Innovation at the edge: Next generation IoT

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Texas Instruments

Outline

- IoT market & projections
- Innovation areas
  - Power reduction
  - Increased integration
  - Improved interoperability
- Conclusions

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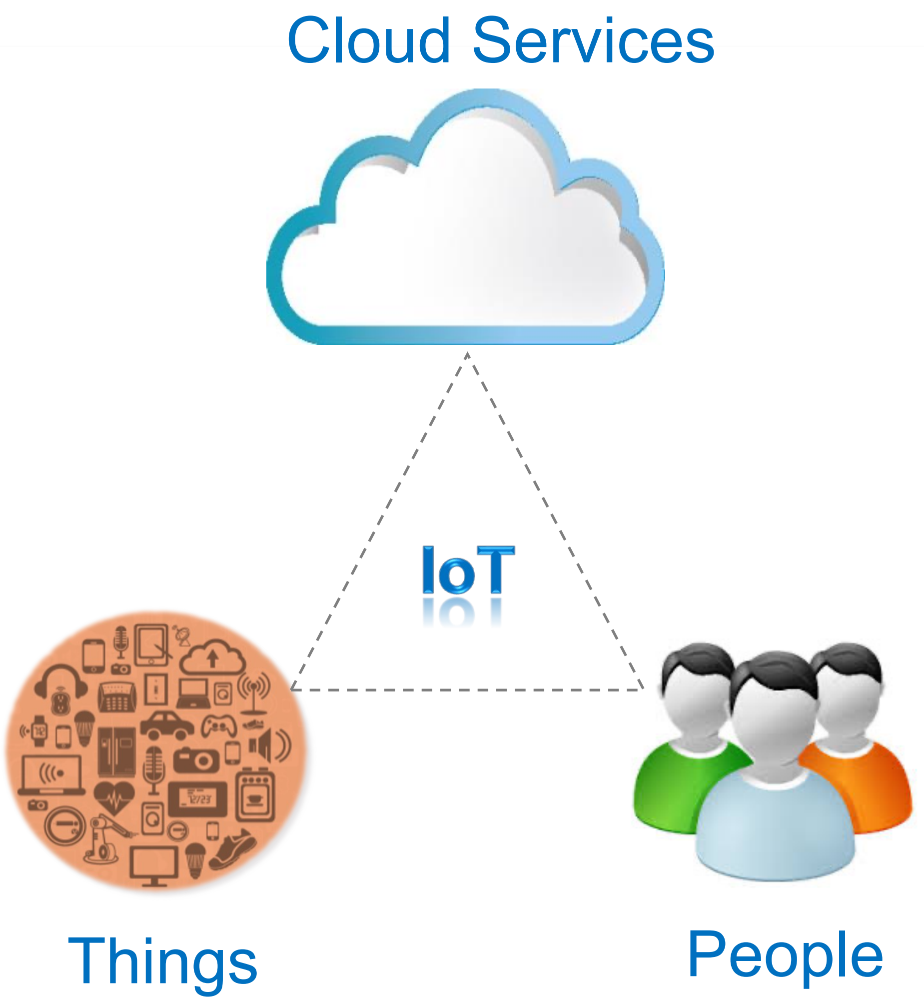
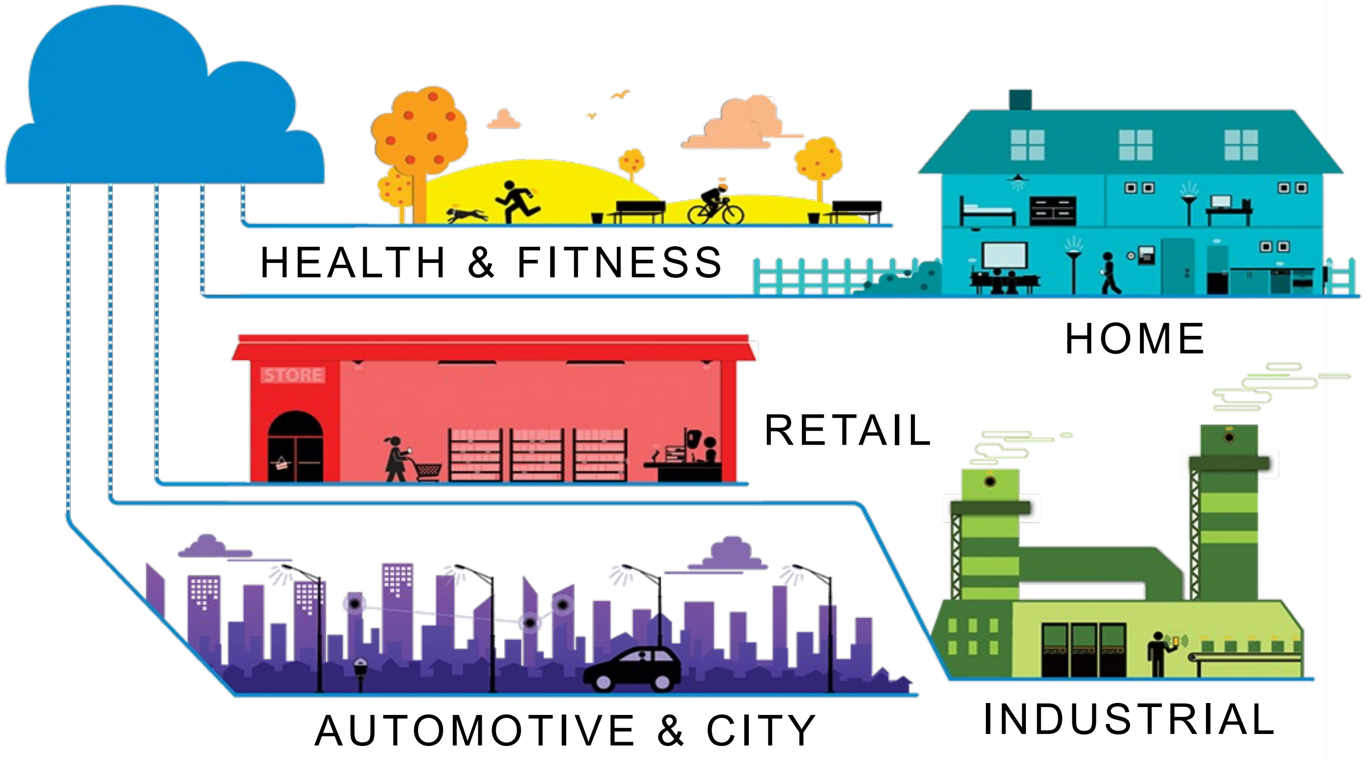
IoT

- "Internet of Things" term first used in 1999
- IoT: things, people and cloud services connected to the Internet to enable new use cases and business models
- Innovation at the edge has enabled explosive growth over the last 20 years
- Now IoT is at an inflection point
  - More innovation needed for IoT 2.0 & to avoid market saturation



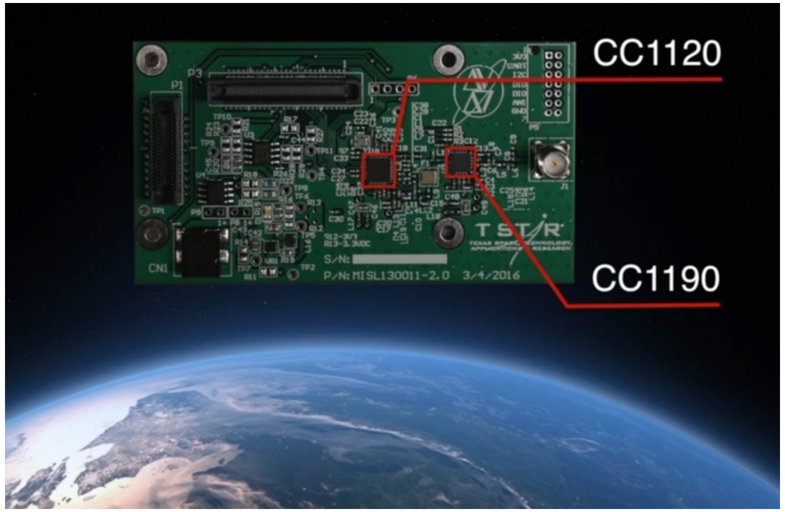
IoT applications & characteristics

- Low power wireless connectivity application space is broad
- Despite being so broad, there are core requirements
  - Low power: battery operated
  - Small size: enables new applications
  - Scalable: 100s to 1000s of nodes in a network
  - Secure: billions of devices must be protected



