



BATTERY POWER
2017
MAY 17-18 • DALLAS



Battery Power 2017 Keynote Address: Energy Harvesting is Changing the Battery Landscape from Consumer to 5G

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Overview

- Some Food For Thought
- The Market / Motivations
- Energy Harvesting (EH)
- EH Applications
- EH Vs. Batteries
- Conclusions



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A Quick Survey

How many folks think EH is more academic than ready for production today?

How many folks think EH has a production ecosystem today?



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Some Food For Thought

All we need is improved battery storage technology so we can go a really long time without having to plug-in and recharge, right?

WRONG!!!

*“There is no such thing as **waste heat**...just underutilized **energy recycling opportunities**.”*

– Brian Zahnstecher

$$ENERGY_{UTILIZATION} = \frac{ENERGY_{IN}}{ENERGY_{OUT}}$$



Some Food For Thought

- **Goals**

- **Short-Term:** Mitigate Battery Usage
- **Long-Term:** Complete Utilization of Free Energy

What?!?
Who invited this jerk to a
battery conference?

- **EH is *NOT* All or Nothing**

- Extend Battery Life
- Standby Power
- Complimentary Technologies



Some Food For Thought

- **Negligible power?**

- Value of saving mW in 10s of Billions or *TRILLIONS* of devices???
- pW → nW → μW → mW
- ICs in standby can run on nW & μW
- Harvest from Multiple Sources with Multiple Methods
- Combine with Improved Utilization and Intelligent Power Management (IPM) to Multiply the Value of Each μW
- **FYI:** a bigger battery is **NOT** the answer!

...much more on EH & IPM later.



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The Market / Motivations

- **Billions of smart devices + Massive Networks = Awesome!**
- **Devices + Consumer Interest/Application = Exponential Growth Market Estimates!!!**

- **Wait a sec, how are we enabling these transformative technologies and fantastic market projections?!?**
 - Innovations in power electronics & energy harvesting will drive the integration and intelligent power management required for enablement.



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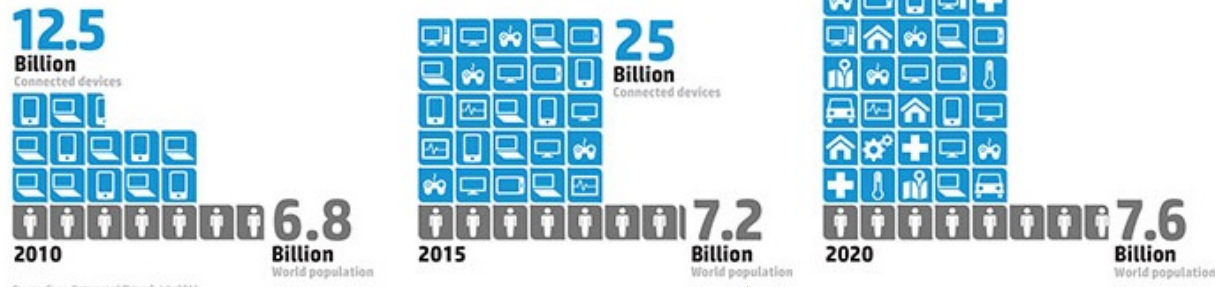
The Market / Motivations

- **50B Devices!!!**

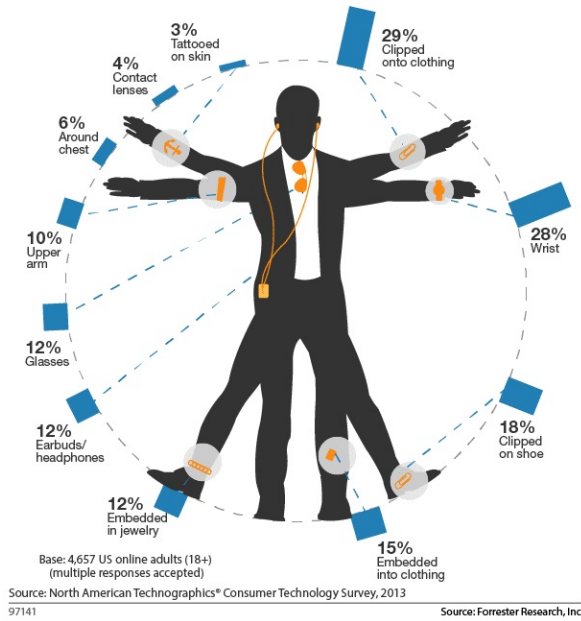
- Ok...more like 15-30B...still not exactly a tiny number.
- Hockey sticks or hype? Why not both?
- Number of devices downgraded...but maybe not with battery mitigation.

The Internet of Things will experience a continued growth spurt into the next decade

The number of connected devices will double every five years, making the world's population growth seem glacial in comparison



Raise your hand if you are sick of this graphic.



That is a lot of stuff for a non-bionic being!

