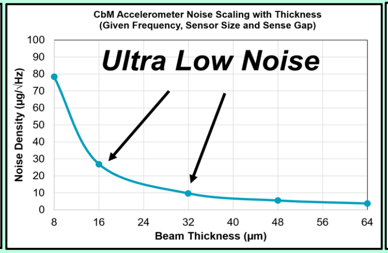
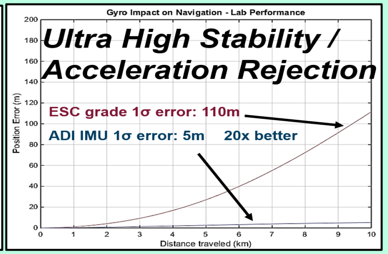
Autonomous Auto | Industrial | ADEF | Techsumer | Healthcare

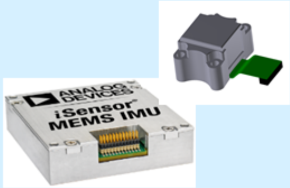




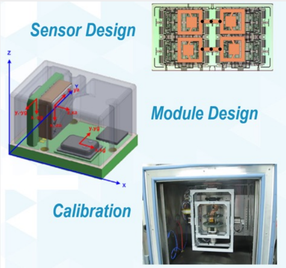


Position | Condition | Recognition

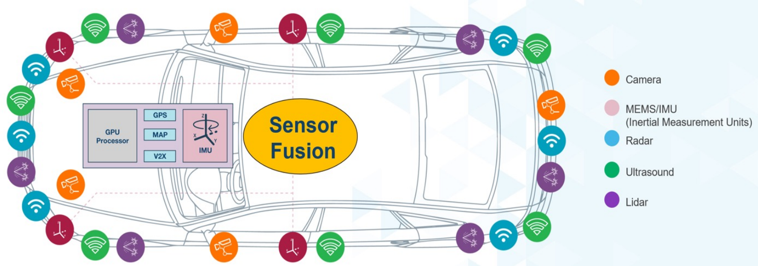
Sub-Systems



Application Specific Design/Quality/Mfg
Low-Level Sensor Fusion Algorithms
Precision Test and Calibration
Safety Critical Processes



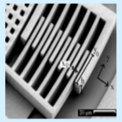
IMU Products



Sensor Fusion Algorithms

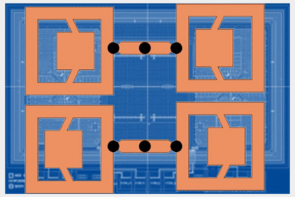
repeatability | stability | bandwidth | noise | power

Technology and Innovation Leadership



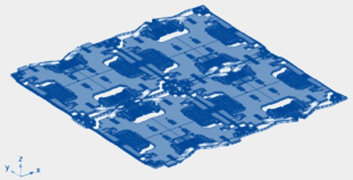
Leaders in Safety ,ULP, ULN & Stability
Innovation : Angular XL

Optimized Sensor Conditioning and Processing



ULN/ULP Accelerometers

2-3 Axis Gyro

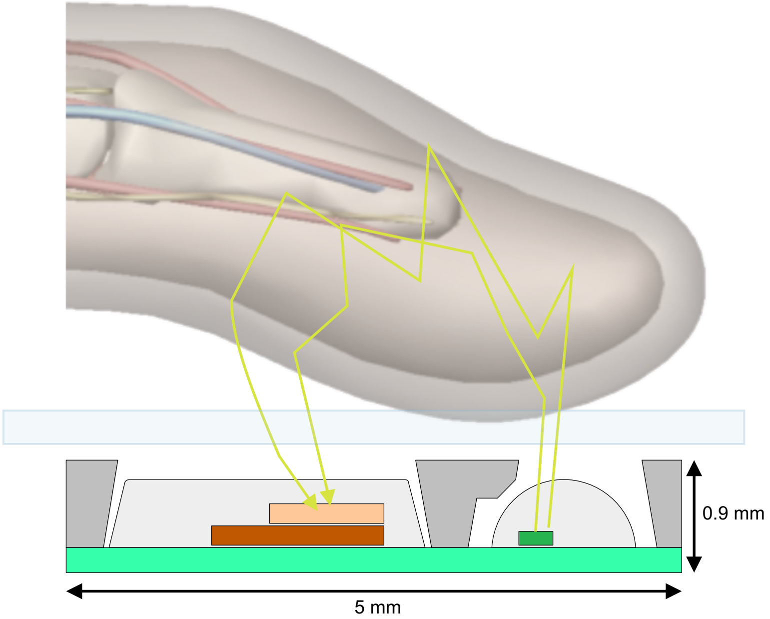


Single Axis Gyro

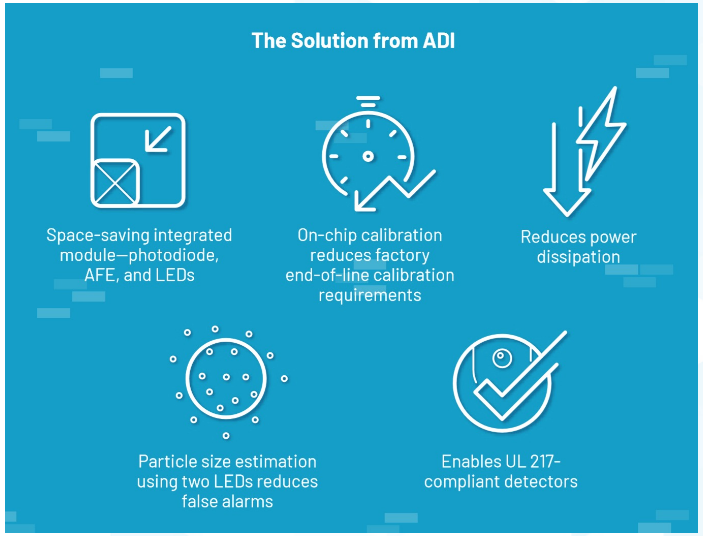
Sensing Technologies at ADI - Optical

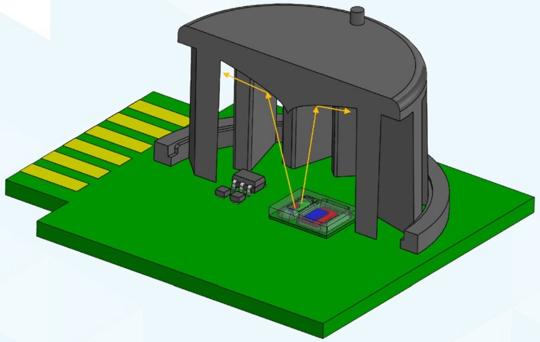
Chamber

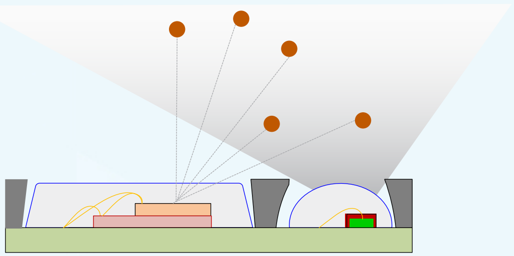
PPG and SpO_2



- Finger or wrist or hearable
- PPG and/or SpO_2
- Immune to ambient light/EMI







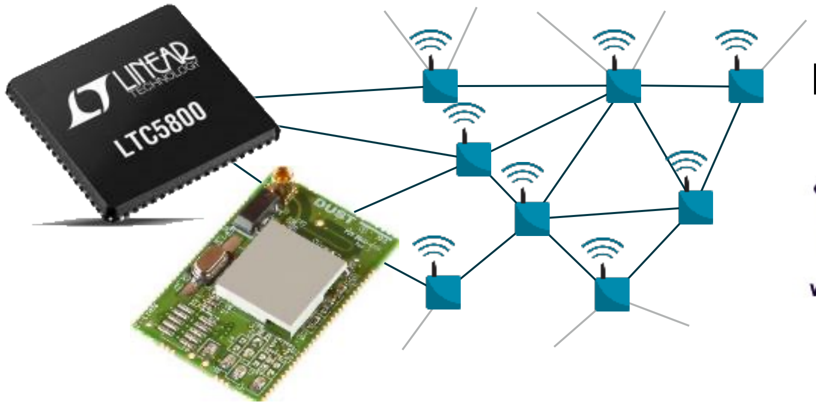
- Smoke detector
- Proprietary photodiodes
- Advanced packaging

