The Design Secrets for Commercially Successful EH-Powered Wireless Sensors

Steve Grady & Jeff Mullin
Cymbet

Designing Commercially Successful Energy Harvesting Powered Systems

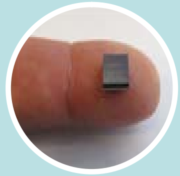
- Identify key trends and market forces driving the need for Energy Harvesting-based power
- The economics behind Energy Harvesting
- Identify important design considerations
- Utilize Energy Harvesting technologies that enable cost effective EH-powered products
- Review reference designs for important info
- Commercial EH-powered sensor deployments

Key Trends Driving Innovation

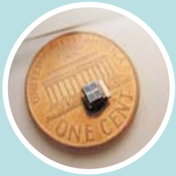
Ultra Low Power Processors & Electronics

Smart Devices and Sensors Everywhere

Wireless is pervasive



Integration with other components



Miniaturization

Eco-Friendly and Renewable Energy

Convergence of Trends into Products

- New innovative products are smarter, smaller and wireless
- Smart devices that must communicate status/control
- There will be billions of new networked smart devices
- Health, Industrial, Buildings, Appliances, Transportation
- New Powering solutions are required

Introducing Energy Harvesting:

Life of Product Energy Generation and Storage…

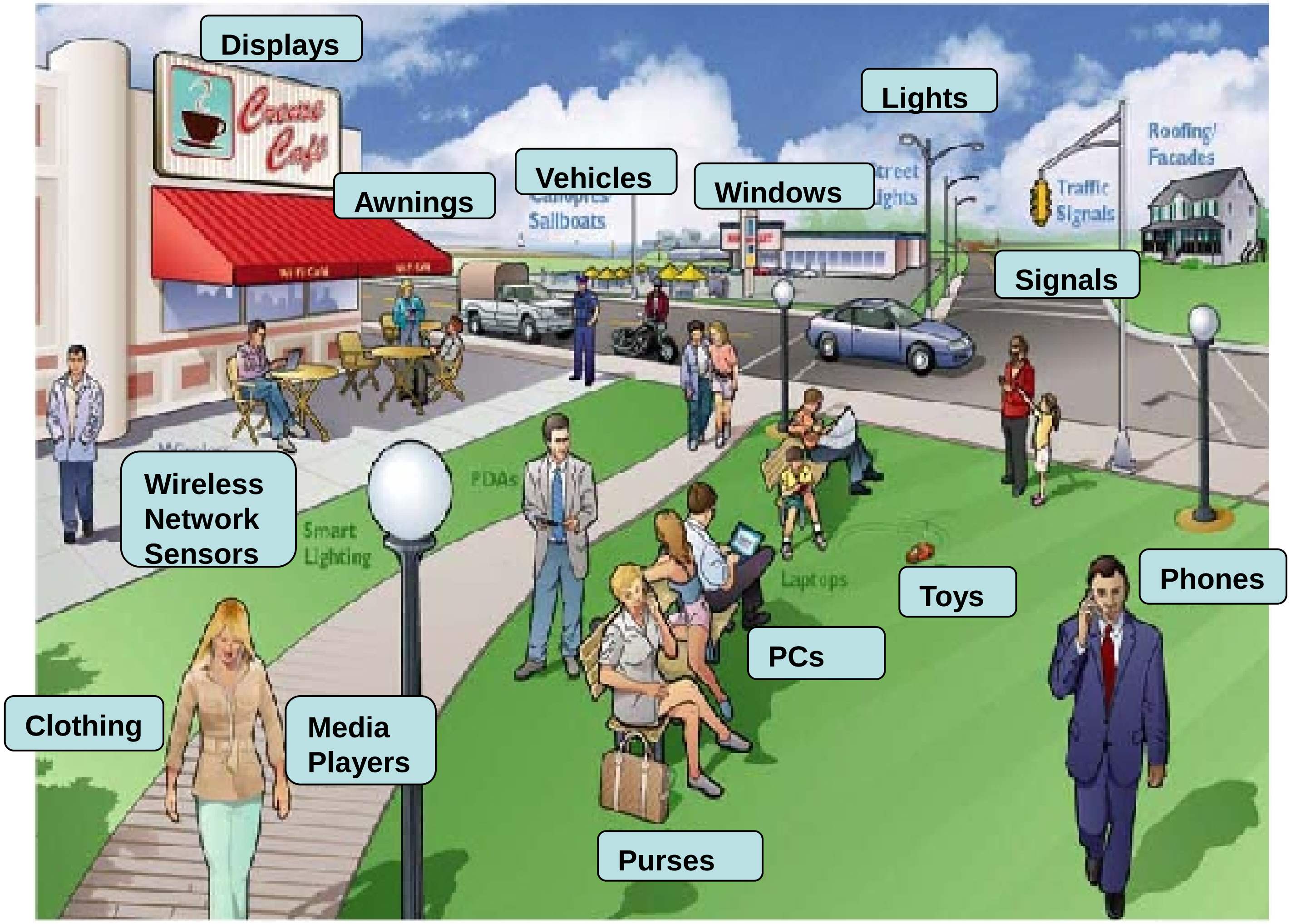
- Energy can be harvested from almost any environment:
  - Light, vibration, flow, motion, pressure, magnetic fields, RF, etc.

- Energy Harvesting applications found in every industry segment

- EH-powered systems need reliable energy generation, storage and delivery:
  - Must have energy storage as EH Transducer energy source is not always available: (Solar @night, motor vibration at rest, air-flow, etc.)
  - Longer operating times – high-efficiency minimizes charge loss
  - Self-Powered allows remote locations & lower installation costs
  - High cycle life enables extended operation – fewer service calls

- Ideal solution is a highly-efficient, eco-friendly, power generation system that can be cycled continuously for the life of the product

EH Powering The "Internet Of Things"



Source Konarka

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HP CeNSE, IBM Smarter Planet

Giving the Planet a Voice with Sensors

CeNSE

Central Nervous System for the Earth

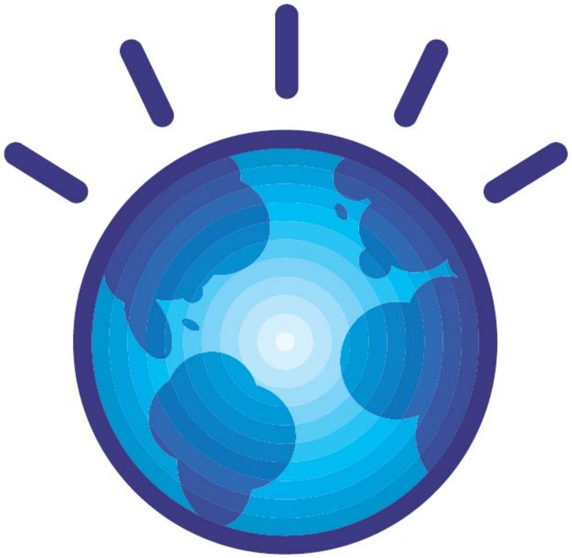
– Awareness of planet
– Measurement of impact
– Taste/Smell/Touch/Sound/Sight

– Safety
– Sustainability
– Security

~1 trillion sensor network

Quantity of data creates quality of data

IBM Smarter Planet

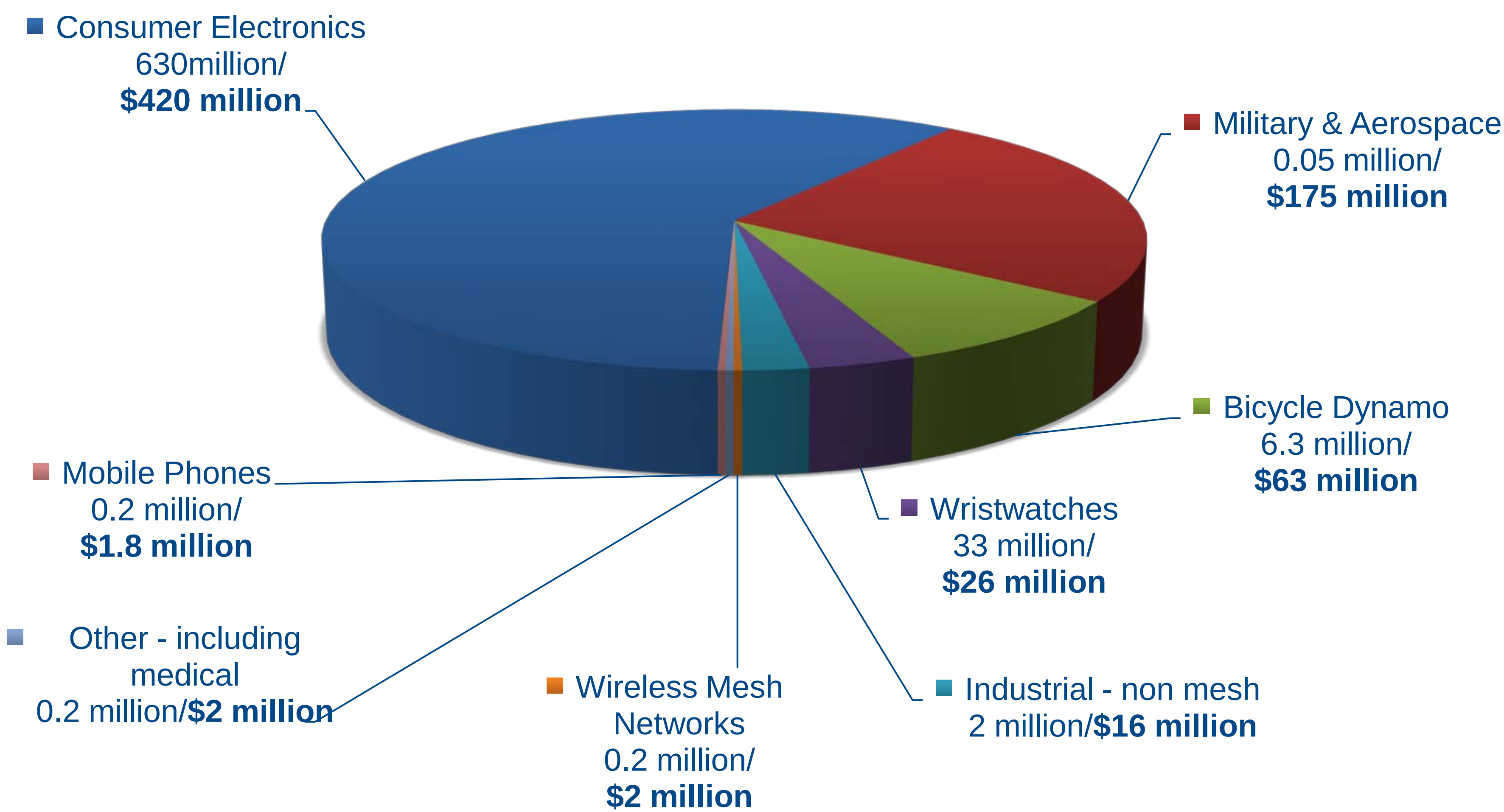


"Trillions of digital devices connected to the Internet, are producing a vast ocean of data…"

Who's going to change 1 Trillion Batteries????!

Energy Harvesting Market in 2012 $0.7Bn

Source: IDTechEx Energy Harvesting Report



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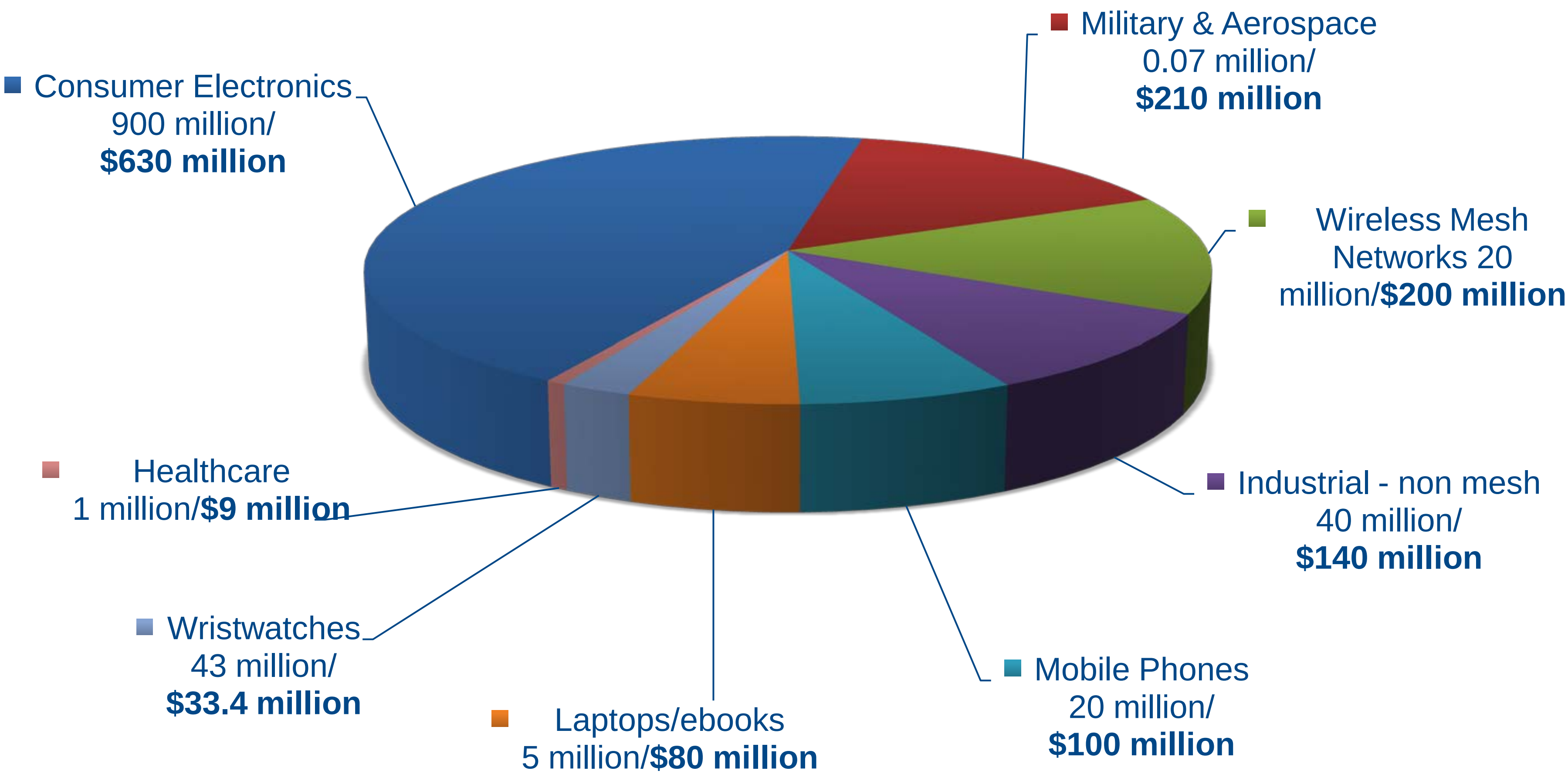
Energy Harvesting Market in 2017 $1.5Bn

