ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

# Development of Ultra Low-Power Self-Powered Systems

## Strategies for System Optimization

Michelle Farrington, Paul Perrault – Analog Devices Inc.

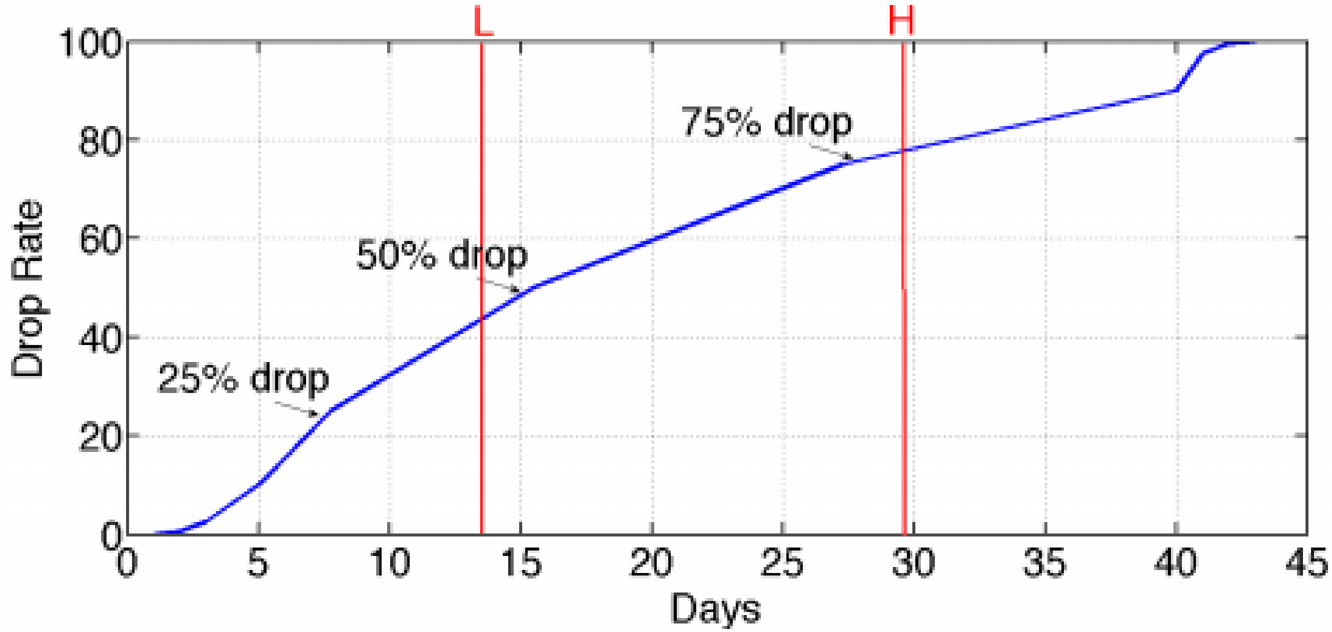
# Agenda

- The Case for Self-Powered Systems
- State of Energy Harvesting Today
- The Energy Balance Equation
  - Machine Health Monitor Use Case
  - Body Worn Use Case
- Sensor Communication Issues
- The Path Ahead

ENERGY HARVESTING BRINGS SELF-POWERED SYSTEMS TO IoT APPLICATIONS

… **BRINGING SENSORS TO PLACES PREVIOUSLY THOUGHT IMPRACTICAL**

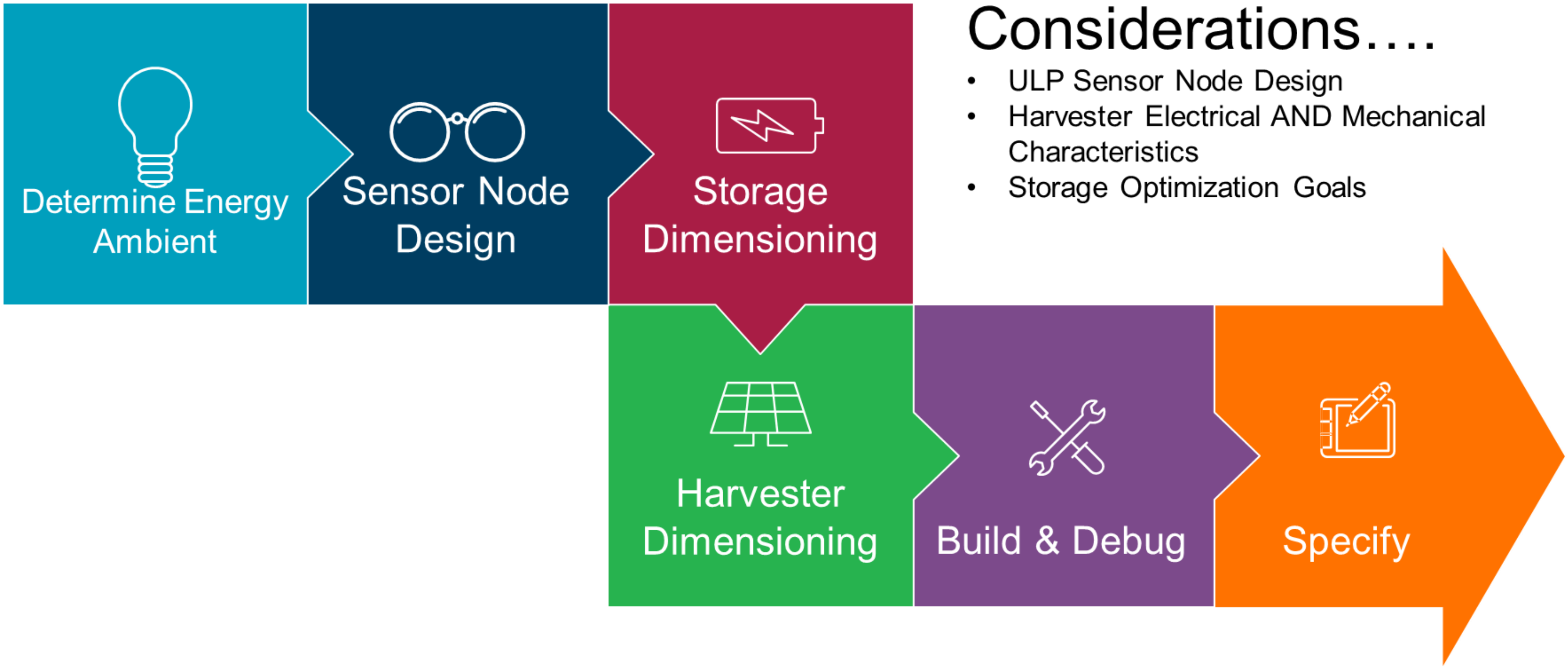
# Why EH?




- **Some studies are showing as high as 75% drop-out rate when customers have to recharge batteries**
- **Over 1/3 of new users stop using their trackers after a year and cite 'recharge usage' as the problem**

Shih, P.C., Han, K., Poole, E.S., Rosson, M.B., Carroll, J.M. (2015). Use and Adoption Challenges of Wearable Activity Trackers. In *iConference 2015 Proceedings*

# What does it take?




## Considerations….

- ULP Sensor Node Design
- Harvester Electrical AND Mechanical Characteristics
- Storage Optimization Goals

