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IOT-104

Energy Harvesting and Conservation for Low-Power Wireless Networks

Tristan Cool | August 2023

IoT

IoT Trend – Energy Harvesting

WHAT IS ENERGY HARVESTING?

WHICH APPLICATIONS ARE ADOPTING ENERGY HARVESTING?

WHAT IS ENERGY HARVESTING *FOR IOT?*

HOW TO GET STARTED?

PERFORMANCE & DESIGN CONSIDERATIONS?

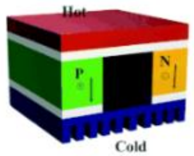
Energy Harvesting Sources

Trickle & Transient

Energy Sources: Trickle vs Transient

"TRICKLE" ENERGY SOURCES

- For applications with nearly *constant energy supplies*
- For applications that are nearly *always-on (rechargeable)*

METHOD	**Photovoltaic**	**Vibration/Piezo**	**Magnetic/Thermal**	**RF/IR**
DESCRIPTION	Dependent on quantity and quality of light	Dependent on resonant freq and magnitude of deflection (oscillation)	Induced from magnetic field or heat differential Peltier/Seebeck plate as current flows	Harvested by receiving and rectifying RF transmissions from AP
PERFORMANCE	Outdoor 120k lux ; 50 mW/cm² Indoor 50 lux ; 100 uW/cm² 0.6~3.6V ; 85~255uA	1 mW/cm² 5V+ ; 20~30mA	10 mW/cm² 1.8~4.6V ; 5~50mA	0.1 mW/cm² 10~20m range Sub-GHz 3V
APPLICATIONS	Smart Building, Home Electronics, MEMS, Asset Tags, ESL	Factory, Construction, Farming machinery	Electric Metering, Condition Monitoring	Smart Building, ESL, Factory, Medical, Charging

"TRANSIENT" ENERGY SOURCES

- For applications with *limited duration energy source*
- For applications that *frequently deep sleep or power off*

METHOD	**Kinetic / Triboelectric**
DESCRIPTION	Outputs energy to be stored from an abrupt physical motion event. Energy created by displacing charged surfaces or oscillating magnet.
PERFORMANCE	7.5 mW/cm² 1.8~4.6V ; 5~50mA
APPLICATIONS	Pushbuttons (Smart Home, Smart Building/Factory) Door lock mechanisms

Energy Harvesting Applications

New Generation Products & IoT Protocols

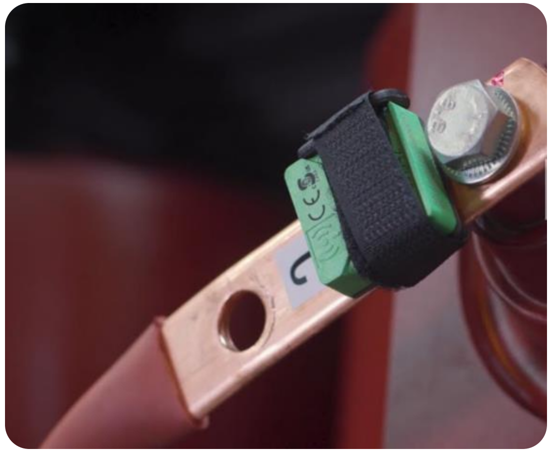
Energy Harvesting – Industrial Applications

SMART BUILDING

- **Kinetic / Piezo**
- Battery-less moveable switch
- *Prop 15.4 ; Bluetooth*
- *200 µJ ; 1.8~3.3V boosted*
- *90 nWh*

SMART FACTORY

- **Kinetic / Piezo**
- Battery-less factory switch
- *Prop 15.4 ; Sub-GHz*
- *200 µJ ; 1.8~3.3V boosted*
- *90 nWh*



SMART METERING

- **Electro-magnetic Induction**
- Battery-less temperature and humidity sensor
- *Zigbee Green Power*
- *100 nWh*

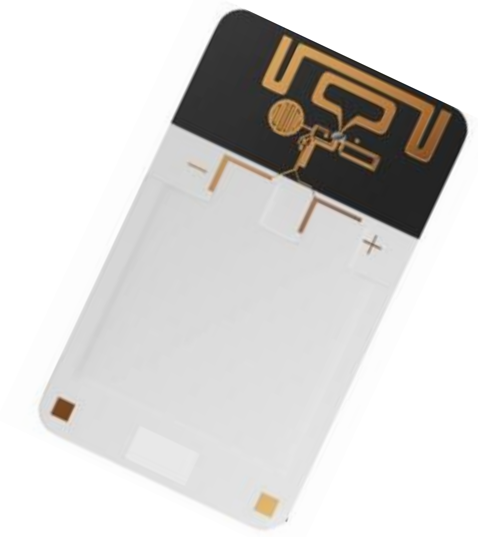
Energy Harvesting – Industrial Applications

PREDICTIVE MAINTENANCE

- **PV, Thermal, Vibration**
- Battery-less valve pressure sensor
- *Prop 15.4 ; Bluetooth ; Sub-GHz*
- *50~100 µWh*

FACTORY AUTOMATION

- **PV, RF, Vibration, Induction**
- Battery-less sensor
- *Prop 15.4 ; Bluetooth ; Sub-GHz*
- *50~100 µWh*