Innovation leads to new applications

Long Range



- >100km range on battery power
- Sub-1GHz ISM band
- Range limited by curvature of the earth
- Used for sensors in space

Low Power

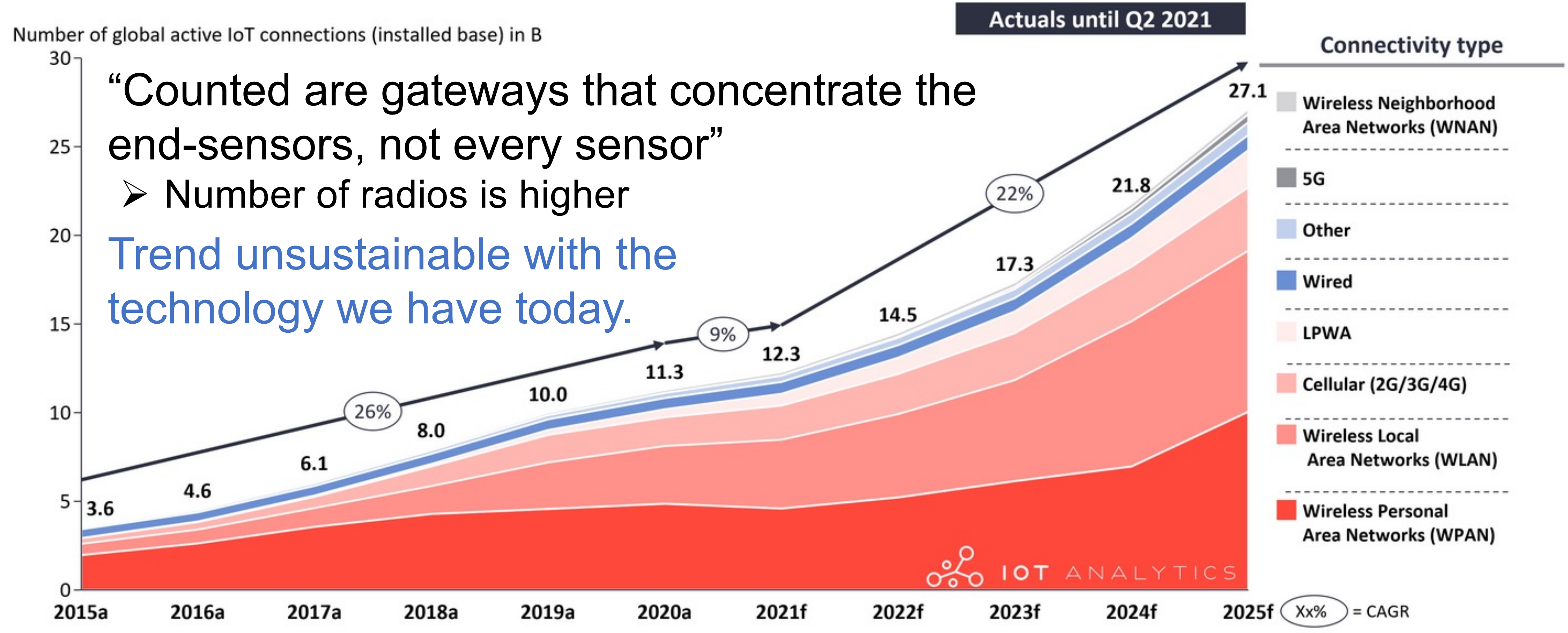
- 20 kilometers on coin cell battery
- 10 years lifetime on coin cell battery
- Coupled with energy harvesting for autonomous battery-free networks

Global IoT market forecast

“Counted are gateways that concentrate the end-sensors, not every sensor”

- ➢ Number of radios is higher

Trend unsustainable with the technology we have today.



Note: IoT Connections do not include any computers, laptops, fixed phones, cellphones or tablets. Counted are active nodes/devices or gateways that concentrate the end-sensors, not every sensor/actuator. Simple one-directional communications technology not considered (e.g., RFID, NFC). Wired includes ethernet and fieldbuses (e.g., connected industrial PLCs or I/O modules). Cellular includes 2G, 3G, and 4G. LPWAN includes unlicensed and licensed low-power networks. WPAN includes Bluetooth, Zigbee, Z-Wave, or similar. WLAN includes Wi-Fi and related protocols. WNAN includes non-short-range mesh, such as Wi-SUN. Other includes satellite and unclassified proprietary networks with any range.

https://iot-analytics.com/wp/wp-content/uploads/2021/09/Global-IoT-market-forecast-in-billion-connected-iot-devices-min.png

Battery limitations

$$\frac{\text{27B (gateway + end nodes)}}{\text{5B people aged 15-65}}$$ → Each person must change/charge batteries for all nodes in >5 networks

- Gateways with 2 end nodes, 1 year battery life
  → 10 batteries / year / person
- Gateways with 200 end nodes, 3 month battery life
  → 4000 batteries / year / person
- Environmental impact
- Power consumption must be reduced to enable market projections
  - How low is low enough?

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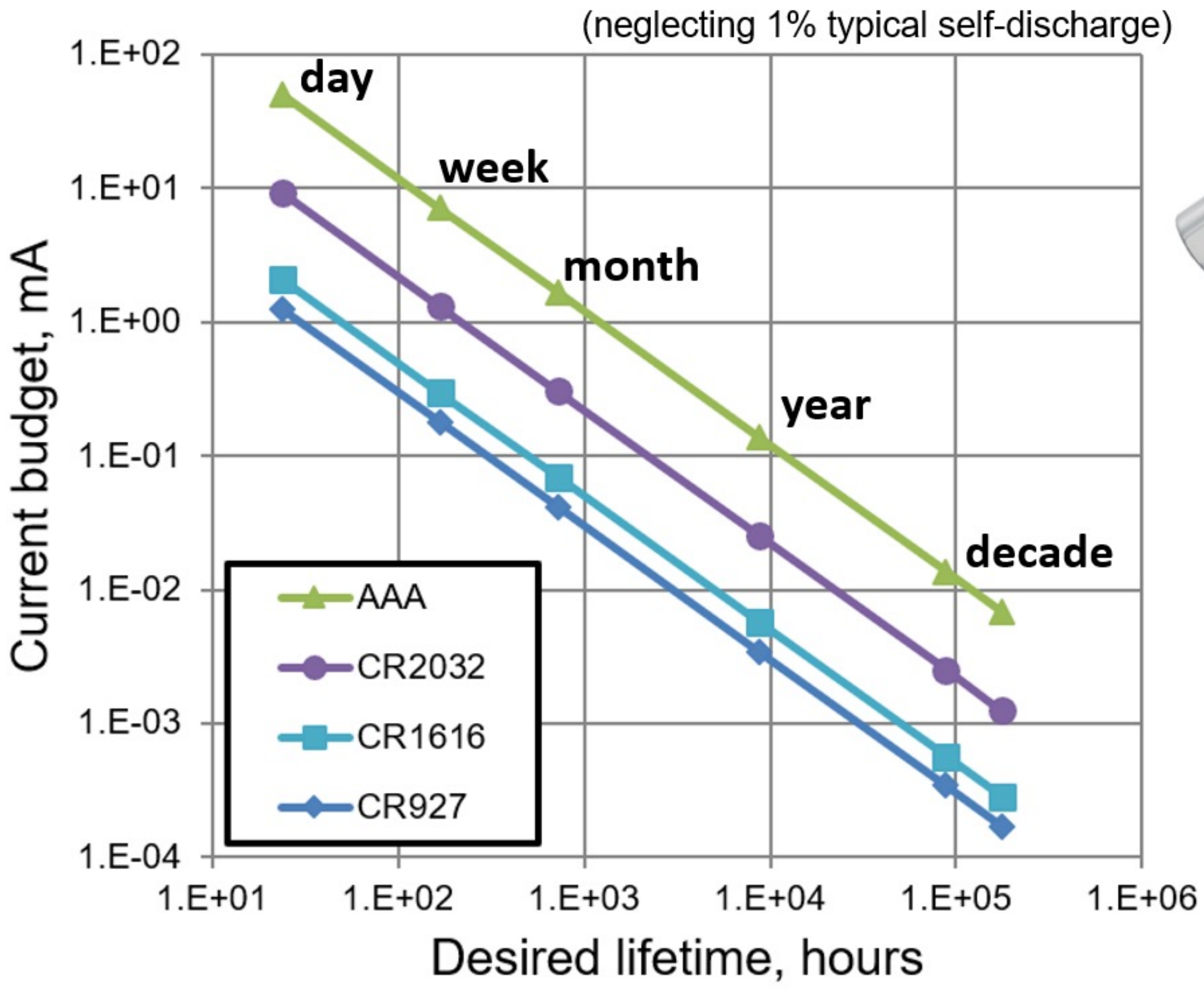
Power consumption & battery lifetime