Source: IDTechEx Energy Harvesting Report



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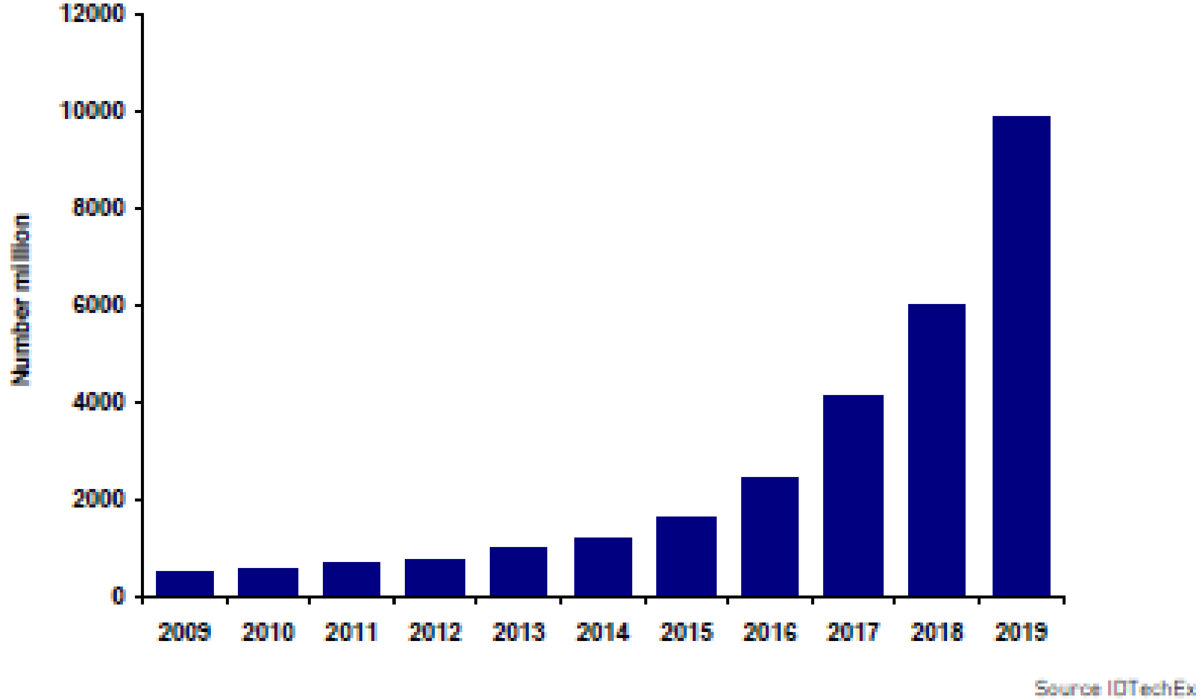
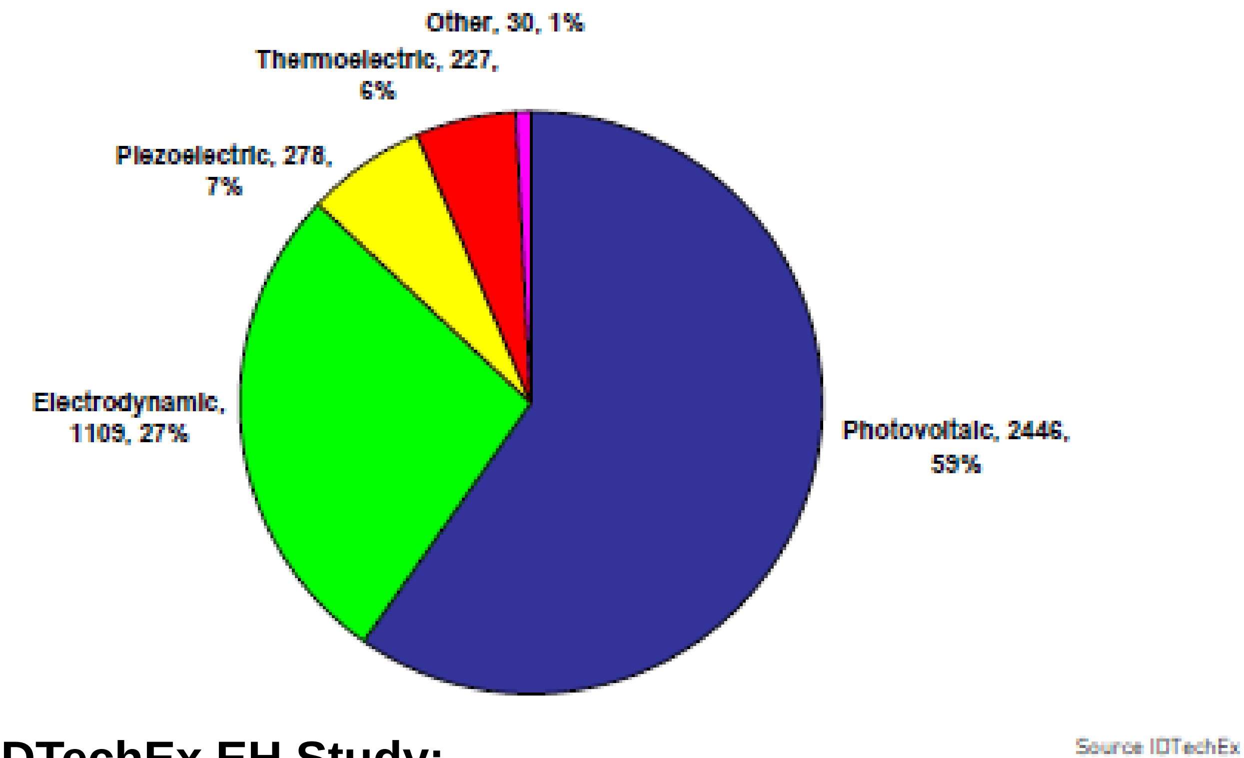
Energy Harvesting Market Forecasts



From the IDTechEx EH Study:

- **90% of envisaged use of wireless sensor networks are impractical without EH**
- **Many installations are inaccessible or prohibitively expensive for replacement**
- **Sensors such as bionics or embedded devices need life of product power**
- **Many standalone products need “off-the-grid” powering solutions**

Total Market Value by EH Technology 2019



From the IDTechEx EH Study:

- **EH from light is 60% of applications**
- **Electrodynamic/Electromagnetic is 27%**
- **Vibration and Thermal 13% but may be low by some estimates**
- **What new energy harvesting technologies are coming???**

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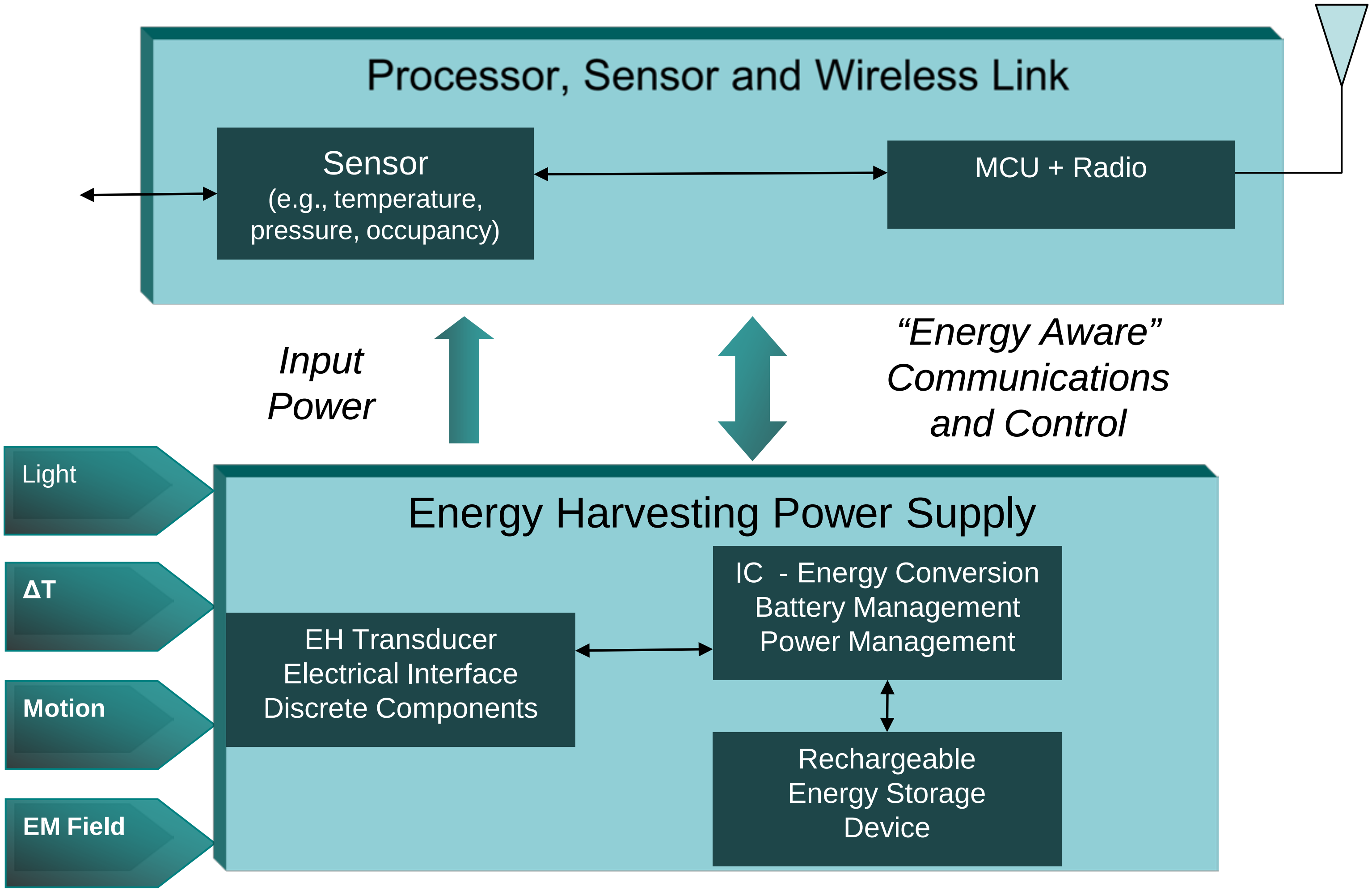
EH-Powered Autonomous Wireless Sensor Block Diagram



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4 Key Design Considerations for EH

1. Determine energy available from your environment
   – Indoor solar is in tens to hundreds of microwatts
   – Thermoelectric in tens to hundreds of microwatts based on delta Temp
2. Harvest energy as efficiently and cost effectively as possible
   – Design for Maximum Peak Power Point
   – Avoid components with excessive leakage or quiescent current
3. Calculate application power requirements in all operation modes and minimize to fit available input EH power
   – Use sleep modes of components when possible
   – Write Energy- Aware code -> no polling loops, check Vcc before running
4. Size storage for times when ambient energy is not available

   Bigger battery is not always better: don’t fill the pool with a paper cup!

EH vs. Battery Business Case Realities

- Small device designs that do not have a charging source – either AC/DC, Energy Harvesting or Wireless Power – use a primary battery
- Primary batteries have reached commodity status with billions/yr shipped
- To compare rechargeable battery $/mAh metric you must use the Lifecycle capacity of the rechargeable battery - #charge cycles x Depth of Discharge per cycle in uAh. This gives the total lifetime energy delivery cost.
- Example using 3Volt batteries 1K Qty on Digi-Key :
  - CR2032 coin + holder: $.36/225mAh x 1 cycle = $0.0016/mAh
  - Tadiran coin: $4.82/1000mAh x 1 cycle = $0.0048/mAh
  - Alkaline 2 AAA + holder: $1.71/1000mAh x 1 cycle = $0.0017/mAh
  - IPS MEC TFB : $13.09/700uAh x 10,000 cycles= $0.0019/mAh
  - Cymbet EnerChip: $2.70/50uAh x 10,000 cycles = $0.0054/mAh
- To charge rechargeable batteries, need to add the Cost for EH power system
- Supercapacitors can be used, but electrical characteristics are a concern

Calculating the Cost of the Energy Harvester

- Think of the Energy Harvester as a variable capacity battery
- The output energy will depend on the ambient energy conditions
- Energy Harvester designs will have a min/max energy output range
- Calculate the EH cost based on the energy output average
- Cost is Transducer + interface components + conversion electronics (IC)

- Example: Simple Solar Energy Harvester at 200Lux with 24/7 operation
  - Sanyo AM1815 4.9V solar cell $4.39 (1K pcs) output is 147uW
  - Assume simple conversion electronic components for $1.25
  - 3.3V x Current = 147uW. Current = 44.7microAmps output
  - Total capacity over 10 year 24/7 life = 3,916 mAh
  - $/mAh for Solar EH = $0.0014. Lower than AAA and Coin cell costs
  - Fewer light hours increases cost, brighter light decreases costs

➢ **Energy Harvesters can be designed as cost effectively as Primary Batteries**

Assigning $ Value to other Attributes

- What is the product power lifetime requirements – 200mAh, 1Ah, 5Ah?
- Life of product duration expectations – 3, 5, 10, 20 years?
- Battery Footprint and overall product size
- Battery Height and overall product size
- \$cost/uAh/mm³ - how much energy for $ in how small a space?
- Assembly Issues and Costs
- Primary Battery Change-out – device access and cost of replacement
- Product Physical design – No doors or customer access
- Electrical Characteristics - flat voltage, fast recharge, low discharge
- Aging Characteristics – chemical leakage, seals drying out
- Transportation Restrictions – UN and Country Air Safety shipping laws
- Safety and End-of-Life Disposal - what are the procedures and costs

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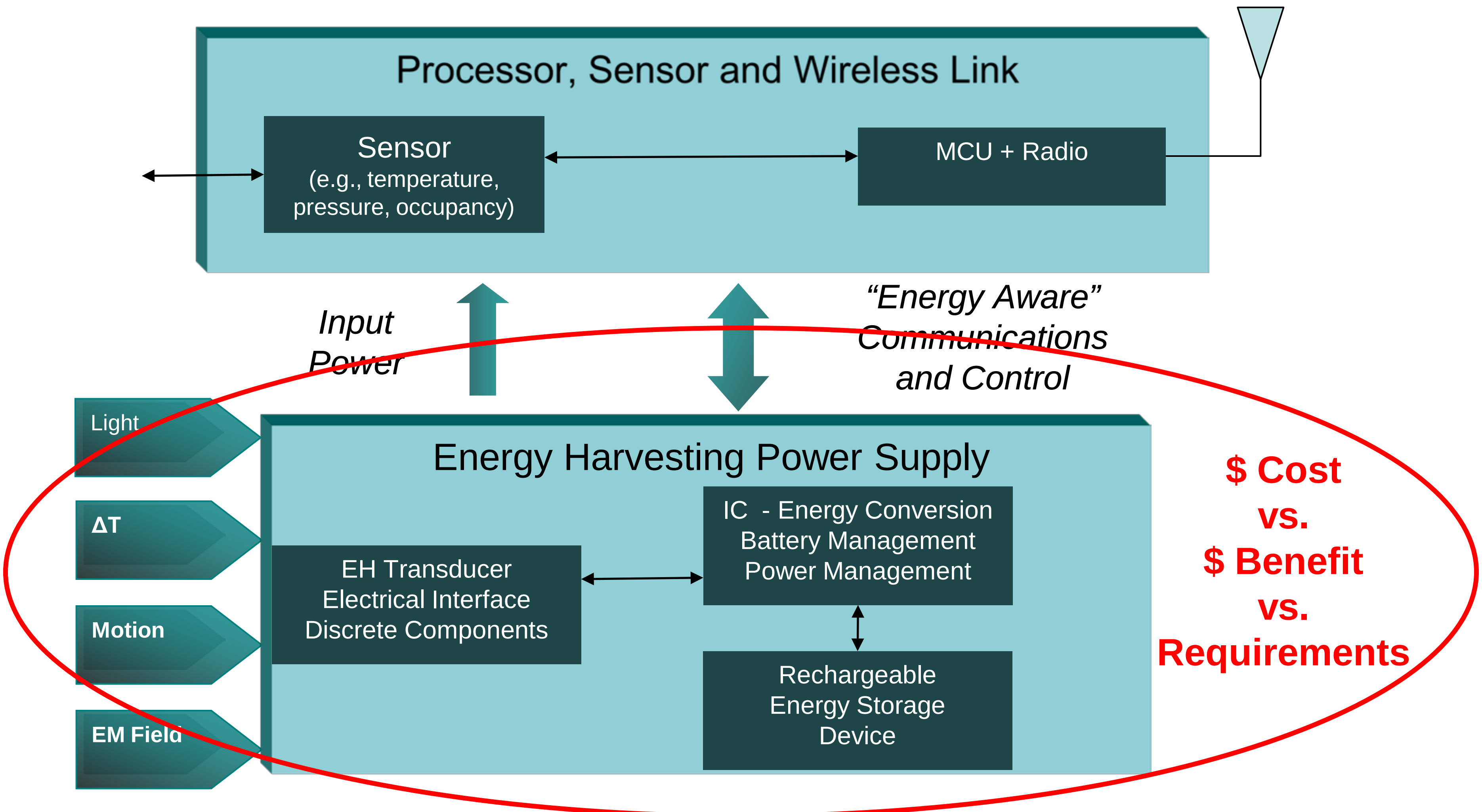
EH Power System Cost vs. Benefit