ADI SmartMesh IP Wireless Mesh Networking Protocol Solution

- 2.4 GHz multihop wireless mesh networking solution
- Established industrial grade solution
- Complete wireless networking solution

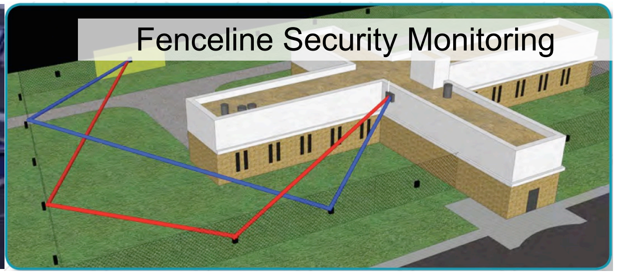
Key Benefits

- **Ultralow power consumption** delivering >10 year battery life
- **High reliability**, robustness, and immunity to interference
- **Scalability** for networks to work in different configurations



IEEE802.15.4e

6LoWPAN
IPv6-based Low-power Wireless Personal Area Networks

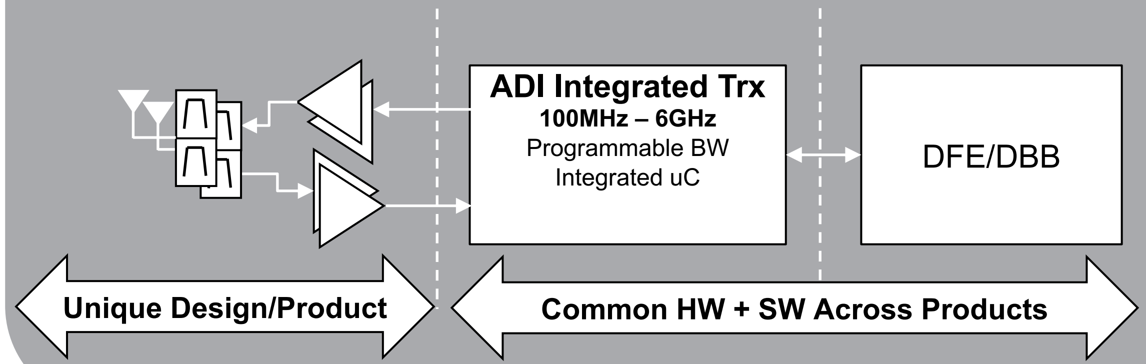


SmartMesh – wireless microchips and embedded PCBs complete with mesh networking software

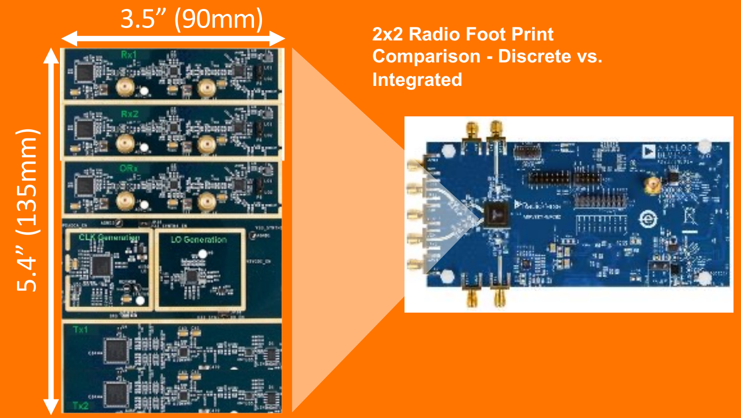
Wire-like reliability, Place Sensors Anywhere Without Wires

5G Technologies at ADI: RadioVerse™ Transceivers

Highly Reconfigurable
Enables reduced time to market through common HW & SW
Small Signal Radio Platform

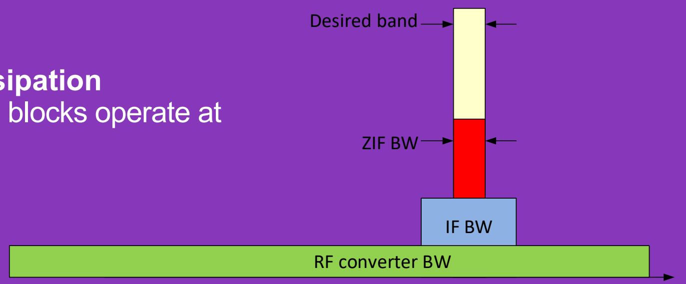


Highest Level of Integration
Enables higher density radio architectures e.g. M-MIMO



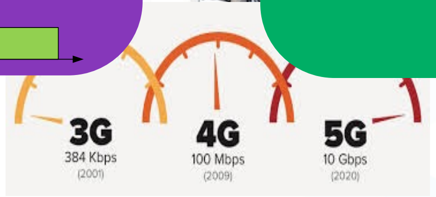
Lowest Power Consumption
Reduce thermal density, enable lower SWAP radios

Lowest possible power dissipation
- Highest power consumption blocks operate at minimum bandwidth

