Everactive Self-Powered SoC with Energy Harvesting, Wakeup Receiver, and Energy-Aware Subsystem

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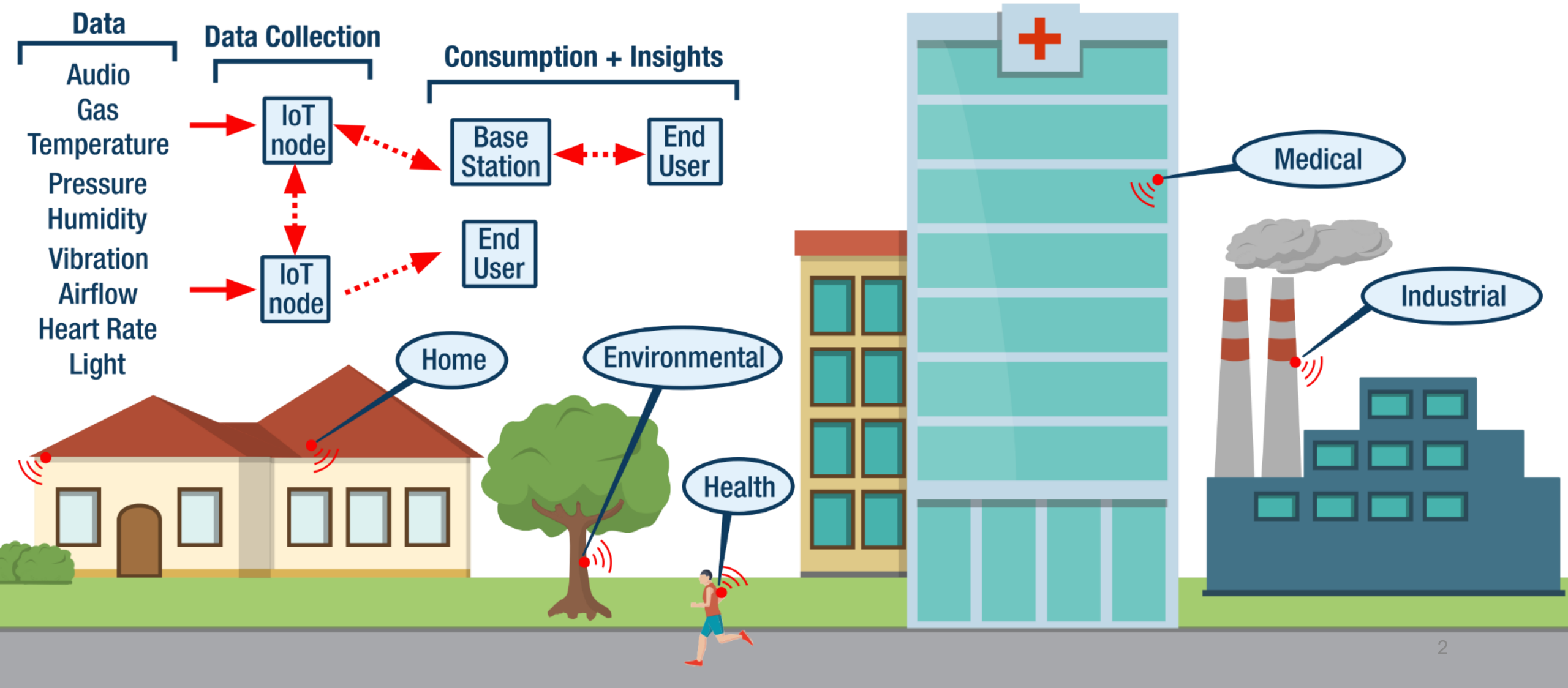
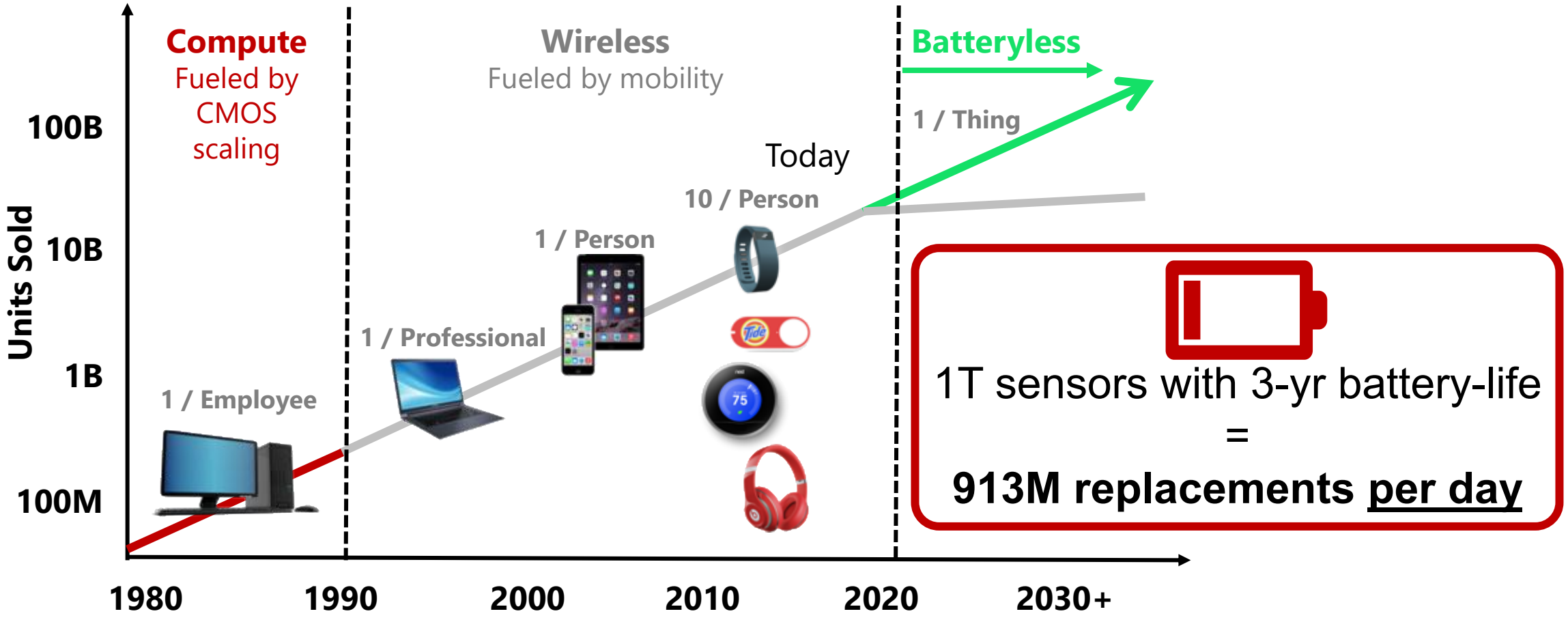
Internet-of-Things (IoT) - Toward a Trillion Nodes



Batteries Won't Get Us to a Trillion-Node (1T+) IoT



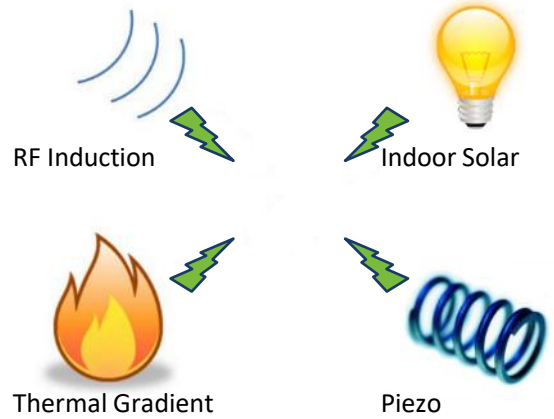
- Number of nodes prohibits use of batteries

Need a self-powered, batteryless solution

Energy Harvesting: Answer to the Power Problem?

IT ***IS*** THE ANSWER, but...

- It only delivers 10s of μWs / cm^2
- Versus 10s to 100s of mWs active power
- It also varies from nW to mW → tunability!