The Market / Motivations

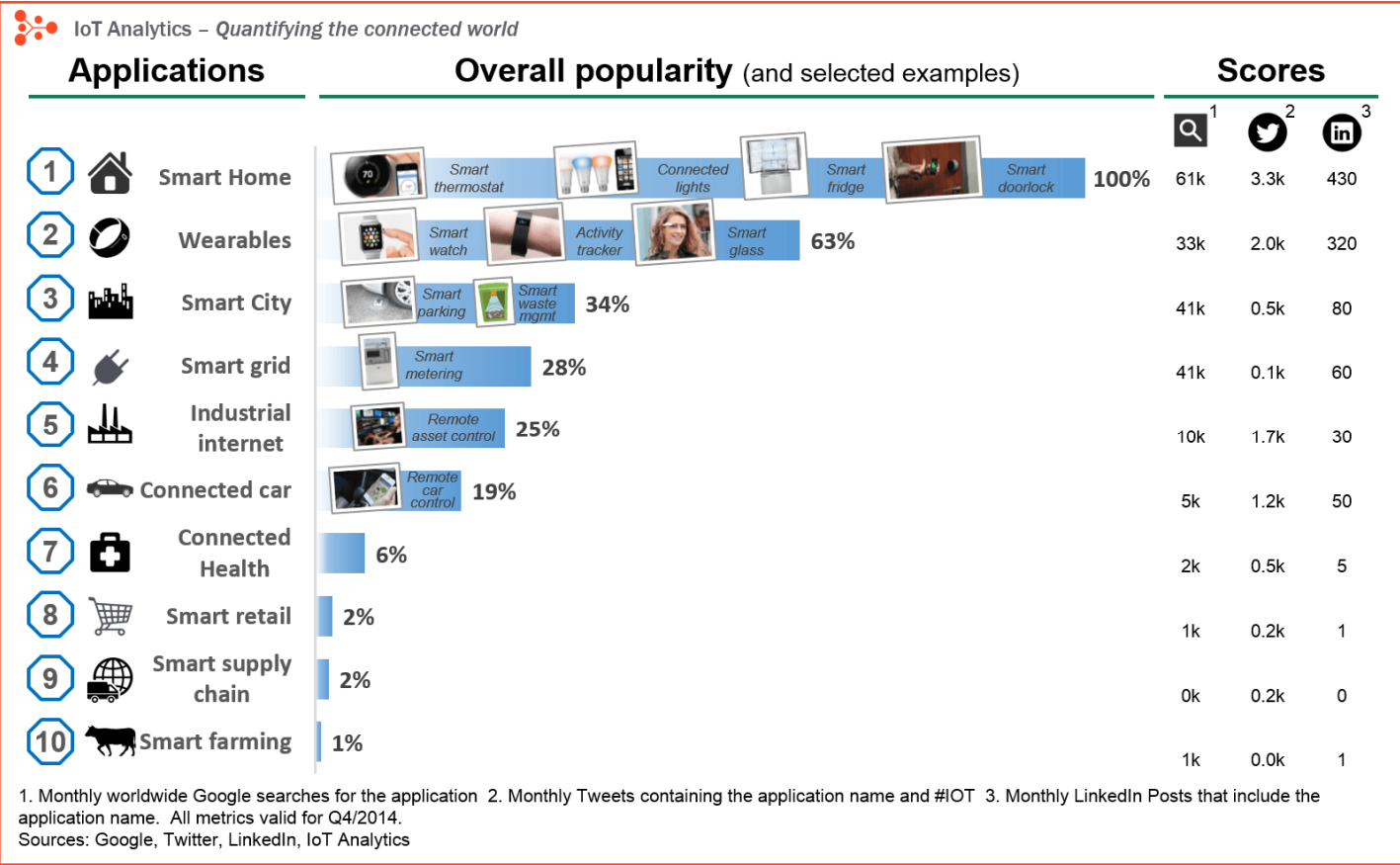


IMAGE CREDIT: Knud Lasse Lueth, "The 10 most popular Internet of Things applications right now," IoT Analytics, February 2, 2015.



The Market / Motivations

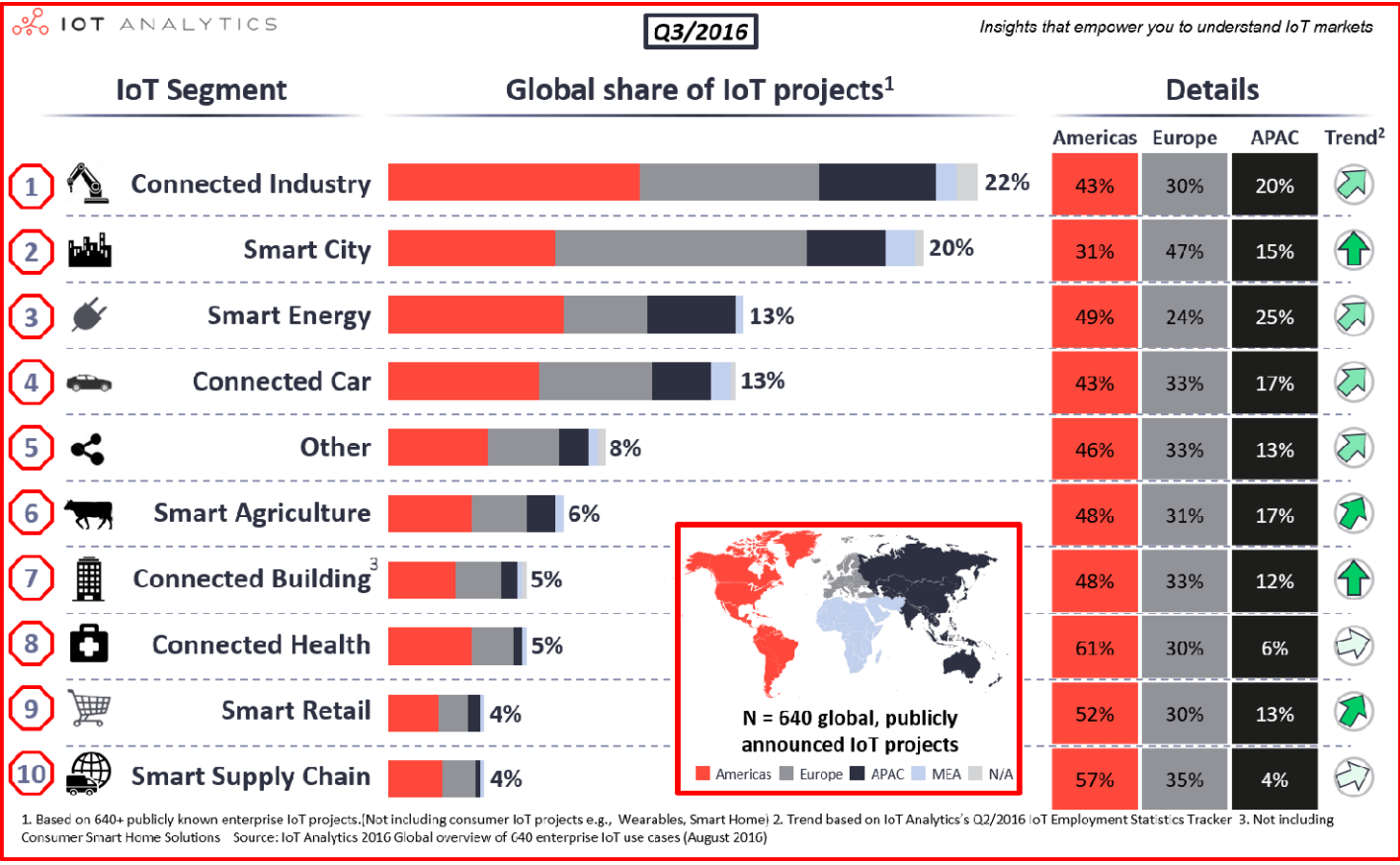
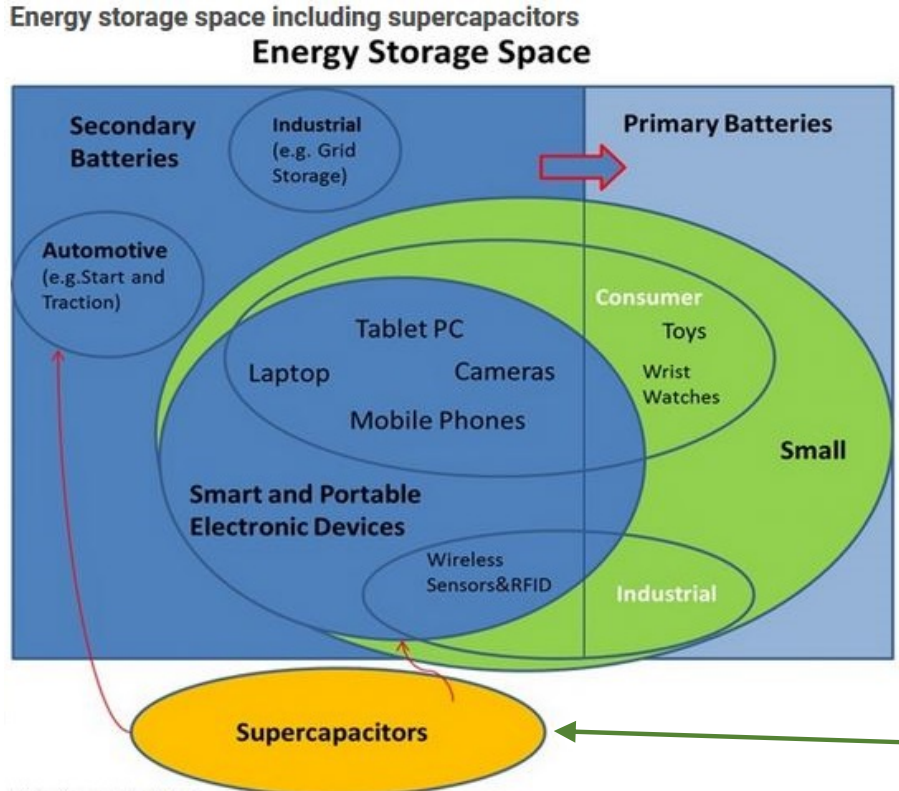