ASSET TAGS

- **PV, RF**
- Rechargeable battery
- *Bluetooth, NFC, RFID*
- *30~40 µWh*

Energy Harvesting – Consumer Applications

ELECTRONIC SHELF LABEL

- **PV, RF**
- Battery-less e-ink display
- *Sub-GHz*
- *10 mWh*

HOME ELECTRONICS

- **PV, RF**
- Battery-less, Battery recharge remote
- *Sub-GHz, IR*
- *10 nWh*

DOOR LOCKS

- **Kinetic, RF**
- Battery-less door lock
- *Bluetooth, NFC*
- *5 mWh*

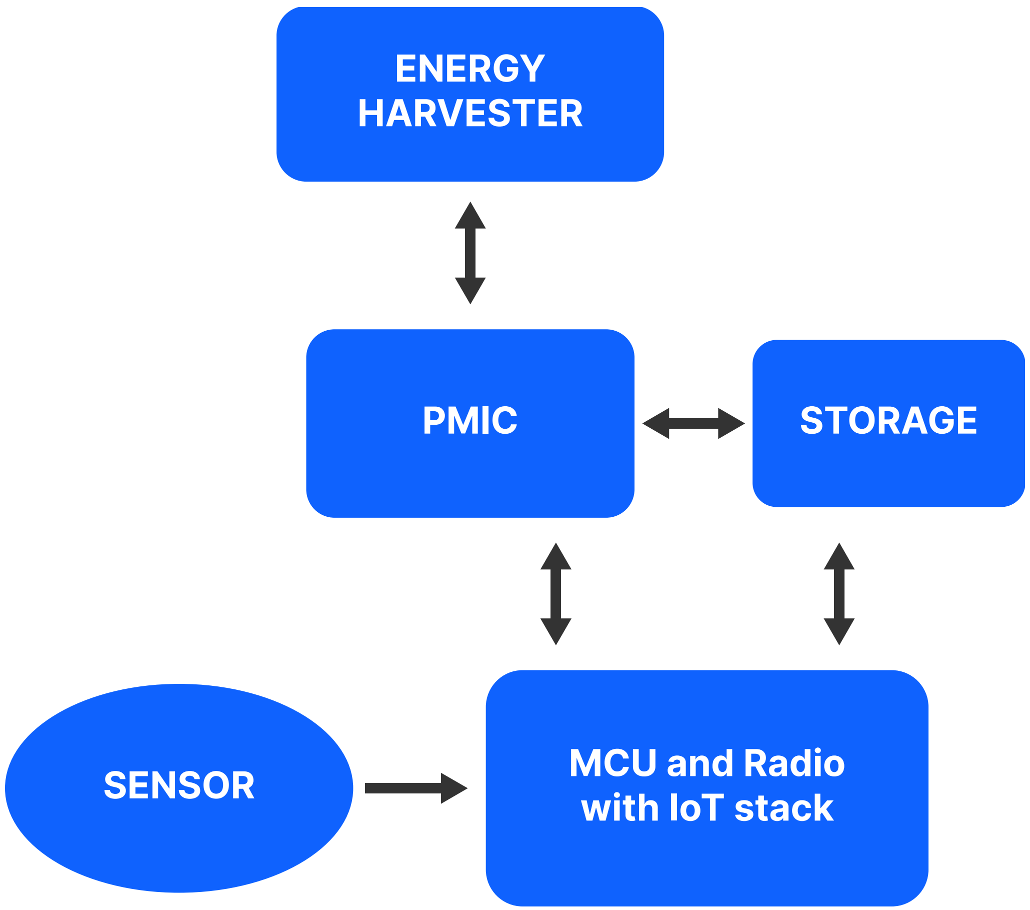
Energy Harvesting for the IoT

IoT Architectures

IoT Architectures for Energy Harvesting

- Energy-harvesting devices require **multiple important technology decisions**
  - Energy Source
  - Power Management
  - Battery, Storage and/or Recharging
  - Sensor
  - IoT Radio with MCU

- Not as simple as replacing battery with charging circuit or harvester!



IoT Architectures for Energy Harvesting

- **Considerations**:

  - Which energy sources are available to harvest?
    - *Single or multiple?*
  - Will the design be battery-less or battery re-charging?
    - *Which methods needed? PWM charging? Max Power Point Tracking (MPPT)?*
    - *What battery chemistry or storage element is required for discharge times and product life-time?*
  - How will this re-design impact BOM cost and footprint?
    - *Additional passives for impedance matching*
    - *DC-DC buck-boost circuitry for voltage input and current output*
  - Which sensor type best suits the application?
    - *Is the sensor fast enough to power up and sample?*
    - *What is the active current consumption?*
    - *What ADC VREF and characterization are required?*
  - Choosing the best radio and MCU
    - *Will the startup time and current consumption be low enough for the energy budget harvested?*
    - *What other peripherals are needed? How best to optimize their initialization?*
  - Design for the IoT
    - *How many transmissions are required? At what rate and range?*
    - *Can the payload size be optimized?*
    - *Which protocol is the most energy-friendly?*
  - Cater the application for energy-harvesting
    - *Will the device be always-on or go into deep sleep?*
    - *Does the software need in-field upgrades OTA?*
    - *How important is security?*
    - *Does the application need to make energy-based decisions?*
      - *before transmitting?*
      - *to dynamically change sensor polling or payload?*

Silicon Labs can be your advisor!