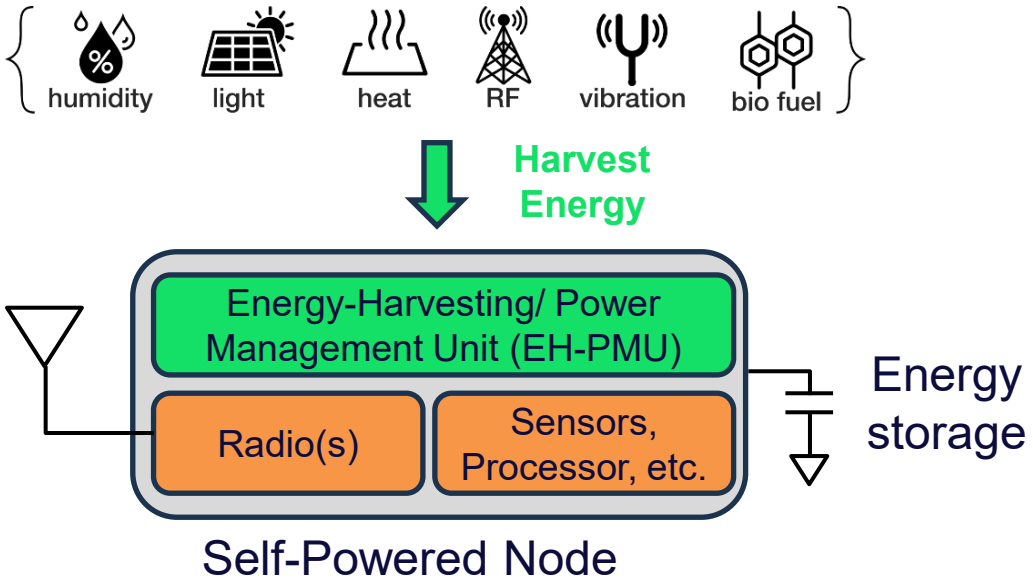
- Need 100x to 1000x improvement

SOLUTION: Reduce active system power to < 10 μW

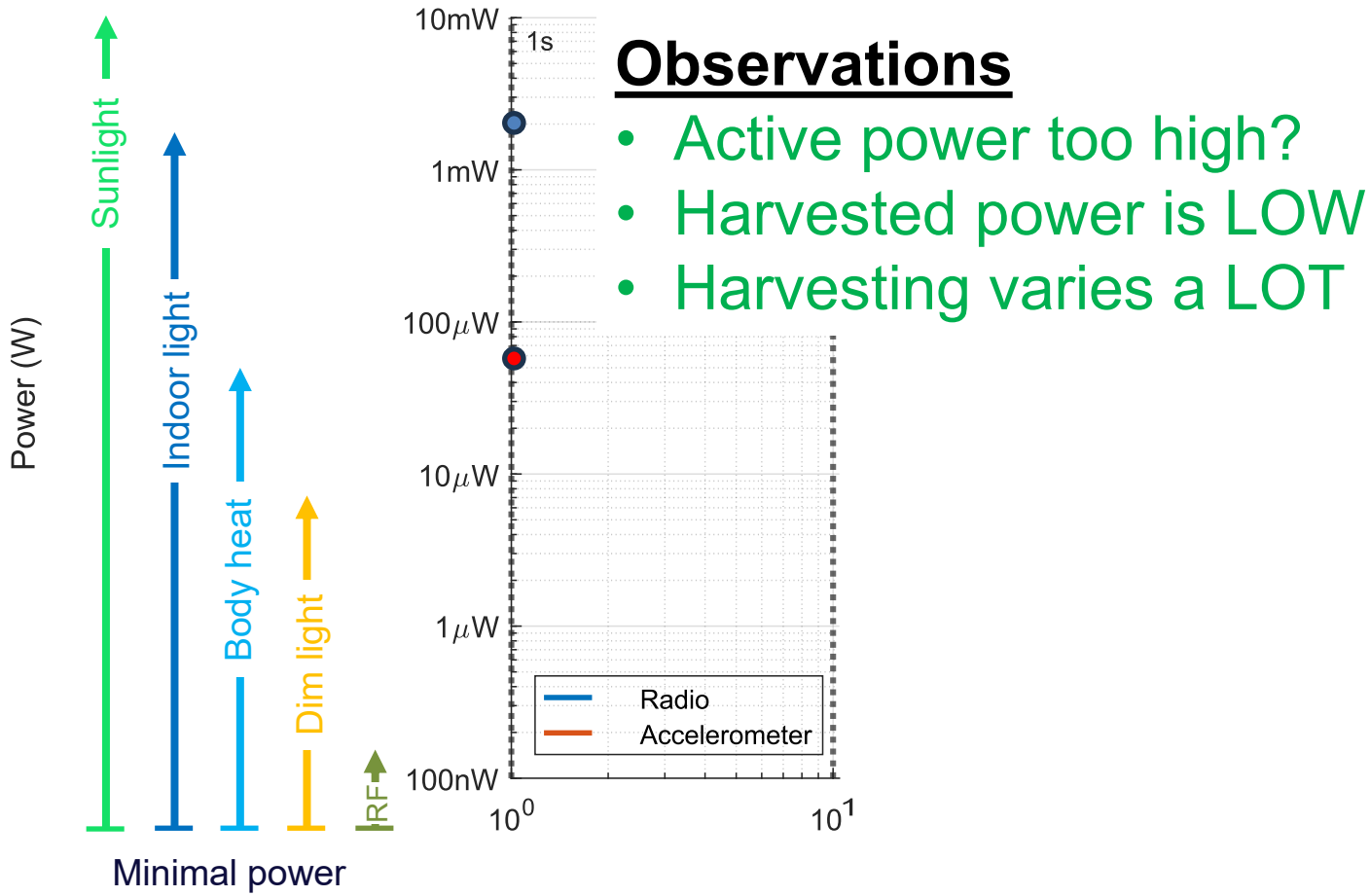
1 Watt = 1,000 milliwatts (mW) = 1,000,000 microwatts (μW) = 1,000,000,000 nanowatts (nW)

Self Powered / Batteryless Wireless Sensor Nodes

Harvest Energy from
"micro-Renewables"



Power-limited:
Low power levels and broad scaling needed



Observations

- Active power too high?
- Harvested power is LOW
- Harvesting varies a LOT

Self Powered / Batteryless Wireless Sensor Nodes

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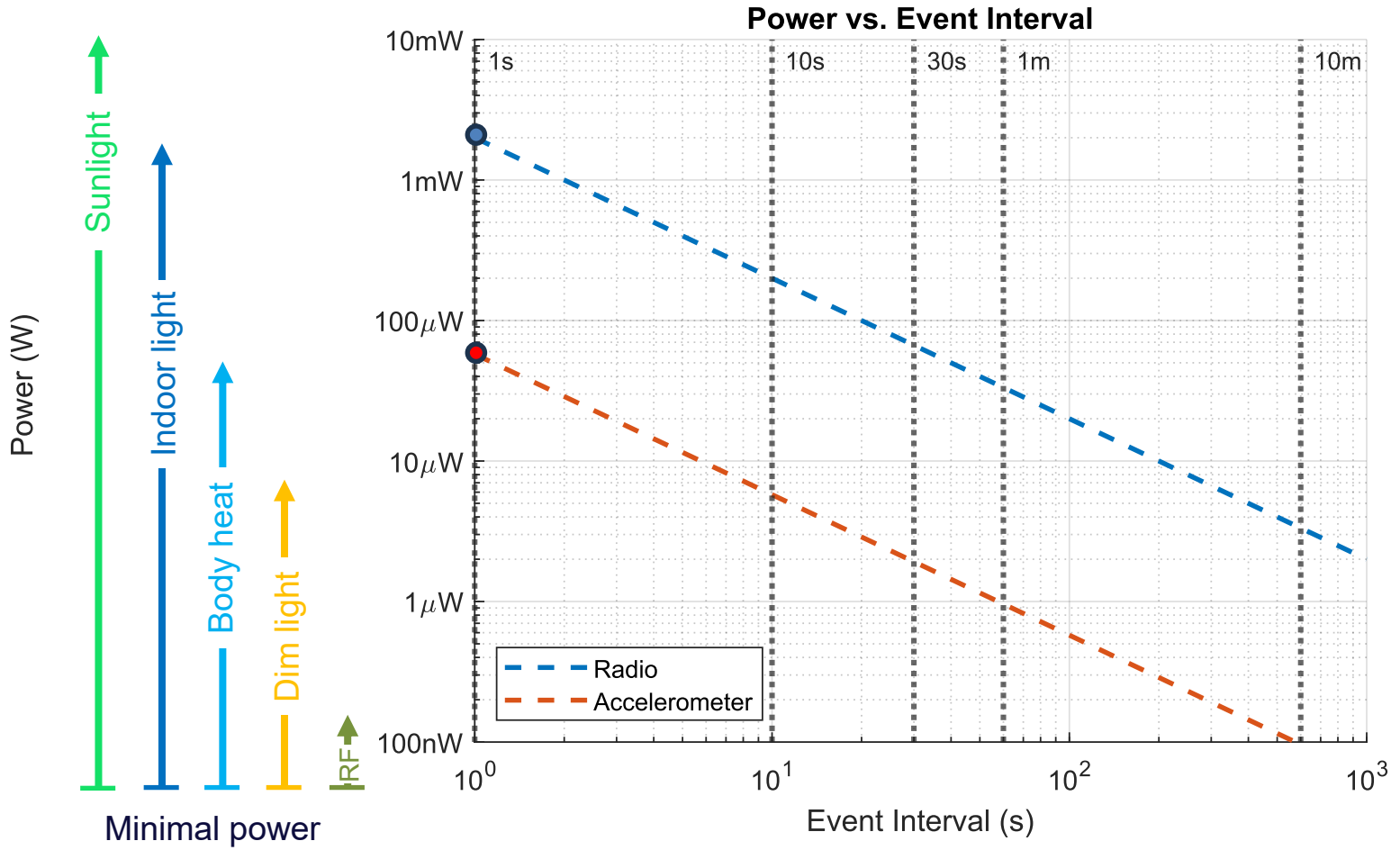

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- … but costs performance

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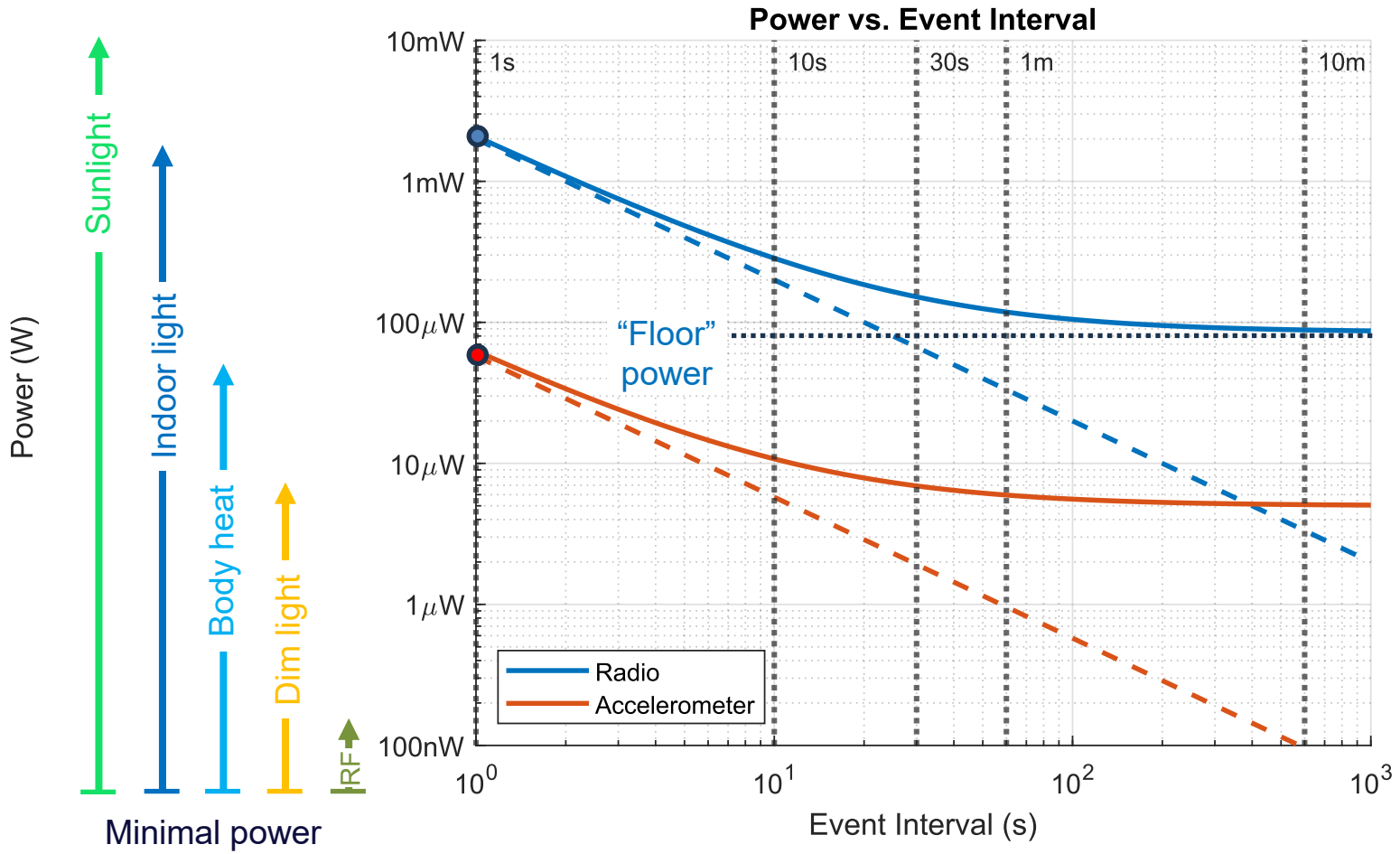