IMAGE CREDIT: Janina Bartje, "The top 10 IoT application areas – based on real IoT projects," IoT Analytics, August 16, 2016.

Look how much changed in only 18 months!



The Market / Motivations



Source: IDTechEx
 IMAGE CREDIT: Mr. Franco Gonzalez & Dr. Peter Harrop, "Batteries & Supercapacitors in Consumer Electronics 2013-2023: Forecasts, Opportunities, Innovation," IDTechEx, 2013.



Energy Harvesting (EH)

- **What is EH?**

- Power Capture from Free, Ambient Energy Sources

- **What is not EH?**

- Wireless Power Transfer (WPT)

- Wireless Commutation Via Resonance = **Wall Source**

- Table-Top Chargers, RFID Tags, Etc.

- Far-Field RF from Ambient = **Energy Harvesting**

- **FYI:** did I mention that a bigger battery is **NOT** the answer?



Remember this? →

$$ENERGY_{UTILIZATION} = \frac{ENERGY_{IN}}{ENERGY_{OUT}}$$

Energy Harvesting (EH)

- **Many Flavors of EH**

- Dynamo (i.e. – kinetic EH, electrodynamic)
- Photovoltaic Cell (PV)
- Piezoelectric Transducer (PZ)
- Fuel Cells (FC)
- Thermoelectric Generator (TEG)
- Radio Frequency (RF)
 - Near-field
 - Far-field (not to be confused with wireless power transfer)
- Vibration (inc. vibroacoustic resonant membranes)
- Metamaterials



Energy Harvesting (EH)

▪ **Typical Energy Harvester Output Power**

- RF: 0.1μW/cm²
- Vibration: 1nW/cm²
- Thermal: 10mW/cm²
- Photovoltaic: 100mW/cm²

▪ **Typical Energy Harvester Voltages**

- RF: 0.01mV
- Vibration: 0.1 ~ 0.4 V
- Thermal: 0.02 ~ 1.0 V
- Photovoltaic: 0.5 ~ 0.7 V typ./cell

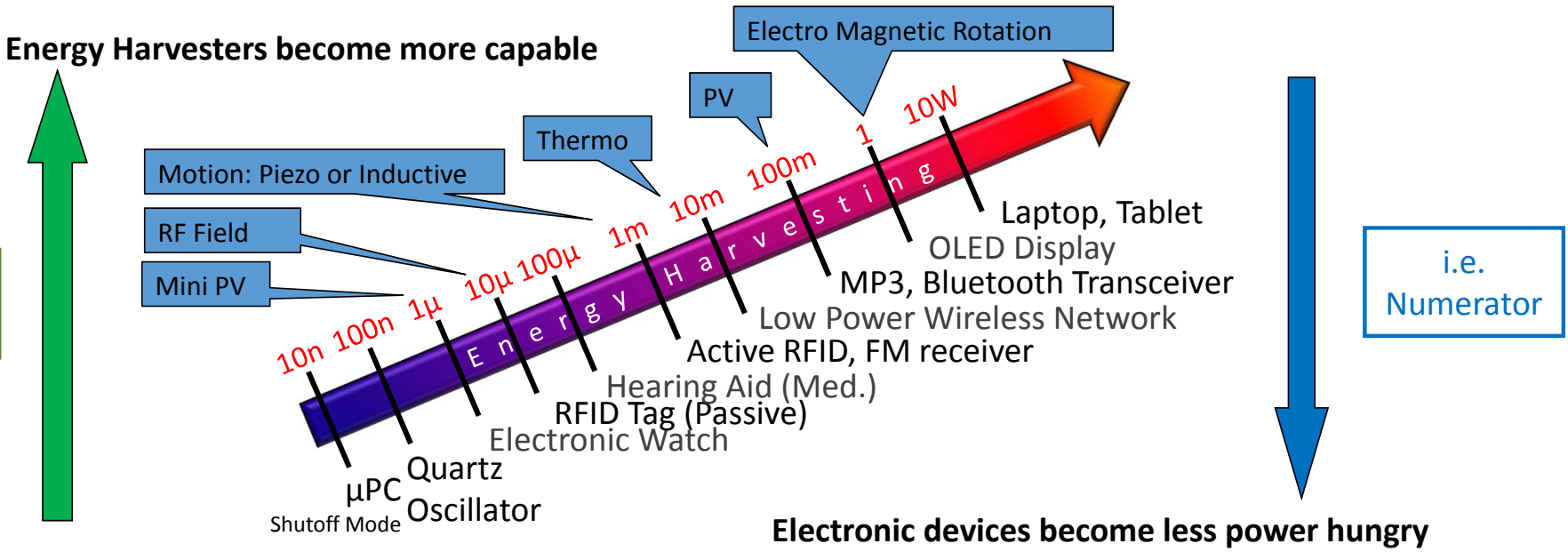


IMAGE CREDIT: Mike Hayes, "Synergies between Energy Harvesting and Power Electronics," Tyndall National Institute, IEEE PELS Young Professionals Webinar, October 20, 2016.