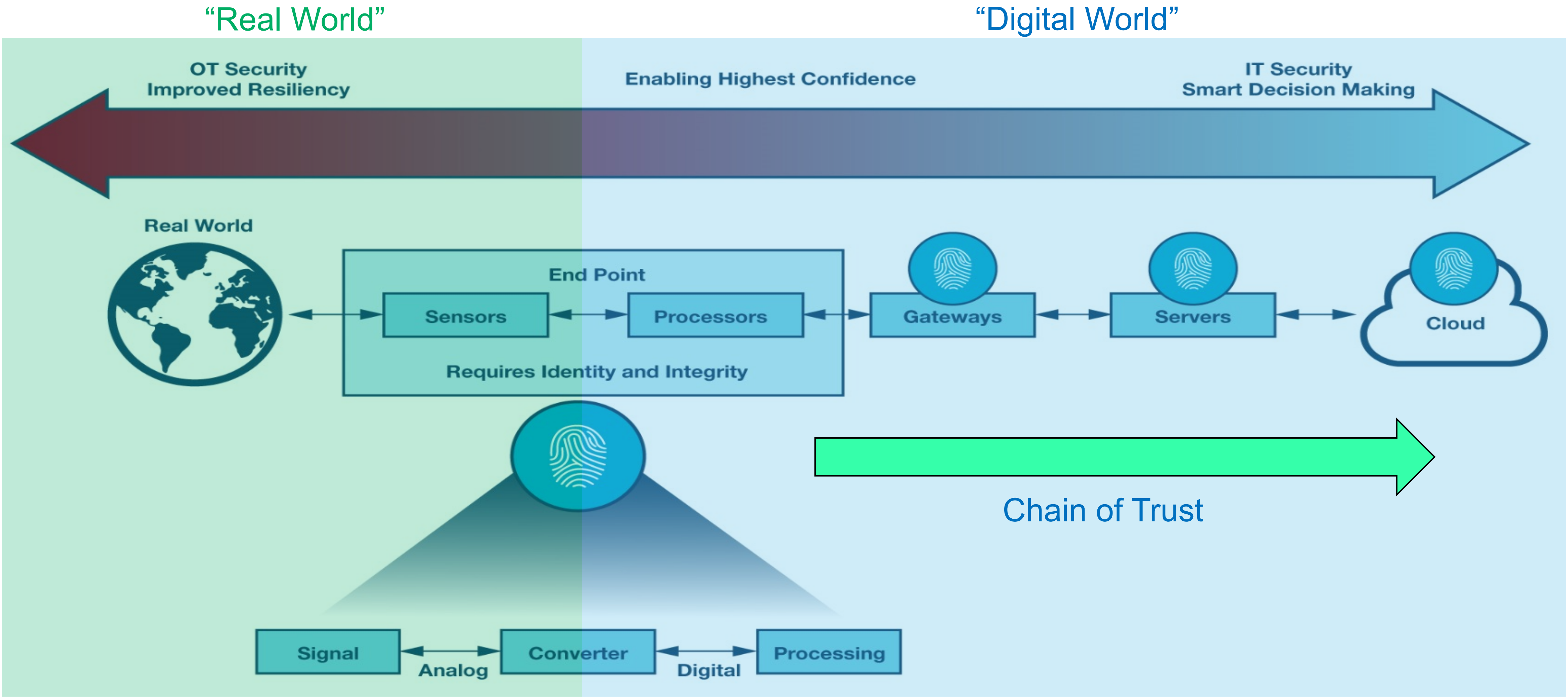


Lowest System Cost

Re-use of architecture used in handsets
- Components such as IF filters are eliminated
- RF filters are simplified enabled by the elimination of out-of-band images or aliases



ADI Securing Data at the Edge: Hardware as Root of Trust



Smart Factory : Machine Health Monitoring

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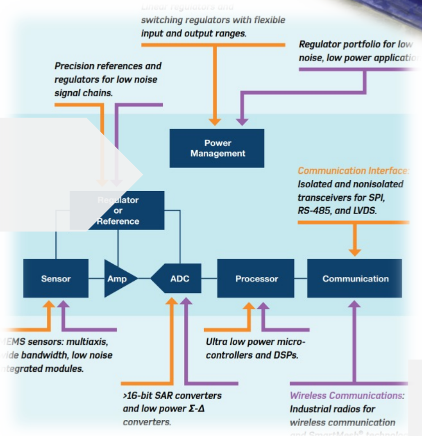
PdM helps on Factory up time

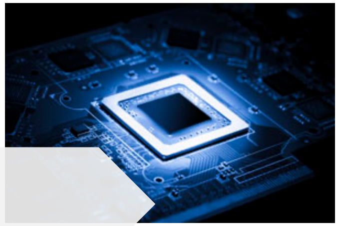
SENSE

- Wide Bandwidth
- Wide Measurement Range
- Low Noise
- Stability over Temp & Life
- Multi-axis
- Small Form Factor