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- Active power too high?
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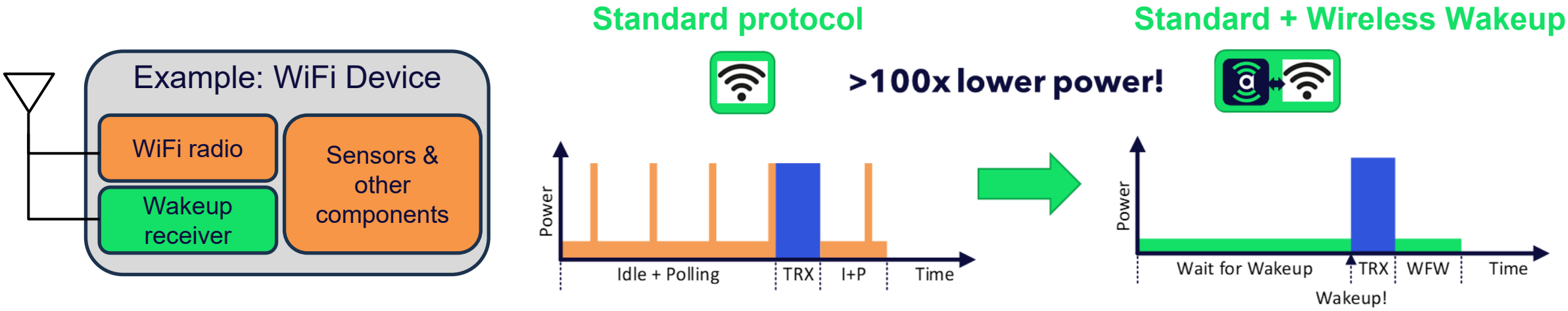
- Harvesting varies a LOT
- Duty-cycling scales active power
- … but costs performance
- FLOOR limits scaling
- LOWER floor power!
- ADD modes!
- STORE energy for availability
- USE the good times!

Wireless Wakeup (WU): Talk to standards with low latency and ultra-low-power



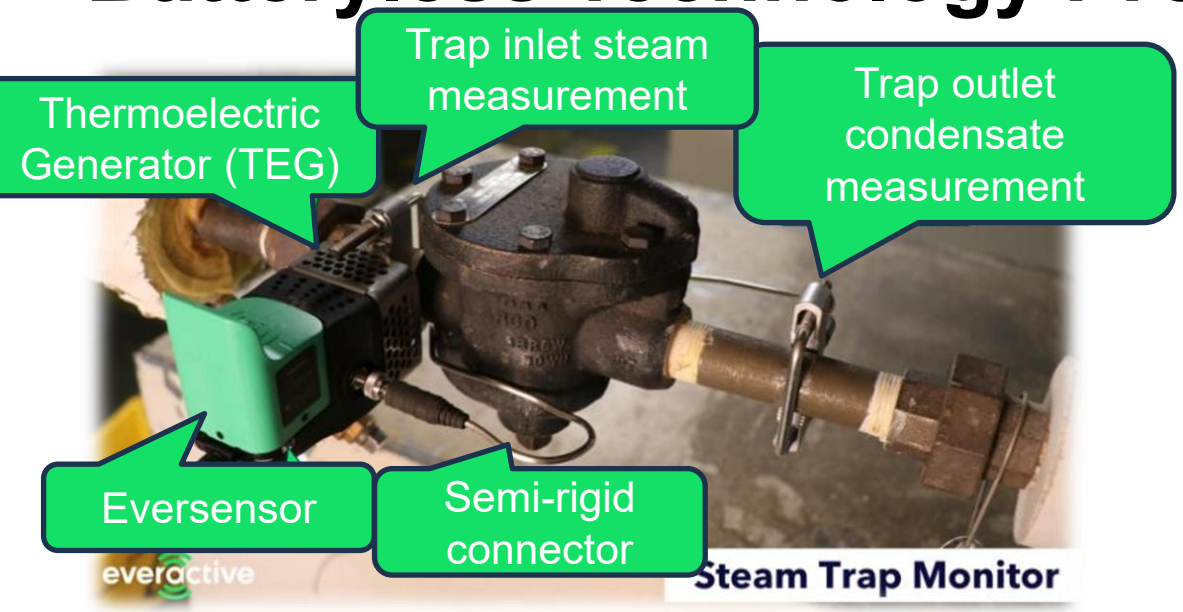
Wakeup at microWatts from standard protocols

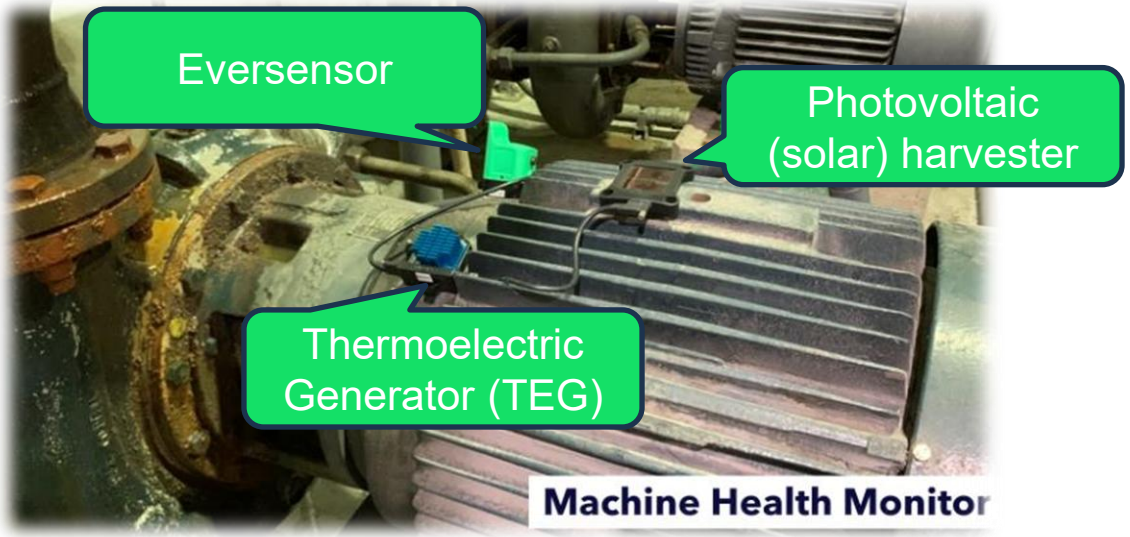
- Devices need to stay network-connected, but it costs POWER!
- Offload network synchronization to a Wakeup Receiver (WRX)
- Wakeup **saves >100X power** for low latency wireless applications
- **Devices extend lifetime by 8x-10x or are batteryless and perpetual**

What APPLICATIONS need self-powered?

- High VOLUME: 1,000s to 10,000s+ sensing points
  - Too many batteries to change!
- LONG LIFE: Need to monitor for years
- Hard to reach: Remote, costly, or dangerous access
  - Cannot support device maintenance
- Un- or under-monitored
  - No good existing solutions
- **LOTS of WORK**: Need to know what's happening **often** (continuous), **in detail** (lots of data), and **now** (time critical)
  - Existing battery-powered sensors get long life by doing less!