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Energy Harvesting (EH)

- **Neat, but just a lab experiment** **WRONG!**

- A **short** list of things that exist **TODAY!!!**

- Transducers (**EH type**)

- Alta Devices (**PV**)
- Murata (**TEG**)
- Jennova (**Electrodynamic**)
- Powercast (**RF**)
- Cherry Electrical Products (**Electrodynamic**)
- Fraunhofer Institute (IP only)
- EnOcean Alliance (IP only)

- Vendor Power Management ICs (PMICs)

- Linear Tech (LT): *25+ EH-related products*
- Analog Devices (ADI): *ADP5090/5091*
- Texas Instruments (TI): *6+ EH-related products*
- ST Micro: *3 EH-related products*
- Cypress Semi: *3 PMICs*
- Dialog Semi: *BLE PMICs*
- On Semi: *NCS36510 PMIC*

- See how little is actually required

- **EXAMPLE:** TI BQ25505

- $I_Q = 325\text{nA}$
- Multiple EH source & storage support
- Includes power conversion/regulation!

- Development / Evaluation Kits

- Würth Elektronik Gleanergy / EH Solution To Go
- ADI ADP5090/5091 Eval Board
- LT DC2080A Eval Board
- Cypress Solar BLE Kit CYALKIT-E02
- TI CC2650 SimpleLink Eval Kit



Energy Harvesting (EH)

- **Challenges**

- Efficiency Dependent on Input
- PMICs with Multiple Input Support
- Developing Ecosystem
- Wariness to Adoption
- Philosophical Approach to Waste Vs. Source
- Maximize Rechargeable Battery Utilization/Compatibility



EH Applications

Table 2.3 Some classical applications with the type of transducer and energy storage typically chosen

Application	Technology	Energy storage
Windmills to wind turbines	Wind energy harvesting	Battery
Bicycle dynamo lighting	Electrodynamic	None or capacitor keeps lights on briefly after the bike stops
Satellites	Photovoltaic	Rechargeable battery to work in night
Garden lights, toys	Photovoltaic	Rechargeable battery
Road furniture	Photovoltaic, wind	Rechargeable battery
Torch	Electrodynamic – shaken or cranked	None if gearing gives slow release or rechargeable battery

Source IDTechEx

IMAGE CREDIT: Dr. Peter Harrop & Mr. Raghu Das, "High Power Energy Harvesting: Off-Grid 10W-1MW 2017-2027," IDTechEx, January 2017.



EH Applications

- **TEG**

- The ASHRAE pocket guide gives the approximate electrical power a person generates while seated as 110 Whrs, and during heavy work it is 550 Whrs.

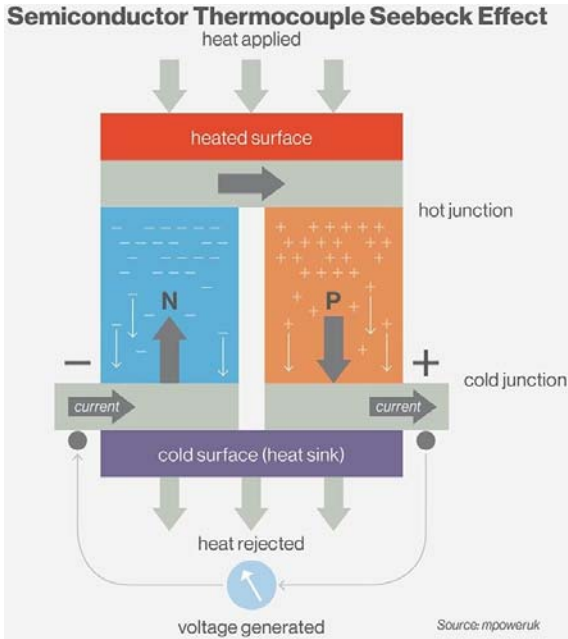


IMAGE CREDIT: Berman, B. (Producer), & The Wachowski Brothers (Director). (1999). *The Matrix* [Motion Picture]. United States: Warner Bros.



EH Applications

- RF (Far-Field)

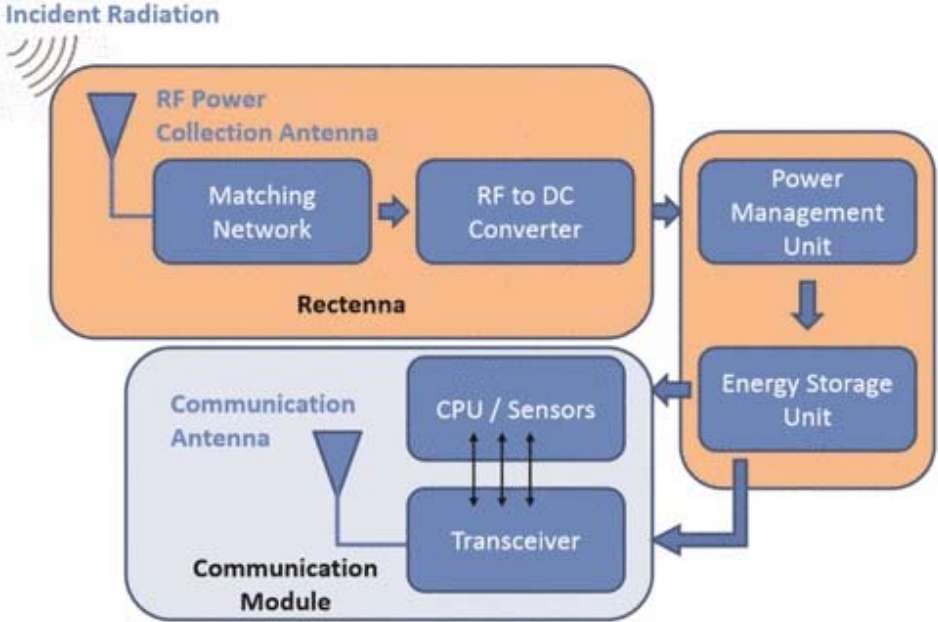


IMAGE CREDIT: "Chair for Digital Transmission: Energy Harvesting Webpage," Institute for Digital Communications, Updated May 19, 2015.



P1110 Powerharvester Receiver

- Designed for battery charging and direct power applications.
- Harvesting range from 850-950MHz.
- Works with standard 50-ohm antennas.
- Configurable overvoltage protection up to 4.2V.
- Connect directly to rechargeable batteries including Alkaline, Lithium Ion, and Ni-MH.