Energy Harvesting – The Problem with Batteries…

- More than **3 billion batteries are thrown in land-fills** in North America…every year (**180,000 tons** of hazardous waste)
- The average household still purchases over 90 batteries annually…most have *much* less than 10 year lifetime
- Batteries are **slowing down the growth of IoT**…
  - 25 billion IoT devices predicted by 2025…would require **6 million battery replacements…every day**
  - For an industrial use-case with 1,000 sensors, over 350 batteries replaced every year…more than one daily…resulting in recurring cost to replace…often **more costly than the battery itself**.
  - Sensor **polling rate, payload size, transmission rate and range are often lowered** based on remaining power.

ALL batteries eventually need replacing.
How to beat 10 year battery? Re-design for rechargeable or battery-less?

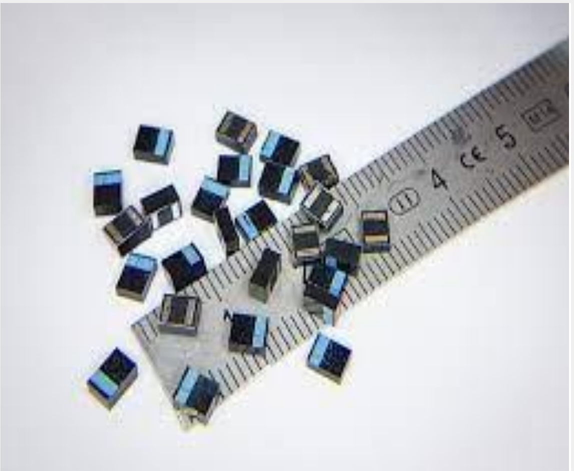

Nobody likes batteries!


Source: healtheplanet.com, Everactive

Energy Harvesting – Battery & Storage Alternatives

RECHARGEABLE BATTERY

- Lithium: (3V ; 270Wh/kg)
  - Pro: Long life (8~10 years)
  - Con: Complex recharging
- Nickel-Cadmium: (1.2V ; 60Wh/kg)
  - Pro: Low cost
  - Con: Low power density
- Nickel-Metal Hydrate: (1.25V 100Wh/kg)
  - Pro:1000+ recharges
  - Con: High cost ; High self-discharge
- Silver Oxide: (1.5V)
  - Pro: Low internal resistance
  - Con: High cost ; Shorter life (not rechargeable)



MICRO BATTERY

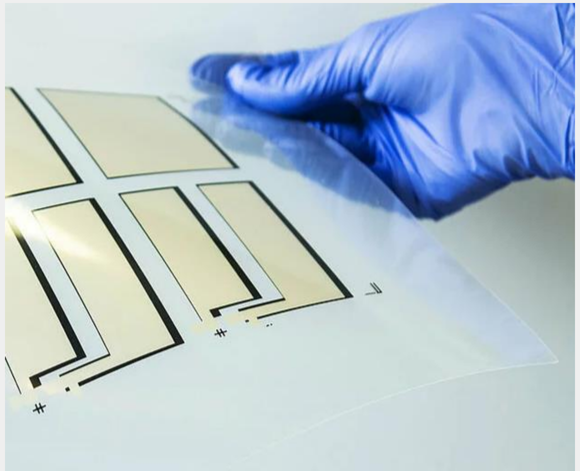
- Solid-state design
  - Steady energy for Always-ON applications
  - Used for power backup assist
- 2.25~3V ; 50~500µAh ; 15-70mA

Pros:

- SMD and high-temp compatible
- Very fast recharge (~minutes)

Cons:

- Footprint/Cost vs Supercapacitors



PRINTED BATTERY

- Inkjet printing anode and cathode with conductive inks
- Ideal for large-area applications with 10mAh range (tags, cards)

Pros:

- Customizable thin pliable form-factor
- Rechargeable (redox)

Cons:

- Degradation

SUPER-CAPACITORS

- More environmentally-friendly than batteries and have longer lifetime.
- Much quicker energy delivery than batteries

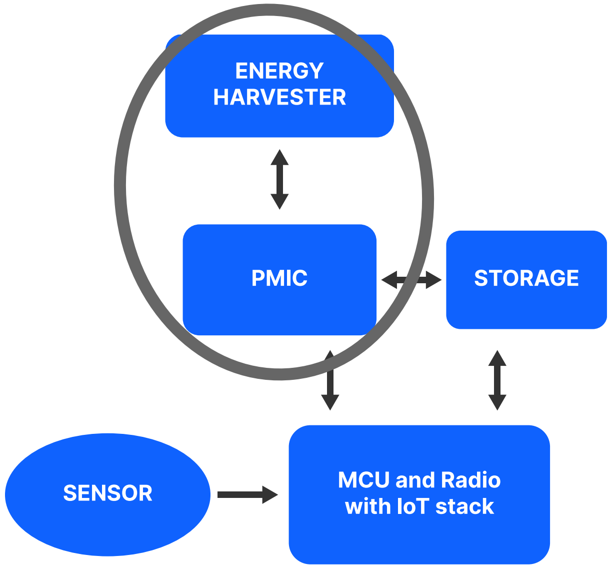
Pros:

- Very high power density
- Can be SMD compatible

Cons:

- Very quick self-discharge (~minutes)
- Non-ideal for cost-sensitive designs

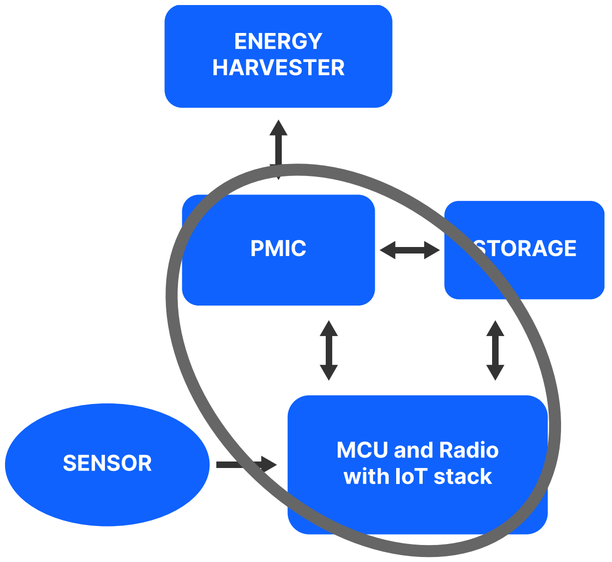
Energy Harvesting – Power Management Considerations



Optimized Power Management for *dedicated* energy inputs:

- PMIC (with integrated logic)
  - DC-DC Buck-boost, Impedance matching circuit, PWM charging, MPPT for specific harvest method
- *Standard platform* and IoT stack

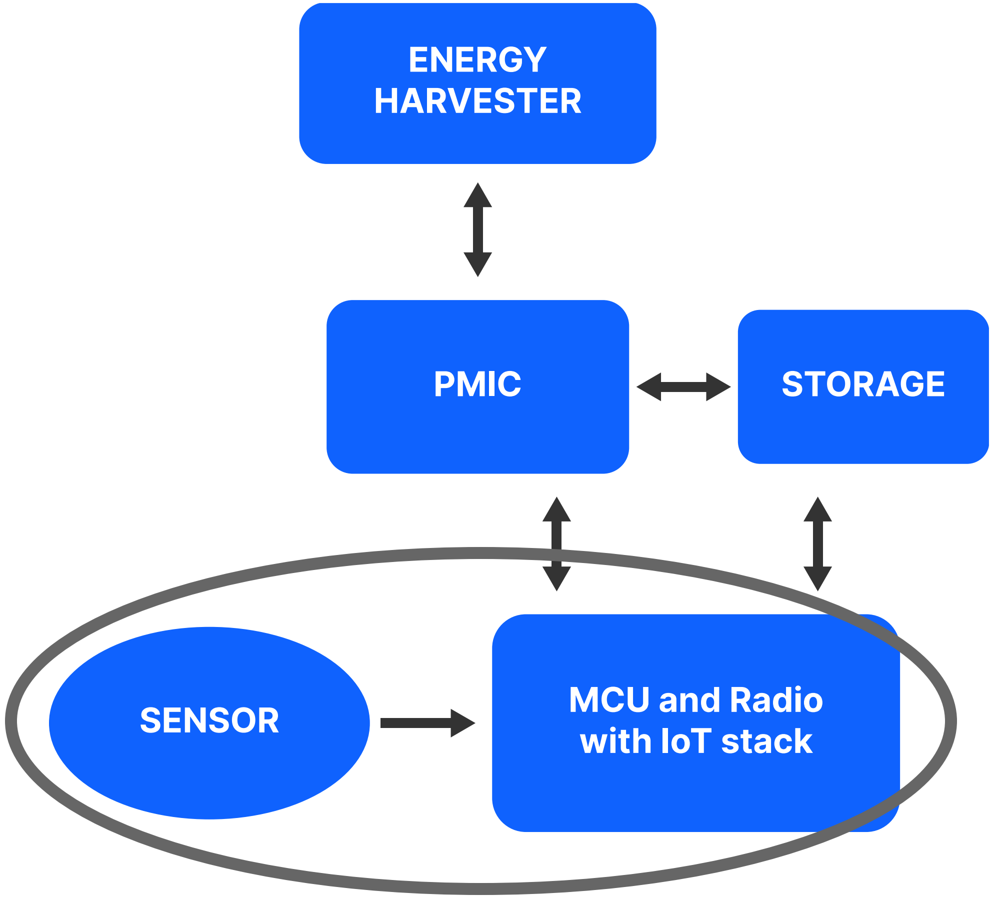
- High Performance, High Cost - **Maximize energy *stored***



MCU, Radio and Platform for *various* energy inputs:

- Energy management integrated into SoC
  - VMON, Coulomb Counter, Brown-out detector
- *Energy mindful platform* for any energy input
  - Cold-start consumption and timing
  - Energy-based sensor and Tx decisions
  - IoT stack and application customizations
- High Performance ; Low Cost - **Minimize energy *consumed***

Energy Harvesting – MCU & Sensor Considerations



High Performance, Low Cost – ***Dynamic* energy use**

- For "always-on" applications using "trickle-charging" approach, the wireless sensor node spends **most of its lifetime in sleep mode**. It is important to **limit wake-up times.**
- The only subsystem that stays awake is the real-time clock (RTC). The RTC keeps time using a free-running counter. (consumes a few hundred nano-amps)
- The RTC **wakes up the wireless sensor node to measure a sensor** input When the free-running counter rolls over, a wake-up **interrupt** is generated.
- Wake up intended to measure a **sensor signal using the analog-to-digital converter (ADC).**
  - It is important to **consider the wake-up time** of the ADC with respect to digital wakeup as well as CPU and LFXO for radio Tx…
  - There is little point in waking up the CPU very quickly **if the ADC or LFXO takes an order of magnitude longer to wake up**
  - Low-power MCUs can wake up CPU and ADC in a couple of microseconds and consume approx. (~30 µA/MHz)
- When the sensor data has been measured, the algorithm running in the **MCU decides whether the data should be transmitted by the radio**

Silicon Labs Whitepaper – Energy Harvesting for Wireless Sensors

Getting Started with Energy Harvesting

IoT Reference Designs

Energy Harvesting – Choosing the right IoT protocol

▪ Data Rate, Power Consumption and Range

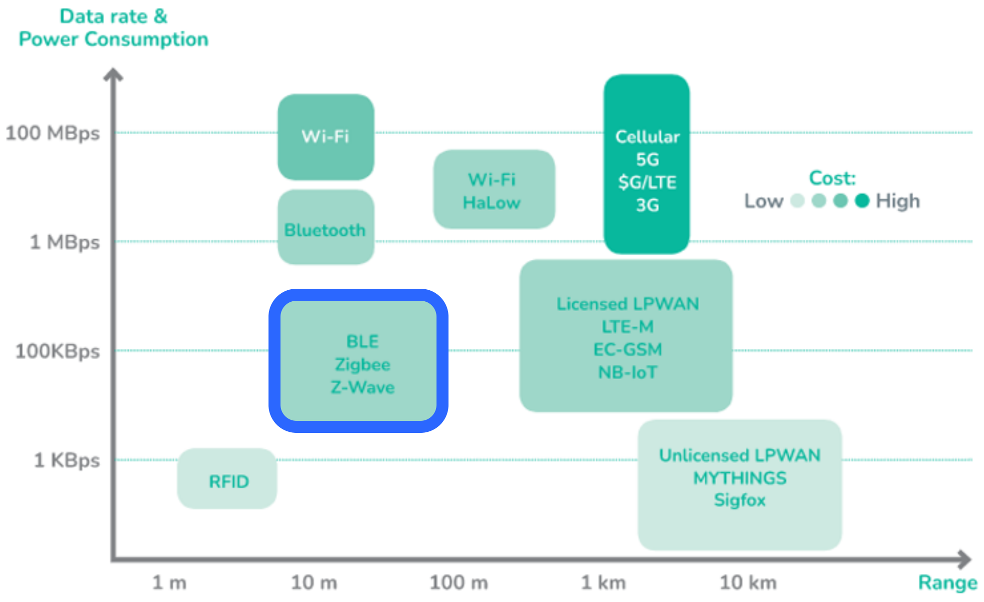
Power Consumption and Data Rates for Various Wireless Technology for IoT

	100 bps		10K bps		40K bps	
1 m	BLE4 / Zigbee	0.15	BLE4 / Zigbee	7.5	Zigbee	30
	BLE Mesh	0.15	BLE Mesh	7.5	Bluetooth	25
	Bluetooth	25	Bluetooth	25	WiFi	50
	WiFi	50	WiFi	50		
50 m	Zigbee	20	Zigbee	30	WiFi	200
	WiFi	100	WiFi	100	NB-IoT, LTE-M	200
	NB-IoT, LTE-M	1.0	LTE, 5G Cellular	150	LTE, 5G Cellular	200
1 km	Sigfox	30	NB-IoT, LTE-M	100	NB-IoT, LTE-M	400
	NB-IoT, LTE-M	20	LTE, 5G Cellular	200	LTE, 5G Cellular	400
	LTE, 5G Cellular	120				

All units in mW

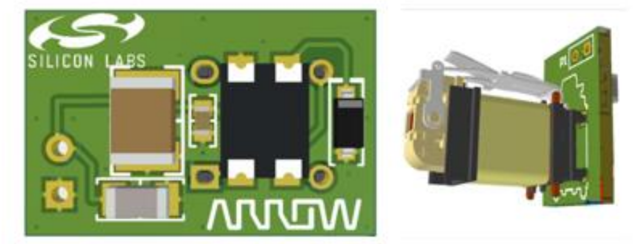
- The data payload and transmission frequency need consideration for energy-harvesting
- Wi-Fi and Cellular likely too demanding for energy-harvesting