# Limits Total Cost of Ownership For Ubiquitous Sensing Systems

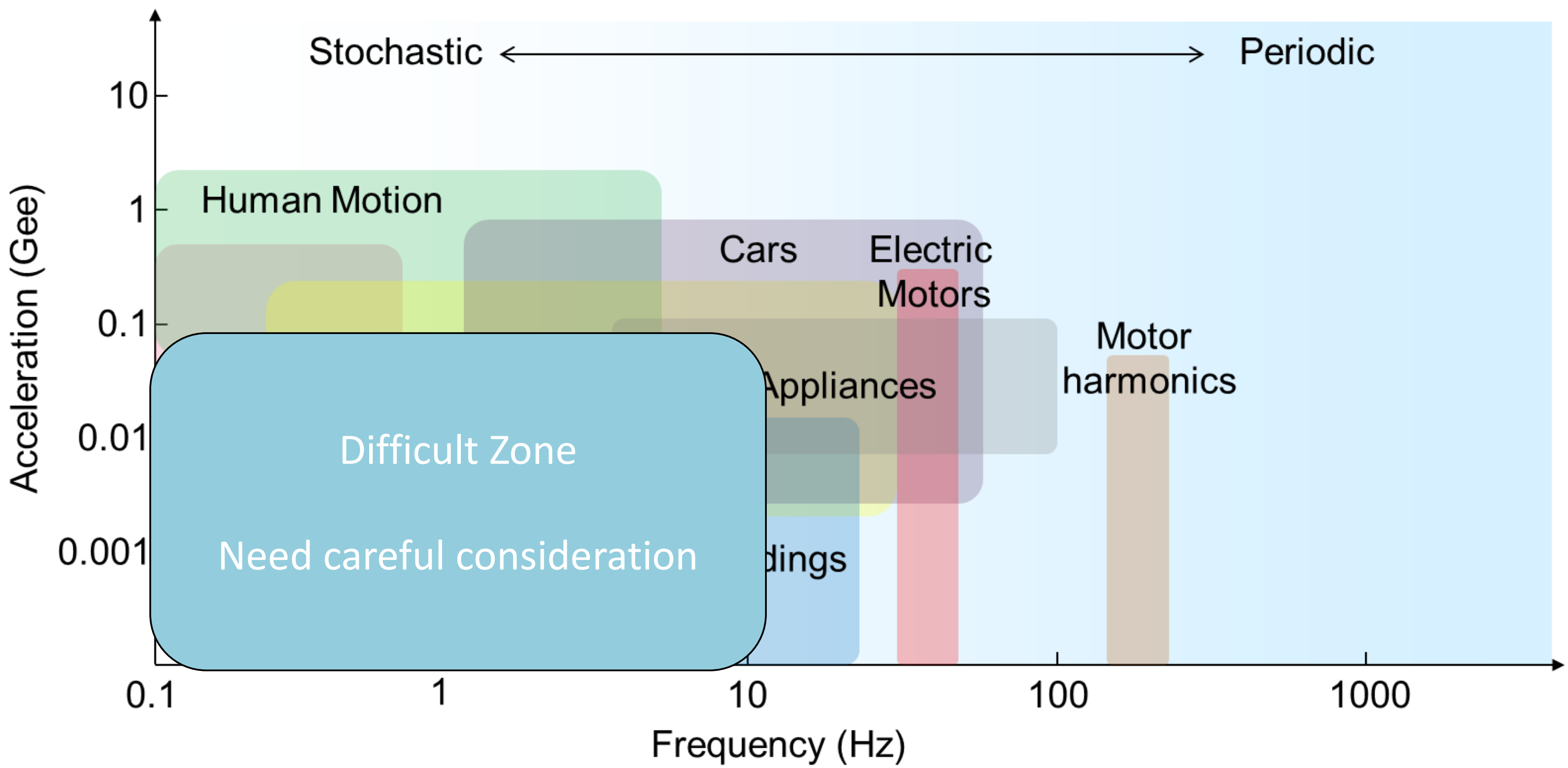
## Primary Battery Only
No Energy Ambient