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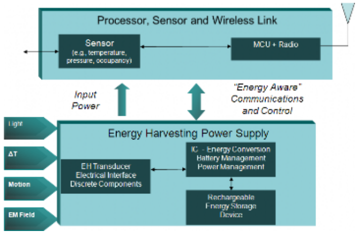
Industry is Providing Cost Effective Sensor Building Blocks

- Low Power Microprocessors with nanoAmp sleep currents.
- Low Power Radio Transceivers:
  - IEEE 802.15.4 standards 2.4Gigahertz
  - MilliAmp to tens of milliAmps currents for transmitters and receivers
  - Quick startup with low sleep power
- Energy Efficient Radio Protocols:
  - Proprietary Ultra-low power protocols
  - ZigBee and ZigBee Green
  - Bluetooth LE
  - ANT+, EnOcean Alliance
  - Dust Networks IP 6LoWPAN
- Micropower Sensors with low sleep currents:
  - Passive IR, Temp, Humidity, Acceleration, Pressure, etc.
- Lower quiescent current peripheral circuits:
  - Clocks, power management chips, etc.

EH Overview Summary

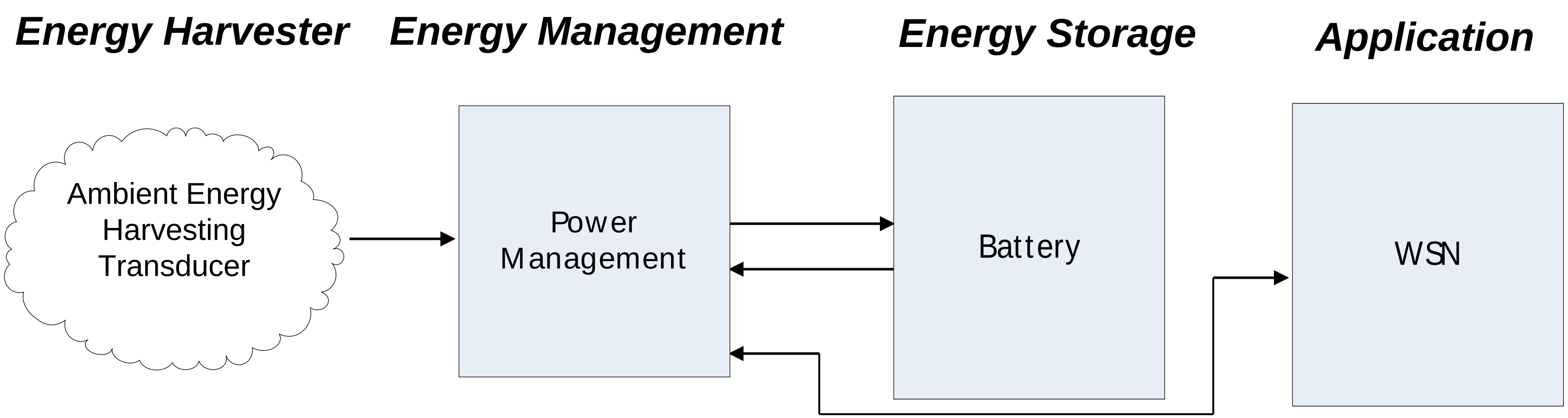
- Billions of smart devices deployed over the next 10 years need:
  - Powered autonomously and be “off-grid”
  - Have a power source that lasts the life of the device
  - Be small, integrated and cost effective
- Cost effective Energy Harvesting solutions can power products
- Success is based on the EH Ecosystem converging:
  - EH Transducers
  - High Efficiency power conversion
  - Life of Product Energy storage
  - Ultra low power Microcontrollers and Sensors
  - Low power wireless radios and protocols
  - Optimized system architecture, hardware and firmware

EH Design Sections



1. Advancements in Energy Harvesting Transducers
2. High Efficiency Designs for Energy Conversion
3. New Technologies for ULP MCUs, Sensors and Actuators
4. Wireless Transceivers, Protocols, SoCs and Architectures
5. Successful Commercial Energy Harvesting Deployments
6. Final Thoughts

Walk Through the Power Chain



- Photovoltaic
- Electro-Mechanical
- Thermo-Electric
- Radio Frequency

- Energy Conversion
- Manage Energy Storage
- Powers Application

- Solid State Battery
- Capacitor
- Traditional Battery

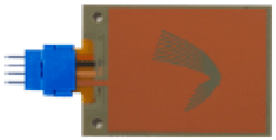
- Wireless Sensor
- Powered Card
- Implantable Medical
- Many, many more…

EH Commercial Transducers

Manufacturers (Advertised Product)


Thermoelectric Generator or Thermopile (Heat)

- Marlow Industries(EverGen), Micropelt(TE-Power),
- Perpetua (Power Puck), Nextreme(eTEG/WPG)

Piezoelectric (Motion / Vibration / Strain)

- Mide (Volture), PI Ceramics (*P-876*) , MicroGen (*BOLT™*),
- Smart Materials (*M8528P2,M8557P2, M8585P2*),
- T.M.S. AUTO PARTS CO LTD;alibaba.com (piezo bending generators)


Photovoltaic (Light)

- G24i(Indy,DOM,COM), Solar Print(SP5848 DSSC), Panasonic(Amorton)


Galvanic (Moisture)

- Components available to work with minimal voltages


Electromagnetic (Motion / Vibration / Induction)

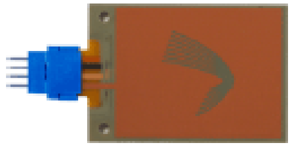
- Perpetuum(PMG FSH)

EH Transducers

Market Challenges


Thermoelectric Generator or Thermopile (Heat)

- Approvals from Field Trials

Piezoelectric (Motion / Vibration / Strain)

- High-Volume Application to Reduce Transducer Pricing


Photovoltaic (Light)

- None – Deployed in many applications

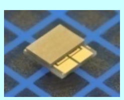
Galvanic (Moisture)

- None – Deployed in farming operations


Electromagnetic (Motion / Vibration / Induction)

- Low-cost small disposable or re-usable transducer would enable large market in asset tracking.


EH Transducer Power Management Challenges

Energy Source	*Challenge*	*Typical Impedance*	*Typical Voltage*	*Typical Power Output*	*Cost*
Light 	**Conform to small surface area;** **wide input voltage range**	***Varies with light input*** ***Low kΩ to 10s of kΩ***	***DC: 0.5V to 5V [Depends on number of cells in array]***	**10μW-15mW** **(Outdoors: 0.15mW-15mW)** **(Indoors: <500μW)**	**$0.50 to $10.00**
Vibrational 	**Variability of vibrational frequency**	***Constant impedance*** ***10s of kΩ to 100kΩ***	***AC: 10s of volts***	**1μW-20mW**	**$2.50 to $50.00**
Thermal 	**Small thermal gradients; efficient heat sinking**	***Constant impedance*** ***1Ω to 100s of Ω***	***DC: 10s of mV to 10V***	**0.5mW-10mW** **(20 C gradient)**	**$1.00 to $30.00**
RF & Inductive 	**Coupling & rectification**	***Constant impedance*** ***Low kΩs***	***AC: Varies with distance and power*** ***0.5V to 5V***	**Wide range**	**$0.50 to $25.00**

How Much Power is Available at the LOAD?

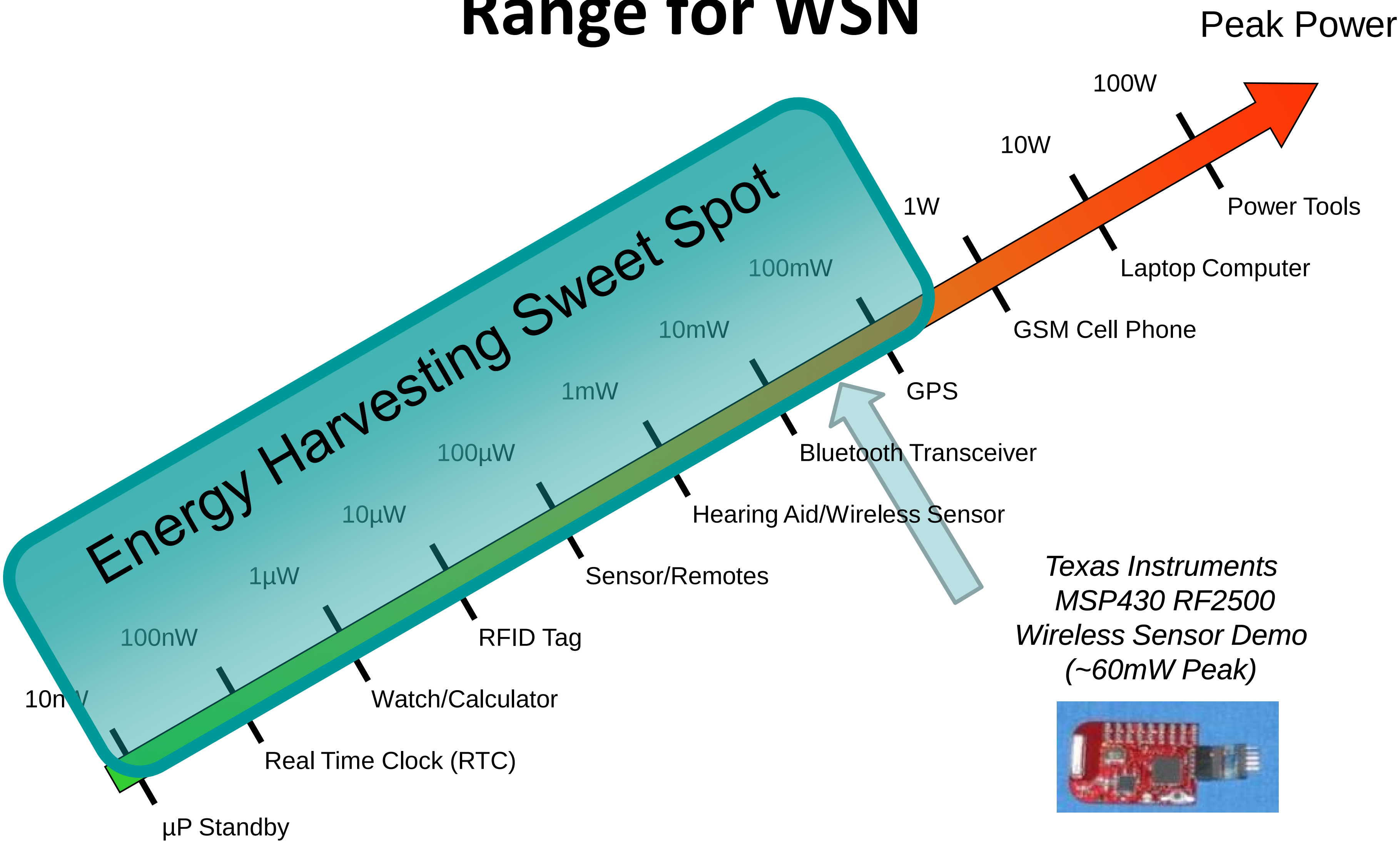
- Available Load power depends on:
    1. Energy source
    2. Transducer characteristics
    3. Power conversion efficiency

- Each energy source needs to be quantified

- Each source requires an optimized transducer

- Each source requires an optimized power manager

Energy Harvesting Power Range for WSN



Various EH Tracking Methods

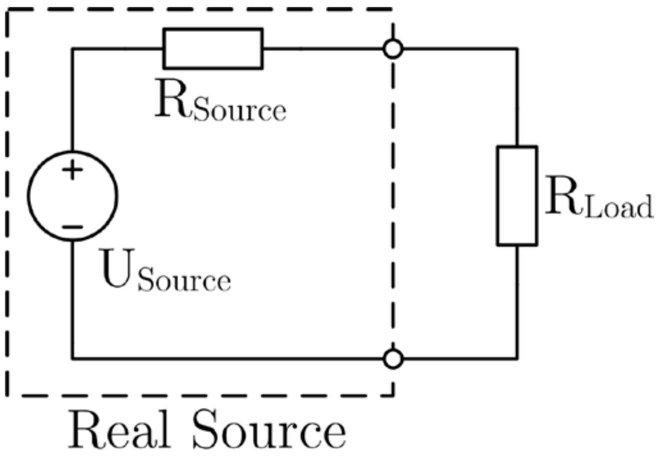
- MPPT algorithms
  - Incremental conductance (ΔP/ΔV)
  - P&O
  - Fractional OCV

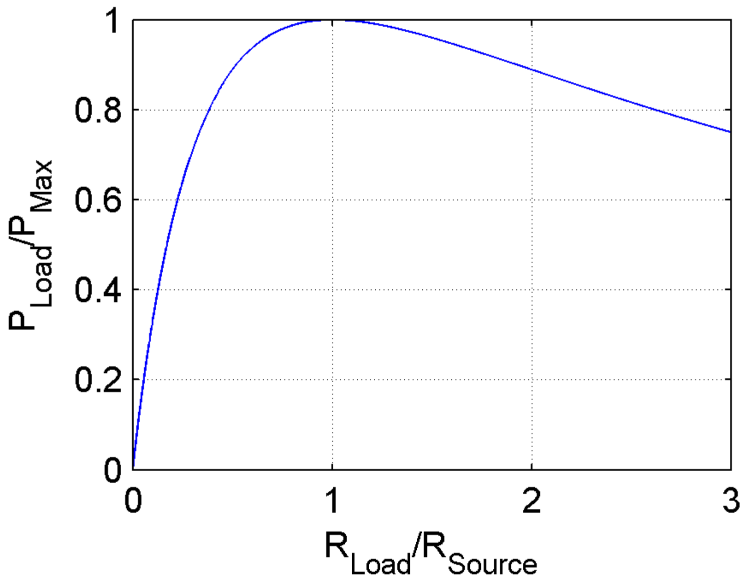
Hill climbing algorithms

- Fractional OCV (Open Circuit Voltage)
  - MPP voltage has a **fixed ratio** to open circuit voltage (0.7 – 0.8)
  - But: Ratio **not constant** and **different** for every generator
- Perturb & Observe
  - **Generic** algorithm
  - **Oscillates** around MPP