44x10mm

20x3.2mm

16x1.6mm

9.5x2.7mm

Battery must last as long as the silicon

10 years → <13μA

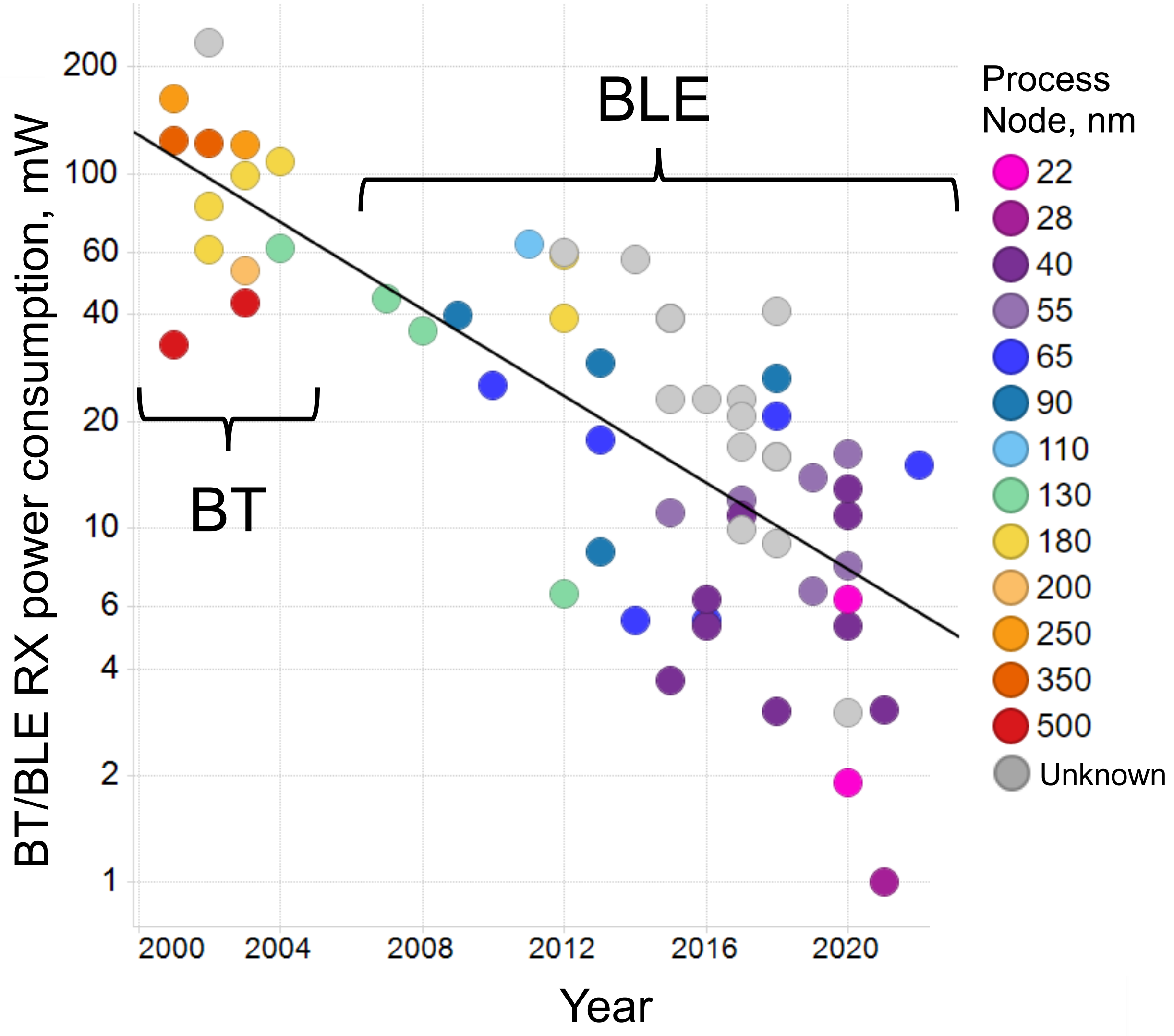
10 years → <2.5μA

10 years → <570nA

10 years → <340nA

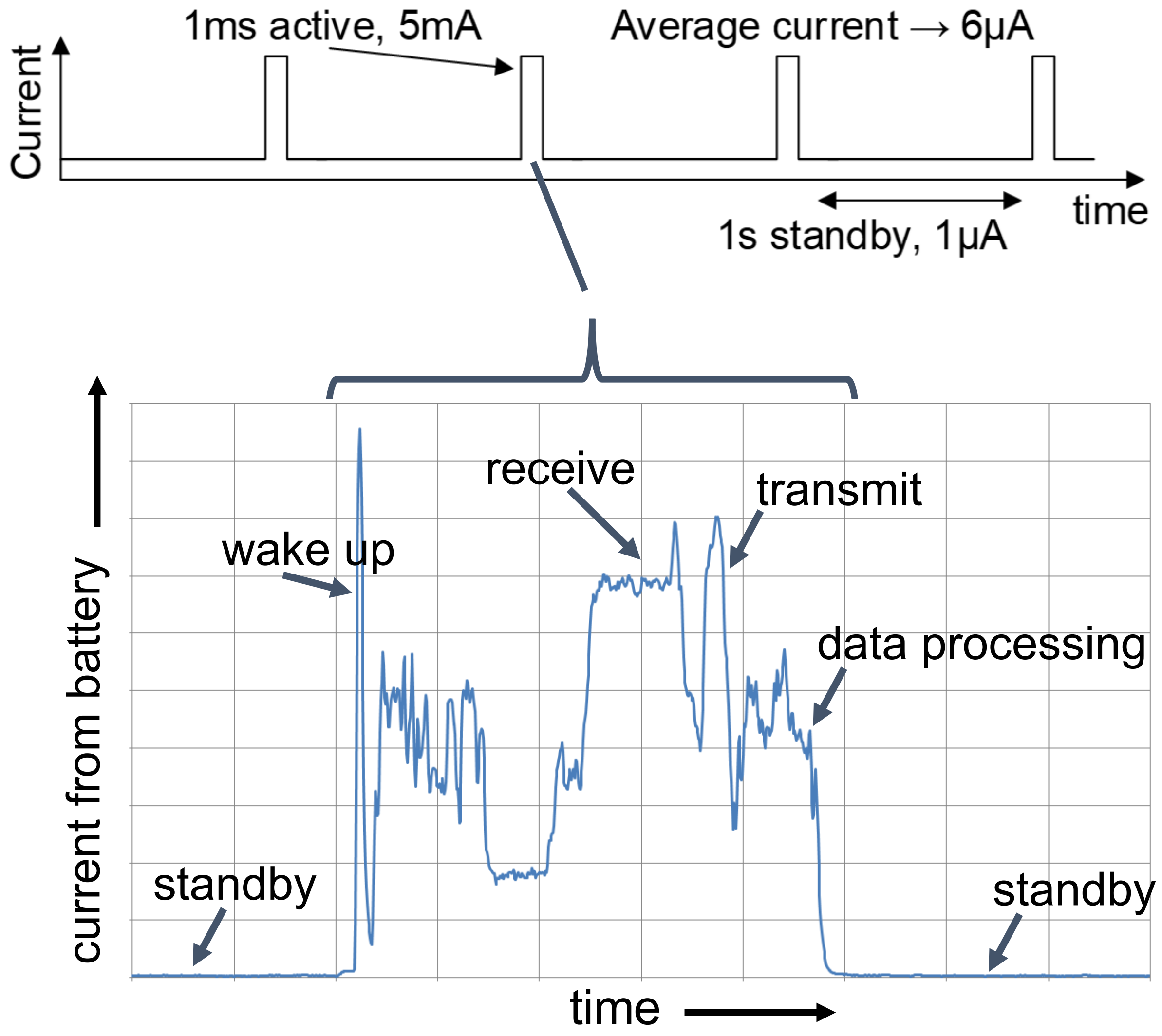
Receiver power consumption trend

- >20x reduction in receiver active power in 20 years
- Power benefits from:
  - Standard optimization
    - BT → BLE
  - Process node scaling
    - High f_T with low current
- Radio active power is only one of several important parameters