Batteryless Technology Proven in Industrial Deployments





87
Plants & Facilities

366
Equiv. US homes energy use saved per plant-year

20k+
Sensors Deployed

20M+
*New Data Points **per Day***

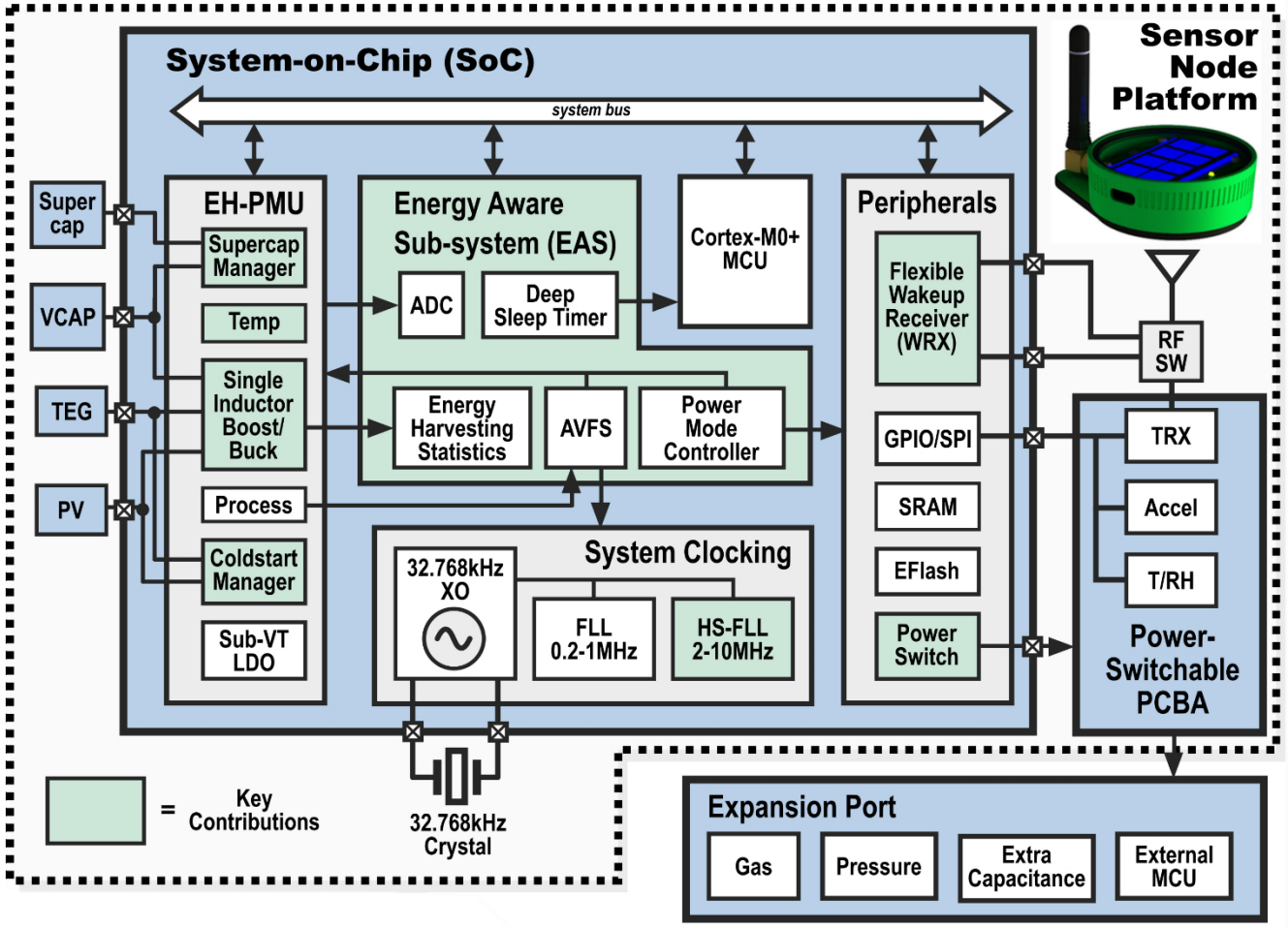
Substantial Work, e.g., MHM

- 3-axis vibration
- Calculate in-band energy
- Calculate FFT
- Measure temp/humidity/pressure
- Measure magnetic fields
- **Send data 1/minute**

Outline

- Introduction
- **System on chip (SoC)**
- Energy Harvesting Power Management Unit (EH-PMU)
- Wakeup Radio (WRX)
- Energy Aware Subsystem (EAS)
- Measured Results

SoC Overview

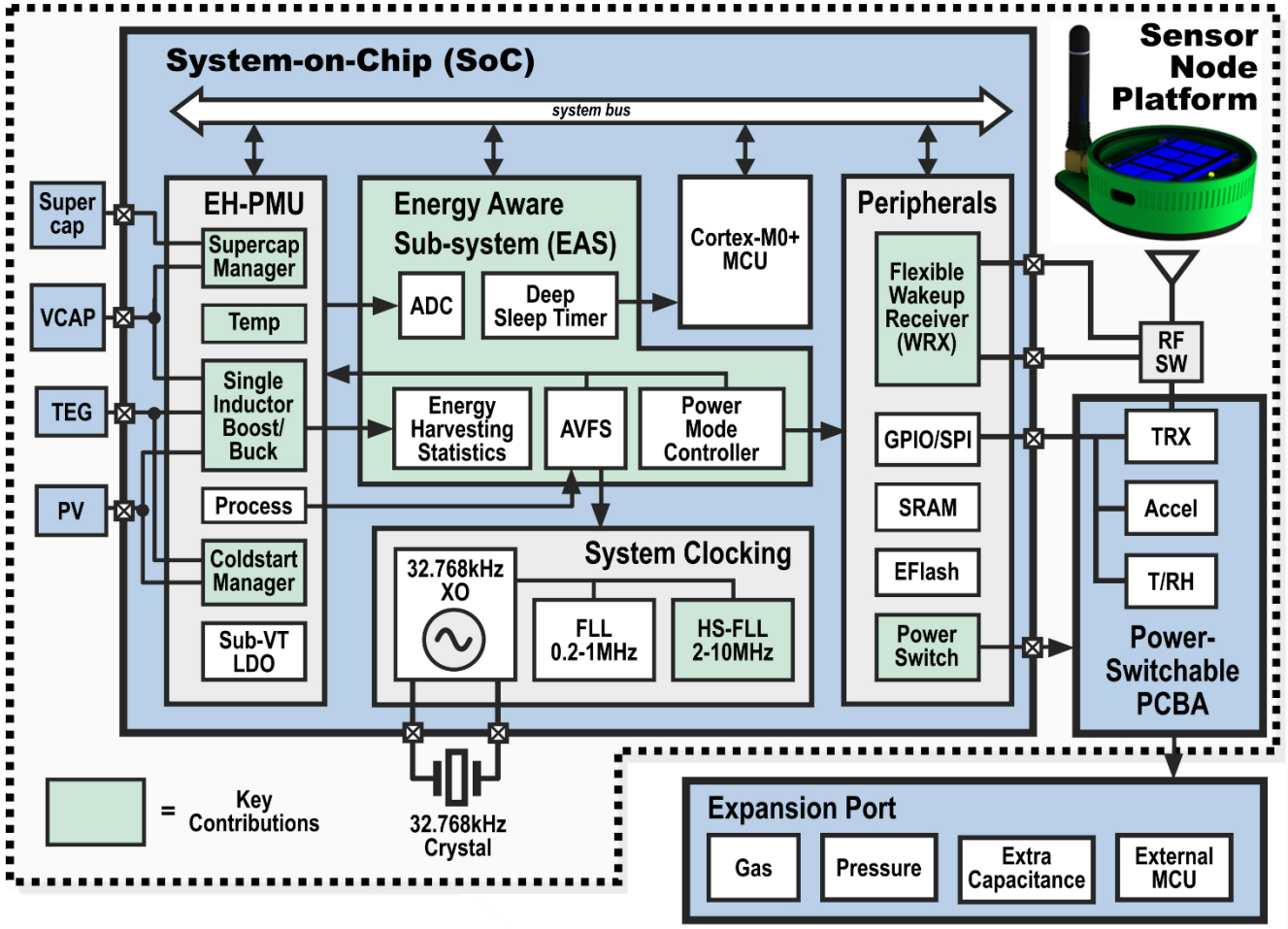


Goals:

- Continuous operation
- Adaptive performance
- Network management

[C. J. Lukas, et al., “A 2.19uW self-powered SoC …,” IEEE International Solid-State Circuits Conference (ISSCC), 2023]

SoC Building Blocks



Main Features:

- Always on!
- Harvests, wakes up, senses, processes, transmits, all without a battery
- Efficient integrated EH-PMU
- Long distance WRX
- Energy-Aware Subsystem (EAS) tightly integrates PMU, WRX, core, memory

[C. J. Lukas, et al., "A 2.19uW self-powered SoC …," IEEE International Solid-State Circuits Conference (ISSCC), 2023]

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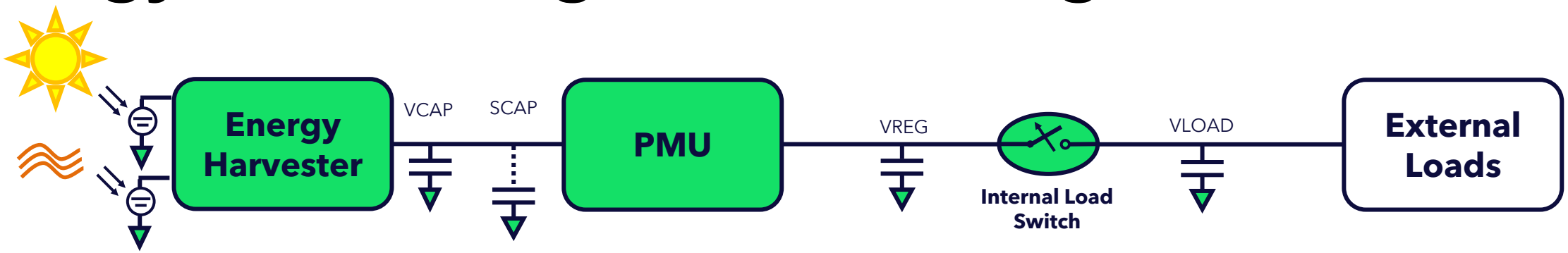
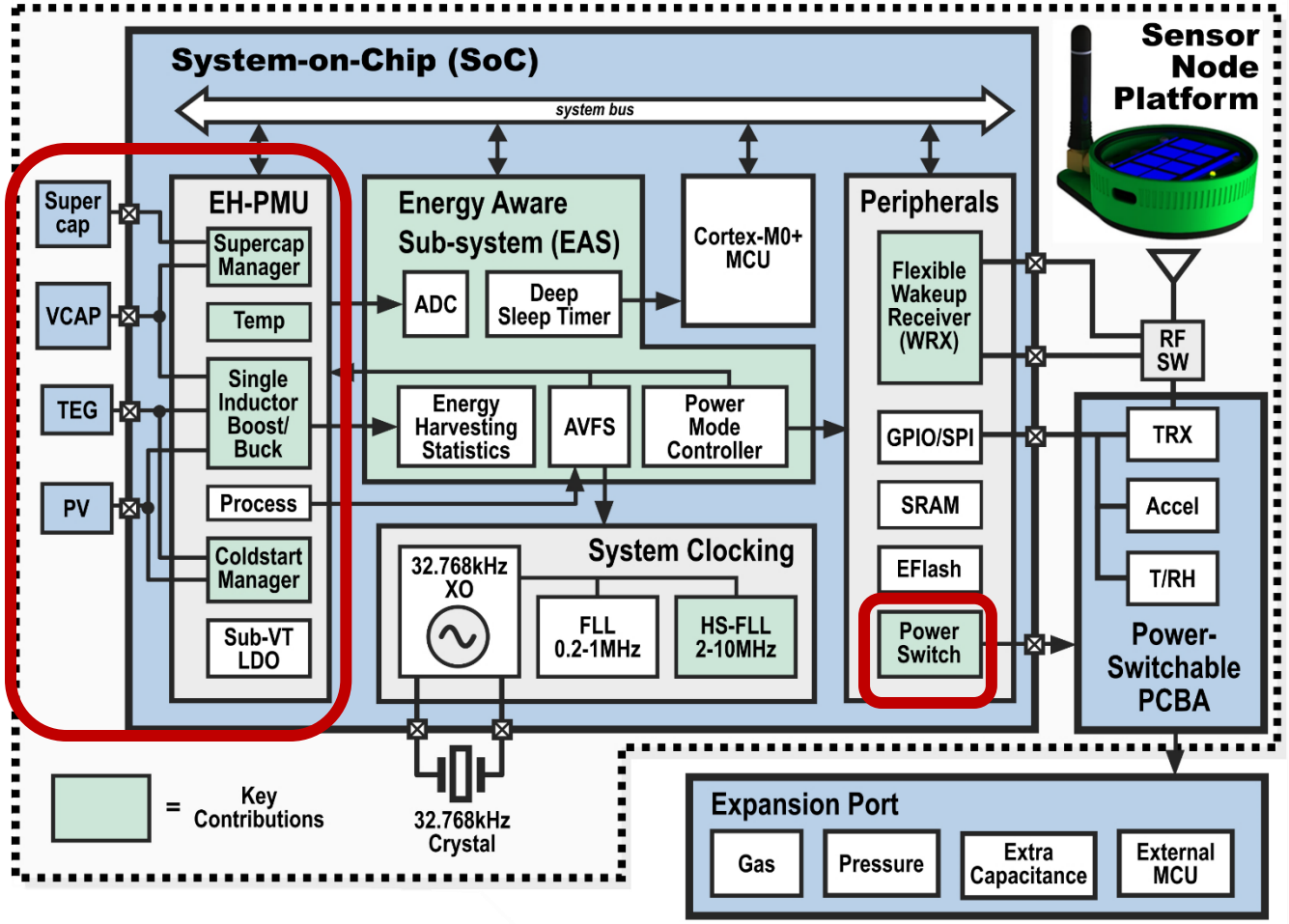
Energy Harvesting Power Management Unit