MEASURE

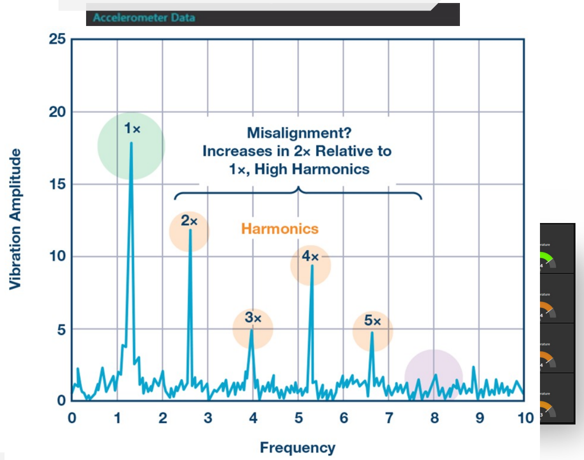


INTERPRET

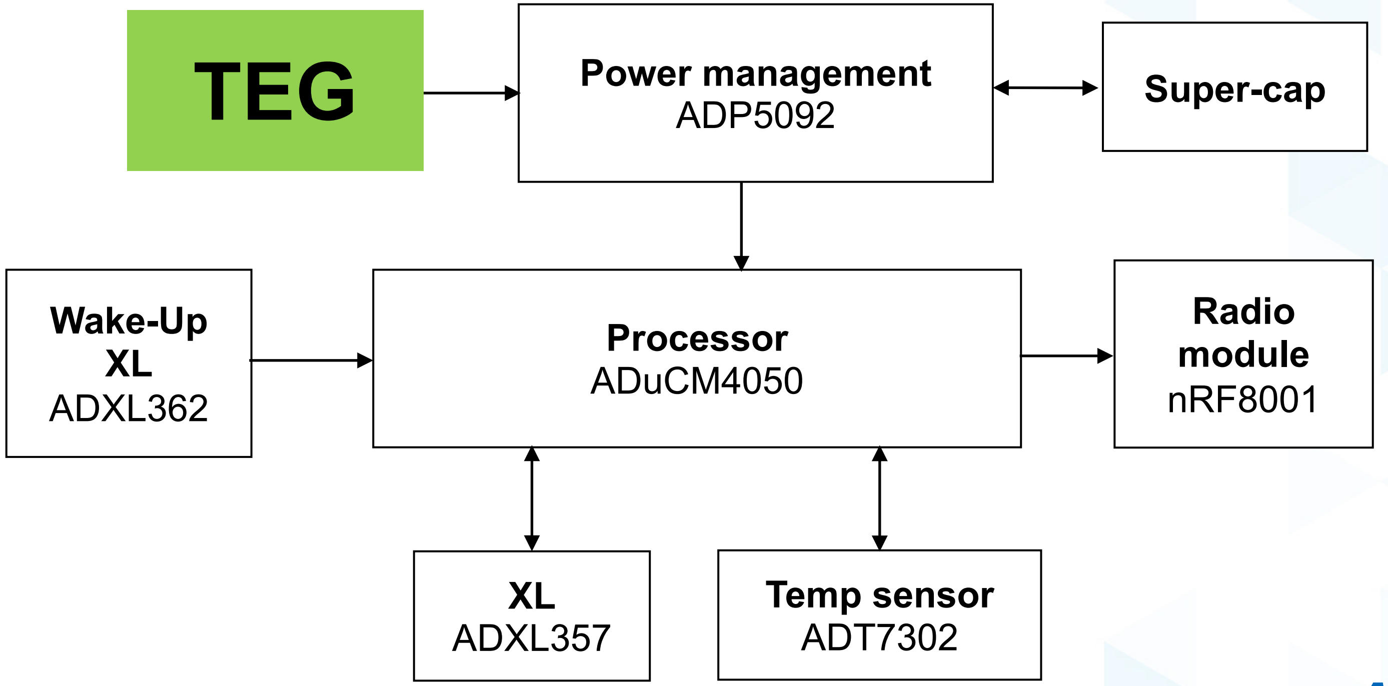


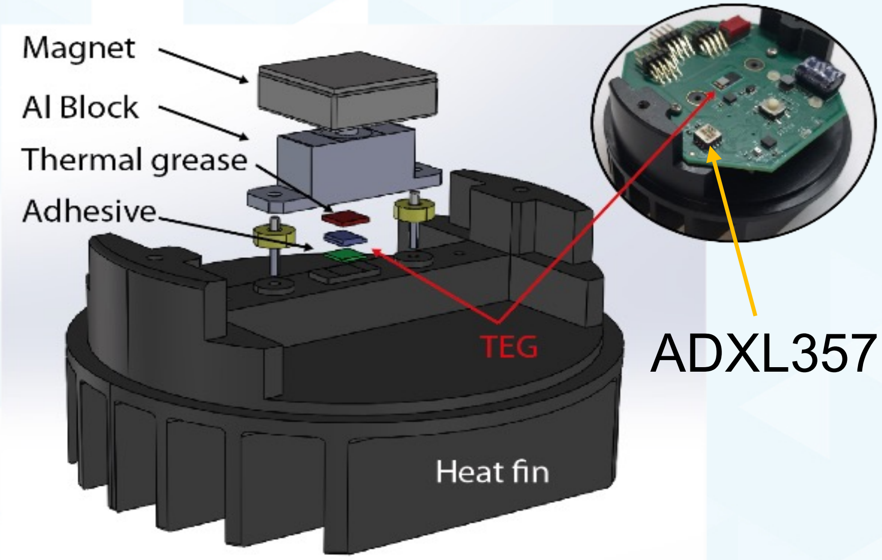
CONNECT

ANALYZE



µTEG-powered CbM Sensor Node





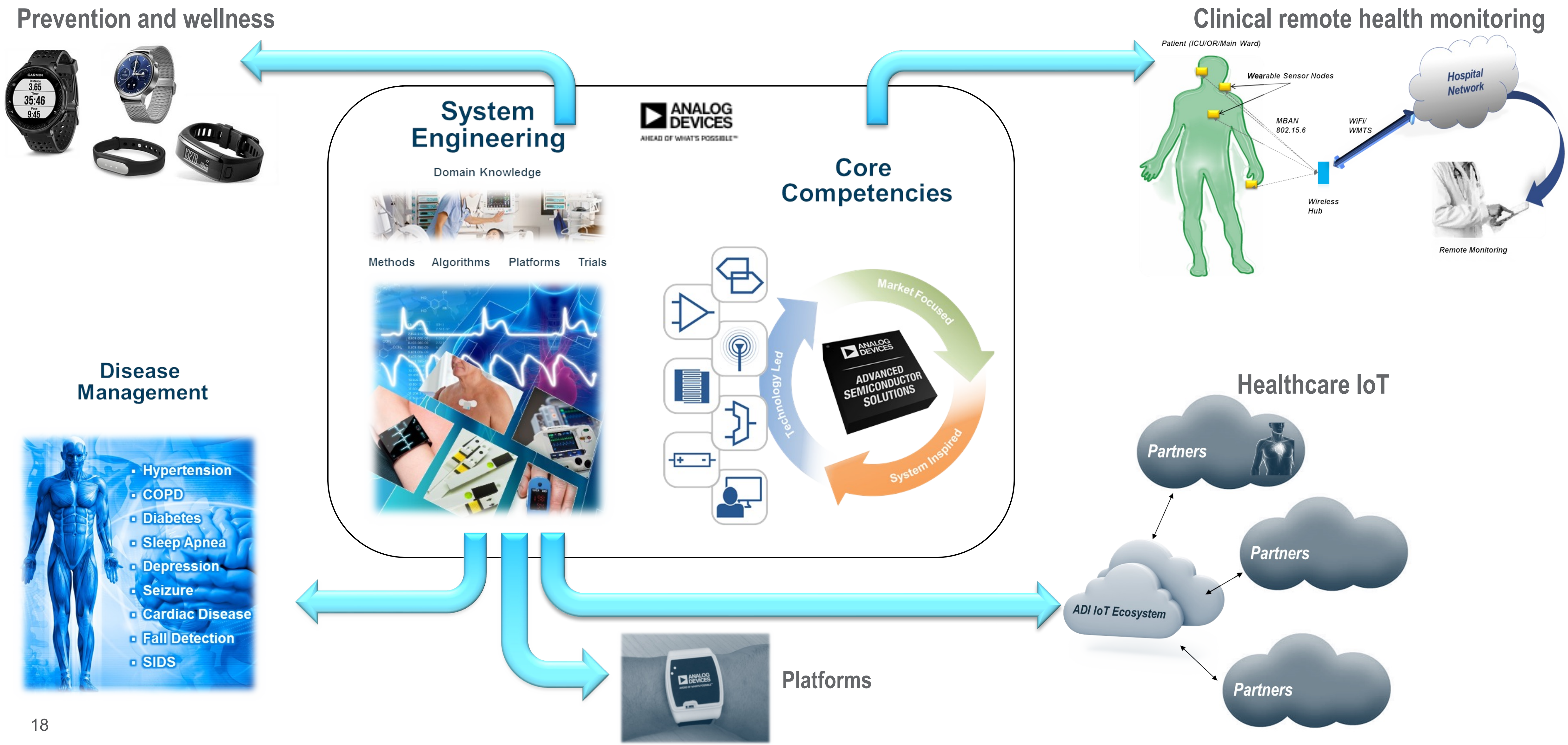
ANALOG DEVICES Technology

- ***Sensors:*** **Ultra-low power XL and temp sensing technology**
- ***uC:*** **4 programmable active and sleep modes, SPI, I²C and UART interfaces**
- ***PMU:*** **Ultra-low power, with MPPT and charge management**

Average Power Consumption (µW)

Update rate	**nRF8001** *BLE*	**ADuCM4050** *uC*	**ADXL357** *XL*	**Total**	**dT**
10 sec	220	247	23	**490**	**15ºC**
30 min	4.6	1.6	0.06	**6.2**	**<1ºC**