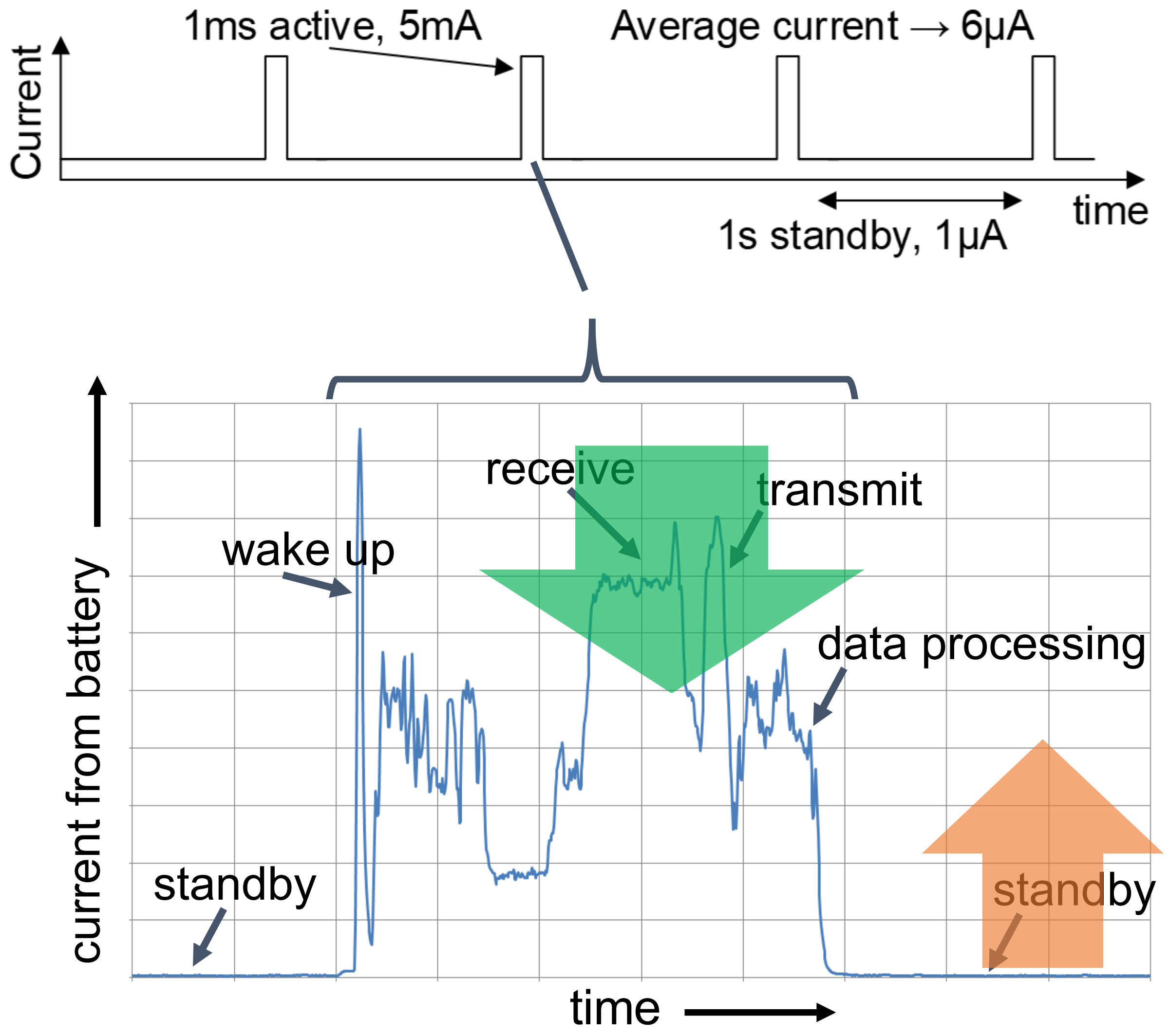
Duty cycling to reduce power

- Data throughput requirements are lower than wireless channel bandwidth
- Duty cycling to reduce average current consumption
- Average current is a function of
  - Radio (Rx/TX) active current
  - Standby current
    - Leakage + memory retention + clocking + PMU
  - Duty cycle



Impact of process technology

- Scaled process technology with higher f_T advantageous for digital, RF
  - But increases leakage, standby current