Utilize MPP Tracking

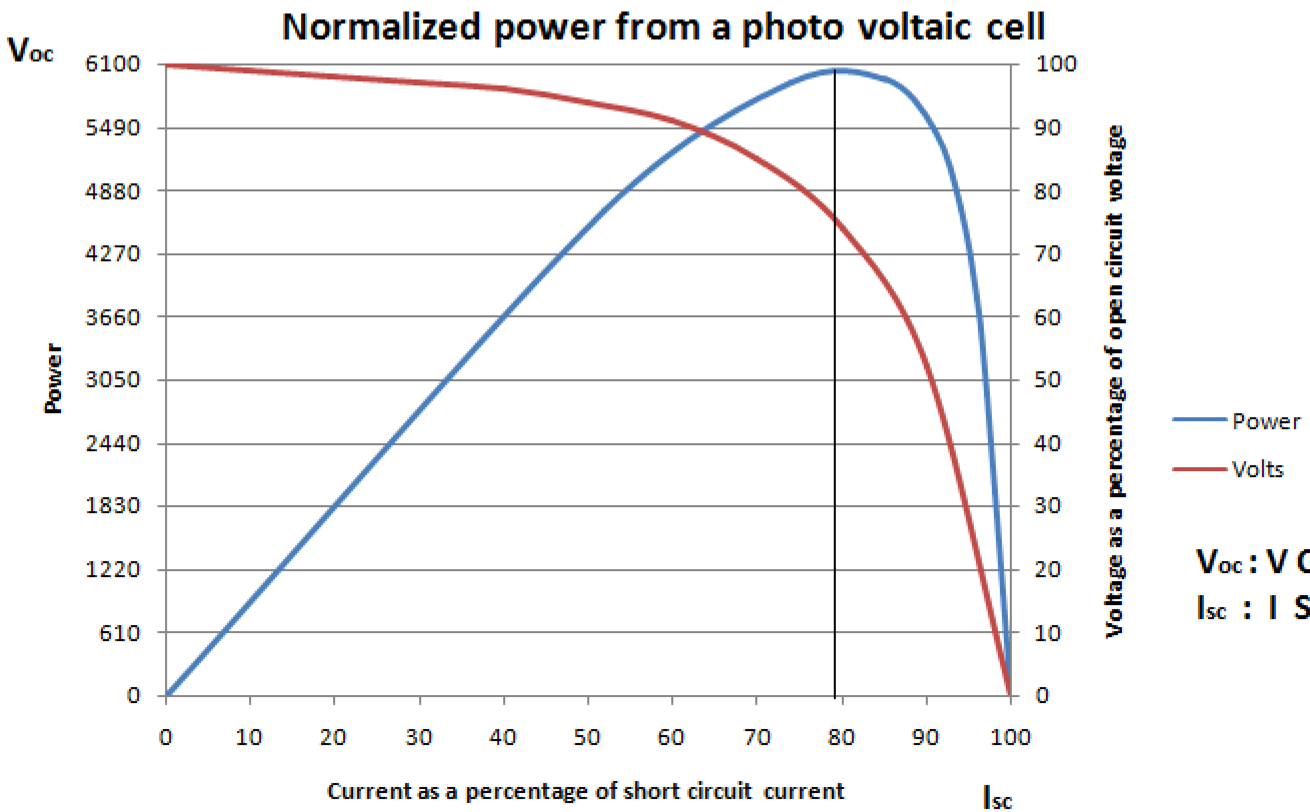
- What is the **Maximum Power Point**?





MPPT with Variable Impedance EH Transducer

Example: Photovoltaic Cell

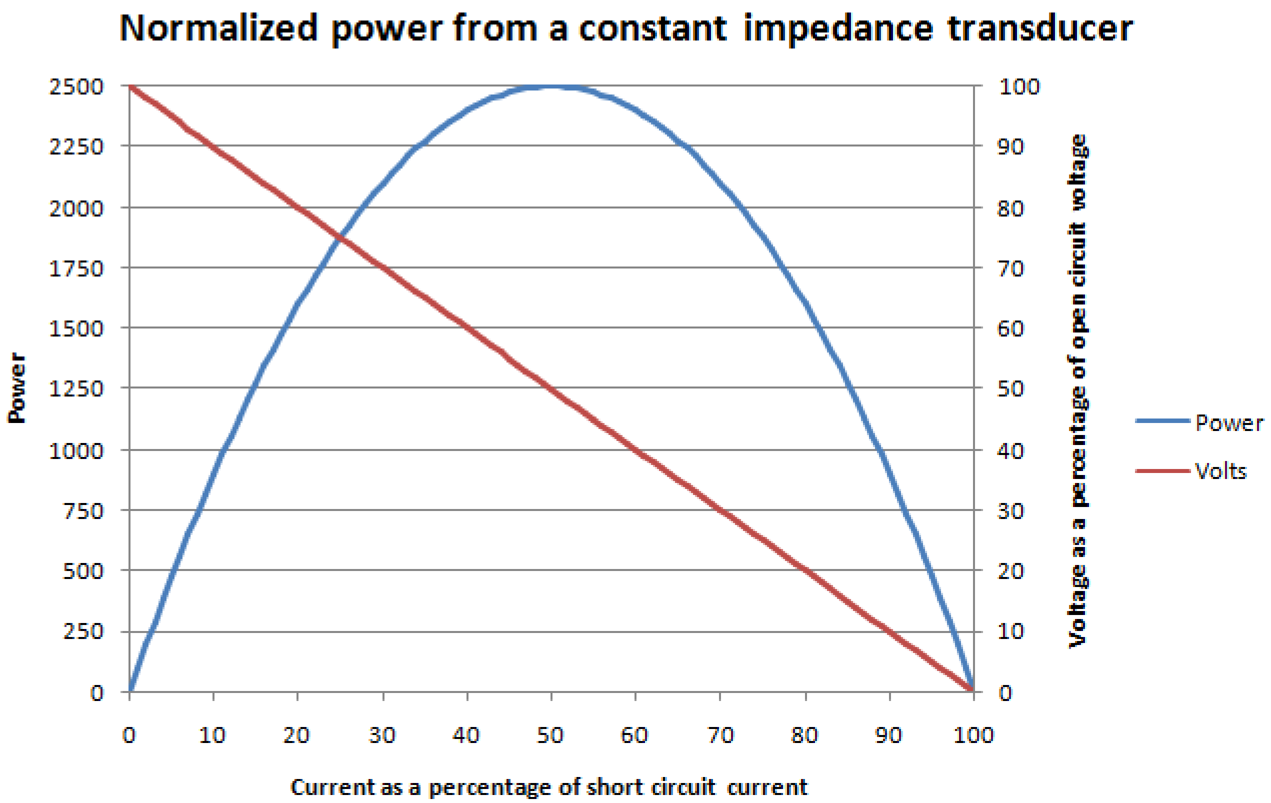


V_{oc} : V Open-circuit

I_{sc} : I Short-circuit

MPPT with Constant Impedance EH Transducers

Examples: Thermoelectric Generators, Piezoelectric Materials, Electromagnetic

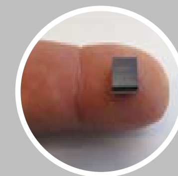


Energy Harvesting Needs New Storage Solutions

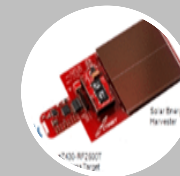
INCREASING PROLIFERATION OF ELECTRONIC DEVICES THAT ARE SMALLER, PORTABLE AND/OR CONNECTED

Ultra-Low Power Processors

Wireless Smart Devices & Sensors Everywhere



Component Integration and Miniaturization



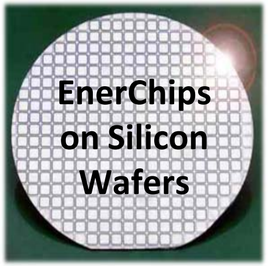
Eco-Friendly & Renewable Energy

Key Trends Driving Billions of New Devices

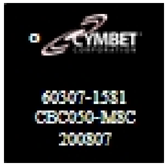
HOWEVER, EXISTING ENERGY STORAGE SOLUTIONS ARE INADEQUATE

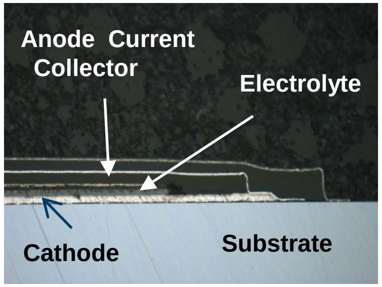
- LARGER PROFILE / BULKY SIZE
- LOW ENERGY FOR SPACE USED
- INTEGRATION ISSUES
- HIGH WEAR-OUT AND FAILURE ISSUES
- TOXIC CHEMICALS – SAFETY & DISPOSAL ISSUES

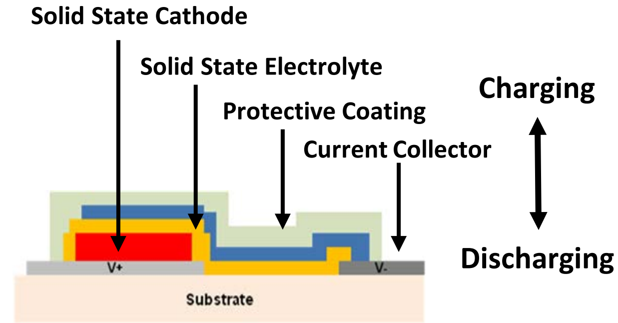
Rechargeable Solid State Batteries



EnerChip Co-packaged
Solid State Battery & PMU







EnerChip™ Solid State Batteries

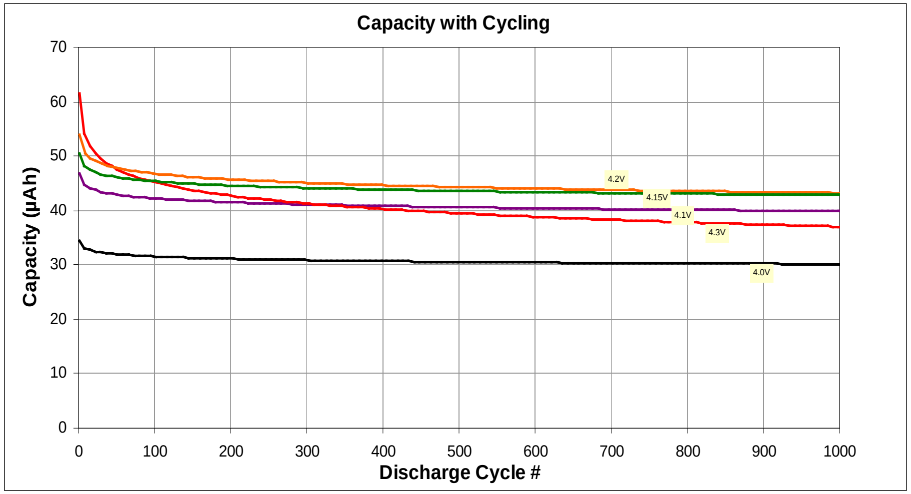
- Key Features: small footprint, long cycle life, fast recharge, ultra-low self-discharge, environmentally friendly
- Solid state energy storage solutions on silicon using common semiconductor manufacturing processes
- EnerChips are 150 microns thick (less than two human hairs) or 1/20th the thickness of a comparable battery
- EnerChips are efficiently co-packaged with other chips: Power Management, RTCs and MCUs – "Packaged Power"

EnerChip with Integrated Power Management/RTC and Energy Processor CBC915

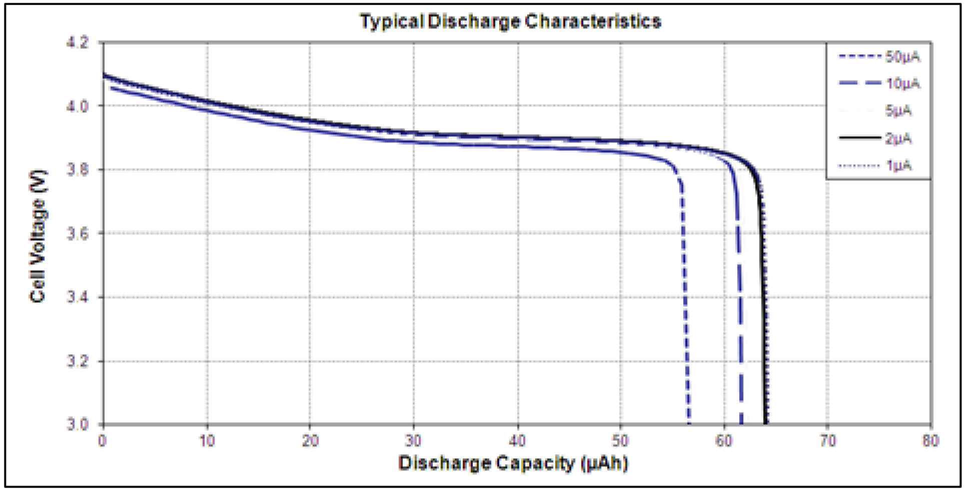
- The EnerChip battery is designed to integrate with other ICs; Cymbet has commercialized the "EnerChip CC", a co-packaged Solid State Battery and custom Cymbet Power Management ASIC for a drop-in solution – a "UPS in a Chip". The EnerChip RTC integrates a Real Time Clock chip with the EnerChip CC CBC3105.
- To enable high efficiency "Plug and Play" Energy Harvesting (EH) solutions, the custom Cymbet EnerChip CBC915 Energy Processor uses an advanced patent-pending Maximum Peak Power Tracking algorithms for high efficiency energy conversion and management