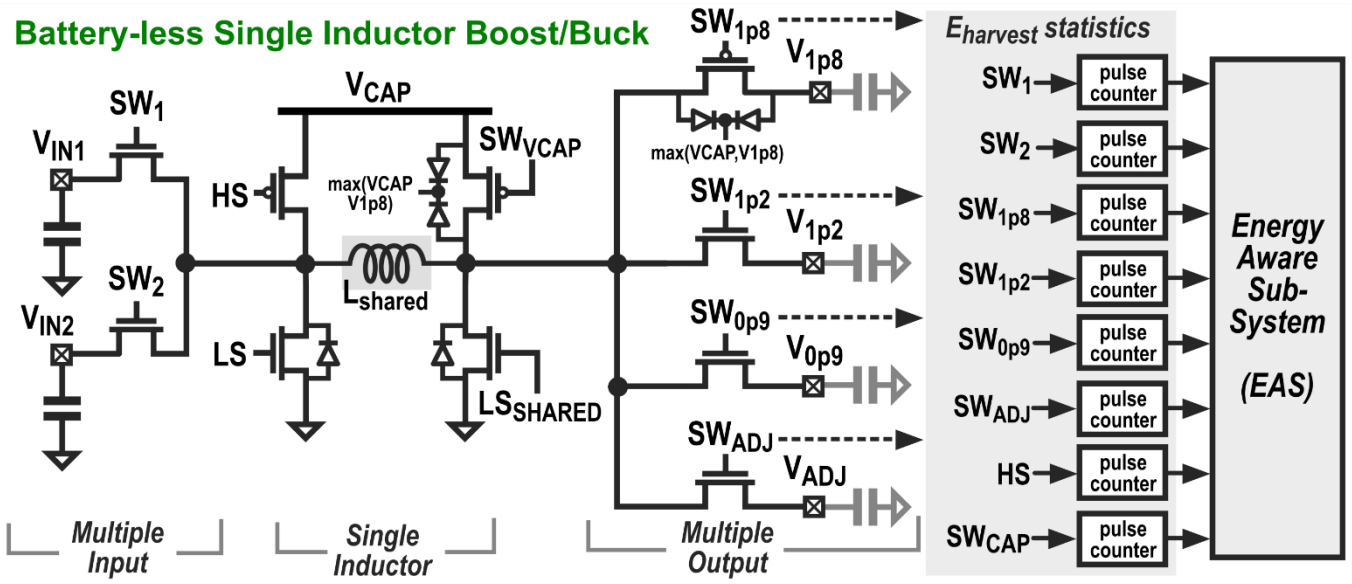
- Harvest from multiple sources → Flexible locations; varying conditions
- Cold-start from either input → Recover from brown outs
- Support no battery → Cannot assume a fixed input voltage
- Multiple energy storage nodes → Fast start up & big reserve
- Power load-switch → Isolate from off-chip components

Energy Harvesting Power Management Unit



- Multiple modes of harvesting
- Multiple node energy storage
- PVT sensing
- Low voltage cold start
- Low voltage LDO

Energy Harvesting Power Management Unit



- **Simultaneously harvest from light and heat directly to the load**
  - Can harvest from EM coil, vibration, air flow

- **Architecture inspired from MISIMO, ISSCC 2018**
  - Single inductor form factor
  - Asynchronous controller
  - **Added energy management**
  - **Added SCAP storage**
  - η_{PEAK} = 80%, I_{DDQ} = 225nA
- **Two cold start circuits**
  - Low voltage (e.g., for thermal)
  - Low current (e.g., for PV)
- **Integrated MPPT**
- **Integrated with EAS to track harvesting quality**

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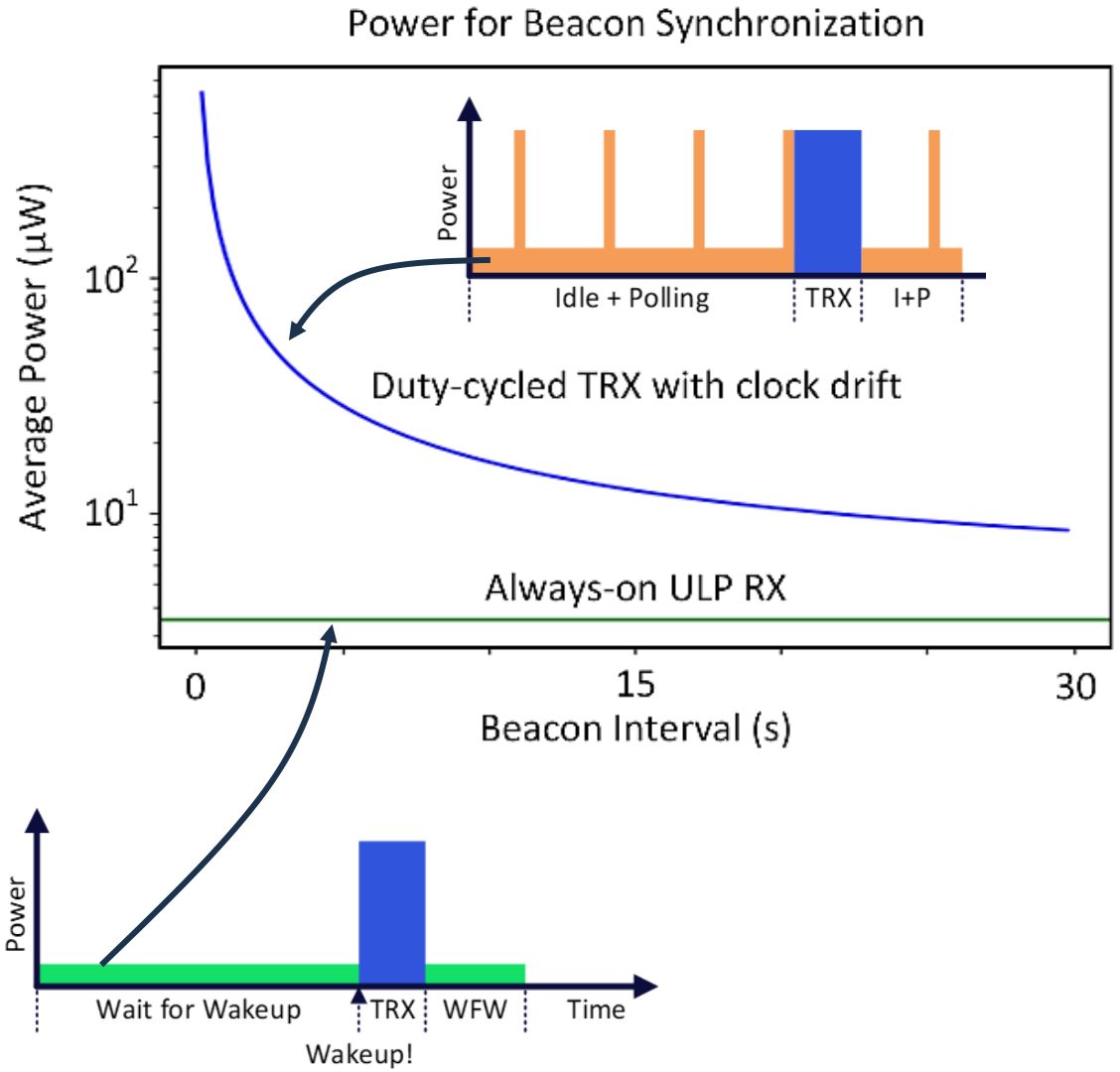
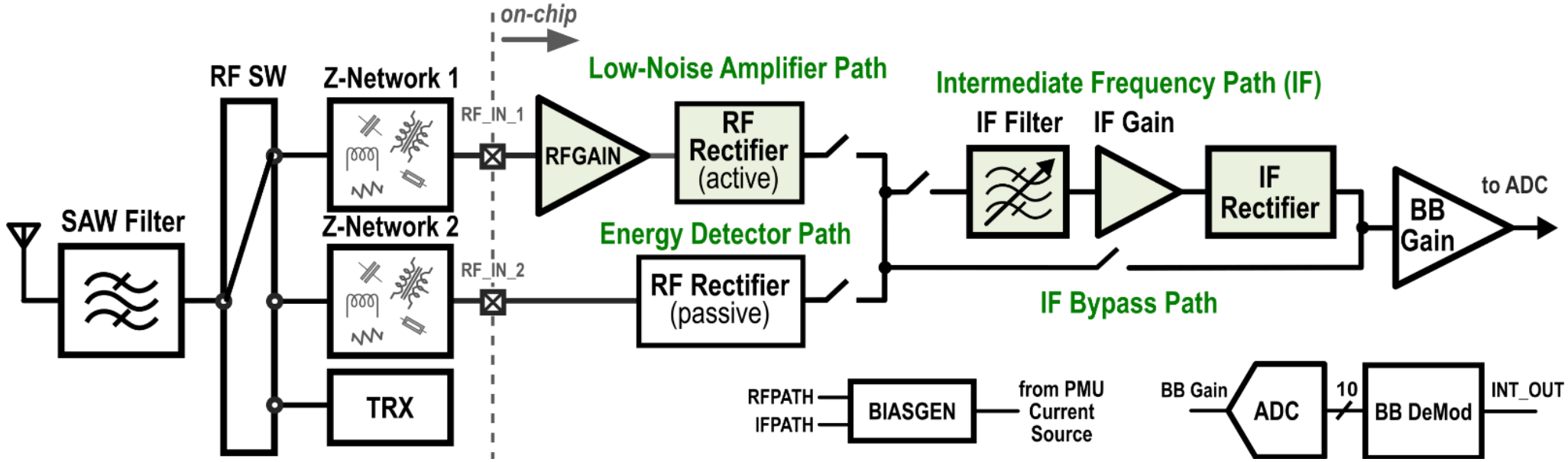
Wake-up Radio (WRX)

- **Always-on WRX sets the power floor**
  - To meet the harvested budget
- **Duty cycled receivers pay power to lower latency**
- **Breaking the traditional radio power/latency tradeoff**



Wake-up Radio (WRX)



- **Integrated WRX enables deeper, longer sleep**
- **Synchronizes network while trading off power, range, selectivity**
- **Two RF paths scale range**
- **IF Path scales in-band selectivity through 2 tone on-off keying (OOK)**
  - Enables multi-channel wakeup (WU)
  - Back-channel WU from standards
- **Shared Antenna with TRX**
- **Adapts to support standards:**
  - WiFi, BLE, 5G, etc.