Impact of process technology

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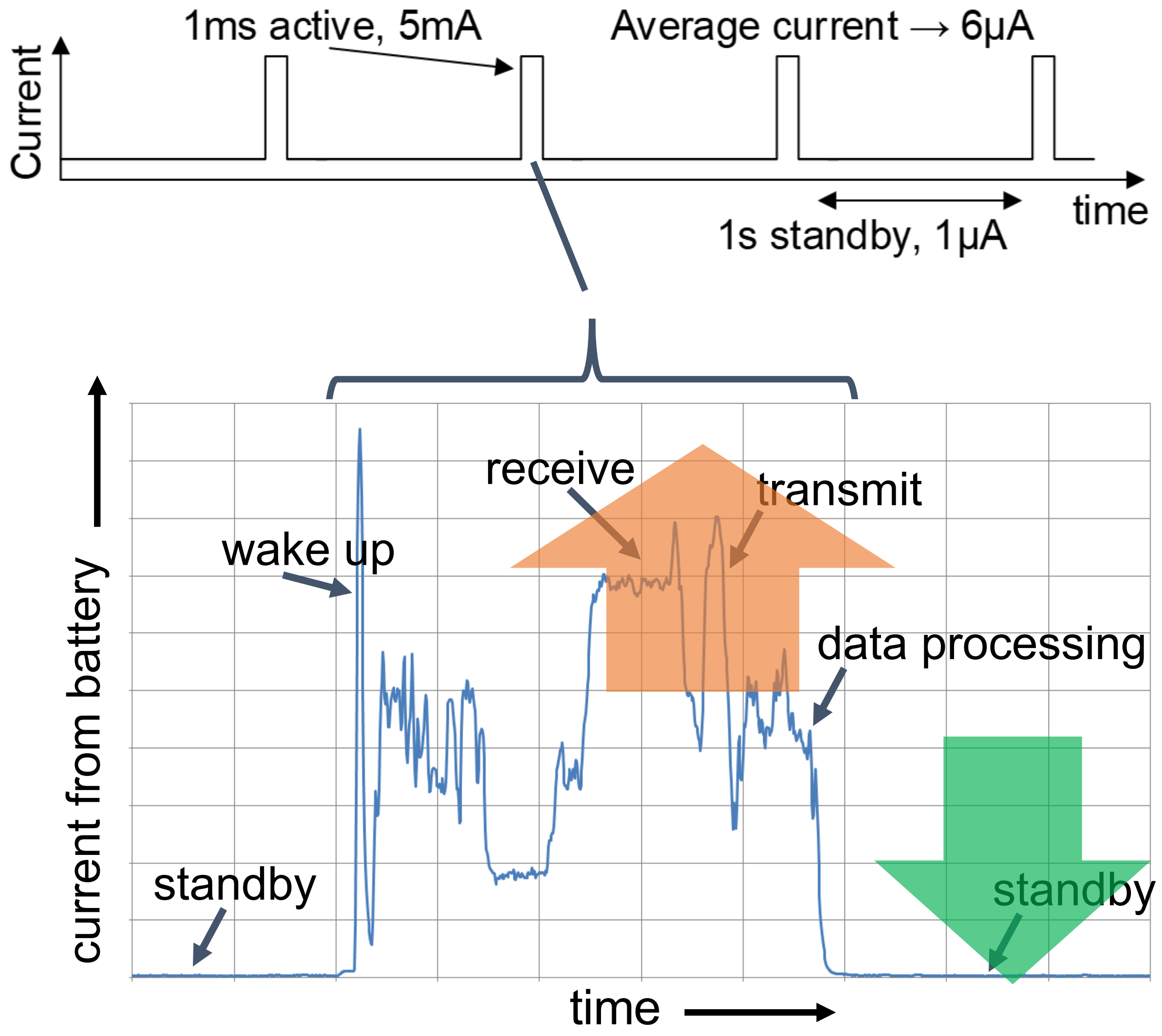
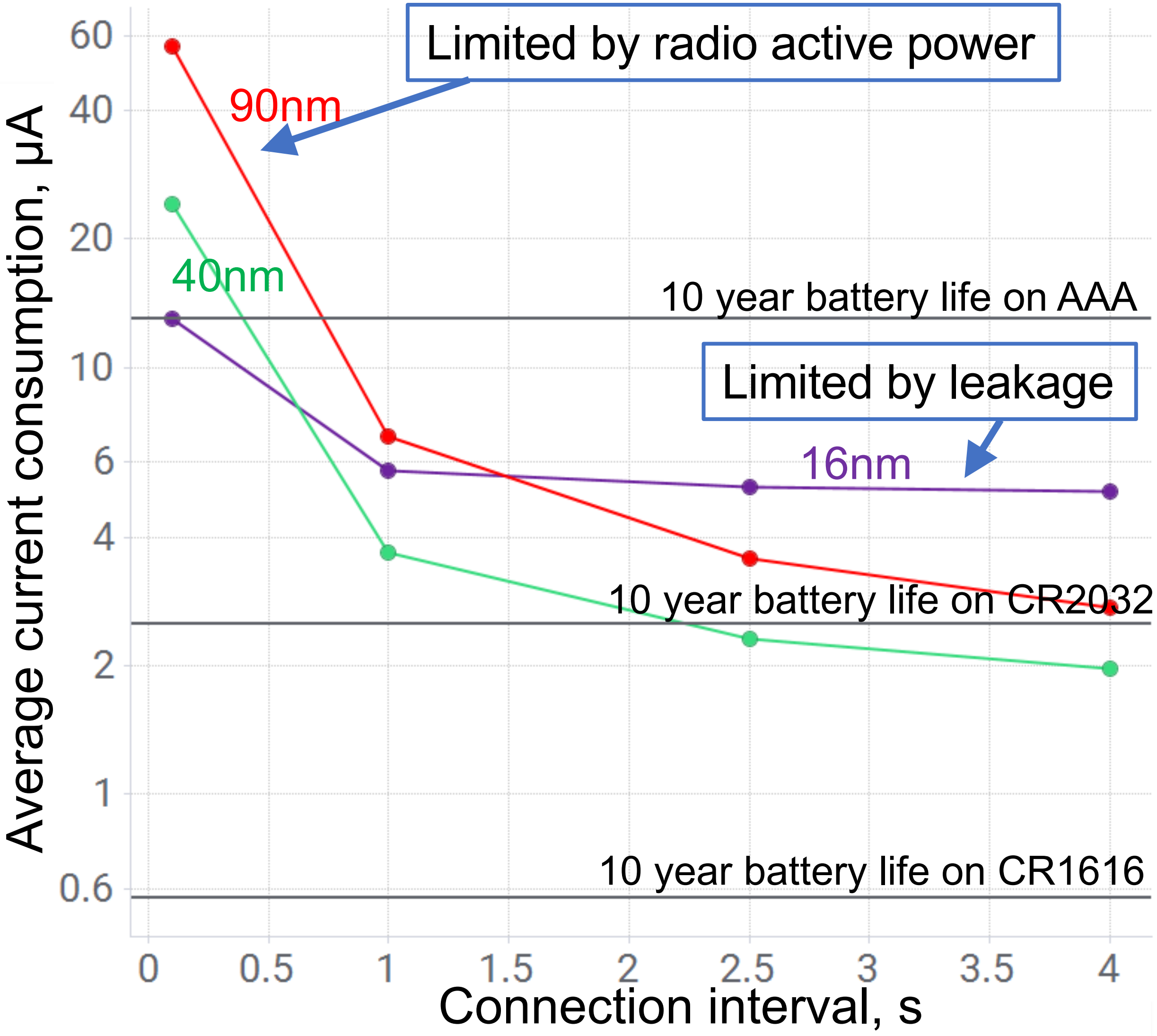
  - But increases leakage, standby current
- Process technology with long channel/low leakage transistors reduce standby current
  - Low leakage → higher V_{TH}, longer L → lower f_T → higher digital, RF current



Impact of data throughput

- Example 1Mbps BLE design vs. process nodes
- Short connection intervals (higher data throughput)
  - Radio power dominates
  - Use smaller geometry technology
- Long connection intervals (low data throughput)
  - Leakage dominates
  - Use process technology with low leakage



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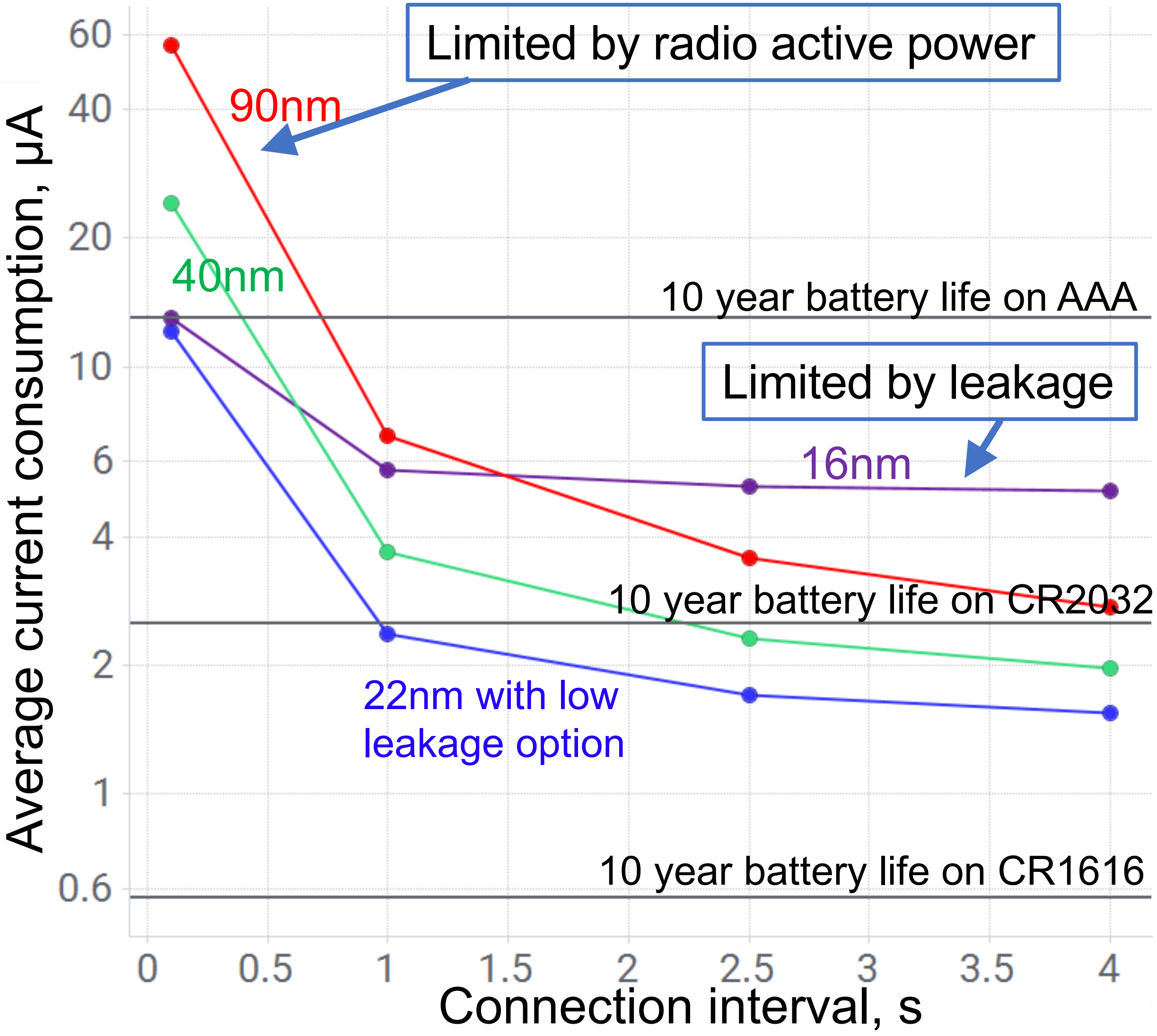
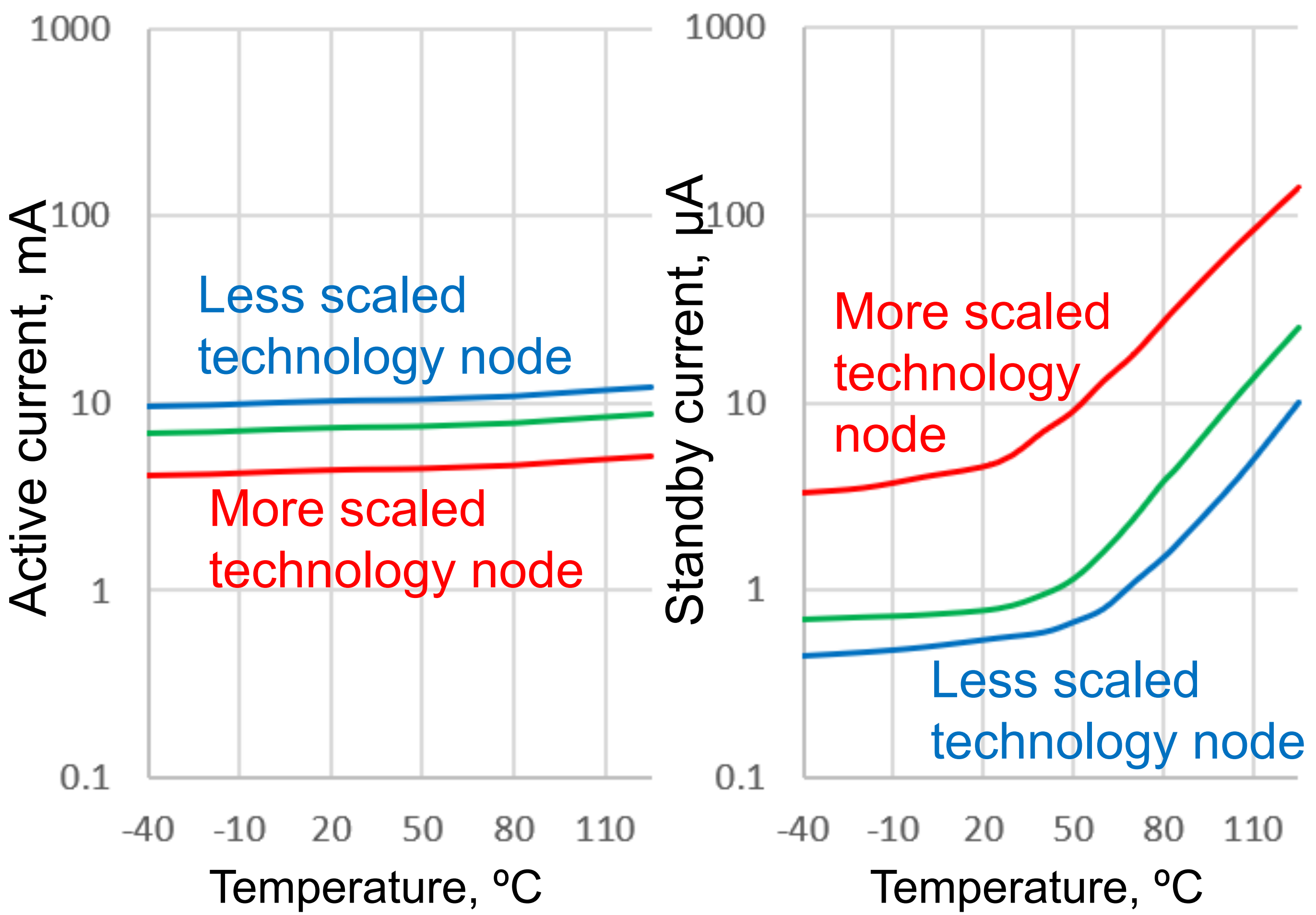