Key EH Battery Requirements

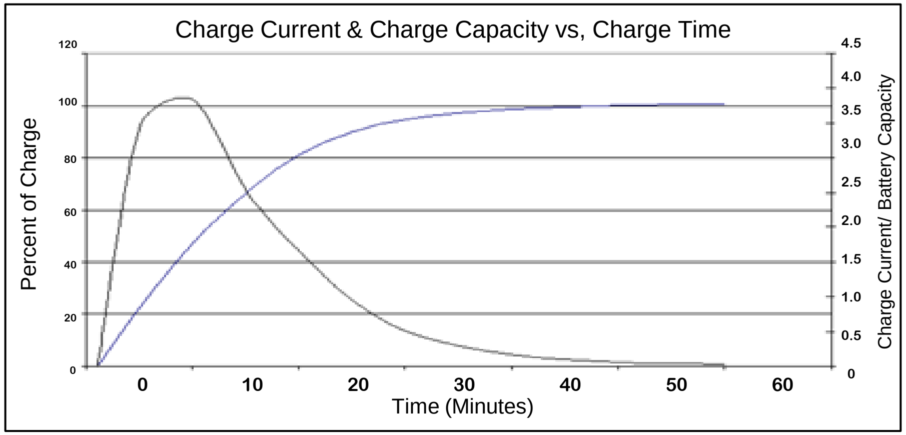
High Cycle Life



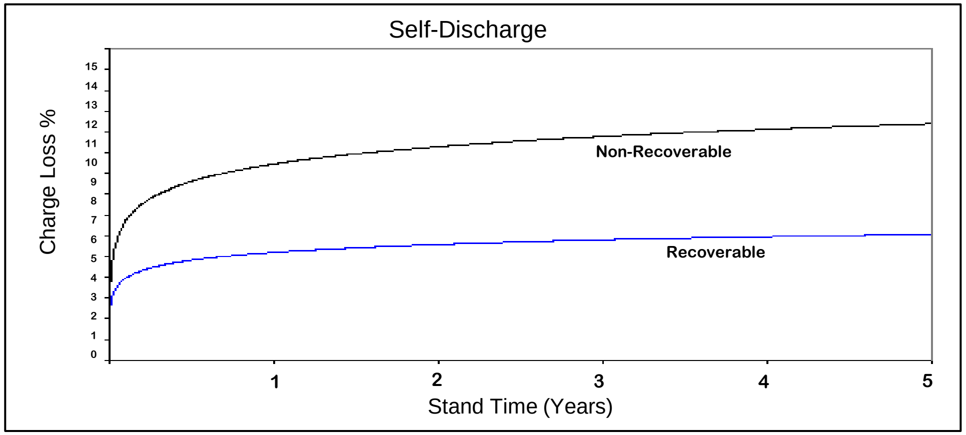
Flat Output Voltage Profile



Fast and Simple Charge



Low Self-Discharge



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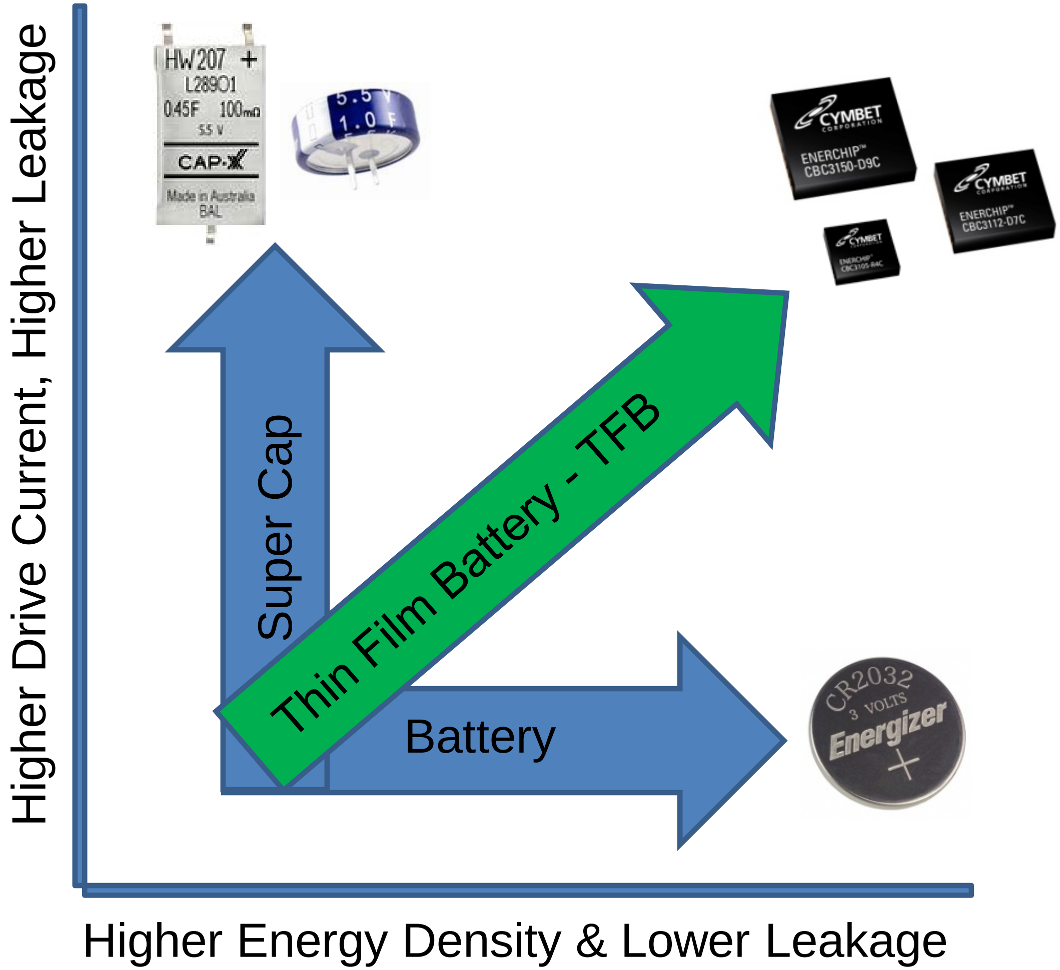
Rechargeable Solid State Batteries



SSB = Best of Both Worlds

- High Drive Current
- High Energy Density
  - *50 X SuperCap*
- Lowest Leakage
  - *4,000 X < SuperCap*
- Rechargeable / Long Life
- Superior Lifetime Energy – never replace a battery

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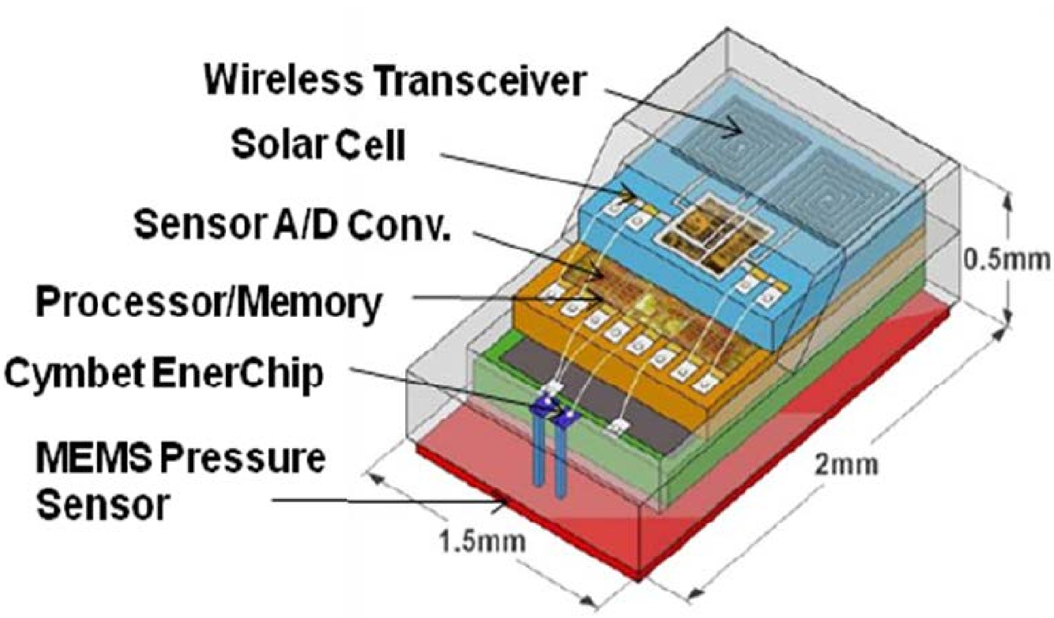
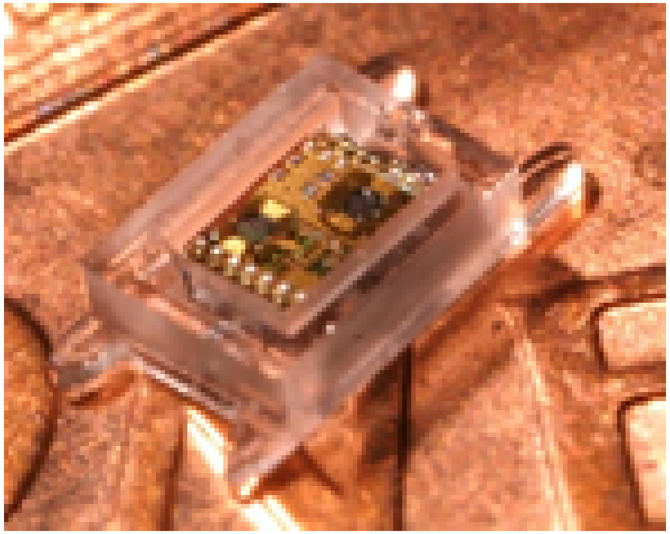
Example of Wireless EH-Powered Intra-Ocular Pressure Sensor



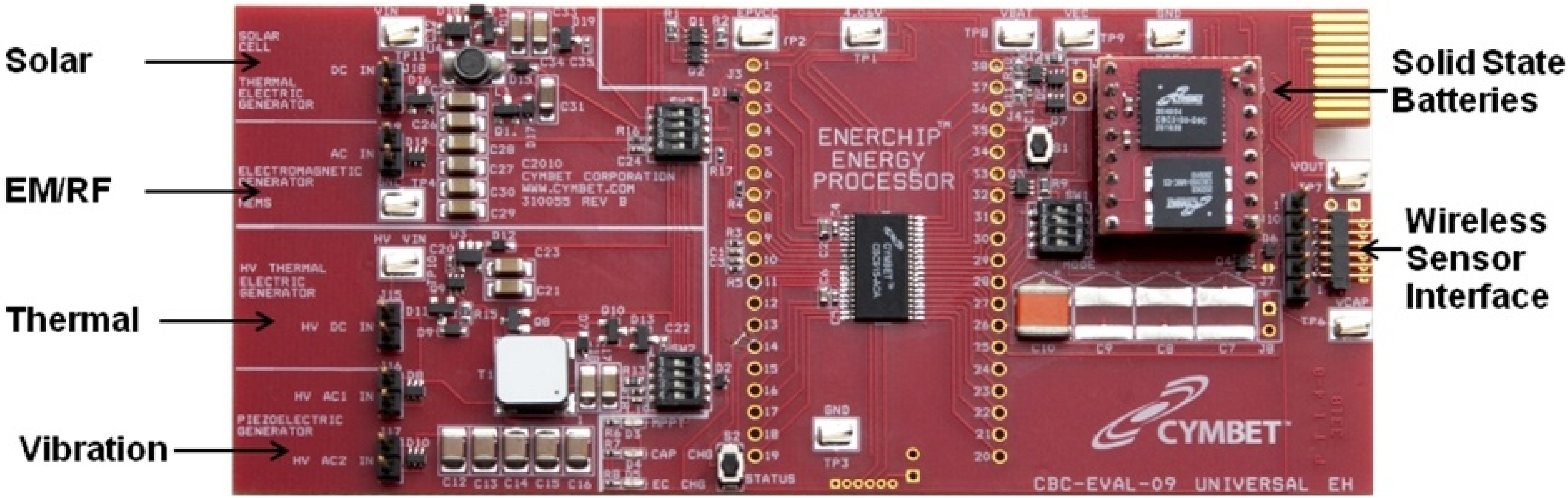


University of Michigan ISSCC Paper: ***http://www.cymbet.com/design-center/wireless-sensors.php***

Power Design Tips Summary

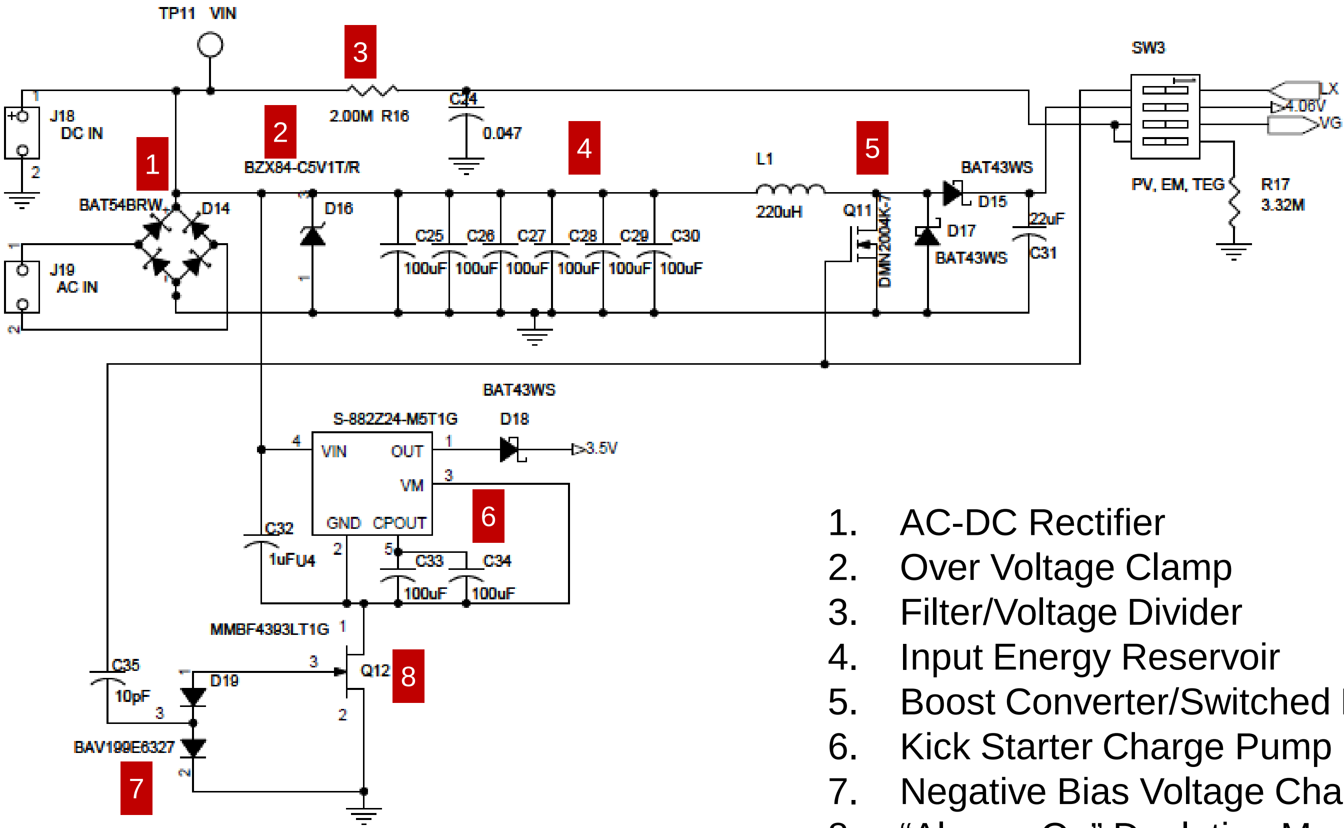
- Most power available if load **matches source**
- **Power management** ensures maximum power output
- **Energy storage** always required
- **Transducer size can be reduced** due to more efficient power management
- System costs **significantly lower** when transducers are smaller

Each EH Transducer has Different Harvesting Circuitry



Example: Cymbet CBC-EVAL-09 Energy Processor
Universal Energy Harvesting Eval kit