Wake-up Radio (WRX) Modes

	LNA-IF on (max LNA gain)	LNA-IF on (min LNA gain)	LNA-IF off	ED-IF off
Measured Sensitivity	-92 dBm	-70 dBm	-80 dBm	-63 dBm
Measured Selectivity	29 dB	30 dB	12 dB	15 dB
Measured Dynamic Range	-92 → -10dBm	-70 → -10dBm	-80 → -10dBm	-63 → 0dBm
Measured Active Power	355 µW	51 µW	96 µW	0.95 µW

- **Power scaling:**
  - Energy detection (ED) when possible
  - Multi-stage WU w/ global sync
  - Active path bit-level duty cycling
  - SoC power at -92dBm is 5.9µW from VCAP using global sync and 802.15.4g payloads

Low Avg. Power and reasonable Time-on-Air

- **EAS selects best radio pathway for conditions**

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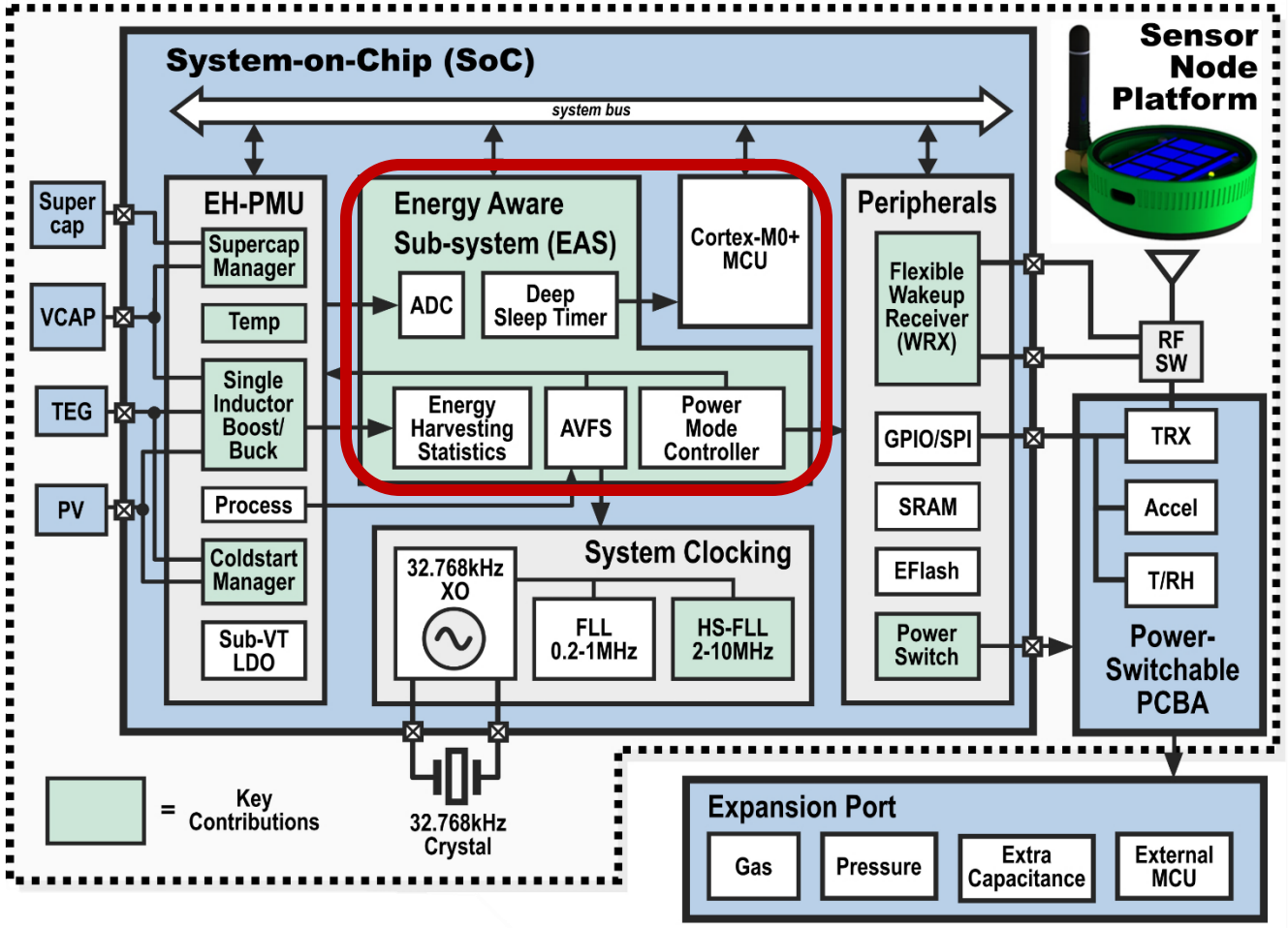
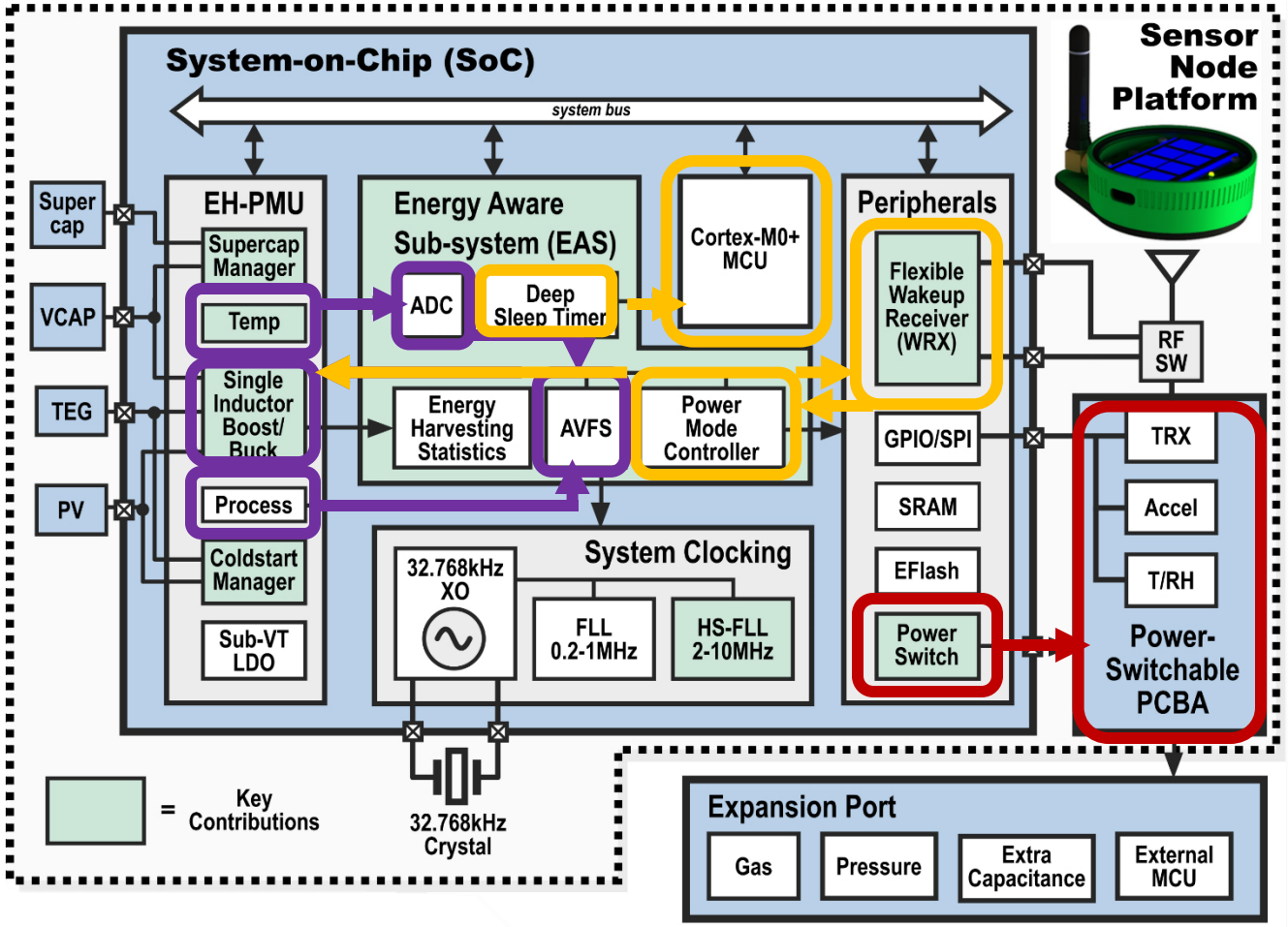
Energy Aware Subsystem Overview