## Energy Harvesting + Secondary Battery
Best Option for Short Lifetime Nodes
Eliminates the Need for Charging

## Energy Harvesting + Primary Battery
Battery Life Extender
Harsh Environments; Long Lifetime Nodes

## Energy Harvesting + Supercap
Persistent Energy
Longest Lifetime

# Vibration Energy Ambient



# What is available?

**Alta Devices**

210 mW, 0.9V
5 x 2 $cm^2$

**Perpetuum**

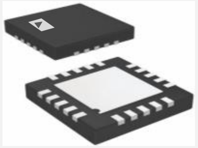
100 mW/gee, 5V
dia. 7 cm, h. 6.5 cm

**Marlow**

0.5 mW/(10°C)$\Delta T$
10 $cm^2$

**Enerbee**

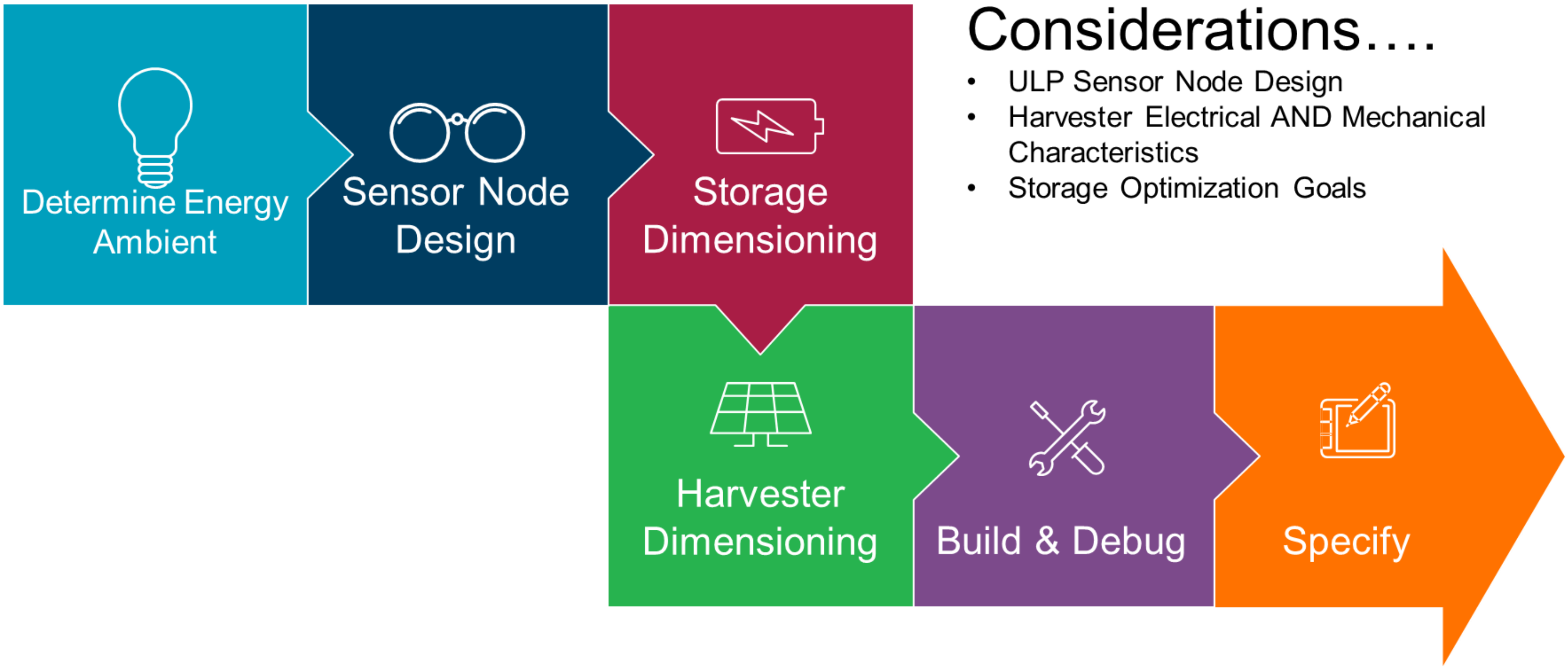
0.4 mW/turn
dia. 4.2 cm



**Analog Devices**

TEG
0.4 mW/(10°C)$\Delta T$
0.1 $cm^2$

# What does it take?




## Considerations….

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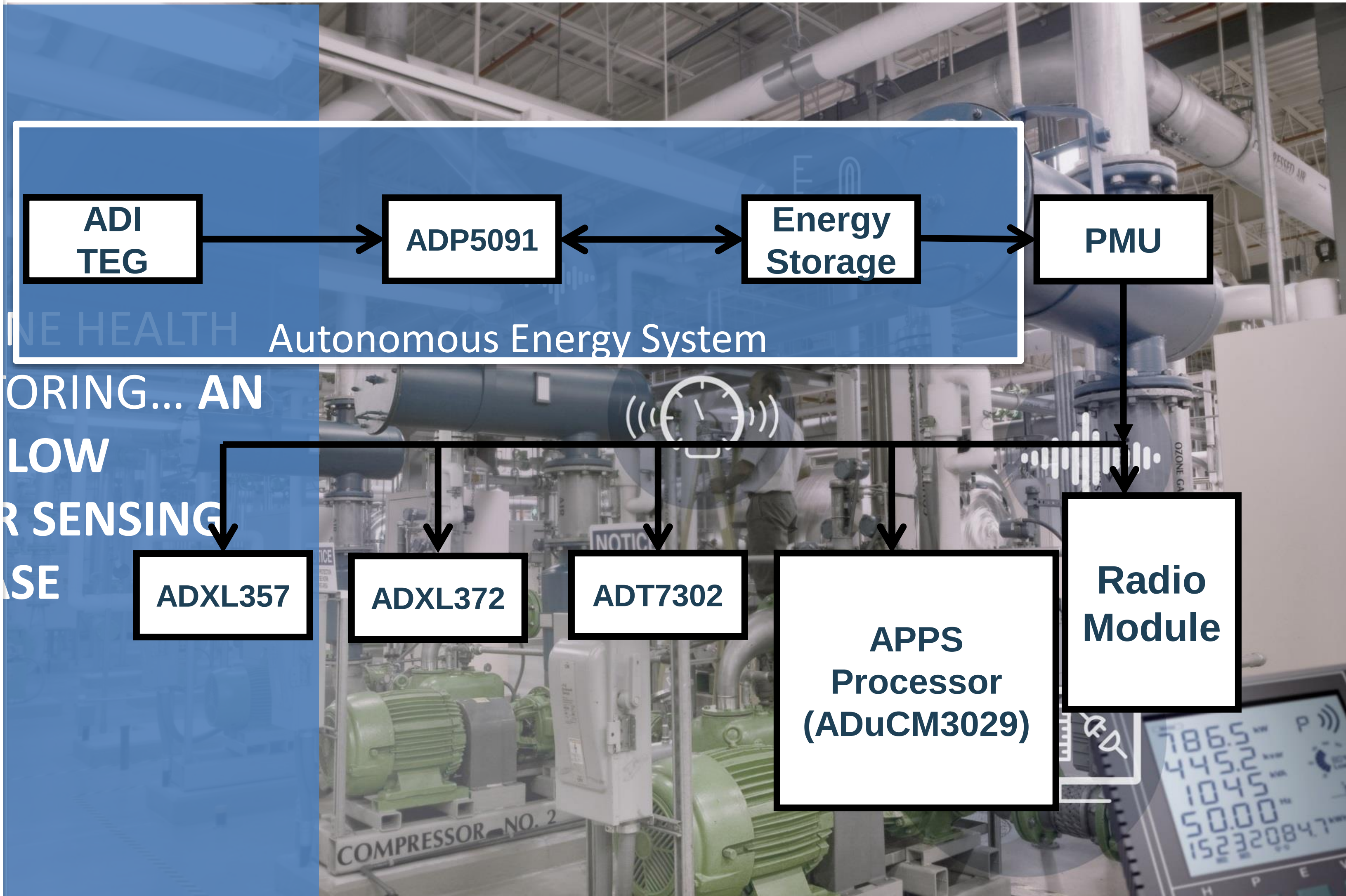
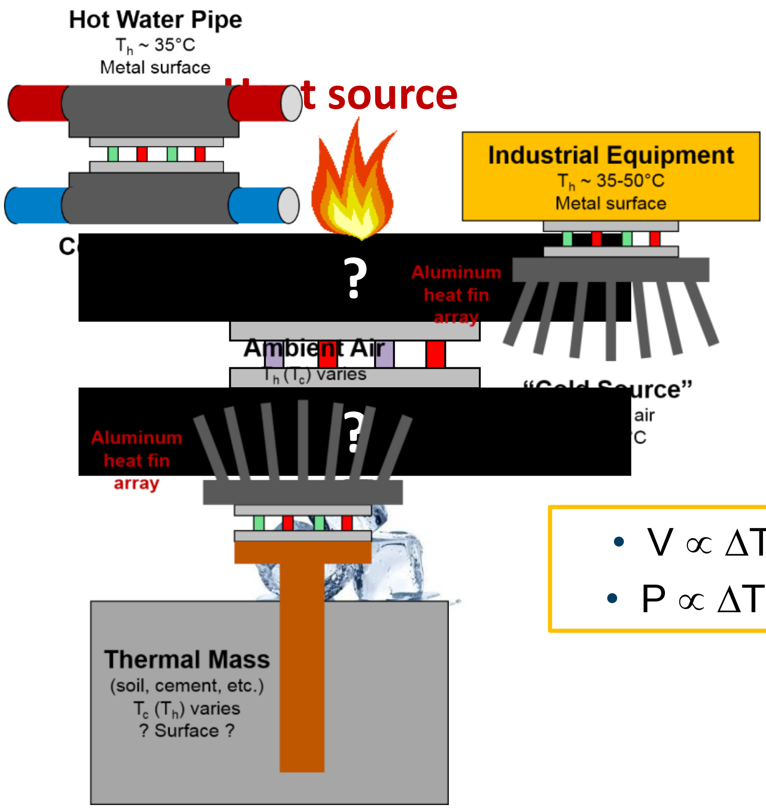
Condition Based Monitoring System



# Thermoelectric Energy Harvester

## System Implementation




- $V \propto \Delta T$
- $P \propto \Delta T^2$

## *System-level Considerations*

### *Geometry*

- Shape and available area of heat source
- Shape and available area of cold source
- Available volume for heat sink

### *Interfaces*

- Surface material of heat source (metal, magnetic, ceramic, etc.)
- Surface material of cold source
- Requirements for adhesion

### *Thermal*

- Typical temperatures of heat source, cold source
- Temperature of ambient
- Typical airflow conditions

# ULP Sensing Techniques – Sensor Strobe

- Choosing the right components is not enough
  - Make use of unique interoperability features
- ADI SensorStrobe feature (ADuCM302x) allows continuous sensing with MCU in **hibernate mode**
- MCU can synchronize measurements with a strobe signal
- When sensor (e.g.. ADXL362 accelerometer) FIFO is full, it interrupts the MCU to download data
- Large power reduction in machine health application!


# Edge Node Processing

- MHM data is sparse in the frequency domain
- In example at right (helicopter rotor shaft), the defect is detectable from the first 10 harmonics
- Save power by only sending the largest N harmonics of the FFT
  - FFT processing takes less energy than transmitting data.
  - Using N=50
- Power reduced from 200µW to 36µW