Smart Health: Vital Signs Monitoring



TEG Body Worn Integration

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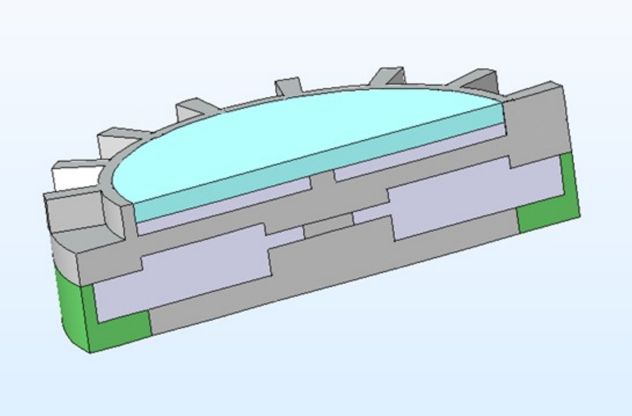
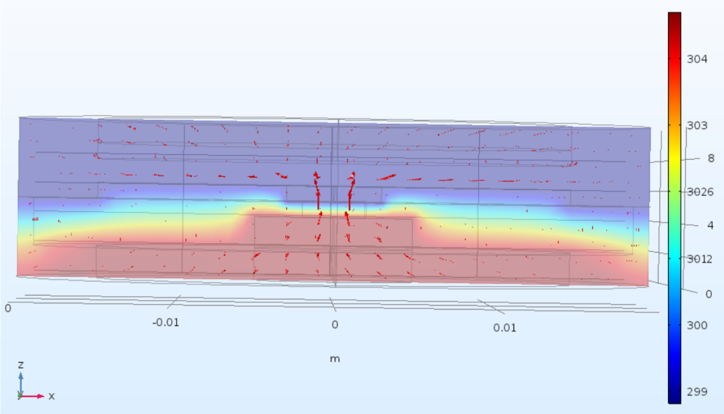
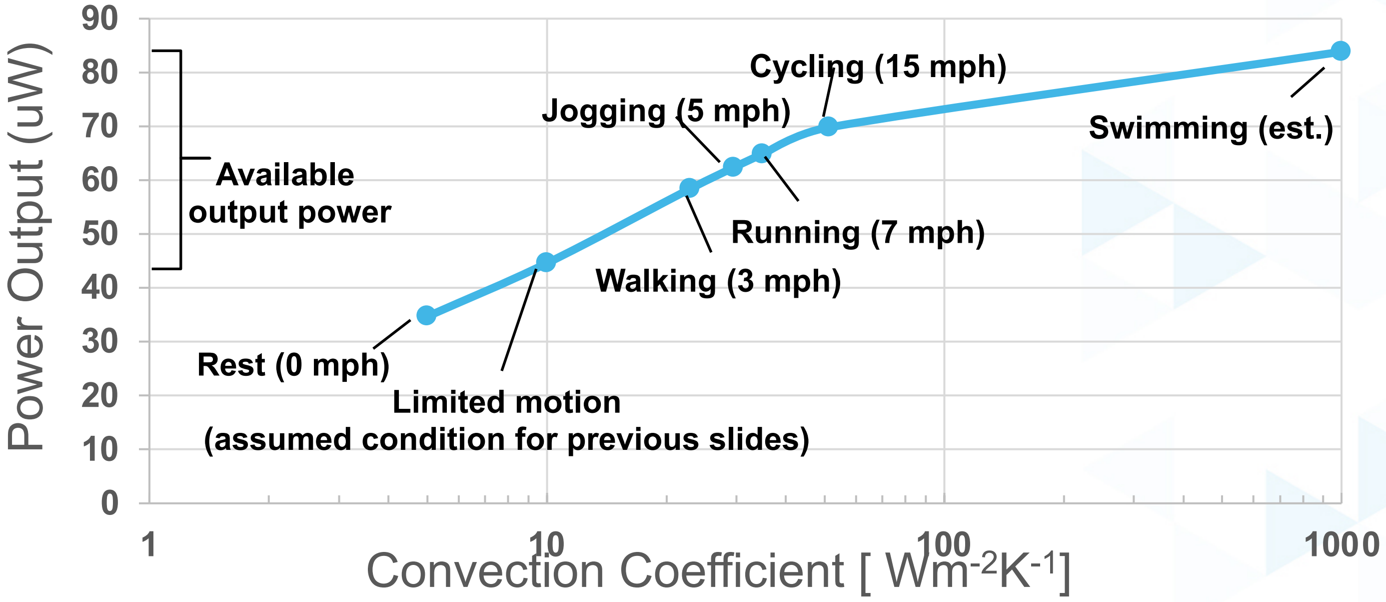
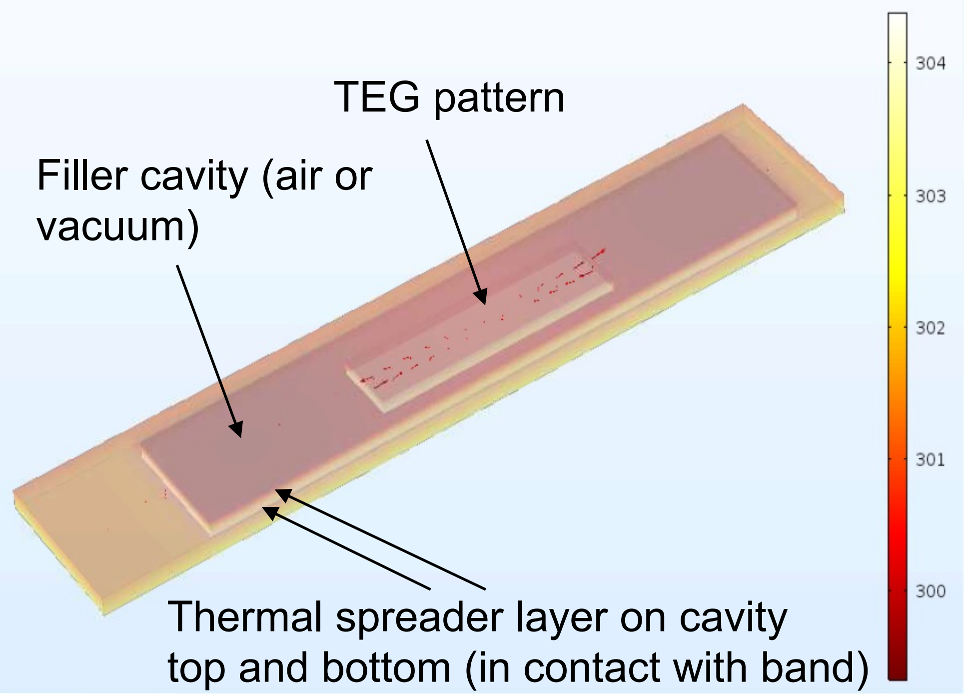
Watch-Body Integration

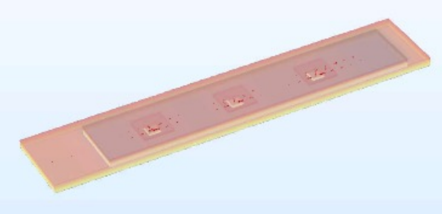






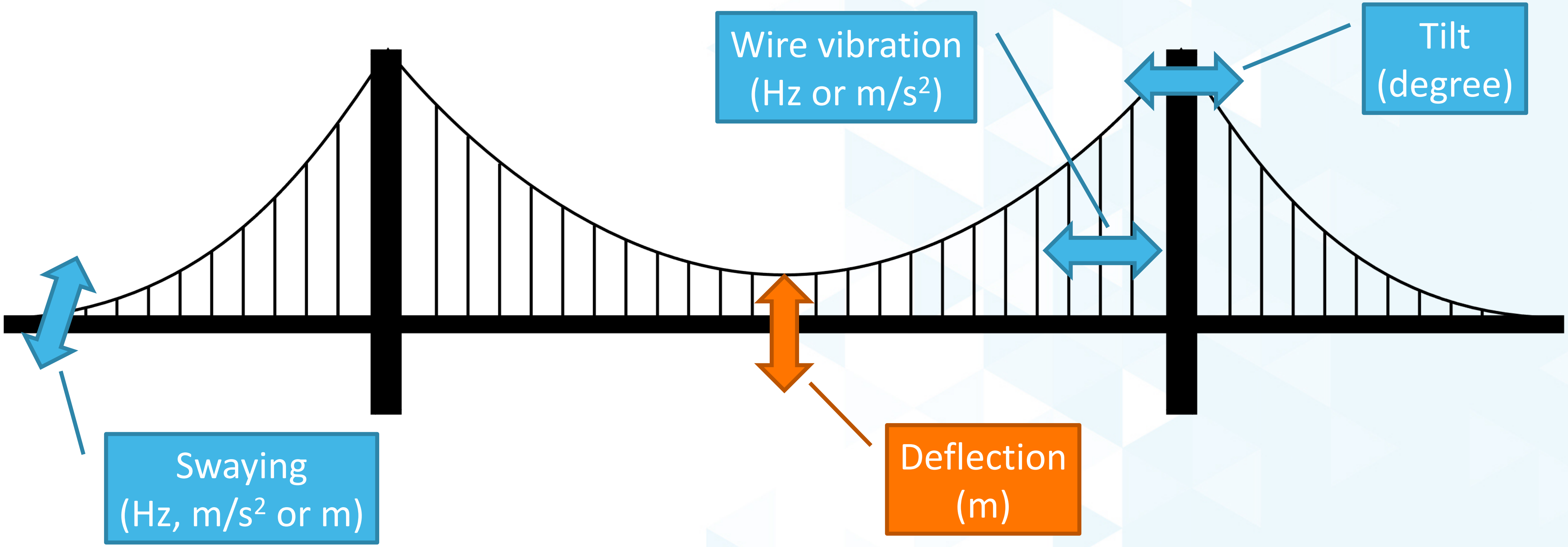
Watch Band Integration



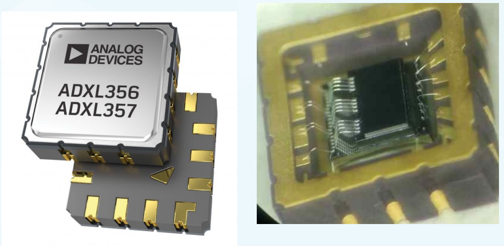


6 chip-scale TEG die per 20cm²->270µW

Smart Infrastructure



- **Best in class, industry leading low noise, low drift, low power 3-Axis Accelerometer**
- FSR: ±8g; Noise density: <25µ*g*/√Hz (XY axis 10µ*g*√Hz)
- Stability: <3mg on XY, < 9mg on Z (over 10yrs)