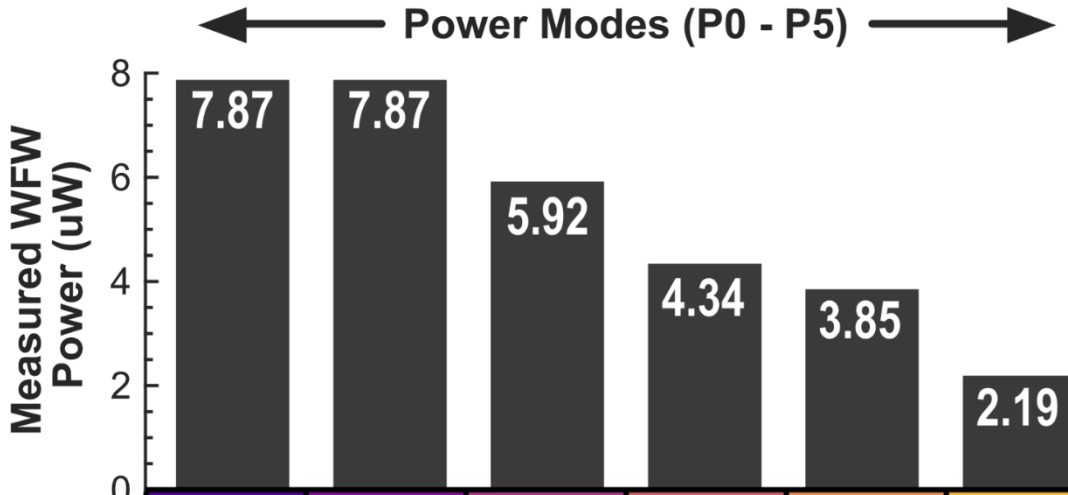
- **EAS hardware periodically monitors available energy**
- **EH-PMU energy counters keep track of switching rates**
- **EAS builds harvest model**
  - Historical, statistical forecasting
- **Insights help firmware decide:**
  - Which power mode
  - Max frequency
  - When to enable off-chip components
  - Wakeup request response rate
  - When to enable OTA updates

Energy Aware Subsystem and SoC Integration



- On-chip PM and temp sensor adapt near or sub-V_T rail for steady performance across temperature and process
- EAS includes a load switch circuit for off-chip components to ensure power floor is achieved
- Wait-for-Wakeup (WFW) mode idles the processor, waiting for an event from environment or radio

Energy-Aware Subsystem Power Modes



		P0	P1	P2	P3	P4	P5
Active	Sample Rate	Max	High	Med	Med	Low	Min
	Transmit Rate	Max	High	Med	Low	Min	Min
	CLK	HSFLL	HSFLL	FLL	FLL	XO	XO
WFW	CLK	FLL	FLL	FLL	XO	XO	XO
	Vadj	High	High	High	High	Low	Low
	Vram	High	High	High	High	RET	Off
	WRX	ON	ON	ON	ON	ON	OFF

- **Energy aware decision tree manages power modes using:**
  - *Harvested power* from energy counters
  - *Stored energy* via CAP measurements
  - *Forecasted power* from EAS statistics
- **P0 highest sample, process, transmit rate, up to 10MHz**
- **P4 lowest on demand WU power**
- **P5 responds to a fraction of scheduled wakeup requests**
  - WRX duty cycled
  - Processor halted
  - EAS state machine and EH-PMU on
  - Longer wakeup from cold start

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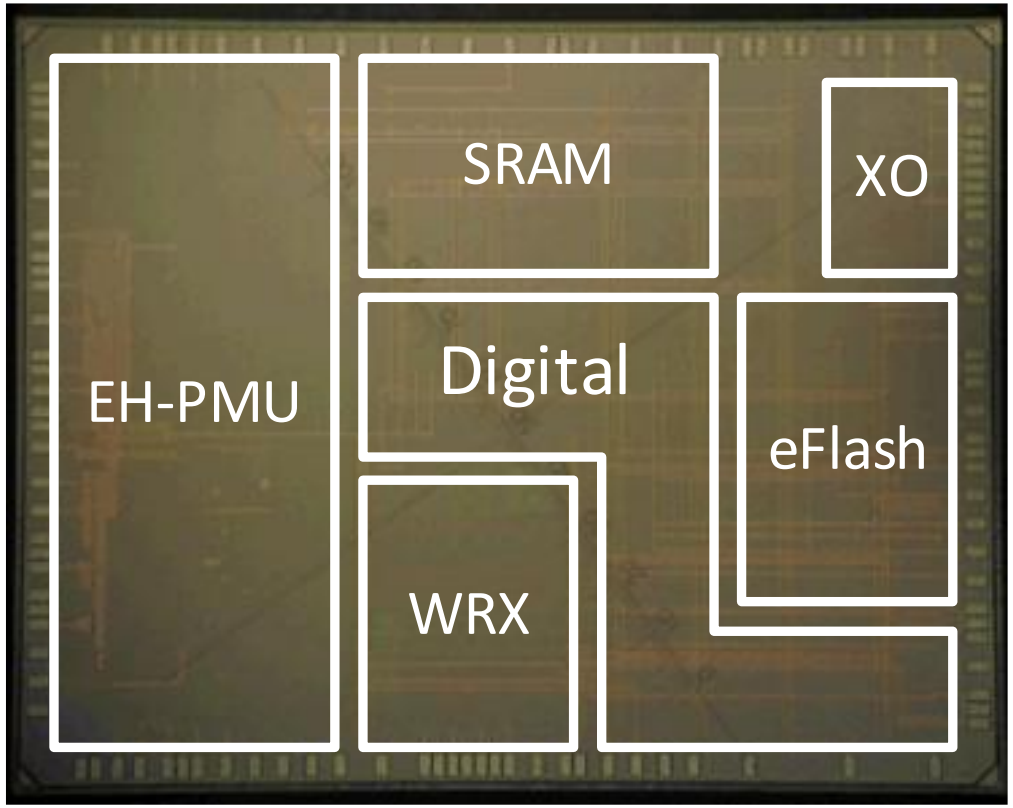
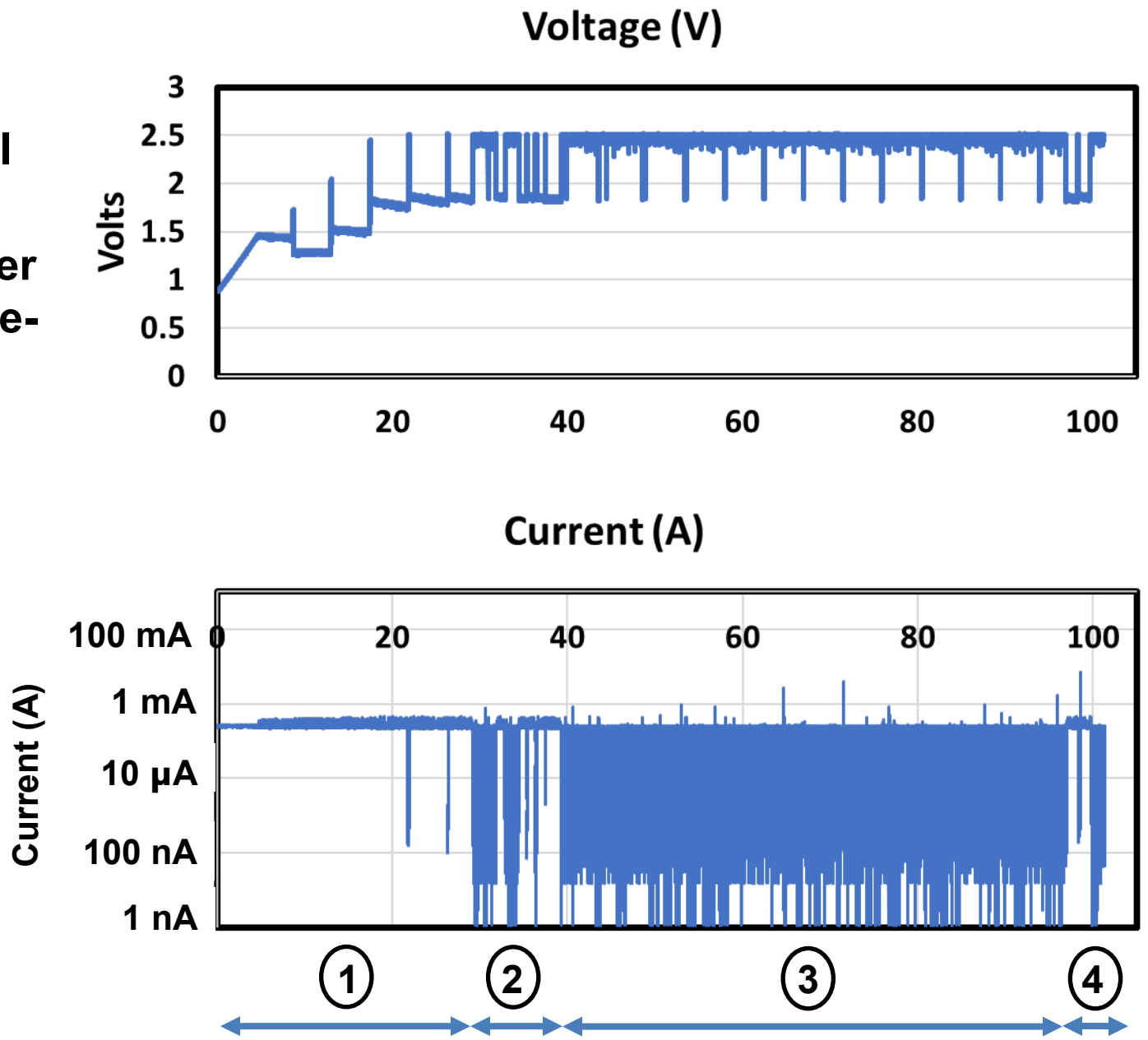
Chip Die Photo



- 2.19 µW floor power
- MCU: ARM Cortex M0+
- Memory: 256 kB flash; 128kB low power RAM
- Clocks: 32 kHz XTAL; 200 kHz – 10 MHz FLLs
- Energy harvesting: 2 concurrent sources
- Sensor interfaces: 8b ADC; SPI; UART; GPIO
- WRX: 300 MHz to 2.4 GHz with wakeup from standards