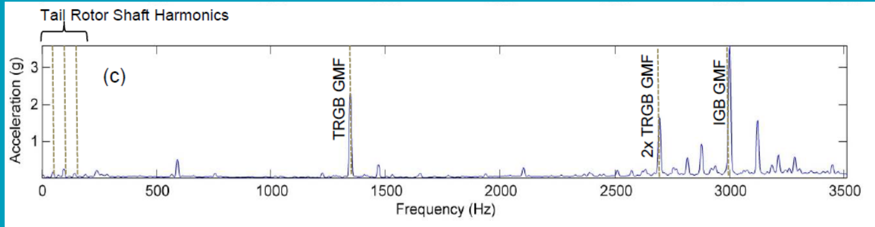



Figure 4 Time-Frequency plot of acceleration for a serviceable TRGB

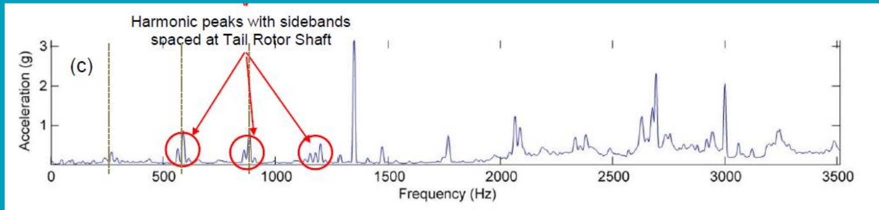
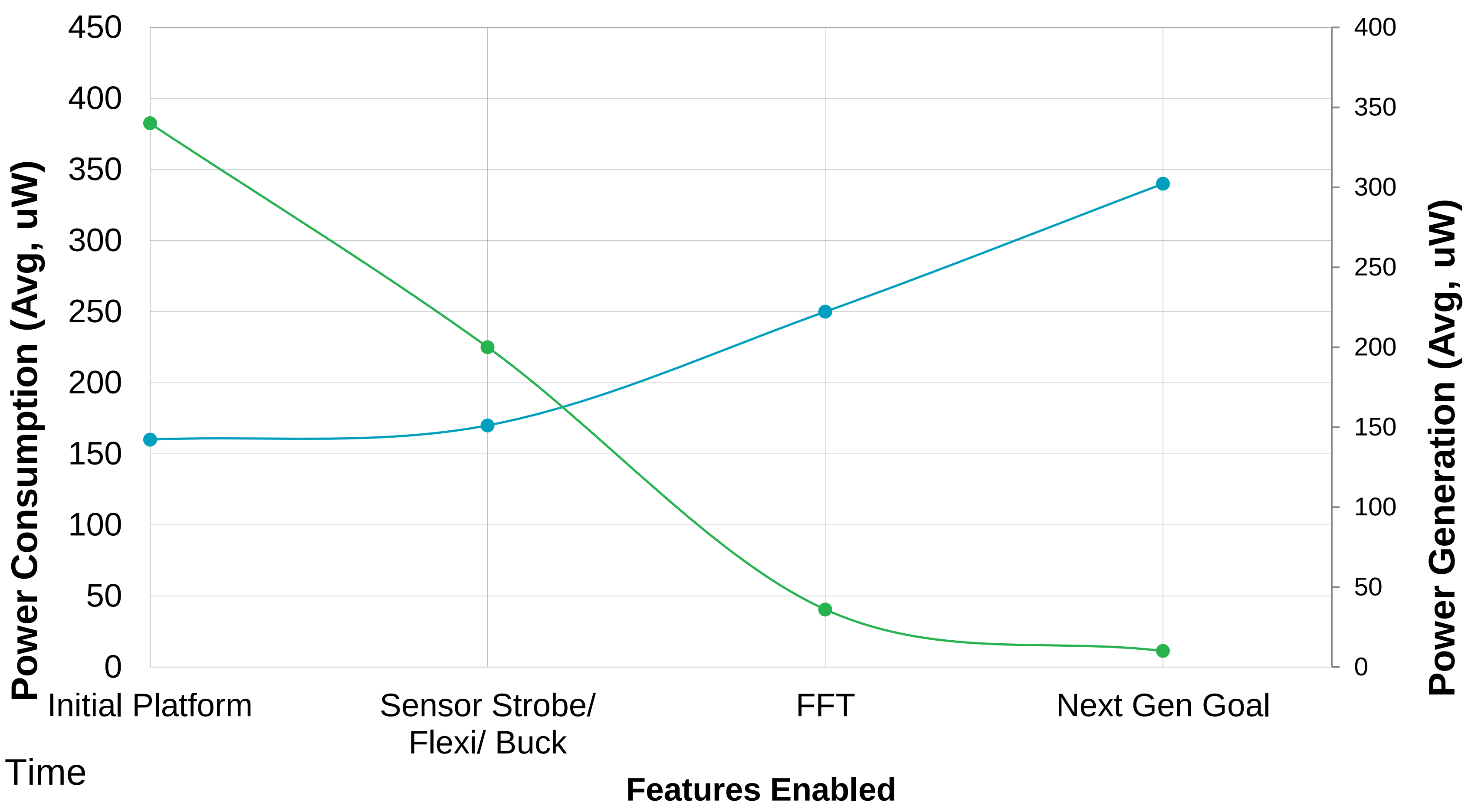



Figure 5 Time-Frequency plot of defective TRGB #1 acceleration FFT

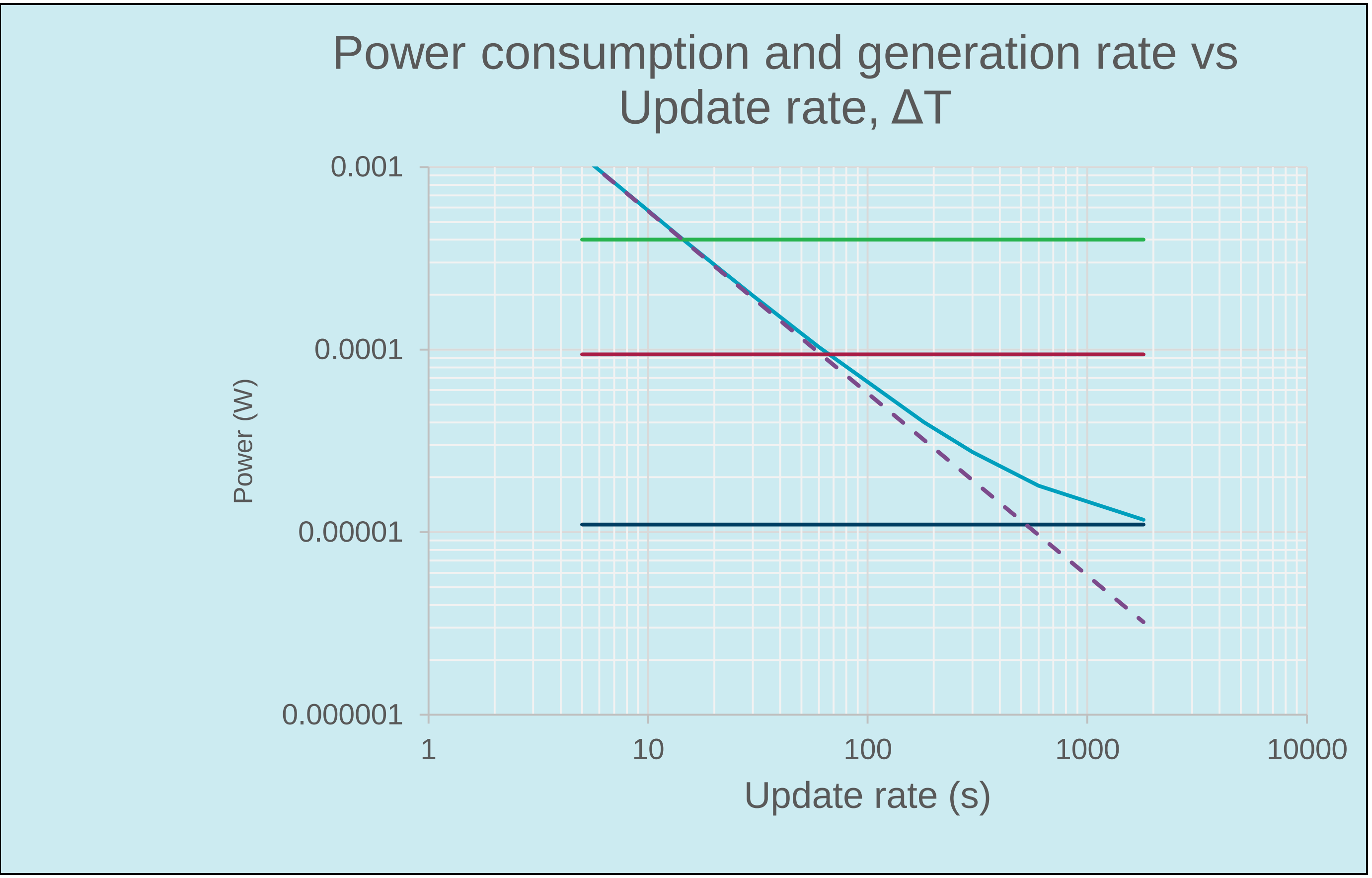
Source: "Bearing Time-to-Failure Estimation using Spectral Analysis Features", Keong et. Al., Structural Health Monitoring, Mar. 2014