IMAGE CREDIT: "Powerharvester® Receivers," Powercast Marketing Brochure, Downloaded July 21, 2016.

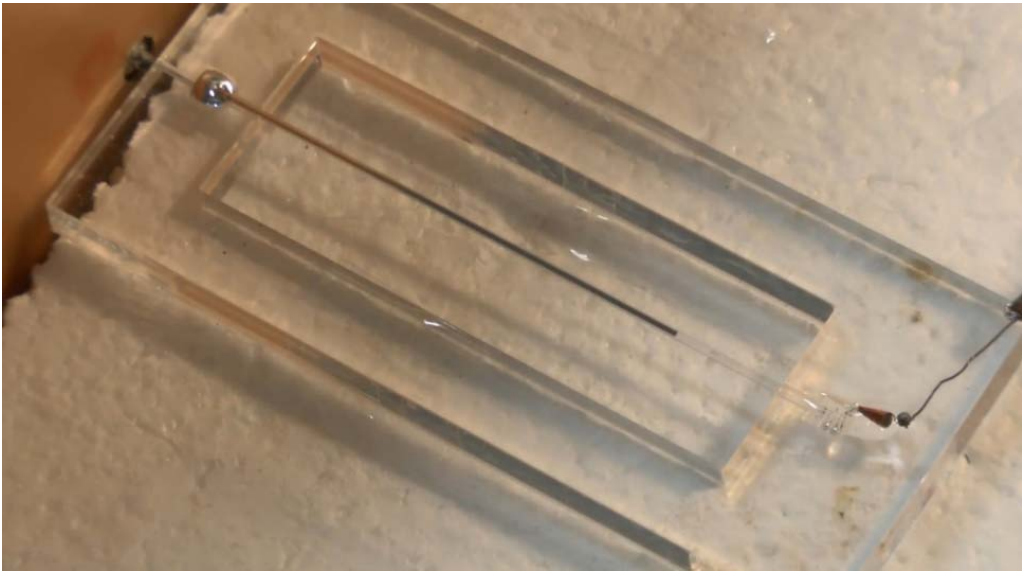


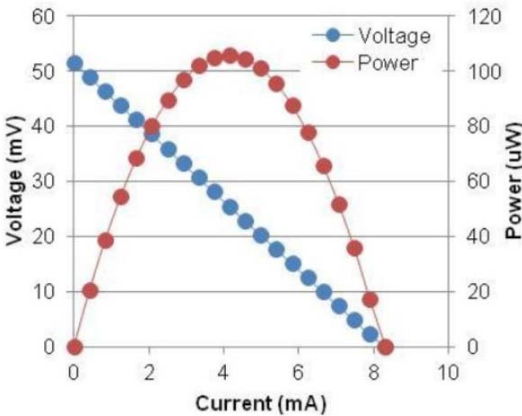
IMAGE CREDIT: David Schneider "Shape-shifting Liquid-Metal Antennas," IEEE Spectrum, Posted 21 Aug 2015.



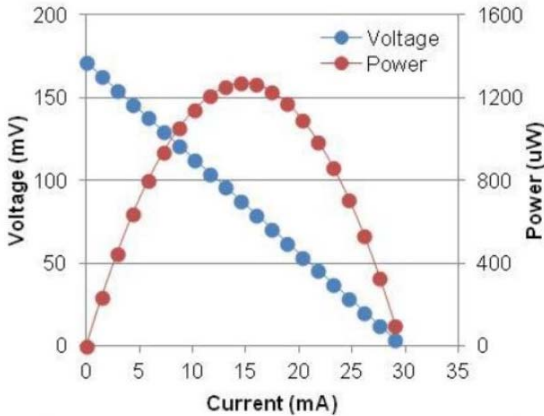
EH Applications

- **EH & Flex**

- Flex is Certainly a Perfect Candidate for Electrodynamic and PZ EH
- Maybe TEG Too (If Enough ΔT)



$\Delta T=10K$	Measured
No-load output voltage	52 mV
Device resistance	7.1 Ω
Output power	105 μW



$\Delta T=40K$	Measured
No-load output voltage	171 mV
Device resistance	7.3 Ω
Output power	1252 μW

IMAGE CREDIT: "Self-powered wireless sensor network node using Thermoelectric Ceramics," Murata Manufacturing Company, April 7, 2016.



EH Applications

- **EH & Flex**

- Flex PV
 - GaAs Solution
 - Thin Film (Organic & Inorganic)

Configurable Shapes and Sizes

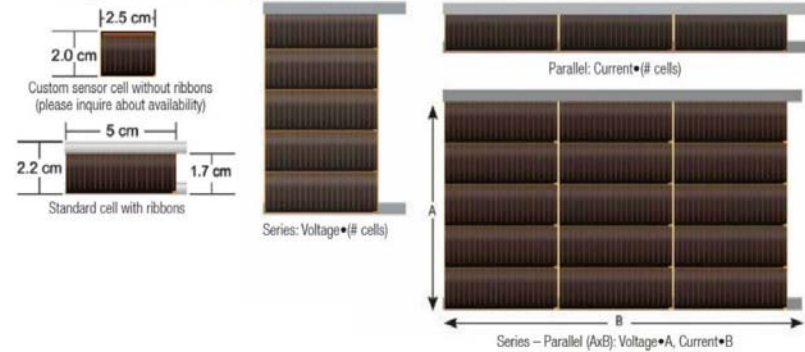


IMAGE CREDIT: Alta Devices Technology Corporate Brochure "AnyLight Mobile Power" (2015)



IMAGE CREDIT: Ascent Solar EnerPlex Surfr phone charging case.
<http://www.qoenerplex.com/products/solar-and-battery-phone-cases/surfr-for-iphone-6-6s>

With Solar you can Fly All Day

AeroVironment Puma AE UAS



No solar = 2-3 Hour Endurance

No Solar:
 Battery: 200 W-Hr. ÷ 60 W load = ~3 Hr.

Add Solar:
 Solar: 50 W * 10 Hr. = 500 W-Hr.
 Solar+Battery: 700 W-Hr. ÷ 60 W = ~11 Hr.