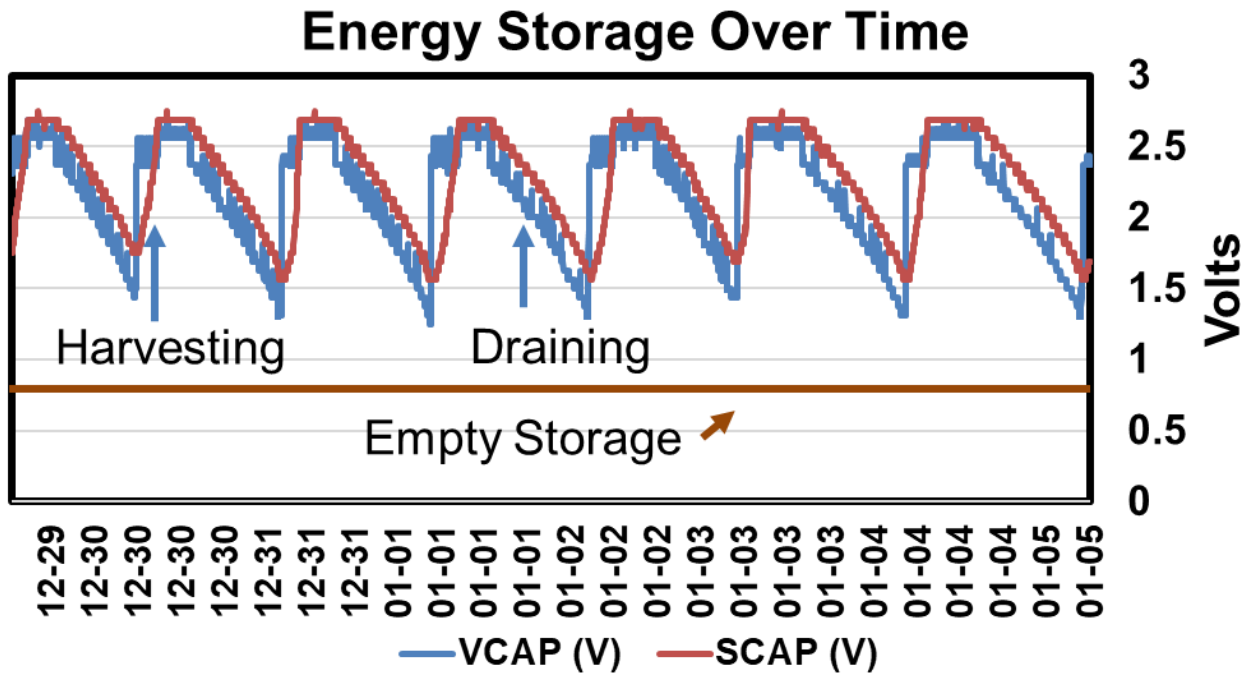
Measured Results

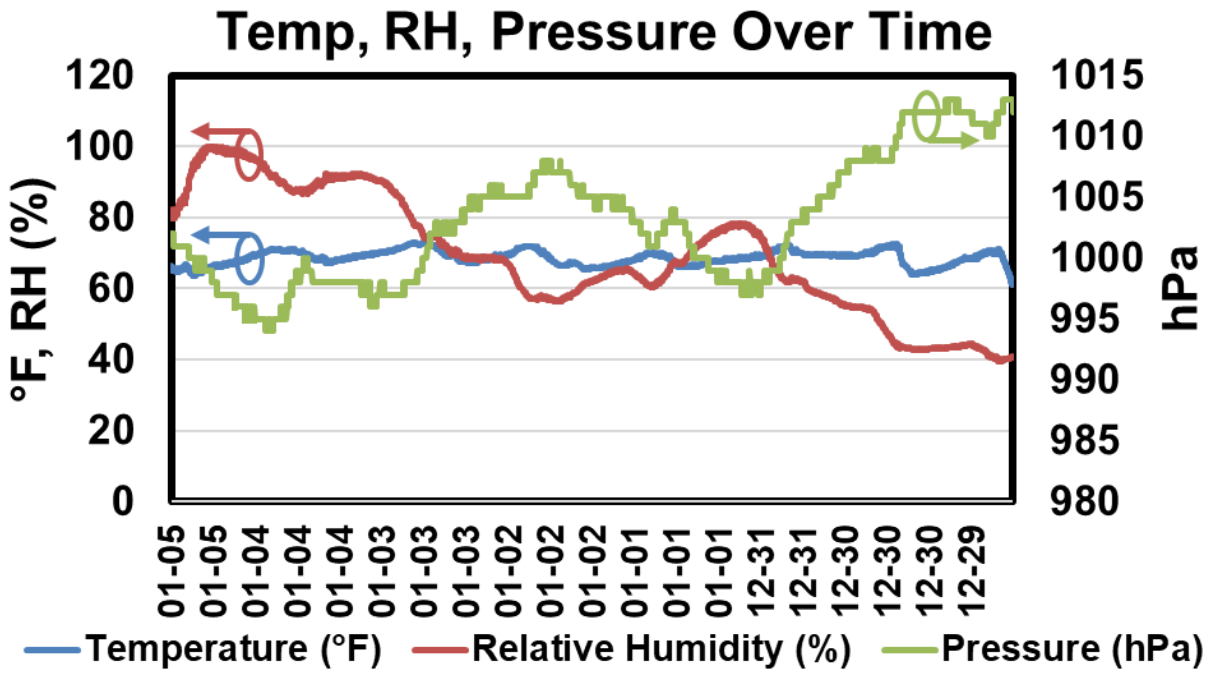
- Cold starts from 42x26mm² PV cell <60 lux or TEG <8ºC
- 13x lower power floor and 6x longer range than comparable state-of-the-art EH-SoCs
- Figure shows:
  1. Cold start
  2. Boot
  3. Deep sleep
  4. Wakeup



Measured Results

- Figures show data collected from the cloud, transmitted from a sensor in the field
- Continuous reliable operation over many days



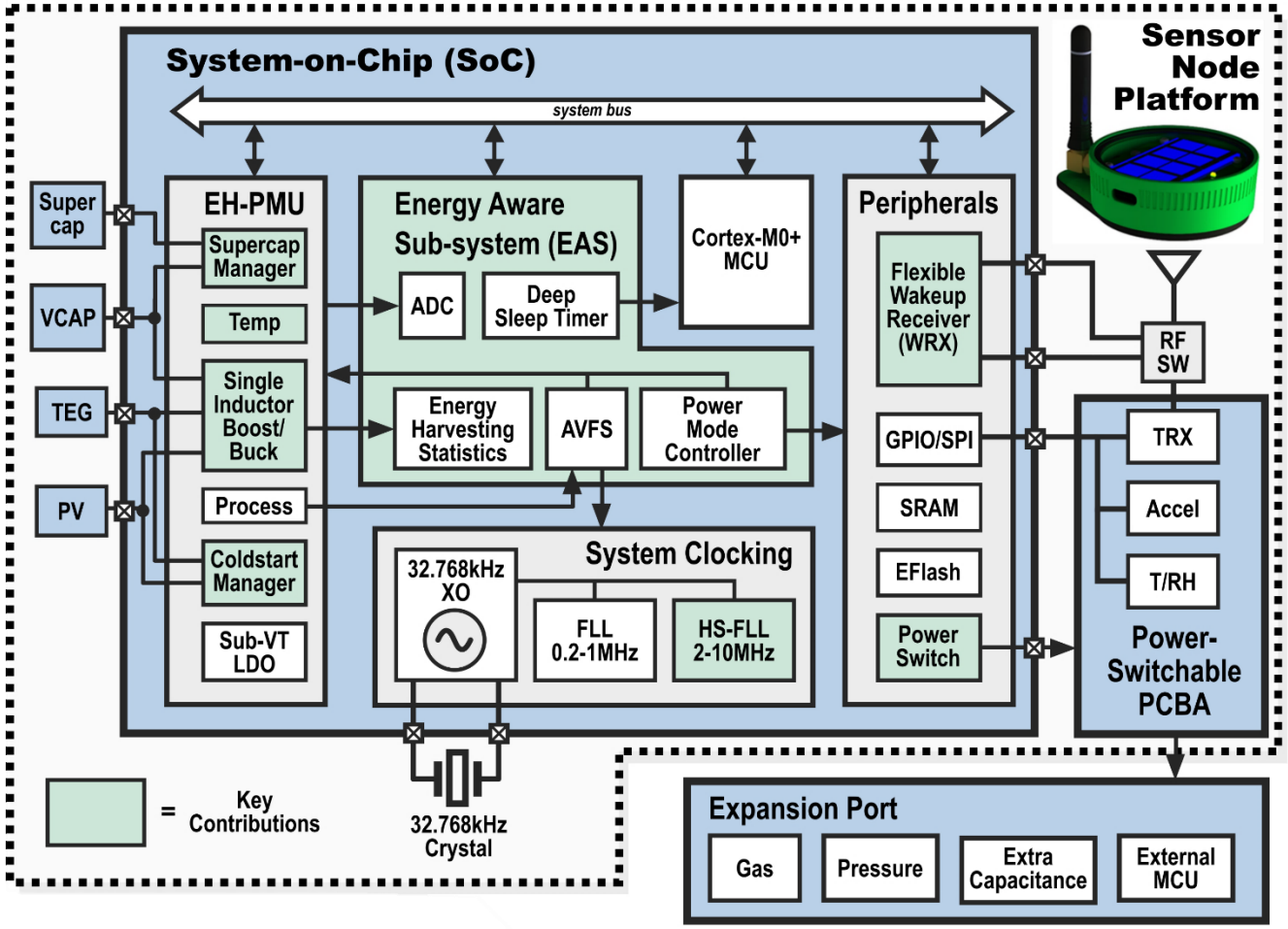


Summary and Conclusions

- Self-powered operation is inevitable for huge-scale IoT
- Self-powered systems need **system-level optimization**
  - Flexibility to match modes to environment
  - System-aware power management
  - Wakeup for low latency and low power networks
- Self-powered systems aren't just possible - they're already powering change!

Questions? ben@everactive.com

SoC Acronyms



Term	Description
ADC	Analog to Digital Converter
AVFS	Adaptive voltage and frequency scaling
CAP/SCAP	Capacitor / super-capacitor
EAS	Energy Aware Subsystem
ED	Energy Detector
EH-PMU	Energy-Harvesting Power Management Unit
FLL/HSFLL	Frequency Locked Loop / High Speed Frequency Locked Loop
GS	Global Sync
IF	Intermediate Frequency
LDO	Low Drop Out power supply
LNA	Low Noise Amplifier
MCU	MicroController Unit
MISIMO	Multiple Input Single Inductor Multiple Output energy harvester
MPPT	Maximum Power Point Tracking
OOK	On Off Keying
OTA	Over The Air software updates
PV	PhotoVoltaic
PVT	Process Voltage Temperature variation
RF SW	Radio Frequency Switch
SoC	System on Chip
SPS	Self-Powered System, usually battery-less, small form factor
TEG	ThermoElectric Generator
T/RH	Temperature / Relative Humidity
TRX	Radio Transceiver
VADJ	Adjustable voltage rail, near or subthreshold
VRAM	SRAM voltage rail
WFW	Wait For Wakeup mode of operation
WRX	Wakeup Receiver radio
WU	Wake Up