Impact of temperature

- Total current = standby + average active current
  - The temperature profile impacts standby current
  - Standby current can dominate in industrial and automotive applications.
  - The optimum process technology is dependent on the application
- Innovation to reduce leakage is needed.



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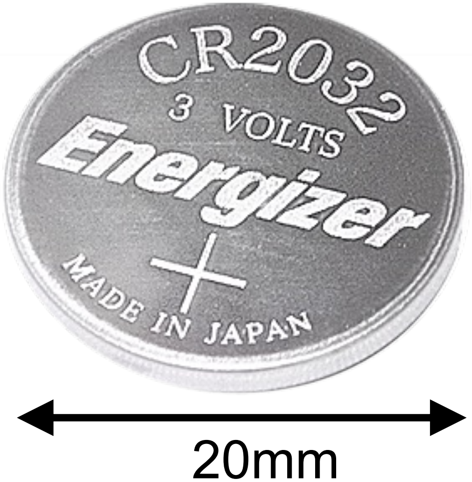
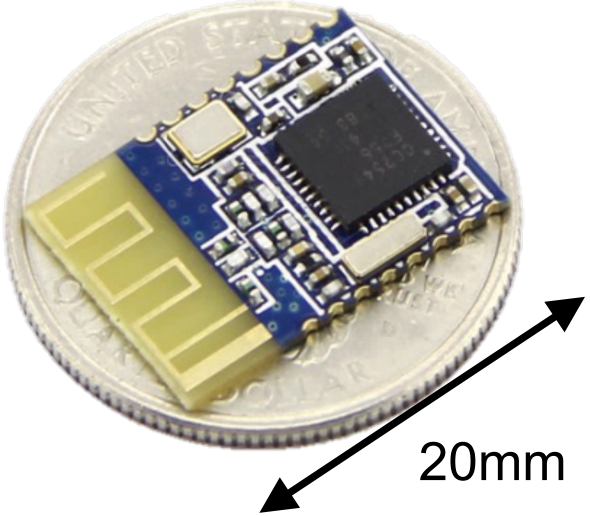
Innovation through integration

- PC, cell phone markets saturated
- IoT applications will also saturate
  - New markets needed to sustain IoT grow rate
- New applications require
  - Lower power consumption
  - Smaller form factor
- Target markets
  - Wearables, medical/implantables, automotive, tags/asset tracking, industrial monitoring

Form factor limitations

- Battery
  - Lower power consumption → smaller battery
- IC
  - Often dominated by memory/IO requirements
- Crystals
- Antenna
  - Chip or printed antenna
- Passive components
  - Balun, RF matching network
  - Power management L+C