Solar = 9-10 Hour Endurance



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ALTADEVICES

A Hanergy Company

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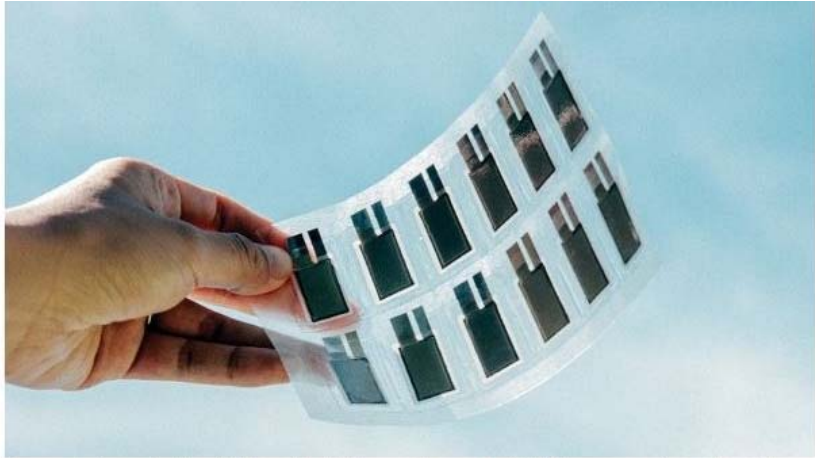
IMAGE CREDIT: Rodney Amen, "Solar for UAV Applications," Alta Devices, IEEE PELS Energy Harvesting Workshop, April 20, 2017.

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EH Applications

- **EH & Flex**

- Flex Battery
 - Ink-Based, Printable
 - Rechargeable, Non-Hazardous
 - Compatibility with Existing, High-Volume Manufacturing Techniques
 - Scalable



Ho says devices using Imprint Energy's batteries could appear by 2018. The company is working with manufacturers to screen-print batteries on sheets like this one.

IMAGE CREDIT: "35 Innovators Under 35: Entrepreneurs," MIT Technology Review, 26 Aug 2016 <https://www.technologyreview.com/lists/innovators-under-35/2016/entrepreneur/christine-ho/>



IMAGE CREDIT: Samsung SDI announces Stripe & Band flexible batteries on 10/20/15. <http://www.samsungsdi.com/about-sdi/pr-center/sdi-news/view?mode=siteSearch&seqno=1708>



EH Applications

- **IoT / Wearables / Consumer**

- Sensors
 - Telemetry Data
 - Low Power RF Communications
 - Harsh Environments
- Self-Contained, Low Power Networks
 - Less Storage = Longer Life
 - Installation/Replacement Cost
 - SoC Key Enabler

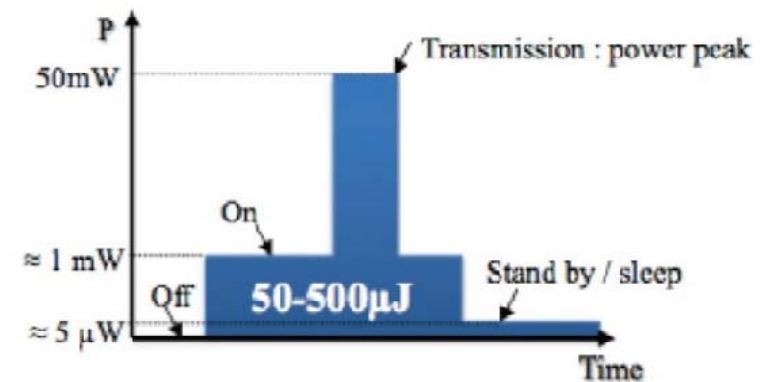
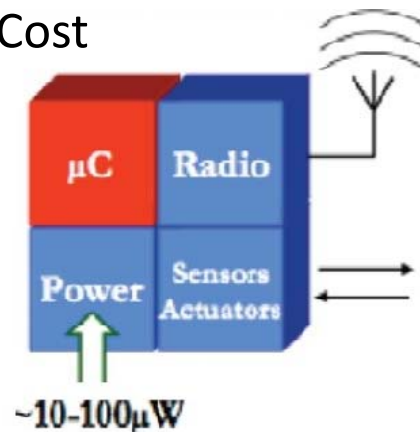


IMAGE CREDIT: Jeffery Funk, "Energy Harvesters Powering the IoT," National University of Singapore MT5009 Lecture, Apr. 23, 2015.

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EH Applications

- 5G
 - Efficiency Optimization More Important Than Ever

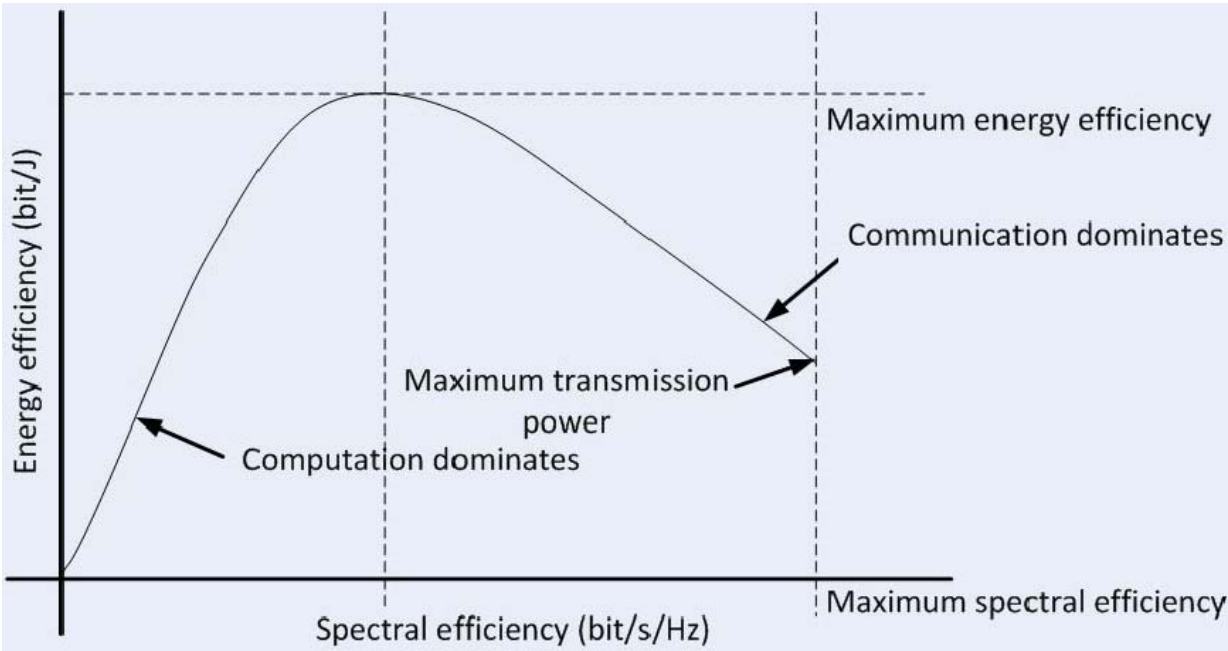


IMAGE CREDIT: L. Deng, Y. Rui, P. Cheng, J. Zhang, Q. T. Zhang and M. Li, "A Unified Energy Efficiency and Spectral Efficiency Tradeoff Metric in Wireless Networks," IEEE Communications Letters, vol. 17, no. 1, pp. 55-58, January 2013.