# Machine Health Monitor: A look at power consumption and generation

Power Consumption and Generation Curves – Machine Health Monitor Powered by TEG



# ULP Operation Improves Energy Ambient Window




Lowering the ΔT required enables more sensors to be deployed

Increases variety of machines to be monitored

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# BRINGING POWER TO BODY WORN SYSTEMS

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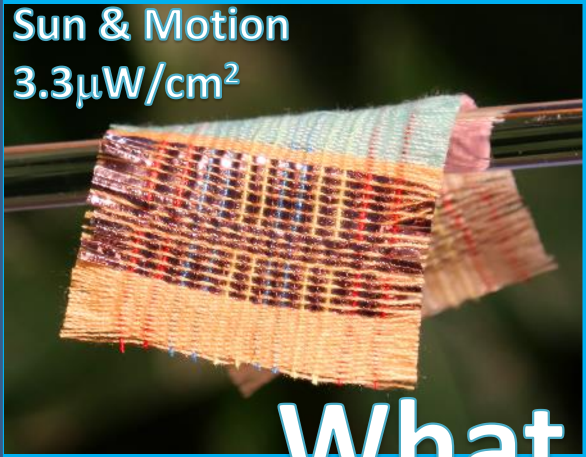
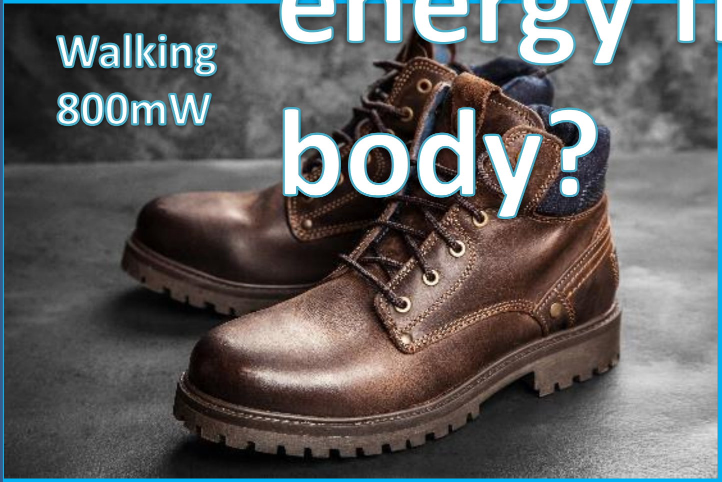
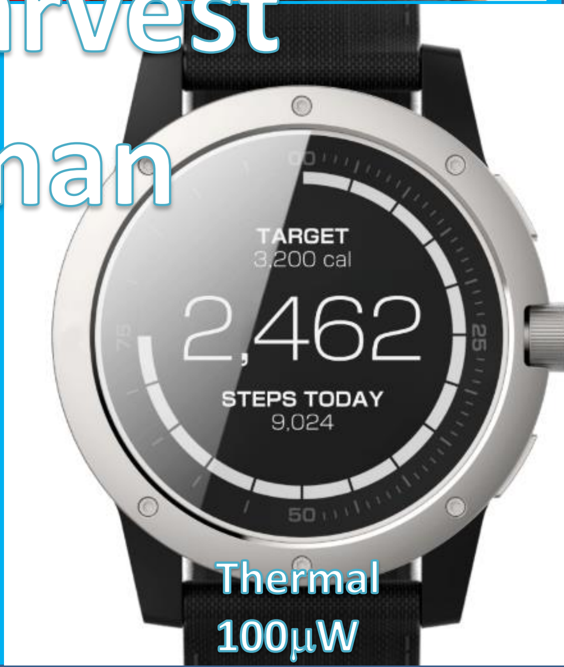




# What if you could harvest energy from the human body?

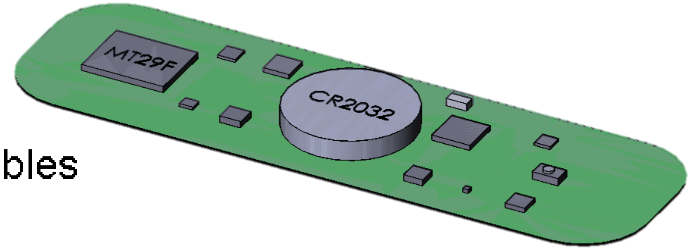


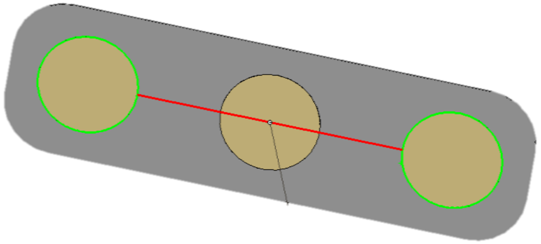



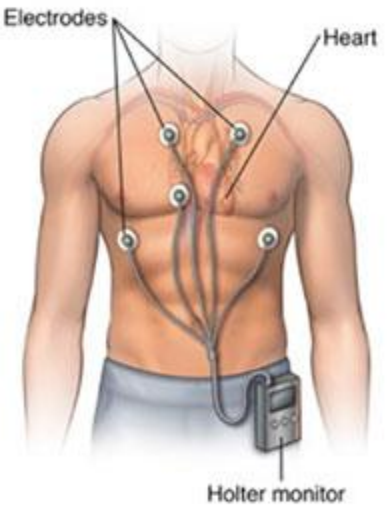

Sources:
NCState, Matrix Industries, SRI, GA Tech

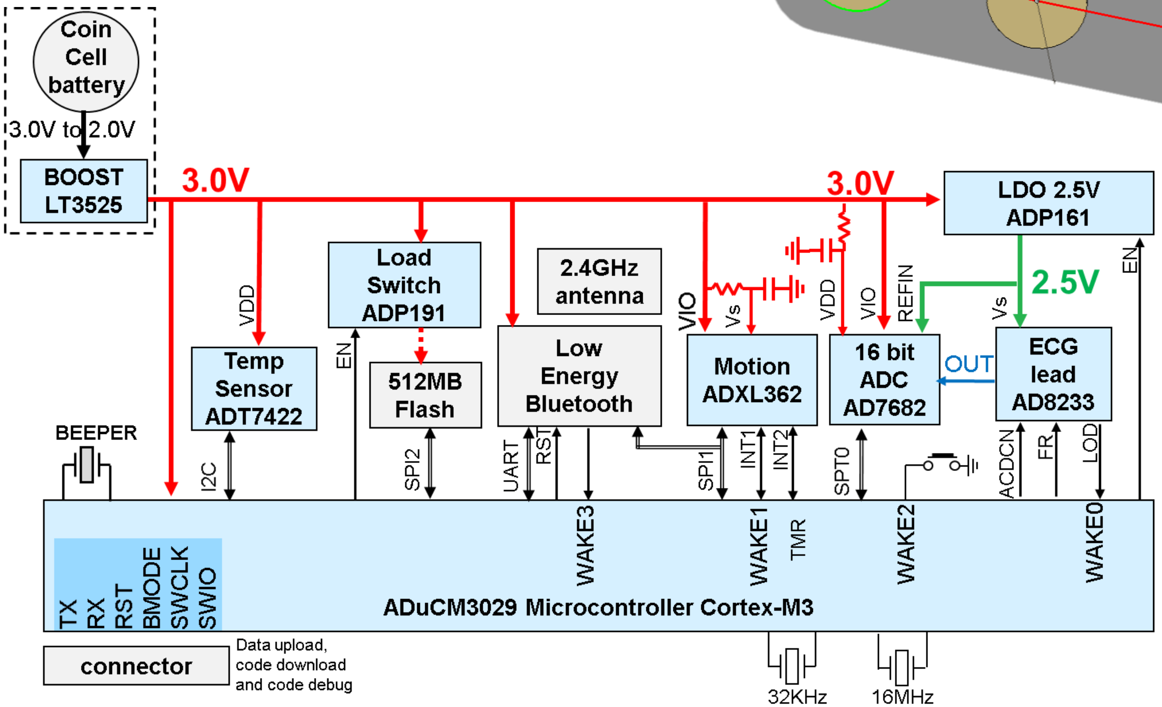
# ECG patch use case

- ECG patch for 24/7 monitoring of patients out of the hospital
- Current devices are bulky, connected to electrodes by long cables and expensive. Goal is to build a cordless disposable patch
- Goal is to achieve a month of data gathering with a single coin cell battery (220mAh -> 305uA average current consumption)