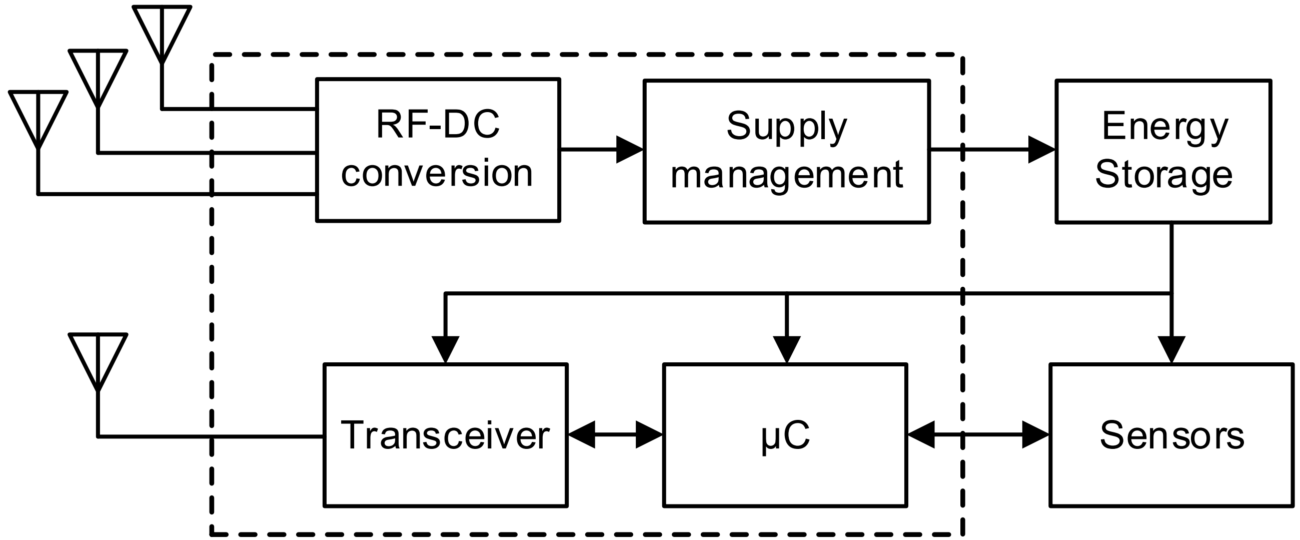
Battery alternatives

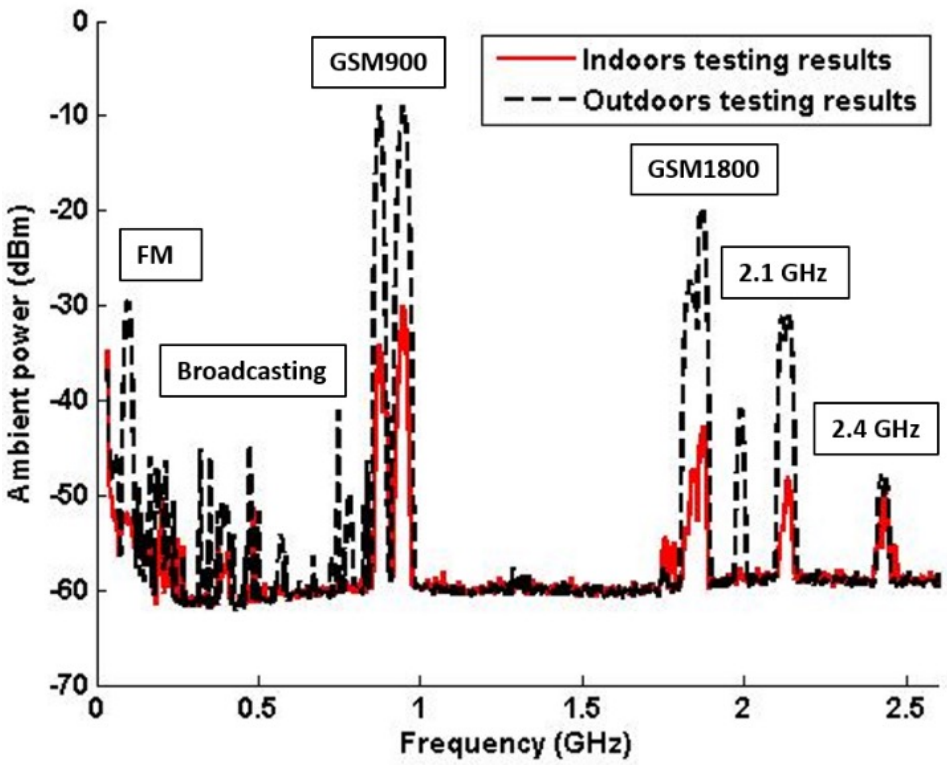
Energy Source	Characteristics	Efficiency	Power Density	Cost
Light (PV)	Outdoor Indoor	10-25%	$100mW/cm^2$ $100\mu W/cm^2$	> $1 (10µA at 200 lux)
Thermal (TEG)	Human Industrial	0.1% 3%	$60\mu W/cm^2$ $10mW/cm^2$	> $3 (SPI848-27145)
Vibration	Hz-Human kHz-Machine	25-50%	$4\mu W/cm^2$ $800\mu W/cm^2$	> $10
Radio Frequency	GSM 900MHz Wi-Fi 2.4GHz	<50%	$0.1\mu W/cm^2$ $0.001\mu W/cm^2$	< $0.1
Need	*Application dependent*			< $0.2 lower throughput, lower power applications <$1 higher throughput, higher power applications

Power density taken from: P. De Mil, "Design and Implementation of a Generic Energy-Harvesting Framework Applied to the Evaluation of a Large-Scale Electronic Shelf-Labeling Wireless Sensor Network"

Ambient RF energy harvesting

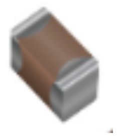
- Shared vs. multiple antennas
  - RX/TX and harvesting antenna match optimized independently
  - Multiband harvesting possible
  - Size impact





F. Khalid, 2018

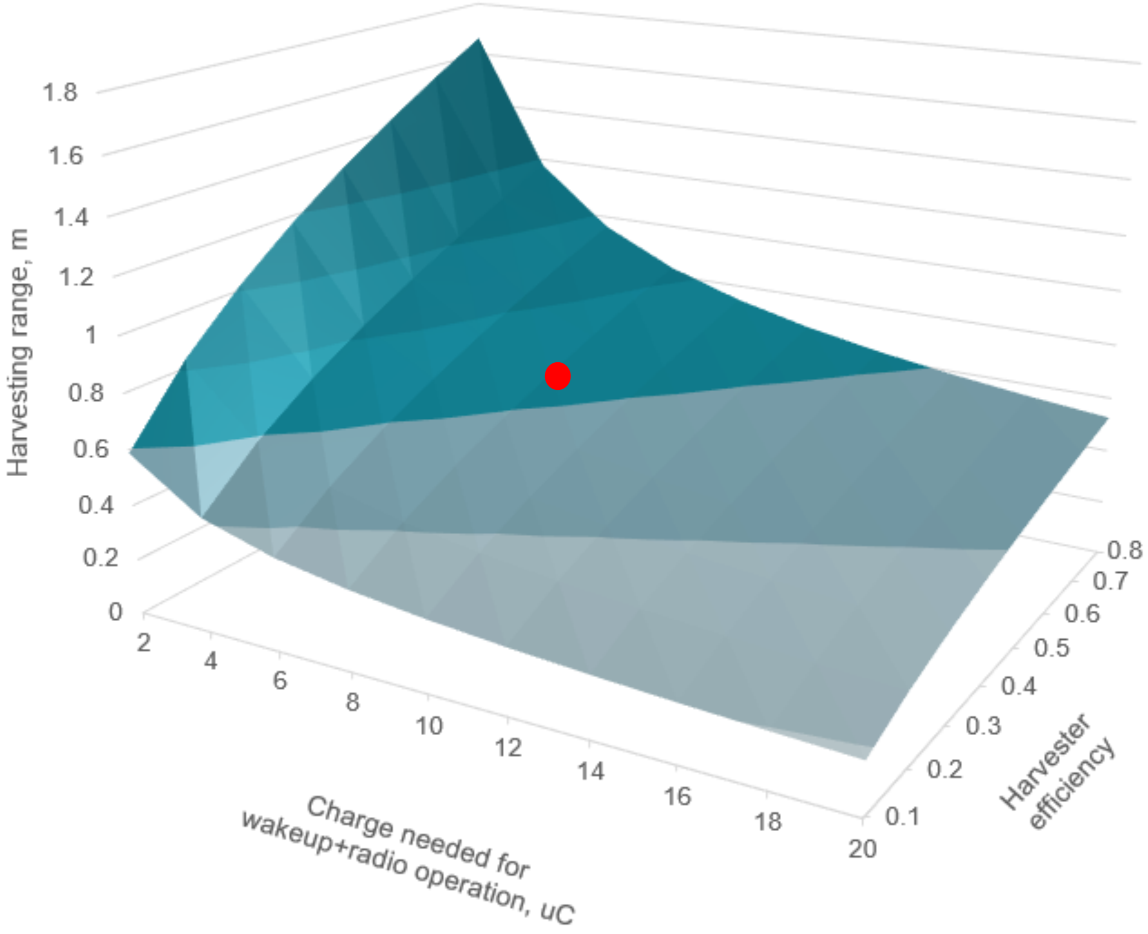
Energy storage options



	Lithium Ion	Thin Film Rechargeable	Super Cap (>1F)	Capacitor (nF-μF)
Recharge cycles	100s	5k-10k	millions	millions
Self discharge	moderate	low	high	high
Charge time	hours	minutes	seconds-minutes	seconds
Physical size	large	small	medium	very small
Capacity	0.3-2500mAh	12-700μAh	10-100μAh	1μAh
Environmental impact	high	low	low	low
Cost compared to coin cell	> coin cell	> coin cell	> coin cell	<< coin cell

Example - continuous blood glucose monitor

- Battery-free use case: Want 5 seconds of wireless power transfer followed by 1 transmission
- Energy required for BLE SoC with 1µF external capacitance:
  - Cold boot: 3µC
  - Radio event: 3µC
- Assuming wireless harvesting from +14dBm 2.4GHz RF source, harvesting range is <1m to complete in 5s
- Only ~half (or less) of energy goes to transmitting data. Startup energy should be minimized