EH Applications

- 5G
 - Microgrid / Nanogrid
 - Assurance of Supply
 - Independence
 - RF Far-Field Harvesting
 - Lots of RF Energy
 - Signal Tradeoff

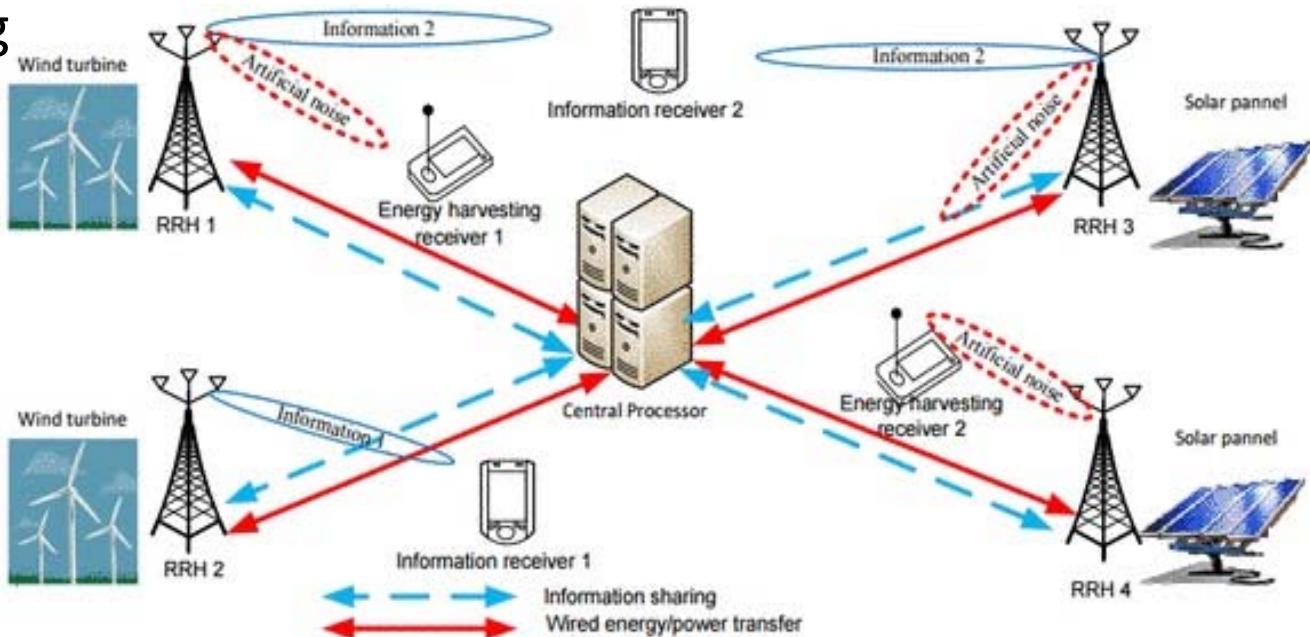


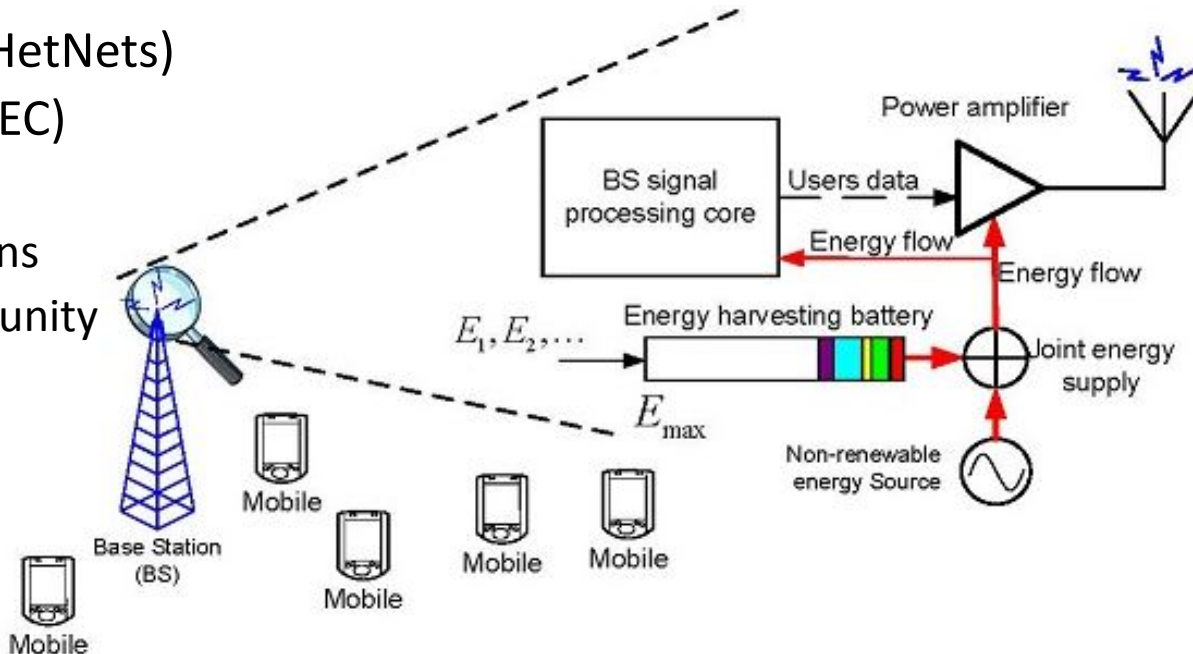
IMAGE CREDIT: "Chair for Digital Transmission: Energy Harvesting Webpage," Institute for Digital Communications, Updated May 19, 2015.
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EH Applications

- **5G**

- Base Stations

- Heterogeneous Networks (HetNets)
 - Mobile Edge Computing (MEC)
 - mmWave
 - Many, Smaller Base Stations
 - Lower Power = EH Opportunity



A system with a hybrid energy harvesting base station. Two energy sources are implemented, i.e., a renewable energy harvesting source and a non-renewable energy source.

IMAGE CREDIT: "Chair for Digital Transmission: Energy Harvesting Webpage," Institute for Digital Communications, Updated May 19, 2015.