Low Voltage EH DC or AC
Solar, Thermal, Electromagnetic



1. AC-DC Rectifier
2. Over Voltage Clamp
3. Filter/Voltage Divider
4. Input Energy Reservoir
5. Boost Converter/Switched Rectifier
6. Kick Starter Charge Pump
7. Negative Bias Voltage Charge Pump
8. “Always On” Depletion Mode JFET

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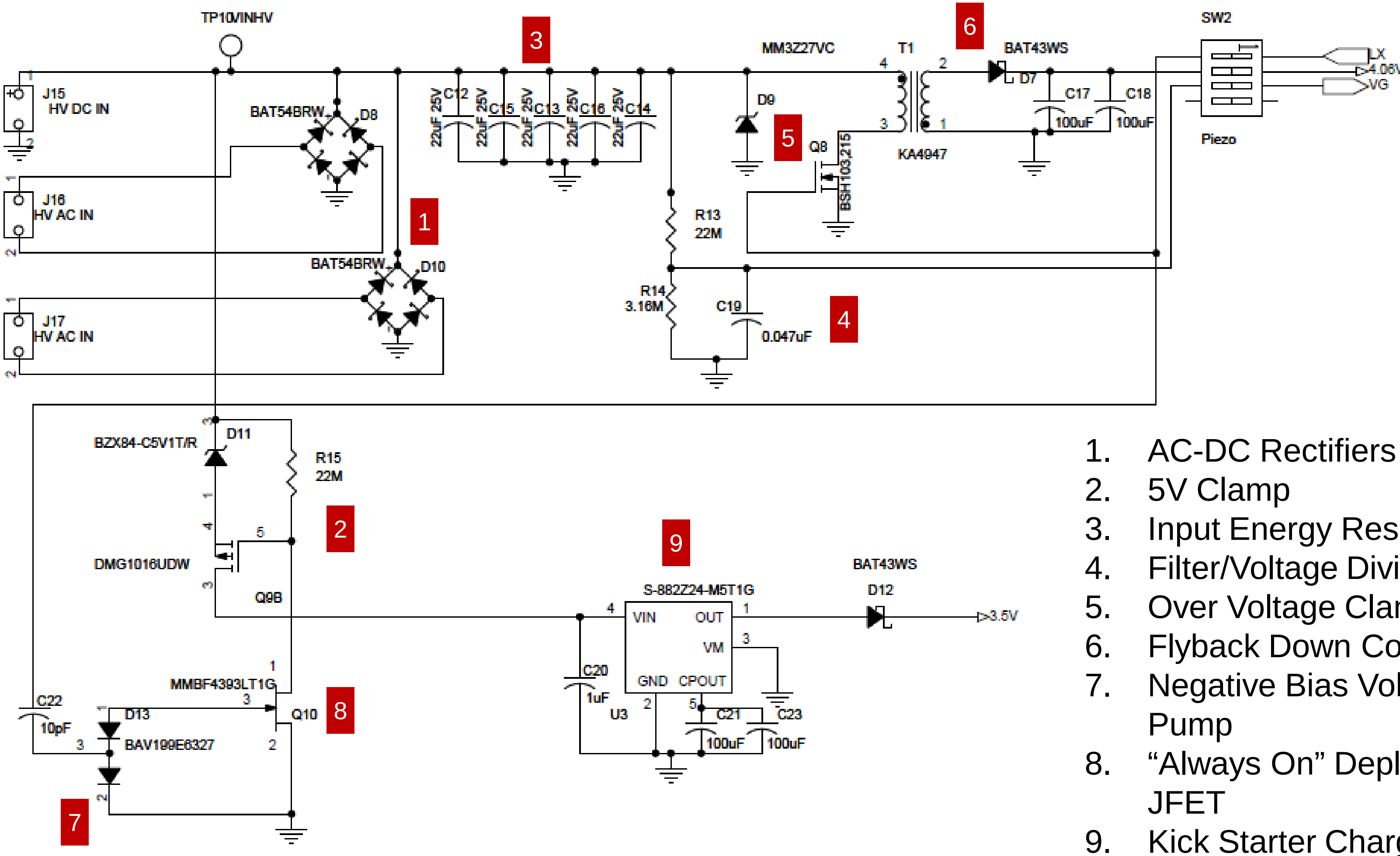
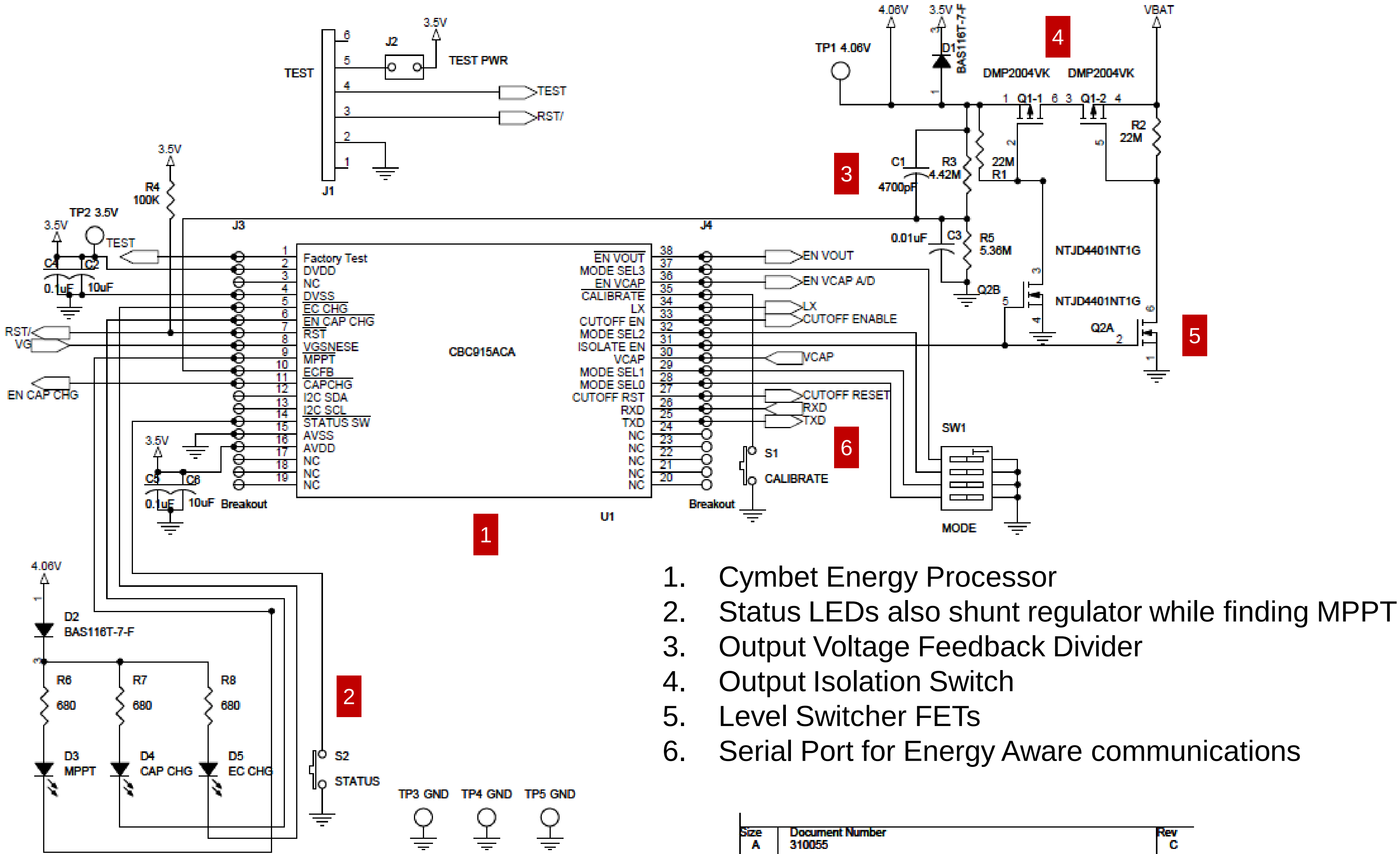
High Voltage DC or AC Piezoelectric, Thermoelectric



1. AC-DC Rectifiers
2. 5V Clamp
3. Input Energy Reservoir
4. Filter/Voltage Divider
5. Over Voltage Clamp
6. Flyback Down Converter
7. Negative Bias Voltage Charge Pump
8. “Always On” Depletion Mode JFET
9. Kick Starter Charge Pump

Energy Processor – MPPT



1. Cymbet Energy Processor
2. Status LEDs also shunt regulator while finding MPPT
3. Output Voltage Feedback Divider
4. Output Isolation Switch
5. Level Switcher FETs
6. Serial Port for Energy Aware communications

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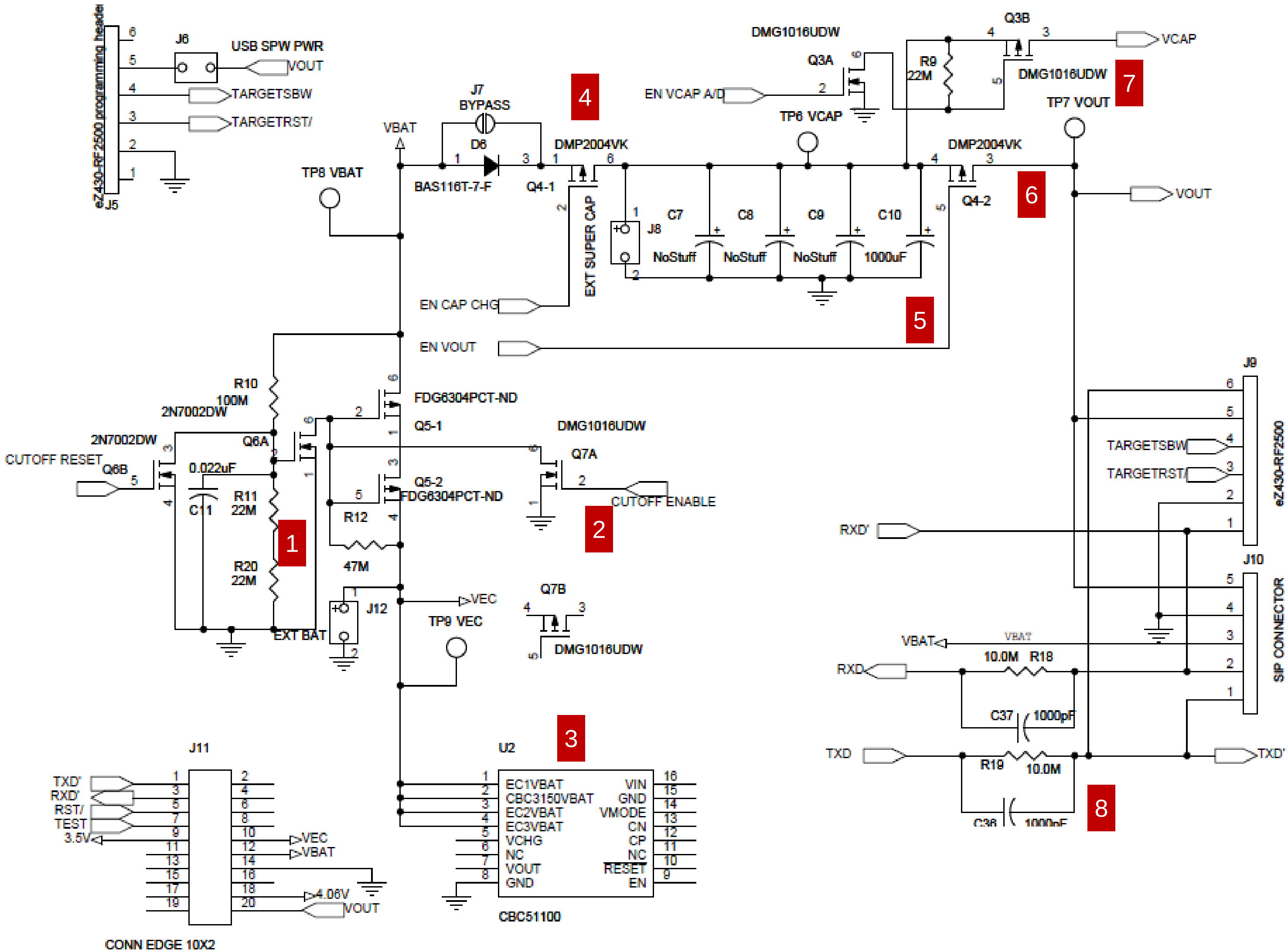
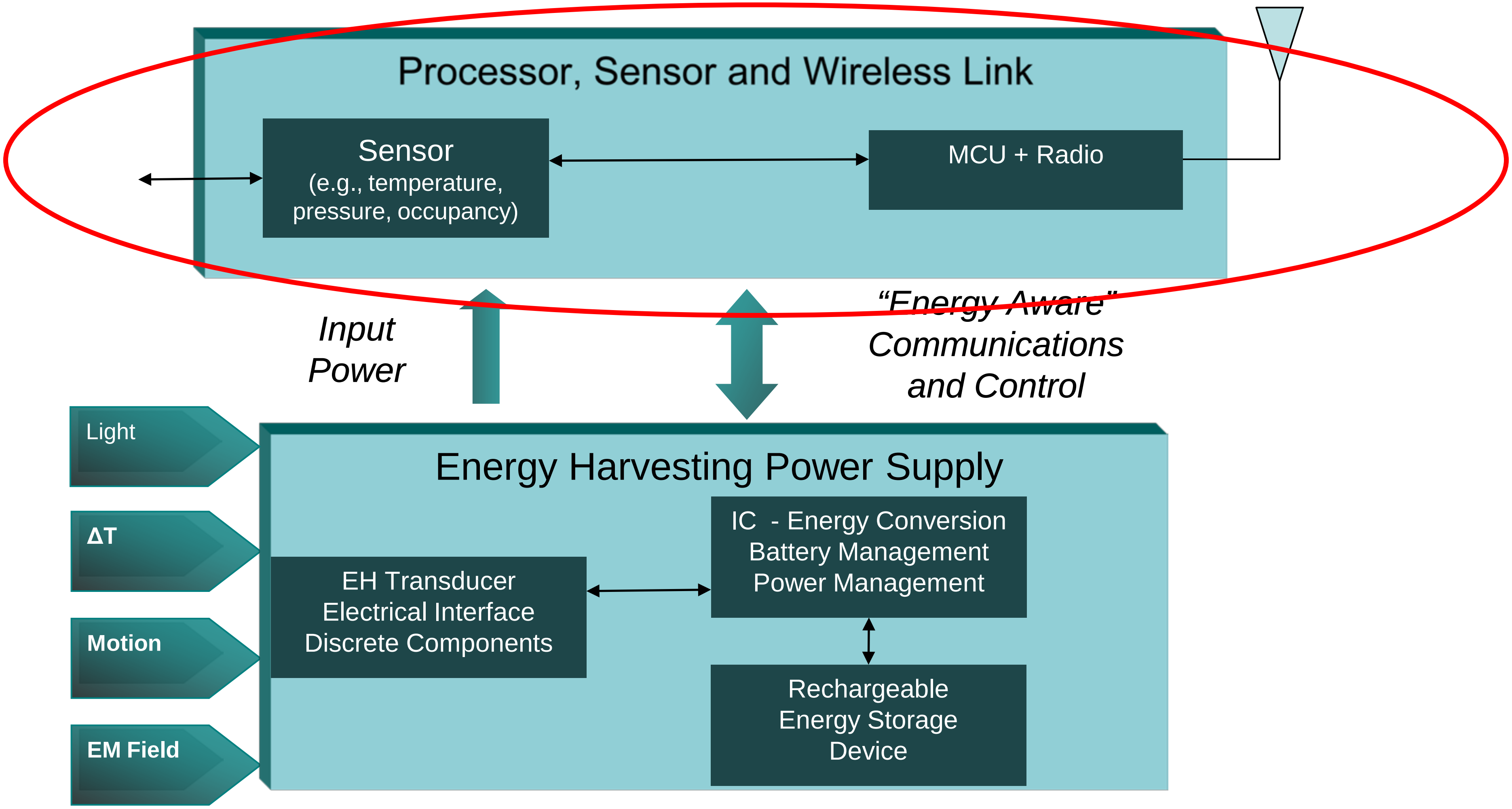
Battery Charging, Powering Load and Comms