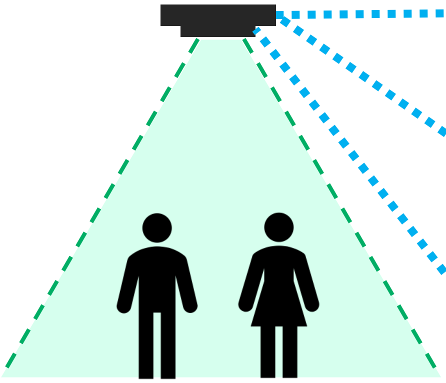


ADXL355

PdM is essential to prevent diaster

Smart City – Example of Remote Occupancy Sensing

ADI EagleEye™



ADI

Insights

- Customer dashboard
- Identity management
- Device management

Deployment Device

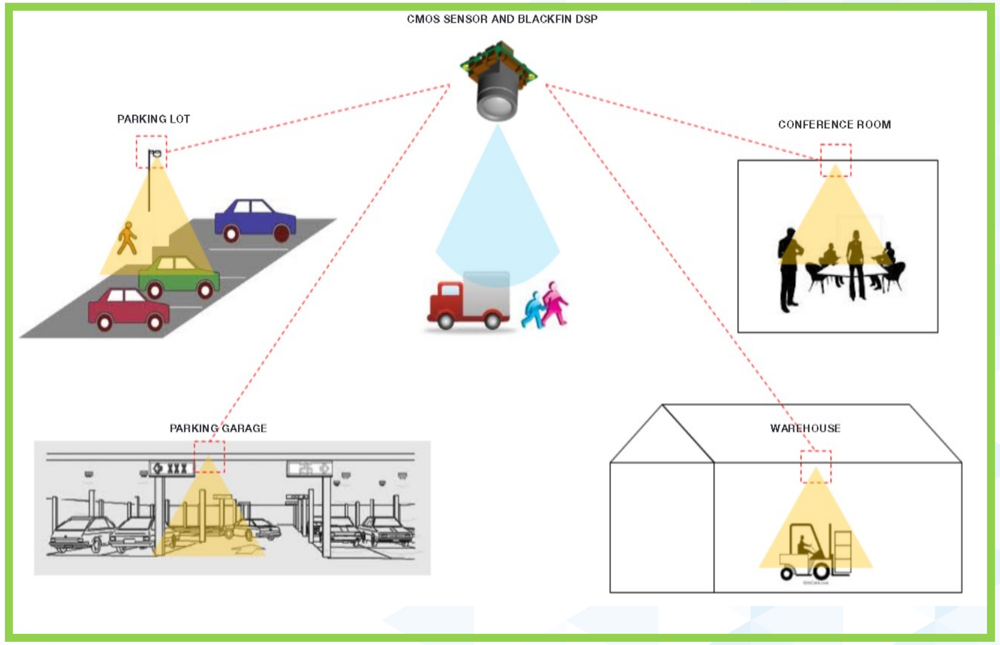
- Secure commissioning
- Secure provisioning
- Rich UX

USB 2.0

Advanced Troubleshooting

ADI EagleEye^{TM} Device

- Image processing at the edge
- Privacy ensured
- Feature based licensing*
- Diagnostics and algorithm OTA



ADI 3D Depth Sensing Enables Precision People Counting

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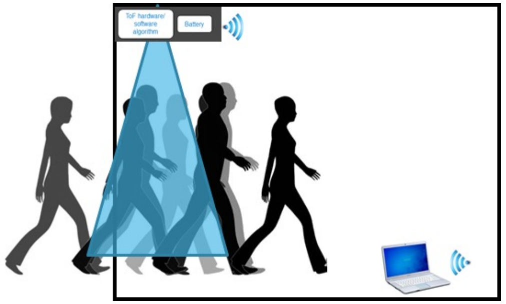
Photographed Image   Distance Image