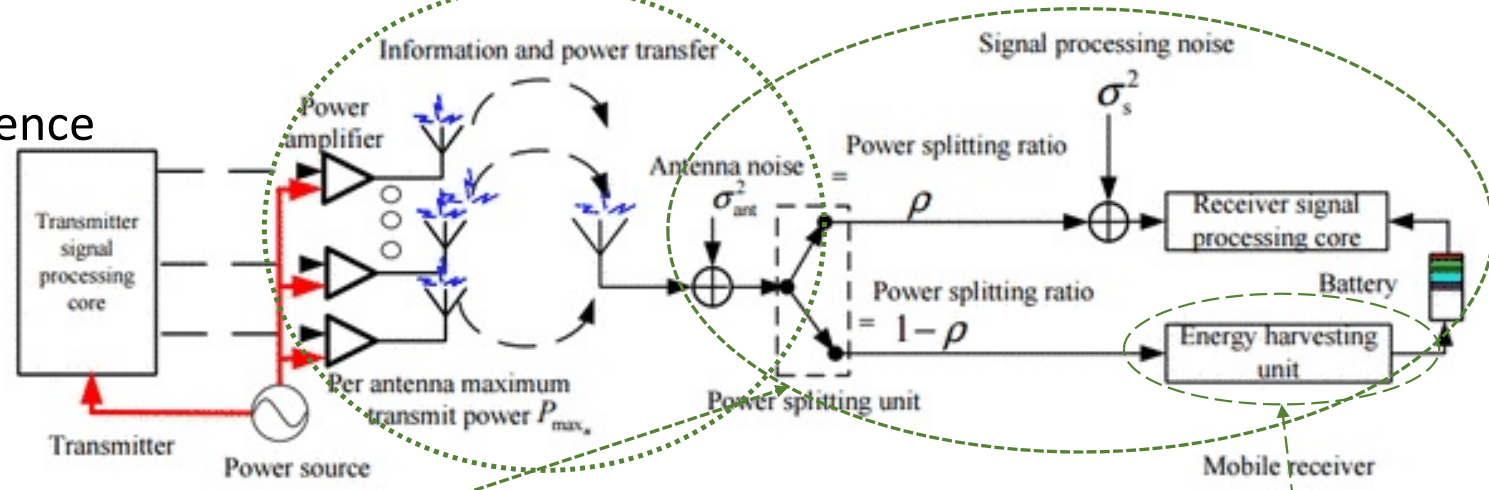
EH Applications

- **5G**

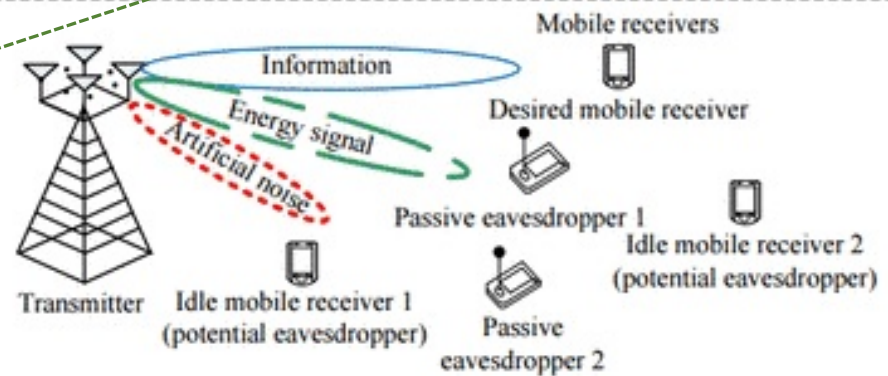
- Security

- Grid Independence
 - Signal Level
 - Encryption

Higher RF Power = Higher Susceptibility of Broadcast



Gaussian Noise = Encryption



BONUS: Jamming signalers can be charged wirelessly!



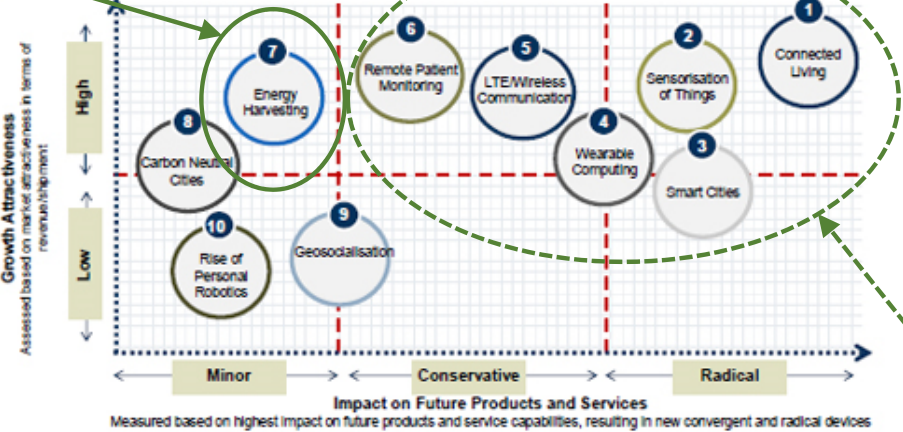
EH Vs. Batteries

This was even 2yrs ago!

Top 10 Transformational Trends in Battery Space by 2020

Connected living in terms of connected home, work and city along with IoT and wearables will drive battery demand.

Key Takeaway: While all Mega Trends are important, the selection and ranking of these trends indicate which shifts will have relevance in shaping the global evolutionary landscape.



Key: LTE—Long Term Evolution
 Source: Frost & Sullivan
 IMAGE CREDIT: Gina Roos, "Four Mega Trends Drive Battery Innovations," EPSNews, July 27, 2015.

Nearly every category has the potential for EH and therefore impact to associated battery markets.



EH Vs. Batteries

- **Complimentary Vs. Adversary**

- Supplement (Maybe not necessarily “Vs” as much.)
- Design of Battery Management System (BMS) with EH In Mind
- Cannibalization To Challenge Battery Market
 - Other Storage (i.e. – Supercaps, Etc.)
 - Analogous to Integrated (“Granular”) Power in SoC/3D Packing Applications

- **Mitigation**

- Garbage / Hazardous Materials
- Replacement Efforts
 - Push For Rechargeable Battery Applications
- Overall Design Effort (i.e. – Redundancy, Overprovisioning, Etc.)



Conclusions

- Power electronics & EH are a critical factor in enabling IoT/Wearable/5G applications.
- If inaccessible sensor products are to have useful lives in application, then they need to operate for very long times (i.e. – forever) without a recharge from the wall or even a battery change.
- Reducing power demand yields far more benefits than simply a bigger battery.
- EH is no longer a lab experiment. The ecosystem, while nascent, exists now!
- The sooner we plan the battery roadmap with EH in-mind, the better.



Q&A



Thanks a lot for your time and attention!

Any questions and/or comments?



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