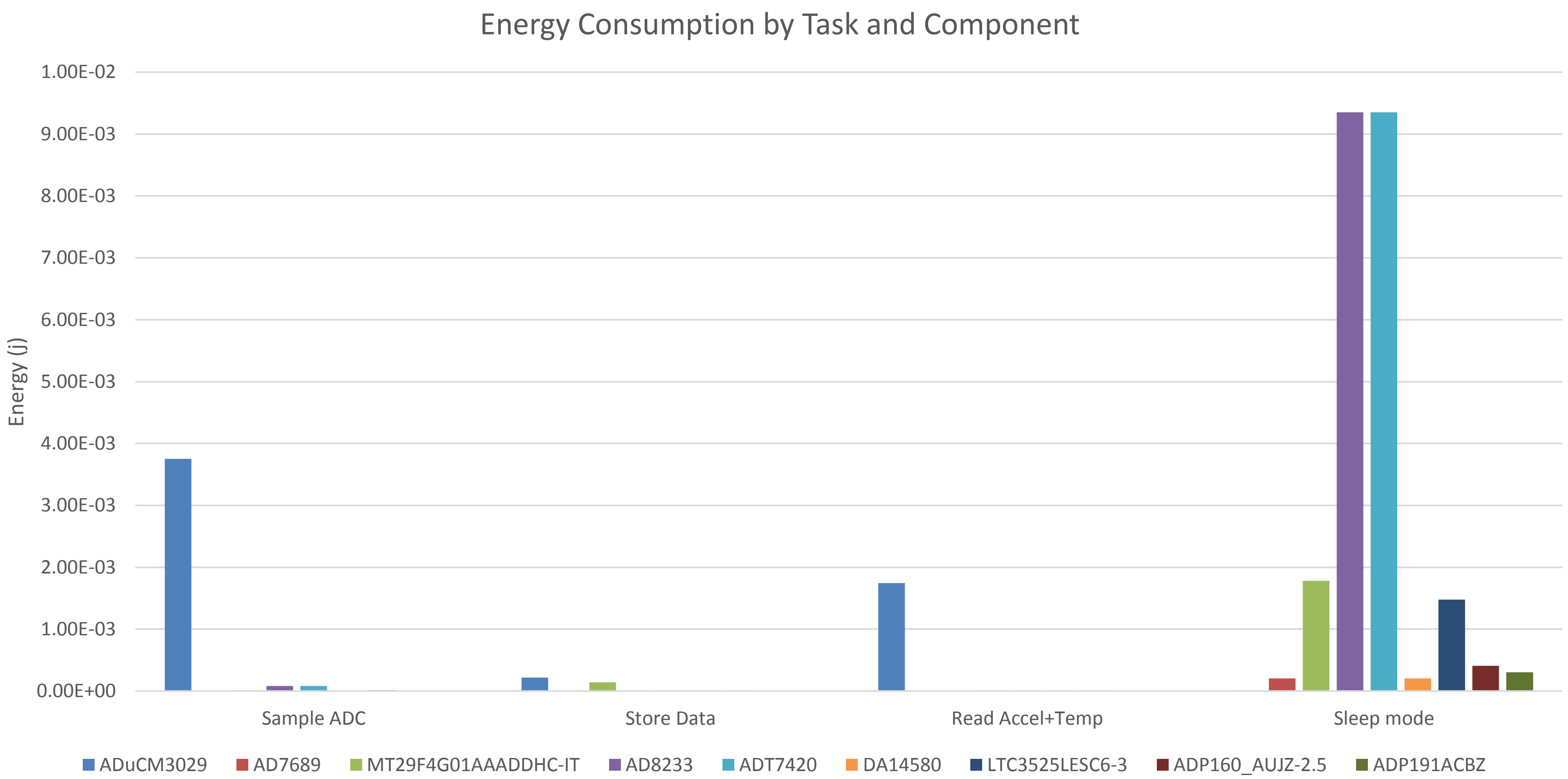



# Energy Balance

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy balance for self-powered nodes | | All quantities in SI units unless otherwise noted. | | | | | | | | | |
| | Signal Chain | | | | | | | | | | | |
| | Component | Total | ADuCM3029 | AD7689 | 9F4G01AAADDH | AD8233 | ADT7420 | ADXL362 | DA14580 | LTC3525LESC6-3 | ADP160_AUJZ-2.5 | ADP191ACBZ |
| | Overall period(s) | 60 | | | | | | | | | | |
| | Active time (s) | 60 | | | | | | | | | | |
| Task 1 | tag | Sample ADC | | | | | | | | | | |
| | Period (s) | 0.005 | | | | | | | | | | |
| | Tasks/period | 1 | | | | | | | | | | |
| | Total time (s) | 5.10E-01 | | | | | | | | | | |
| | Energy/Task (J) | 3.29E-07 | 3.13E-07 | 1.46E-10 | 1.28E-09 | 6.69E-09 | 6.69E-09 | 2.62E-10 | 1.46E-10 | 1.06E-09 | 2.91E-10 | 2.18E-10 |
| | Energy/Period (J) | 3.29E-07 | 3.13E-07 | 1.46E-10 | 1.28E-09 | 6.69E-09 | 6.69E-09 | 2.62E-10 | 1.46E-10 | 1.06E-09 | 2.91E-10 | 2.18E-10 |
| | Total Energy (J) | 0.003953 | 3.75E-03 | 1.75E-06 | 1.53E-05 | 8.03E-05 | 8.03E-05 | 3.14E-06 | 1.75E-06 | 1.27E-05 | 3.49E-06 | 2.62E-06 |
| | Average active power (W) | 6.59E-05 | 6.25E-05 | 2.91E-08 | 2.55E-07 | 1.34E-06 | 1.34E-06 | 5.24E-08 | 2.91E-08 | 2.12E-07 | 5.82E-08 | 4.37E-08 |
| Task 2 | tag | Store Data | | | | | | | | | | |
| | Period (s) | 3.4 | | | | | | | | | | |
| | Tasks/period | 1 | | | | | | | | | | |
| | Total time (s) | 5.74E-02 | | | | | | | | | | |
| | Energy/Task (J) | 3.06E-05 | 1.25E-05 | 1.11E-08 | 8.01E-06 | 5.12E-07 | 5.12E-07 | 8.01E-06 | 5.12E-07 | 5.12E-07 | 2.00E-08 | 1.11E-08 |
| | Energy/Period (J) | 3.06E-05 | 1.25E-05 | 1.11E-08 | 8.01E-06 | 5.12E-07 | 5.12E-07 | 8.01E-06 | 5.12E-07 | 5.12E-07 | 2.00E-08 | 1.11E-08 |
| | Total Energy (J) | 0.00054 | 2.20E-04 | 1.96E-07 | 1.41E-04 | 9.03E-06 | 9.03E-06 | 1.41E-04 | 9.03E-06 | 9.03E-06 | 3.54E-07 | 1.96E-07 |
| | Average active power (W) | 8.99E-06 | 3.67E-06 | 3.27E-09 | 2.36E-06 | 1.51E-07 | 1.51E-07 | 2.36E-06 | 1.51E-07 | 1.51E-07 | 5.89E-09 | 3.27E-09 |
| Task 3 | tag | Read Accel+Temp | | | | | | | | | | |
| | Period (s) | 1 | | | | | | | | | | |
| | Tasks/period | 1 | | | | | | | | | | |
| | Total time (s) | 5.18E-02 | | | | | | | | | | |
| | Energy/Task (J) | 2.97E-05 | 2.91E-05 | 2.95E-09 | 2.59E-08 | 1.36E-07 | 1.36E-07 | 2.59E-08 | 1.36E-07 | 1.36E-07 | 5.32E-09 | 2.95E-09 |
| | Energy/Period (J) | 2.97E-05 | 2.91E-05 | 2.95E-09 | 2.59E-08 | 1.36E-07 | 1.36E-07 | 2.59E-08 | 1.36E-07 | 1.36E-07 | 5.32E-09 | 2.95E-09 |