Far   Near

High Resolution and Depth Accuracy

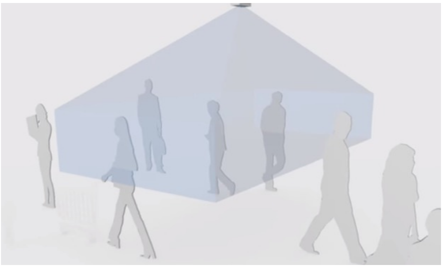
Operates in Strong Light/ No Light

Highly Integrated, Small Form Factor



Precise People Tracking/Counting

Facility Management Building Entry/Exit Count

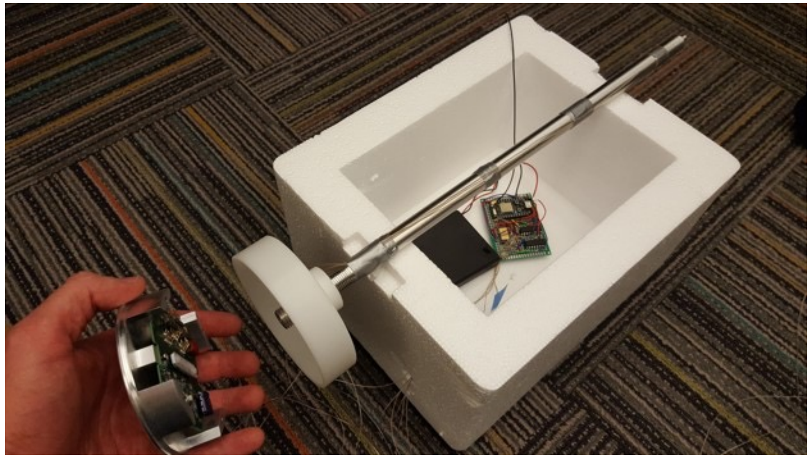


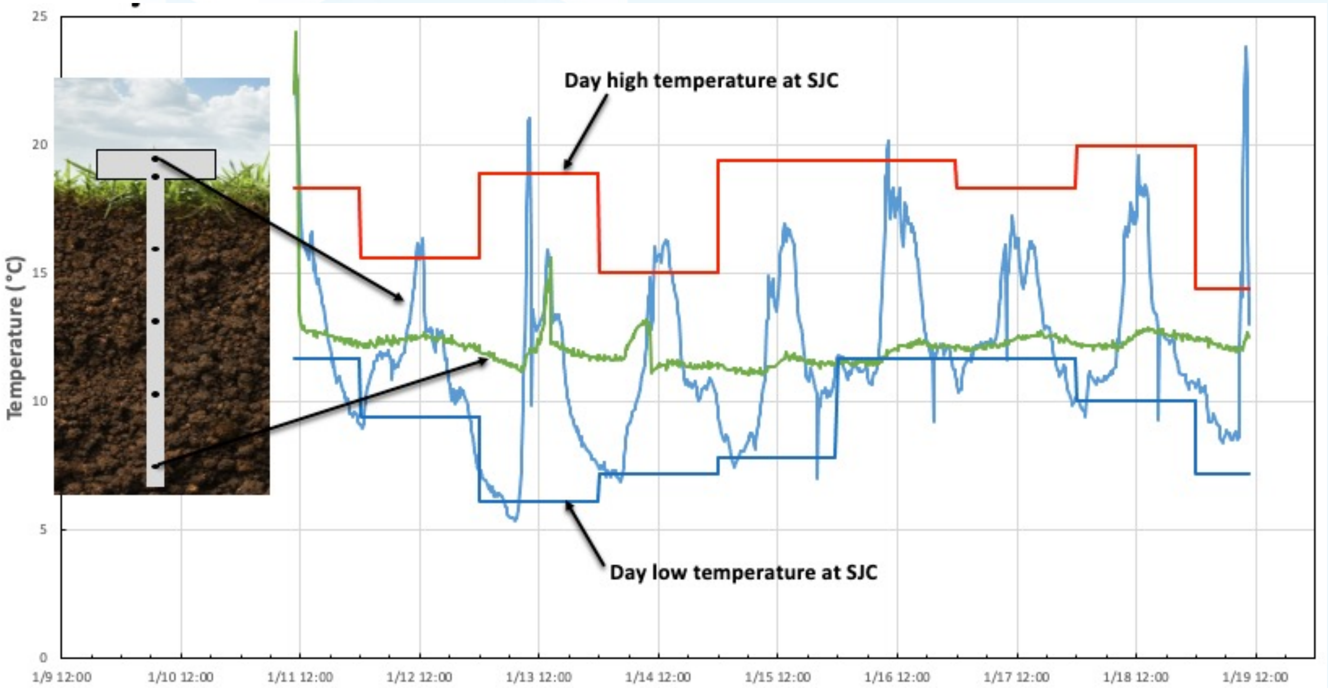
People Classification

Indoor and Outdoor Commercial Space Management

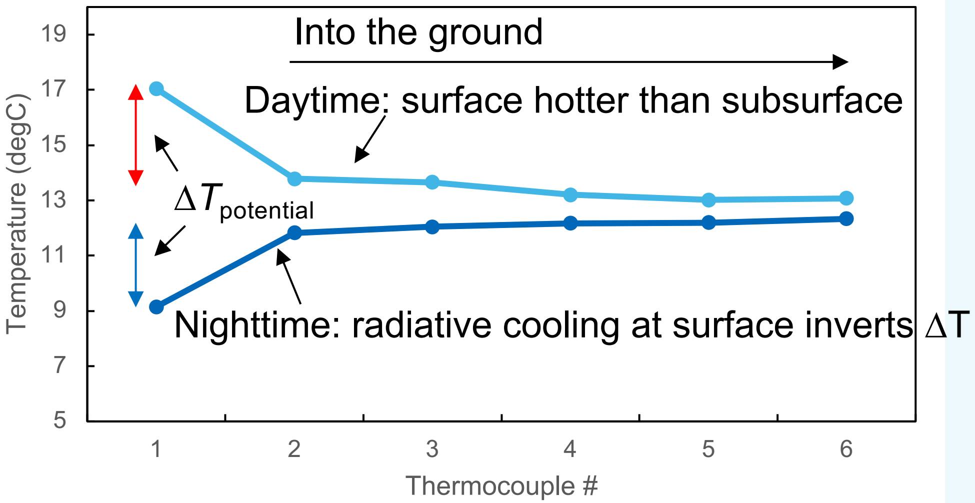
- *Offices*
- *Halls*
- *Outdoor Areas*
- *Automatic Door Opening*

Smart Agriculture: Thermal Ground Spike





Embedded in ground for testing



7-Day Totals
Daytime: 41 J → 68 μW (20% increase)
Nighttime: 34 J → 57 μW (60% increase) Day+Night → 125 μW

IoT Evolving to More Intelligence at the Node

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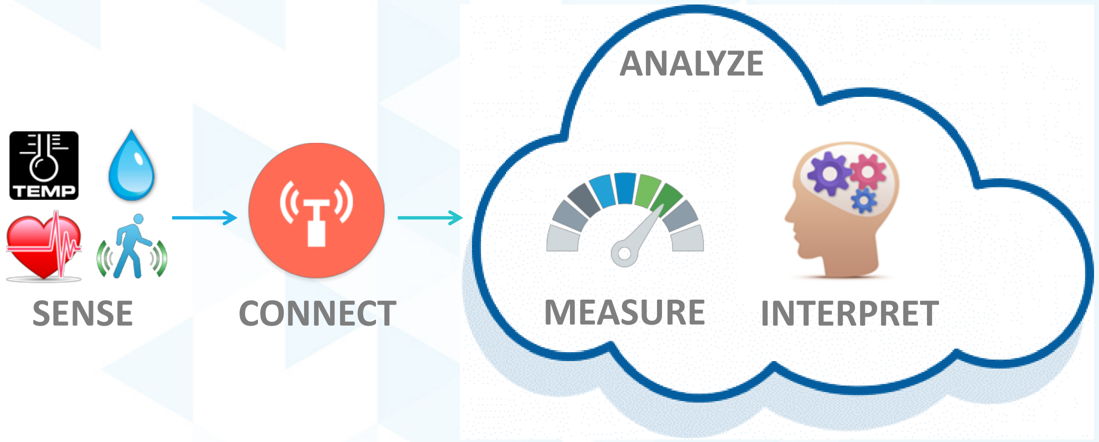
TODAY

- Data stays data: never generate wisdom and knowledge at the node
  - Power hungry and bandwidth intensive to convert and send all data



TOMORROW

- Intelligent "Smart" Sensing: node turns data into information
  - Lowers overall power consumption, enabling self-power, lowers latency, reduces bandwidth waste
  - More intelligence with AI and ML
  - Enables move from reactive IoT → predictive & real-time IoT

AI Accelerated Micros MAX78000/2

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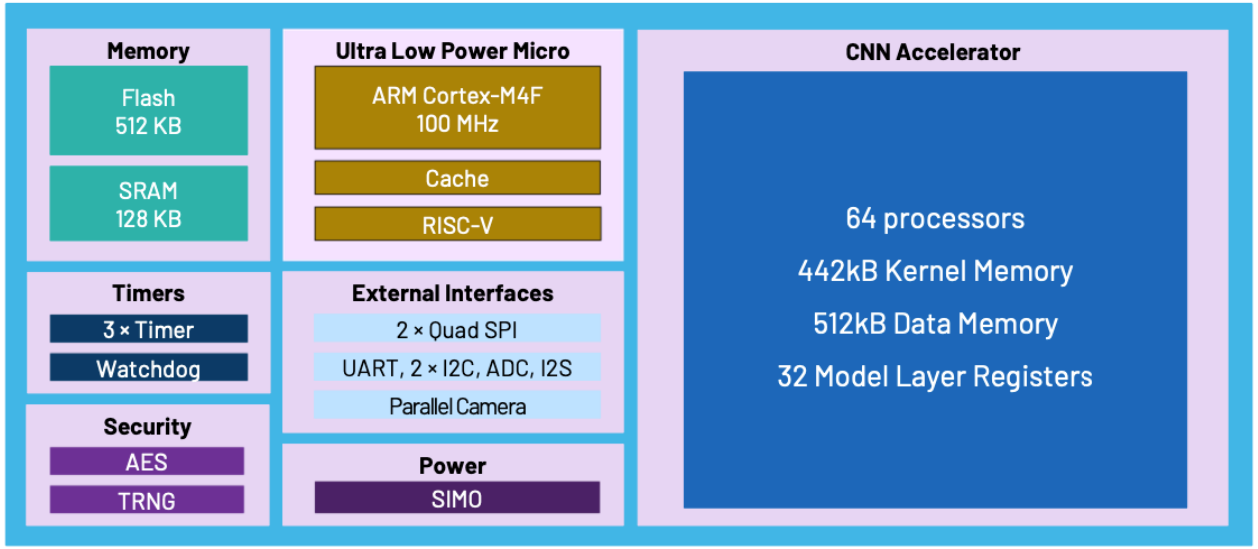