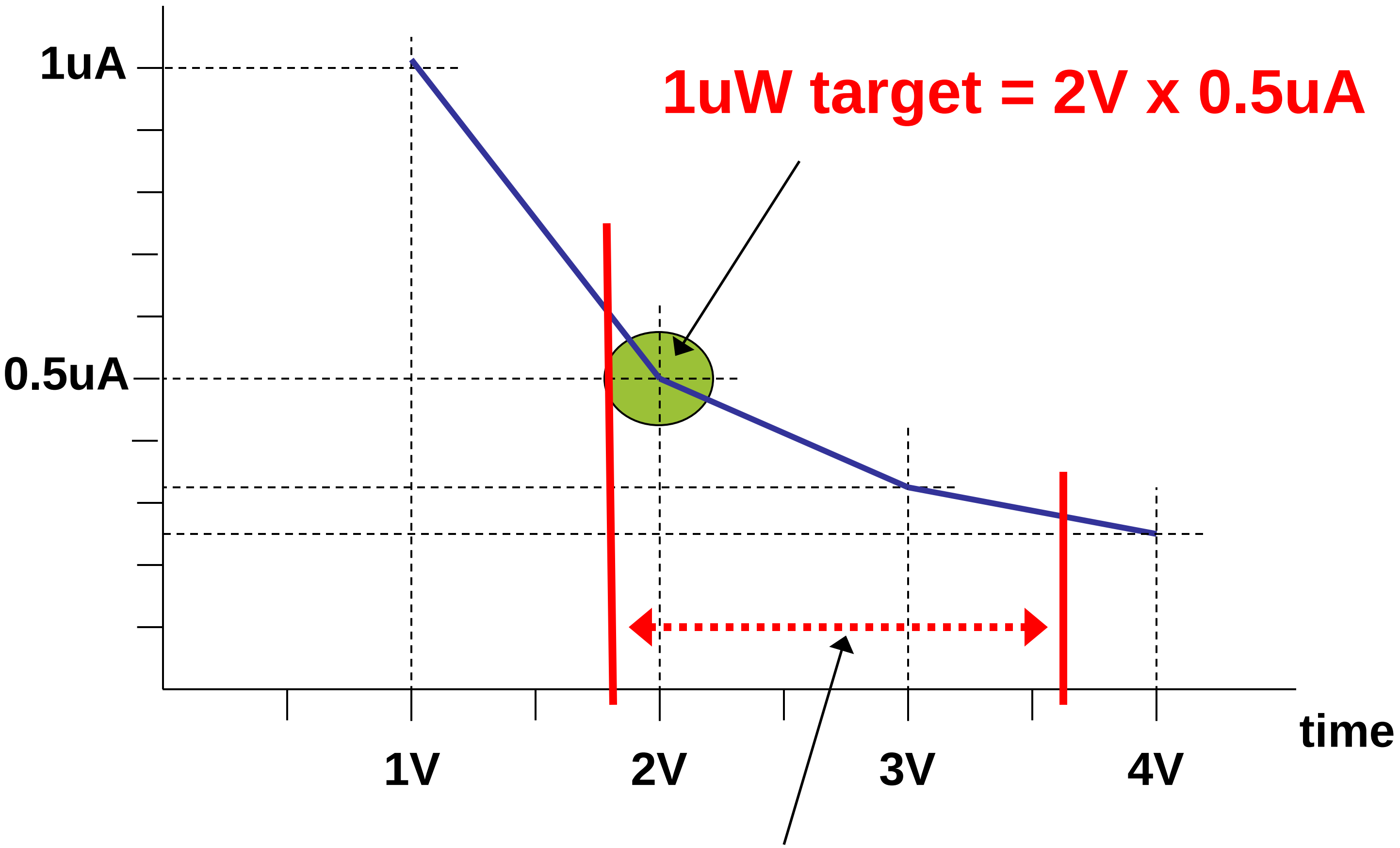


1. Cutoff Trip Point Bias
2. EnerChip Low Voltage Cutoff
3. EnerChip Solid State Batteries
4. Boost Capacitor Charge Isolation
5. Output Boost Cap (Radio)
6. Output Isolation Switch
7. Isolation Switch to CBC915
8. Serial Port Isolation

Focus on MCU, Radio and Sensors

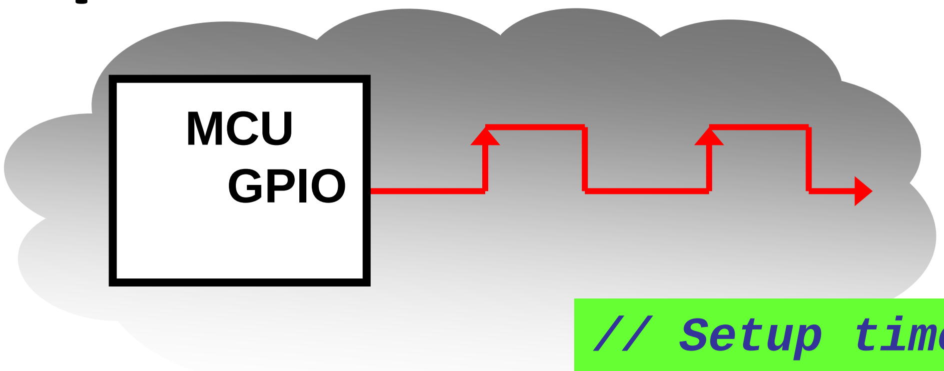


1uW MCU Operation



Target MCU operating range = 1.8V – 3.6V

Optimized Code is Critical



0% CPU Load!

```
// Setup timer output unit
 CCTL1 = OUTMOD0_1;
 _BIS_SR(CPUOFF);
```

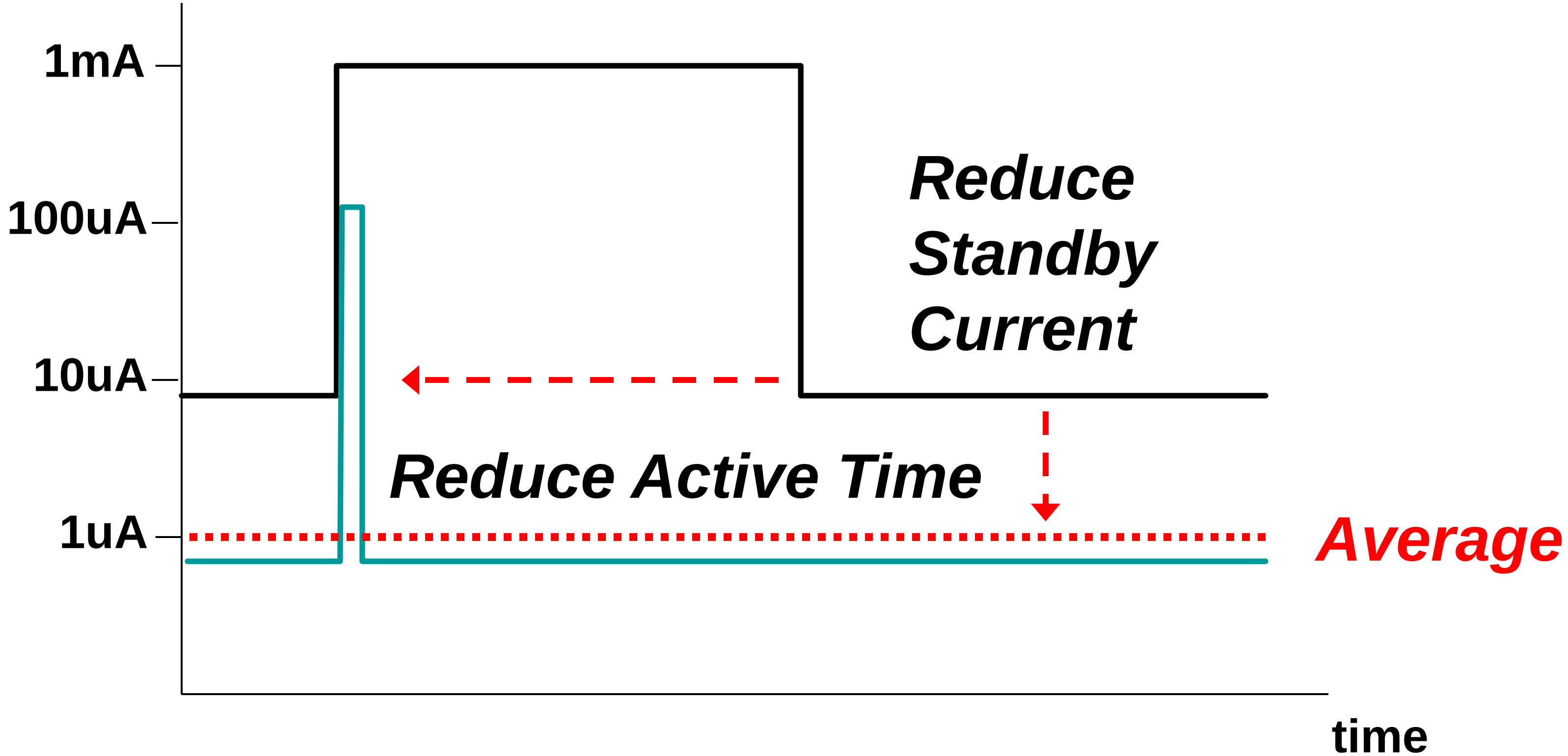
0.01% Load

```
#pragma vector=WDT_VECTOR
_interrupt watchdog_timer (void){
  P1OUT ^= 0x01;  // Toggle
}
```

100% CPU Load

```
while (1){
 P1OUT ^= 0x01;              // Toggle
 __delay_cycles(10000);  // Delay
}
```

Ultra-low Power Activity Profile



Average approaches standby

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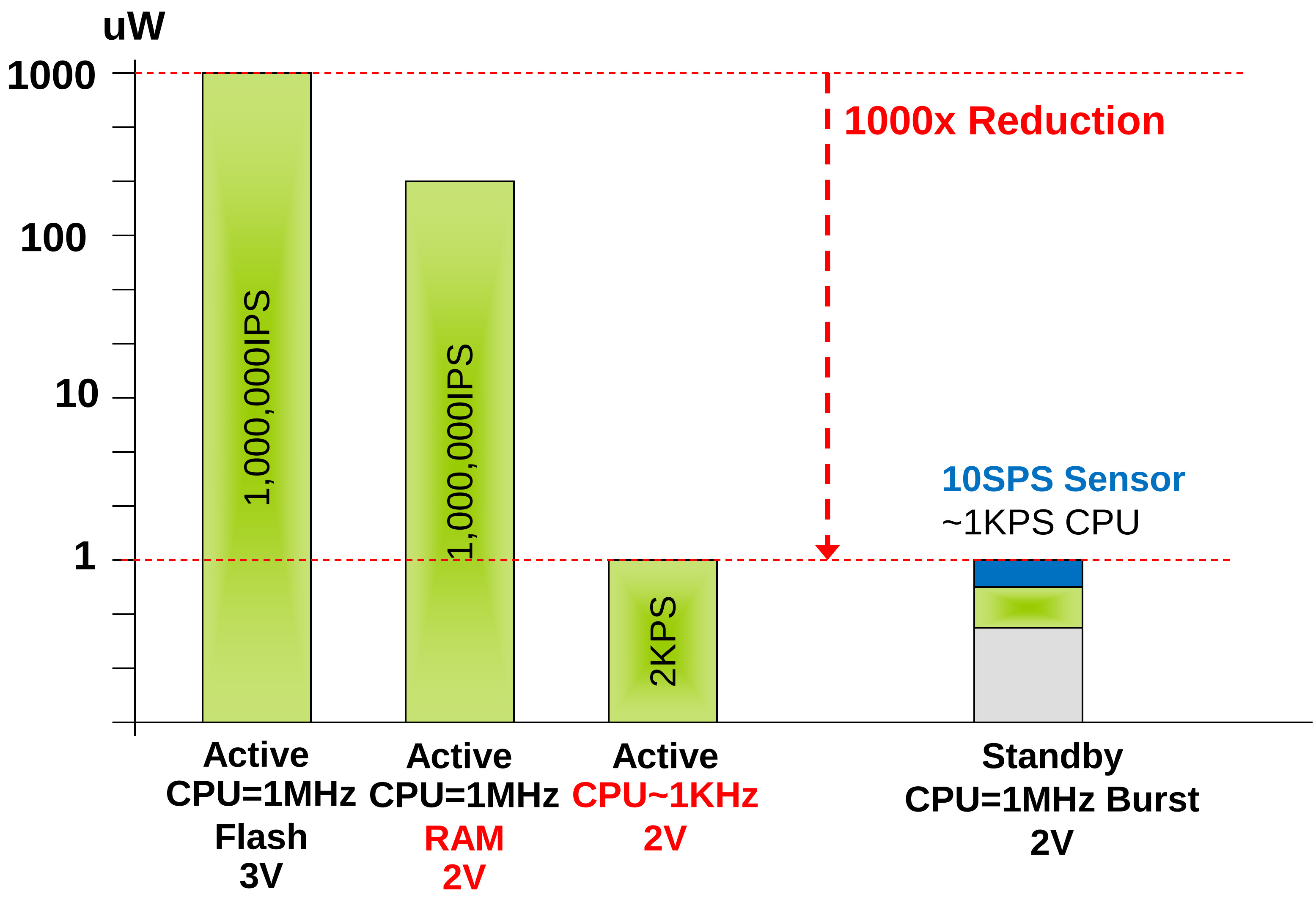
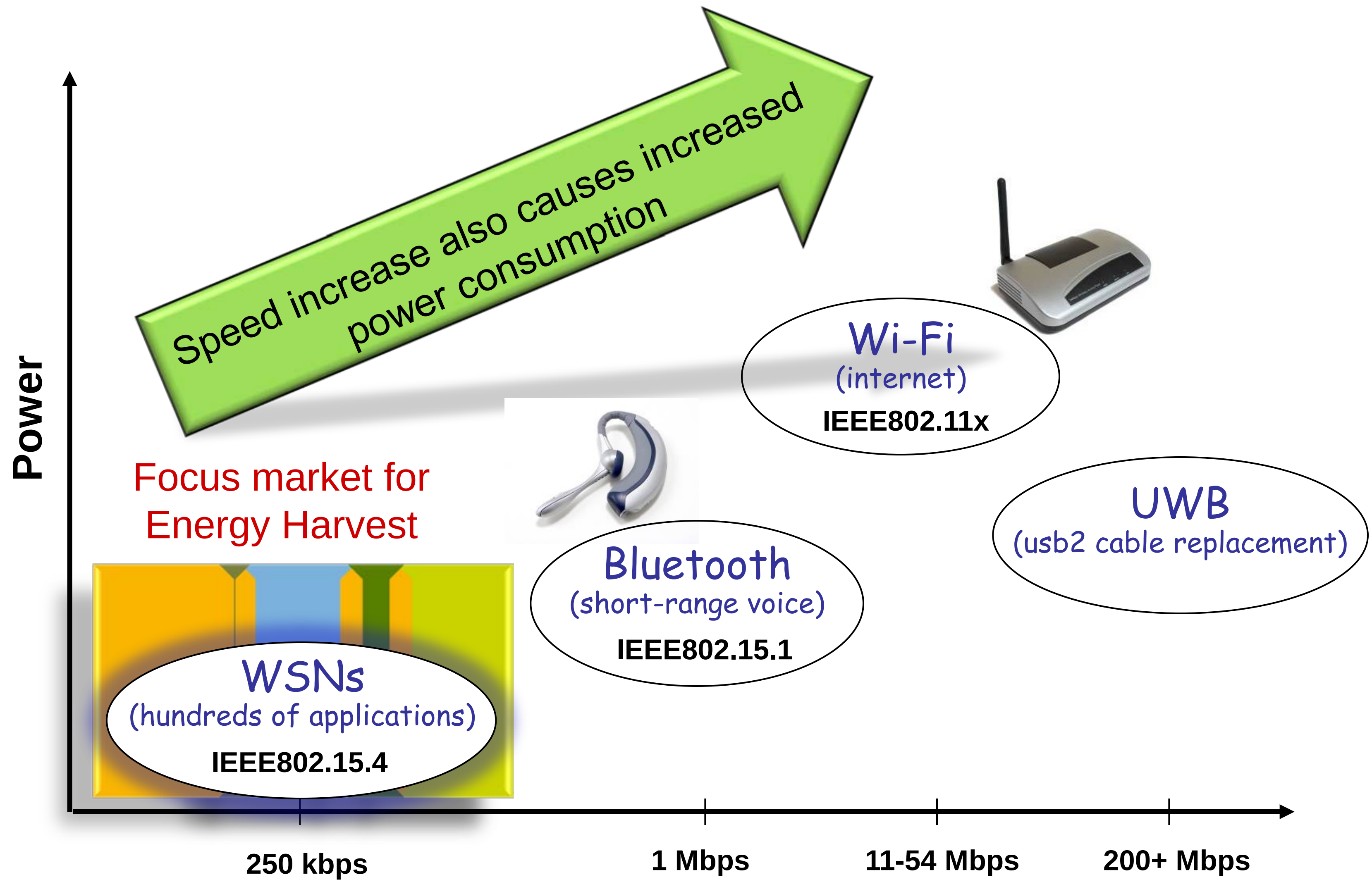
1uW Computing + Sensor Processing