| | Total Energy (J) | 1.78E-03 | 1.74E-03 | 1.77E-07 | 1.55E-06 | 8.15E-06 | 8.15E-06 | 1.55E-06 | 8.15E-06 | 8.15E-06 | 3.19E-07 | 1.77E-07 |
| | Average active power (W) | 2.97E-05 | 2.91E-05 | 2.95E-09 | 2.59E-08 | 1.36E-07 | 1.36E-07 | 2.59E-08 | 1.36E-07 | 1.36E-07 | 5.32E-09 | 2.95E-09 |
| Task Null | tag | Sleep mode | | | | | | | | | | |
| | Time (s) | 5.94E+01 | | | | | | | | | | |
| | Power | 3.95E-03 | 1.92E-07 | 3.42E-06 | 3.00E-05 | 1.58E-04 | 1.58E-04 | 6.16E-06 | 3.42E-06 | 2.49E-05 | 6.85E-06 | 5.14E-06 |
| | Energy (J) | 2.35E-02 | 1.14E-05 | 2.03E-04 | 1.78E-03 | 9.35E-03 | 9.35E-03 | 3.66E-04 | 2.03E-04 | 1.48E-03 | 4.07E-04 | 3.05E-04 |
| | | Total | ADuCM3029 | AD7689 | 9F4G01AAADD | AD8233 | ADT7420 | ADXL362 | DA14580 | LTC3525LESC6-3 | ADP160_AUJZ-2.5 | ADP191ACBZ |
| Grand total | Energy (J) | 2.97E-02 | 5.73E-03 | 2.05E-04 | 1.94E-03 | 9.45E-03 | 9.45E-03 | 5.12E-04 | 2.22E-04 | 1.51E-03 | 4.11E-04 | 3.08E-04 |
| | Average power (W) | 4.96E-04 | 9.55E-05 | 3.42E-06 | 3.23E-05 | 1.58E-04 | 1.58E-04 | 8.53E-06 | 3.70E-06 | 2.51E-05 | 6.85E-06 | 5.13E-06 |
| | Average battery current (A) | 1.65E-04 | | | | | | | | | | |

**Battery life = 220mAh/165uA = 1333h = 55.5 days ✓**

# Energy Balance



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# Talk to Me!

- Once you have your data, and have power available to use, you need to **communicate** your high-value data!
- How best to do this?
- RF protocols, frequency choices, range, mesh/star, data rate for updates?

# Frequency options

## ISM Bands - Industrial, Scientific and Medical

***900MHz***
*vs.*
***2.4GHz***
*vs.*
***5GHz***

### *900MHz*

***Advantages:***
- More robust, less prone to interference
- Lower attenuation, travels further through more obstacles

***Disadvantages:***
- Low bandwidth prevents large data transfer, speed
- Components are larger at lower frequencies

### *2.4GHz*

***Advantages:***
- Higher bandwidth allows large data transfer, speed
- Components are smaller, cheaper

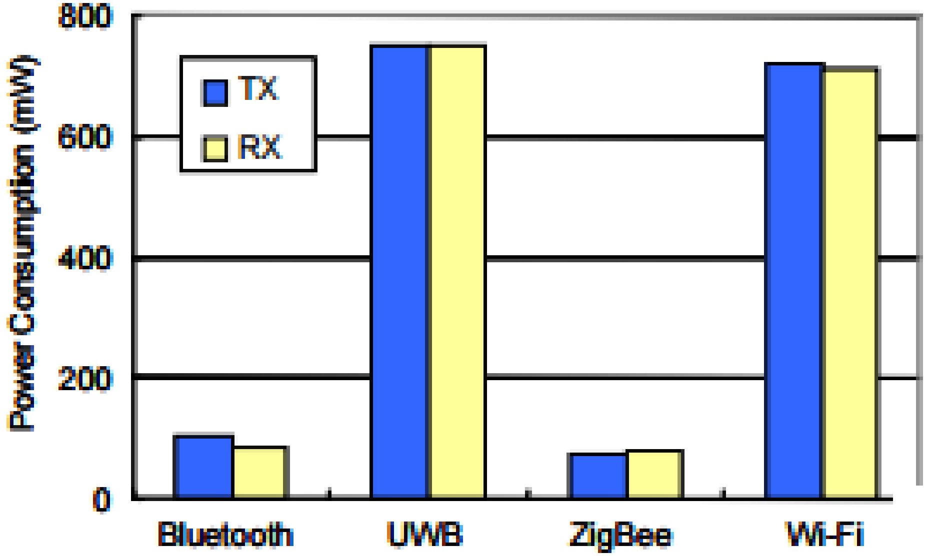
***Disadvantages:***
- Congested band due to abundance of Wi-Fi, Bluetooth, microwaves, cordless phones
- Attenuates much more quickly, will not pass through metal

### *5GHz*

***Advantages:***
- Higher bandwidth allows large data transfer, speed
- Less congested, few RF devices in this band

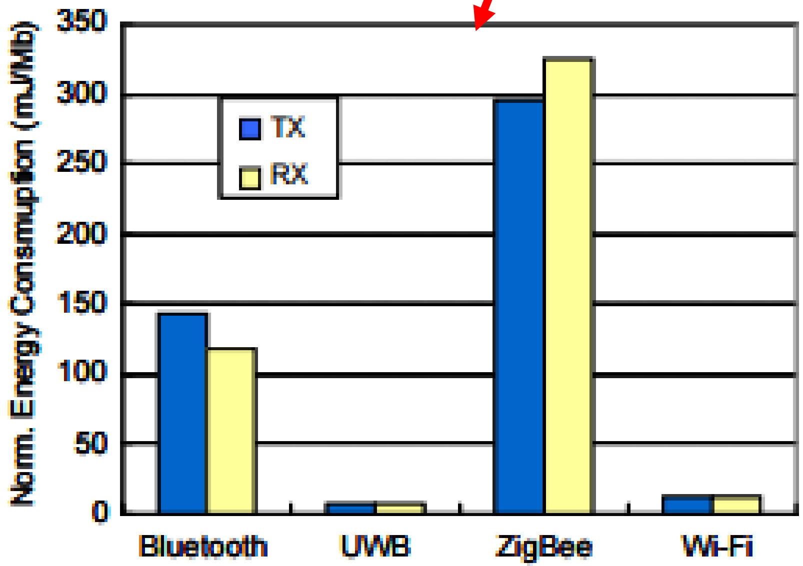
***Disadvantages:***
- Low transmit power limitations
- High attenuation in cables, requires very high gain antennas