▪ Data Rate, Power Consumption and Range (graph)



- Most applications' data-rate and range for energy-harvesting are well suited by **BLE and Zigbee**…and with the most reasonable cost-point

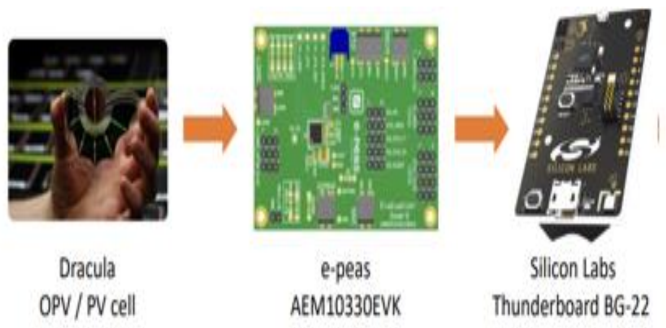
Energy Harvesting - Reference Designs



KINETIC BUTTON

Whitepaper
Smart Switch – MG22
Zigbee Green Power
~580uJ ; 61ms ; 9.6mW

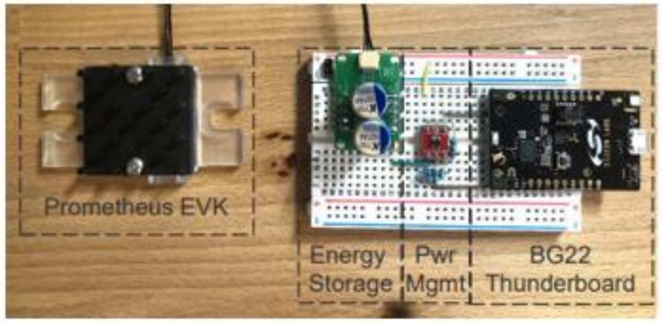
- ZF Harvester switch bi-directional AC generator
- Voltage doubling rectifying to maximize capacitor charging
- DCDC regulated to 3V3 ; 3mA with Analog Device LTC3106
- 1 Transmission – then Deep Sleep EM4
- 4 button pushes to commission



PV CELL

Webinar
Asset Tag – BG22
Bluetooth

- Ambient light (35 µW/cm² under 1000 lux) + Temp. sensor
- Charging in less than 1h
- Fully charged operating time of 24h in dark
- Boost Vin min: 50mW ; 20~80mA output
- ePEAS AEM manages cold-start (3µW) and MPPT (7 passive components) + dual supercapacitor



THERMAL

WorksWith 2021
Condition Monitoring – BG22
Bluetooth

- Harvest heat from machinery or steam trap
  - 0.82mW ; 3V at 10ºC
  - 15mW ; 3V at 64ºC
  - 42mW ; 3V at 143ºC
- Dual 1000µF supercapacitors
- PMIC MIC2779L
- BLE Advertise + measure and send data

Energy Harvesting Performance & Design

Optimizations for IoT

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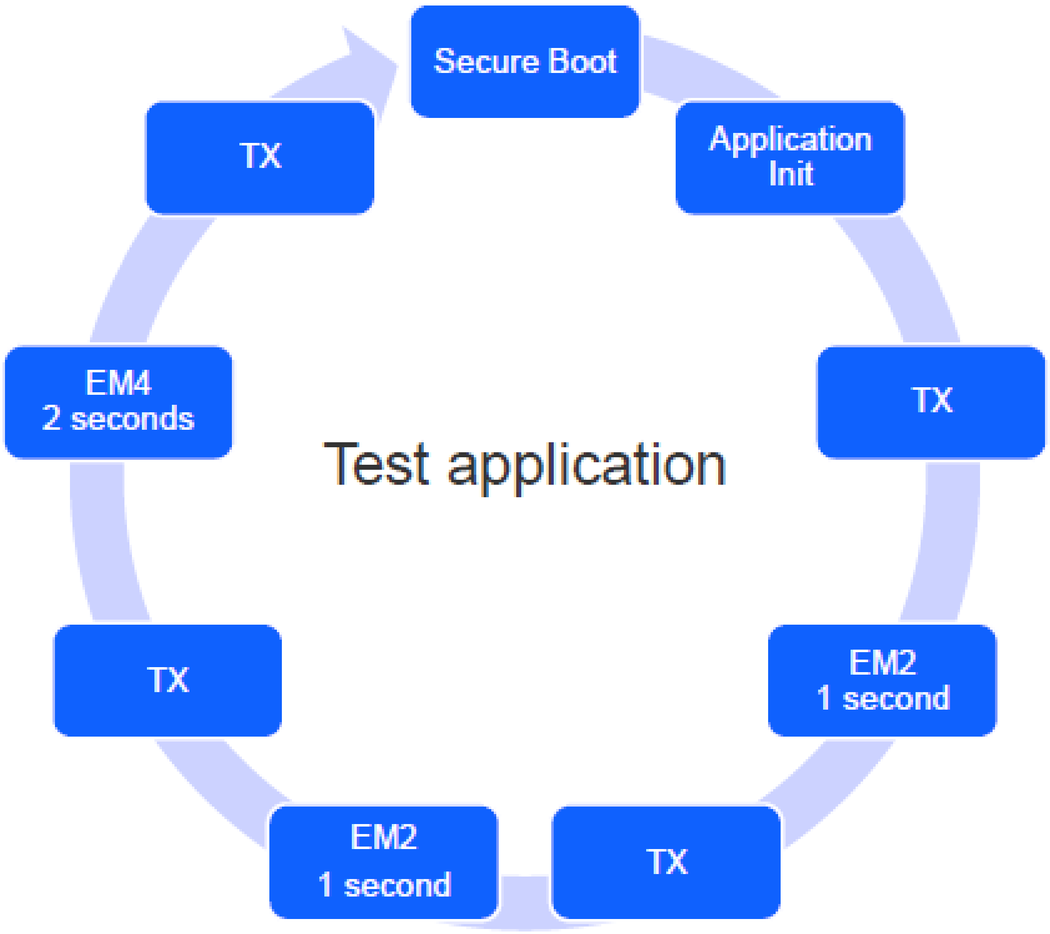
Energy Harvesting – Improved Performance Reference Sample App