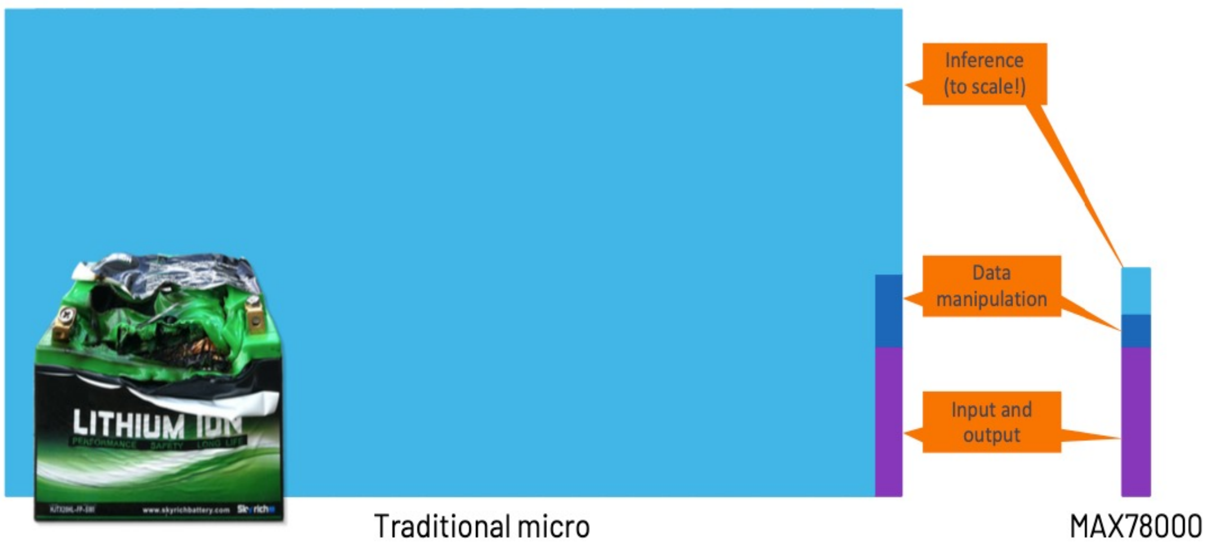

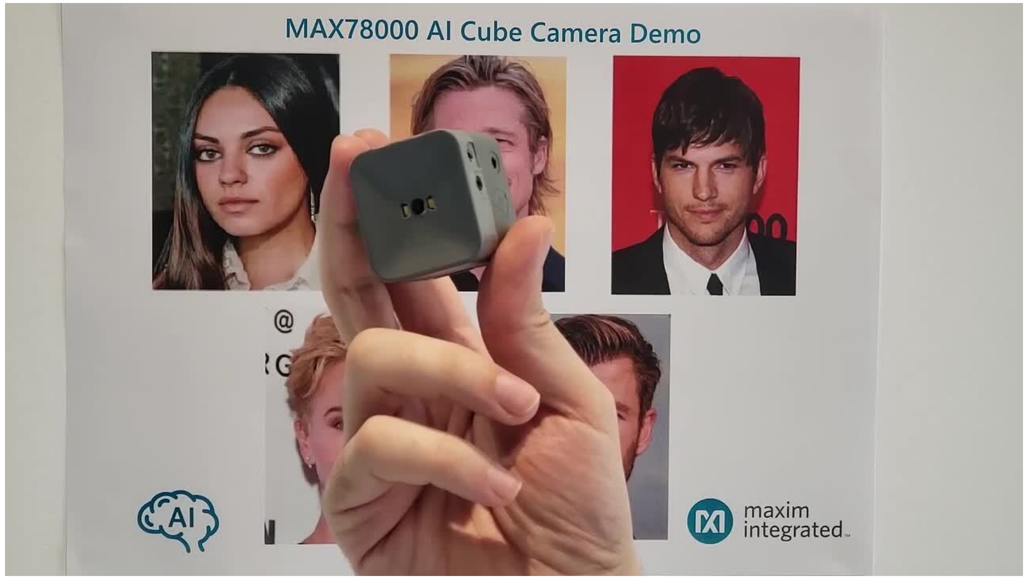

Platform	Energy per inference (mJ)	Battery Lifetime
Apollo3	1.31	80h00'
Spresense	8.09	16h45'
PULP	0.52	140h15'
xCORE.ai	1.26	81h50'
MAX78000	0.09	244h00'

*M. Magno et al, Tiny ML EMEA Technical Forum 2021

Energy Harvesting Enables Sustainable IoT

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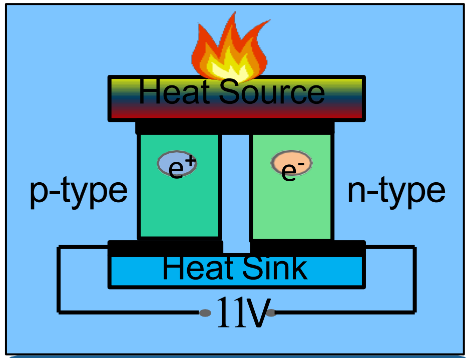
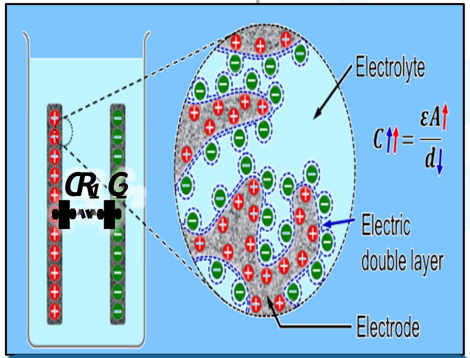
Technologies



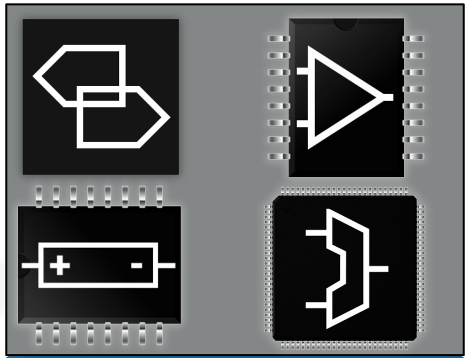
Energy Harvesting

Power Management



Storage

Sensing



Processing with AI

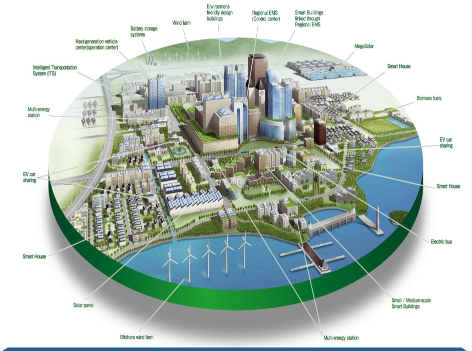
Network

Markets

Smart Factory

Smart Transportation

Smart Healthcare



Smart City/Agriculture

Q & A

Thanks very much for your time and attention!

Questions/comments???

- Acknowledgement of contribution from my collaborators including Jane Cornett and other members of ADI energy harvesting community