# What Language to Use?




BTLE/ANT/Dust/Zigbee are all lower power consumption than Wifi/UWB

Once you start moving LARGE amounts of data though, this inverts



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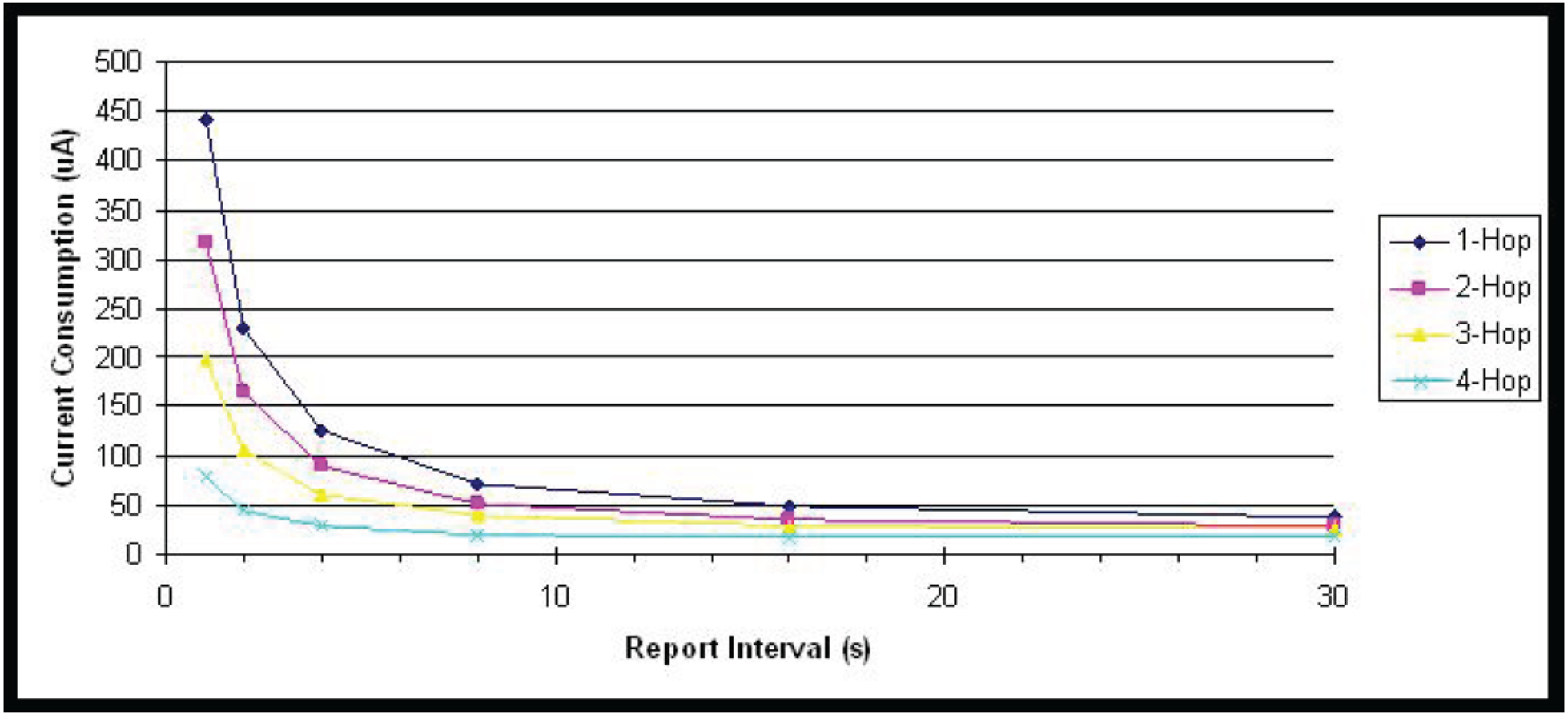
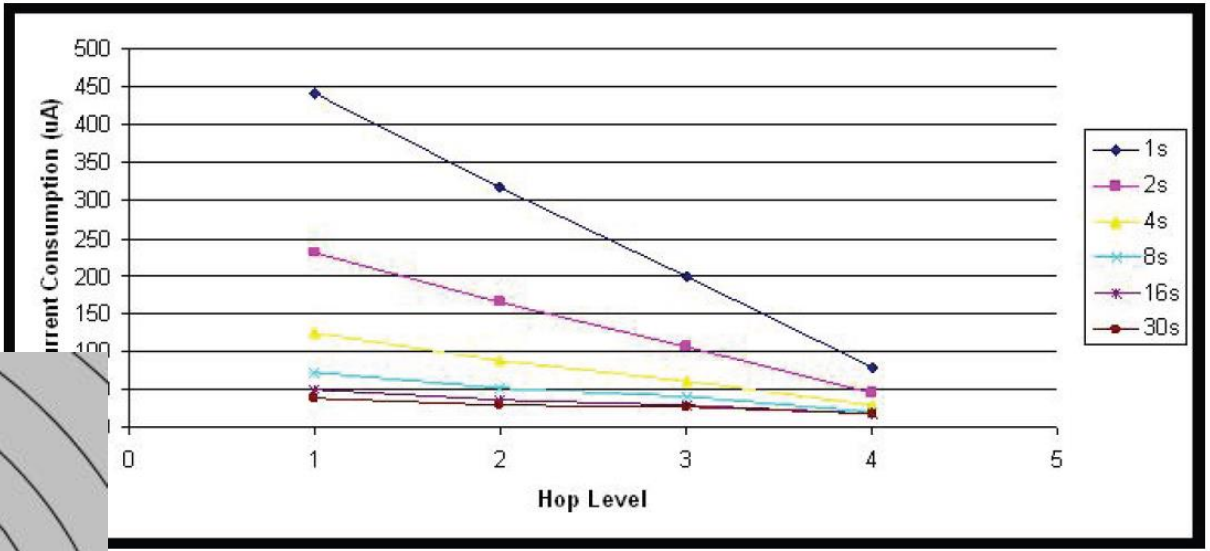
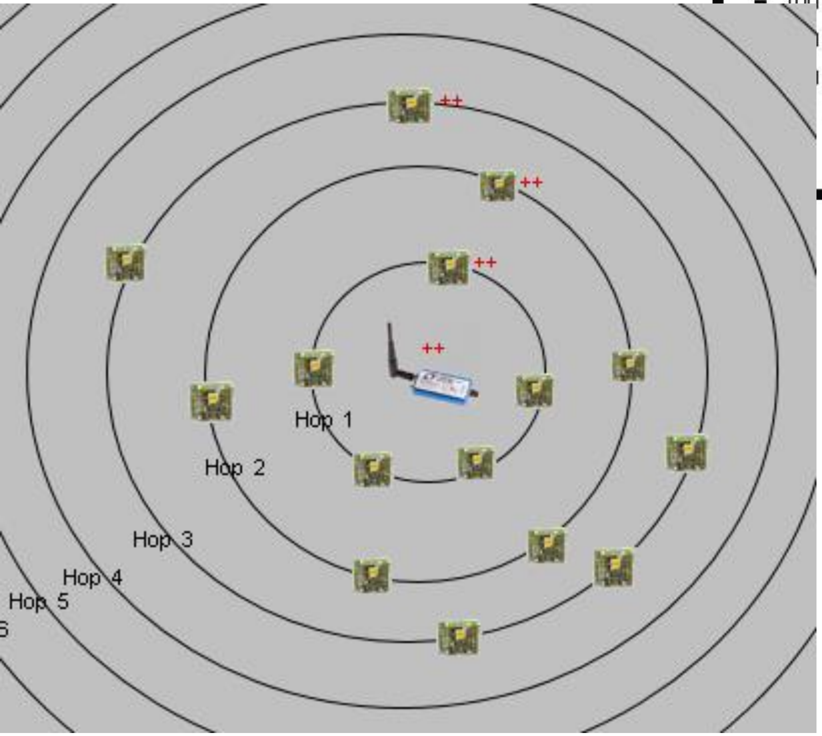
# Talk to me Less



# To Mesh or Not to Mesh



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THE FUTURE OF SELF POWERED SYSTEMS …
**STARTS HERE**

# THANK YOU

Let's Talk About Energy Harvesting!

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