- Previous examples used standard BG22 hardware and existing sample application code.
- Application code should be optimized to allow for higher data payloads and more frequent transmissions.
- **New application created:**
  - Ideal for multiple harvest modes (kinetic piezo, PV) and power management circuits
  - Sends beacon and/or sensor data
  - Basic RAIL example – minimized MCU utilities
  - Can be ported to BLE, Zigbee, Prop 15.4 (following best low power practice guides)
  - Uses LFXO or LFRCO
  - DCDC enabled – 2.4V
  - 3 Transmissions – no CCA – 16B payload – 0dBm
  - *Measurements for coldstart, boot, init, EM2 and EM4 wakeups*

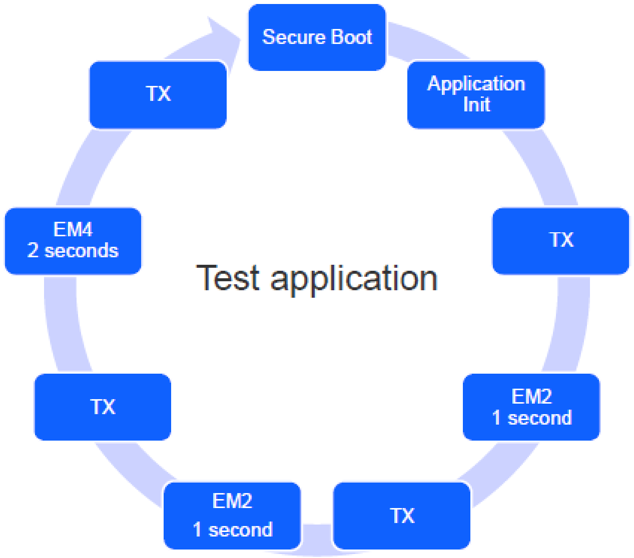


github: link

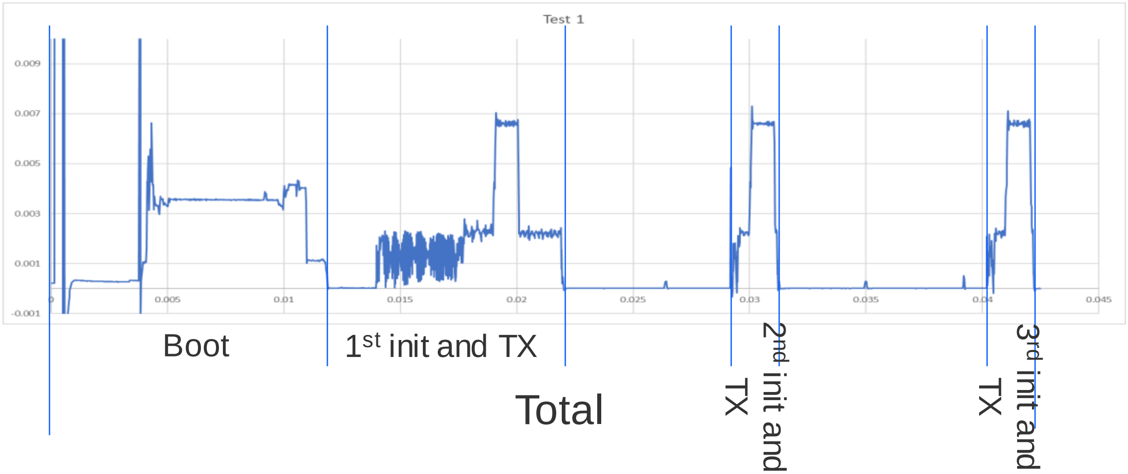
Energy Harvesting – Improved Performance Reference Sample App

SEQUENCE	TIMING (ms)	CURRENT (mA)
BOOT	12.1	4.6
INIT	42.3	2.0
ON AIR (Tx)	1.6	4.1
EM2	-	1.75 (µA)
EM4	-	0.17 (µA)