Tips for Achieving 1uW Computing

- **Off-the-shelf 'F20xx is capable of 1uW computing**
  - Performance of 1-2KIPS
  - Including Sensor sample 1-10 Samples Per Second
  - ULP standby clock
  - Instant-on and very accurate high-speed clock
  - I/O, interrupt capability, BOR and all RAM retained
- **Traps**
  - Firmware
  - Temperature increases leakage significantly
  - Floating inputs
  - Multiple voltage domain satiation
  - Watch for un-deterministic clocking
  - Where to get a 2V supply in a real application?

Wireless Evolution



Comparing Wireless Options

Increasing priority ←

	Implementation Price	Power	Co-existance with other networks	Large-scale Networking stack	Small-scale Networking stack	Wireless Microcontroller design route	Interoperability	Encryption	Datarate
Bluetooth	Low	High	Poor	No	Yes	No	Yes	Fair	High
BT LE	Low	Low	Poor	No	Yes	No	Yes	Fair	High
Proprietary	Low	Low	No	No	No	Yes	No	No	Low
802.15.4	Low	Low	Good	Yes	Yes	Yes	Yes	Good	Low
WiFi	High	High	Good	Yes	Yes	No	Yes	Good	High

- **IEEE802.15.4 offers optimal solution**
  - Designed to operate in large networks of devices
  - Lowest cost. Flexible design solution for many different applications
    - » No ‘application-profiles’ ensures design flexibility
  - Lowest power with prospect of interoperability
  - Co-existence with other wireless networks (e.g. Wi-Fi)

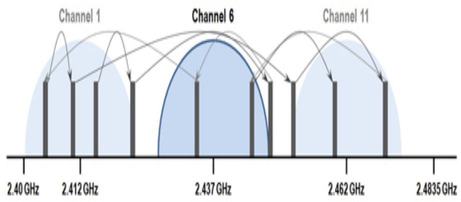
What about range?

Bluetooth versus 802.15.4

When to use Bluetooth

Stereo Audio

Cell phone already has BT



No WiFi interference or use AFH

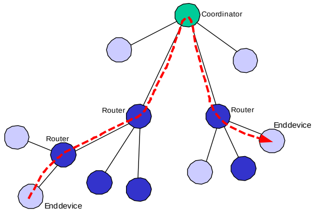
Problems with Bluetooth

Spec changes every 18 months

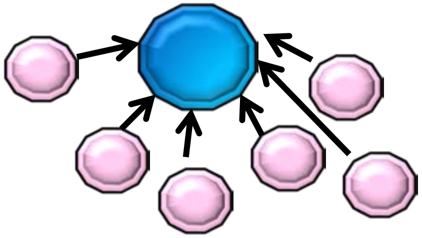
Channel hopping will cause interference

Benefits of 802.15.4

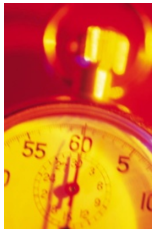
Multiple channels



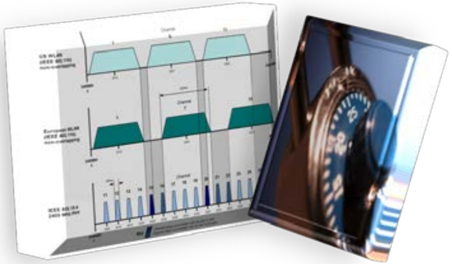
Network of devices



Large number of connections



Fast connect times of 6mS



Coexist by locking onto a clear channel

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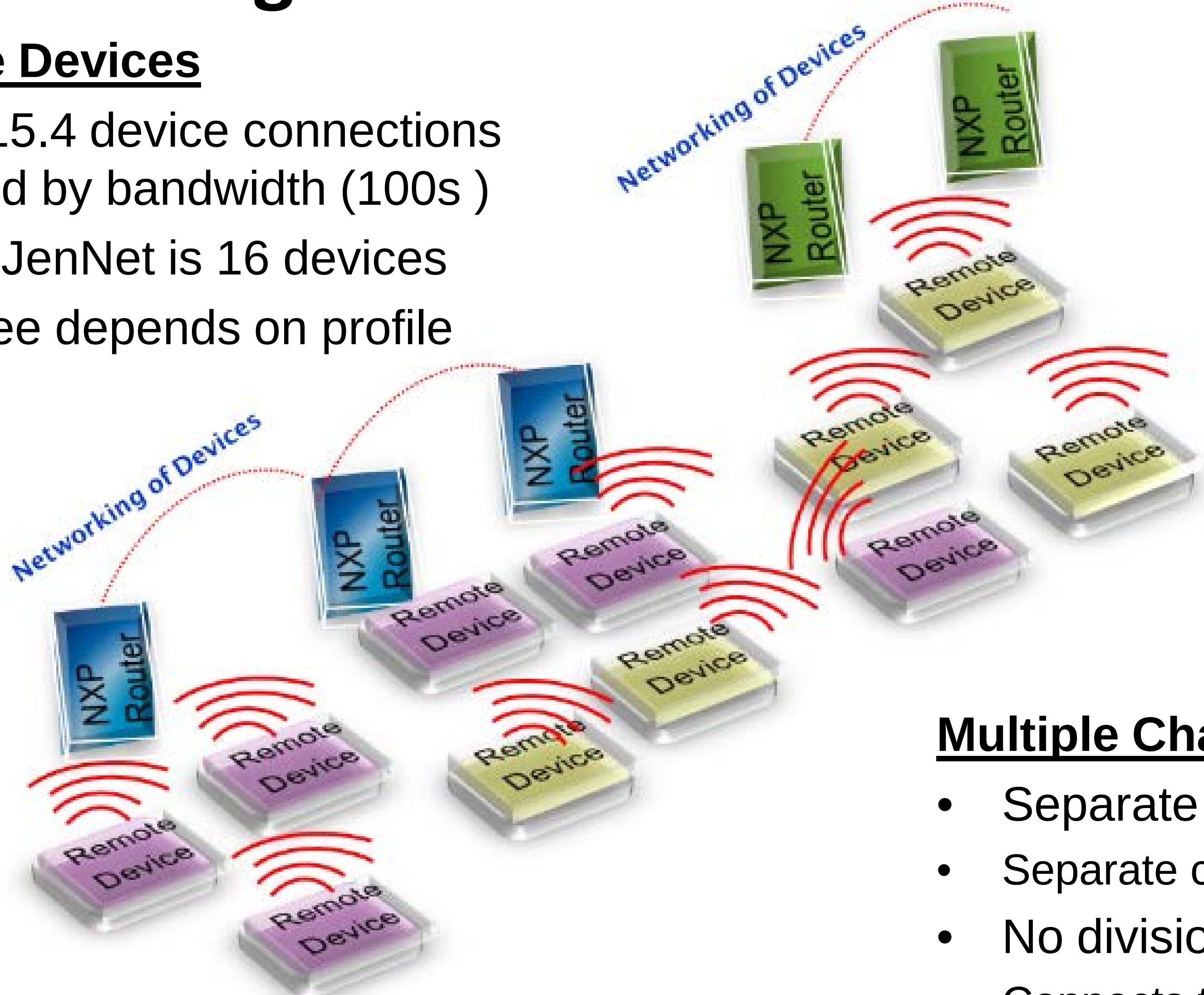
Using Wireless Mesh Networks

Multiple Devices

- 802.15.4 device connections limited by bandwidth (100s)
- NXP JenNet is 16 devices
- ZigBee depends on profile

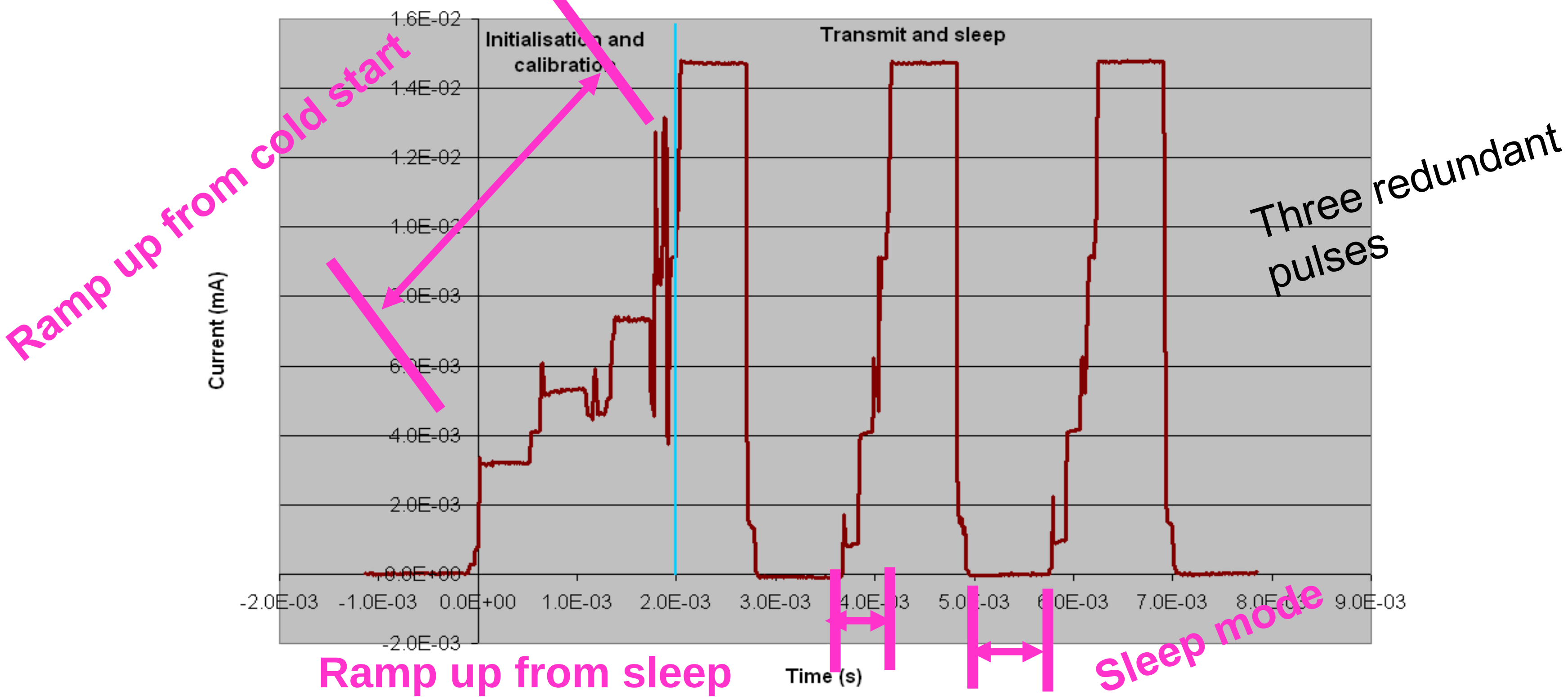


Multiple Channels

- Separate PAN id
- Separate channels
- No division of bandwidth
- Connects to its router

802.15.4 Current Profile (Minimum Required)

- Very low overall energy consumption due to very low TX current
- Significantly lower energy usage than competing single chip products



Full solution is achieved using just 50uC of charge (100uJ at 2v)

EH Sensors and Controls Example

Owner: Local Government Lombardei

OEM-Partner: Siemens

Situation
- 39 Floors
- 530 ft.
- 72.000 sqm Floorspace

Solution
- Flexible BMS
  - 400 EnOcean-KNX-Gateways for Full-Radio Coverage
  - 1580 EnOcean-Rocker for Lighting Control (DALI)
  - 2500 EnOcean Room-Units Temp./Setpoint

Benefit
- Flexible Roomstructure
- Quick and easy installation
- Saving of time Initialinstallation and Retrofit

Echoflex Solutions, Tambient

Glumac "Office of the Future"

- Irvine, CA
- New Construction, Lighting/HVAC
- 8,500 sq. ft.

BACnet

- EnOcean wireless extension to wired BACnet
- Occupancy based-lighting and climate control
  - Task-ambient luminaires & controls helped Glumac beat California Title 24 lighting allowances by 75%
- USGBC LEED PLATINUM
- (file picture)

Summary

- Cost effective Energy Harvesting power based systems can be designed using new technologies and intelligent design techniques
- Utilize appropriate EH transducers
- Implement high efficiency energy conversion, rechargeable energy storage and energy aware power management
- Ultra low power MCUs, Wireless links/protocols and sensors
- Ideal solutions are highly-efficient, eco-friendly, power generation systems that can be cycled continuously for the life of the product