SEQUENCE	TIMING (ms)	CURRENT (mA)
LFXO Boot → Tx → EM2	248	1.49 (µA)
LFRCO Boot → Tx → EM2	124	1.79 (µA)
EM2 Wake → Tx → EM2	1.2	4.1
EM2 Wake → Tx → EM4	3.4	4.1
EM4 Wake	11.8	2.96
LFXO EM4 Wake → Tx → EM2	238	2.96
LFRCO EM4 Wake → Tx → EM2	100	2.96



*consumes ~200-300µJ



BG22: Optimized for Battery Powered Bluetooth LE

Secure Bluetooth 5.3 SoCs for High-Volume Products

Radio
Bluetooth 5.3
+6 dBm TX*
-99 dBm RX
AoA & AoD

Ultra-Low Power
3.6mA Radio TX
2.6mA Radio RX
1.4uA EM2 with 32kB RAM
0.54uA in EM4
RTC in EM4

World Class Software
Bluetooth 5.3
Bluetooth mesh LPN
Direction Finding

Compact Size
5x5 QFN40 (26 GPIO)
4x4 QFN32 (18 GPIO)
4x4 TQFN32 (18 GPIO)

ARM Cortex-M33 with TrustZone
76.8 MHz
FPU and DSP
352/512kB of flash
32kB RAM

Peripherals Fit for Purpose
2x USART, 2x I2C, 2x PDM and GPIO
16-bit ADC
RFSENSE wake-on radio
Built-in temperature sensor with +/- 1.5 ^{o}C
32kHz, 500ppm PLFRCO

Security
AES128/256,SHA-1, SHA-2 (256-bit)
ECC (up to 256-bit), ECDSA and ECDH
True Random Number Generator (TRNG)
Secure boot with RTSL
Secure debug with lock/unlock

Getting Started with EFR32BG22

BG22-EK4108A

BG22 Bluetooth SoC Explorer Kit

[UG509](#) - *BG22 Explorer Kit User's Guide*

Small Form Factor Kit

- Aligned with breadboard dimensions

Target device

- BG22 Wireless SoCs
  - 76.8 MHz, ARM Cortex-M33 with 512 kB of flash and 32 kB RAM
  - Bluetooth 5.2 Radio with supported for direction finding and LE coded PHY
  - Best-in-class device security including Secure Boot with Root of Trust and Secure Loader (RTSL)
- 38.4 MHz HFXO crystal
- 32.768 kHz LFXO crystal
- 2.4 GHz matching network and a chip antenna

On-board Board controller

- J-Link debugger
  - SWD physical layer
- Packet trace over UART/async protocol
- Virtual COM with hardware flow control

USB Micro-B connector for debug connection

User interface features

- 1x button (with EM2 wake-up)
- 1x LED

Mini Simplicity Debug Connector (SLSDA001A compatible) with access to:

- AEM
- PTI
- VCOM
- SWD

Third-party add-on connectors

- mikroBus socket
- Qwiic connector

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xG27: Most Battery Versatile Series-2 SoC

Battery Versatile

Ultra-Low Power

Multi-Protocol

Secure

DEVICE SPECIFICATIONS

High Performance 2.4 GHz Radio
- Up to +8 dBm TX
- -99.2 dBm RX @ BLE 1 Mbps
- -106.9 dBm RX @ BLE 125 kbps

MCU Core
- ARM Cortex®-M33 (76.8 MHz with FPU & DSP)

Memory
- Up to 64kB RAM
- Up to 768kB Flash

Ultra Low Power
- 4.1 mA TX @ 0 dBm
- 3.6 mA RX (BLE 1 Mbps)
- 1.6 µA EM2 with 64 kB RAM
- 0.18 µA EM4

Multiple protocol support
- Bluetooth 5.4 (1M/2M/LR)
- Bluetooth mesh
- Zigbee 3.0
- Proprietary 2.4 GHz

Package
- 2.3x2.6 WLCSP (19 GPIO) +85ºC
- 5x5 QFN40 (26 GPIO) +125ºC
- 4x4 QFN32 (18 GPIO) +125ºC

DIFFERENTIATED FEATURES

Extremely small form-factor
- 2.3 x 2.6 WLCSP package[1]

Flexible battery support
- DCDC Buck/Boost
- Supports 0.8 to 1.7 volts
- Supports 1.8 to 3.8 volts

Enhanced security
- Secure Vault™ Mid
- Tamper detect
- Customer Key Management w/PUF

Battery management
- Coulomb counter

Wake-up pin (BOOST_EN)
- allows the device to be off (<20 nA) for long-term storage
- Up to 10 years of shelf storage

[1]Only on BG27

BG27 and MG27: Smallest and most battery versatile SoC

- Battery versatile
  - DCDC Boost allows operation down to 0.8 volts
    - Enables support for single cell alkaline and 1.55v button cells
- Battery charge estimation
  - Coulomb counter to provide visibility into counts of charge pulls from battery
- Low active current
  - Provides longer battery life

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CONCLUSION

- Silicon labs believes energy-friendly MCU, Radio and IoT stacks are the key for enabling energy-harvesting.
- Consult Silicon Labs experts for assistance in designing your energy-harvest applications.
- Stay tuned for more announcements and publications on energy-harvesting in 2024
- Join Silicon Labs in creating the battery-less future for the IoT!

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