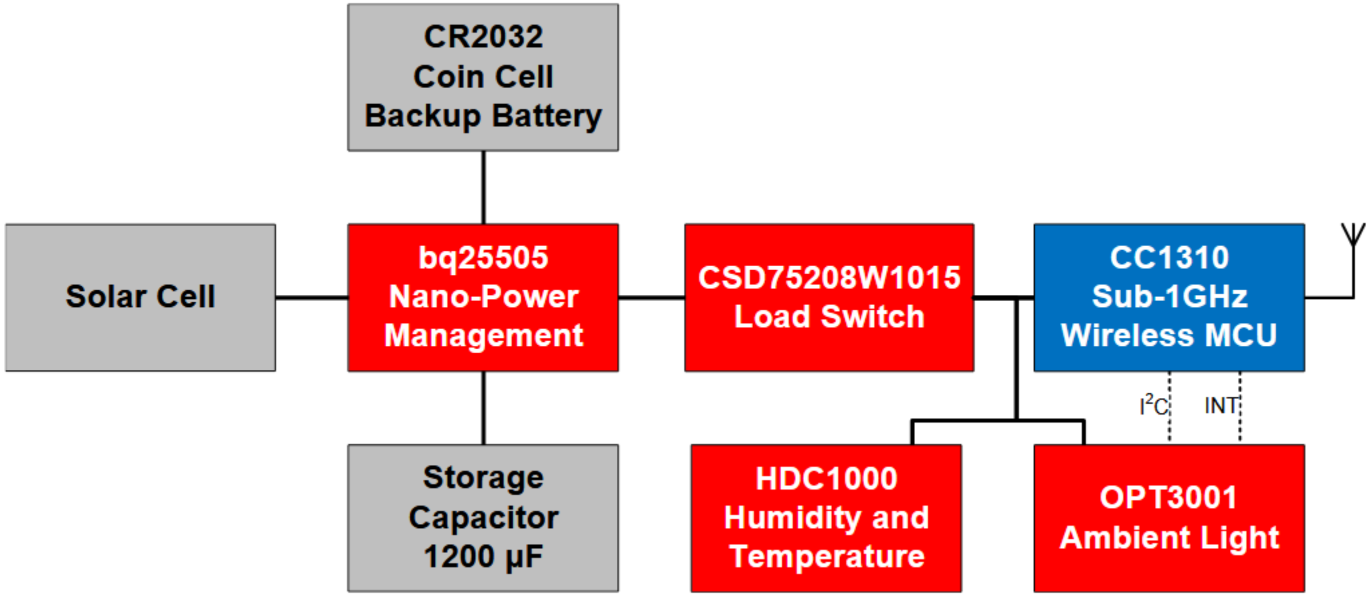
Energy harvesting product examples

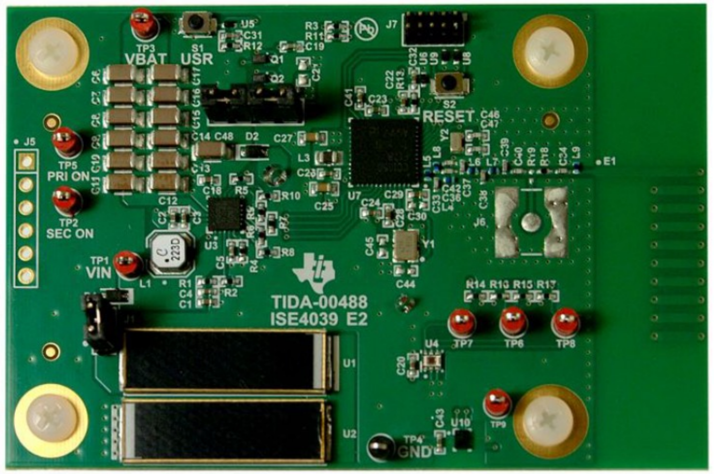
Company	Radio	Solar	Thermal	Vibration/ Mechanical	RF
EnOcean		X	X	X	
Jeeva	BLE				battery free in some cases
Wiliot	BLE				battery free
Atmosic	BLE, wakeup radio	X	X	X	dedicated antenna
ONiO	BLE+UWB	small PV cells			650MHz-2.4GHz
Bluerange	BLE mesh	X			
Texas Instruments	BLE, sub-1GHz, Wi-Fi	reference design (TIDA00488)	reference design (TIDU808)	reference design (TIDA00690)	reference design (TIDM-RF430-TEMPSENSE)

Not a complete list

Ambient light energy harvesting for sub-1GHz

- Runs entirely from solar energy when lux level is sufficient (continuous mode)
- Backup battery supplies energy when lux level conditions are not met
- Monitors ambient light, temperature and relative humidity
- Suitable for smart lighting, building automation, and HVAC sensor applications

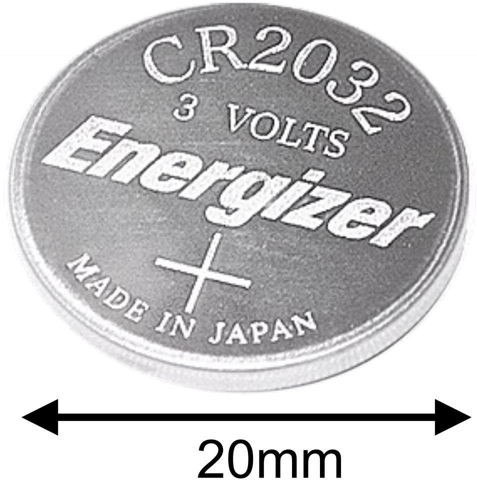


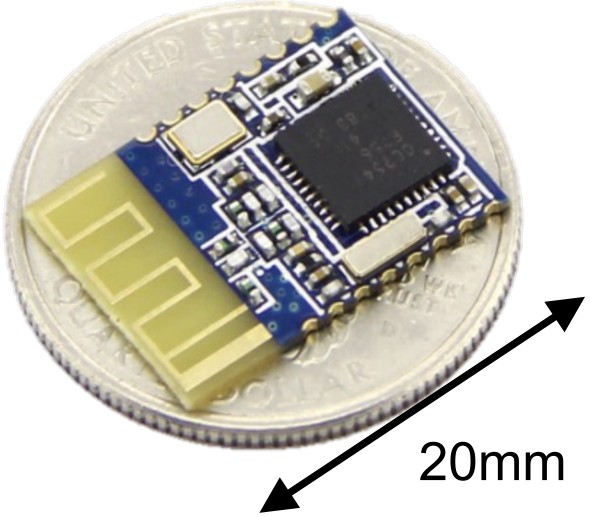


https://www.ti.com/lit/ug/tidub22b/tidub22b.pdf

Form factor limitations

- Battery
  - Lower power consumption → smaller battery
- IC
  - Often dominated by memory/IO requirements
- Crystals
- Antenna
  - Chip or printed antenna
- Passive components
  - Balun, RF matching network
  - Power management L+C





Piezo-MEMS: Crystal alternative

- Microelectromechanical systems (MEMS) are
  - CMOS compatible
  - Small size (<100s of microns)
- Piezoelectric MEMS
  - Passive device converting electrical ↔ mechanical energy with high quality factor (Q>1000)
- Piezoelectric MEMS examples:
  - SAW (Surface Acoustic Wave) resonator
  - BAW (Bulk Acoustic Wave) resonator
  - Used extensively in filters/duplexer products (20+ per phone)

Aigner, 2019

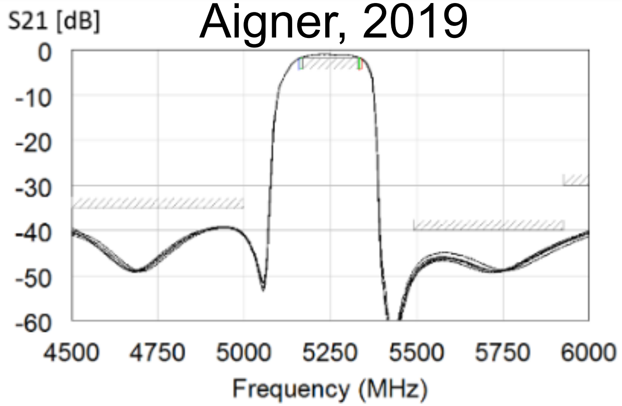


Figure 8: Passband insertion loss and nearby rejection of 5.25 GHz BAW filter.

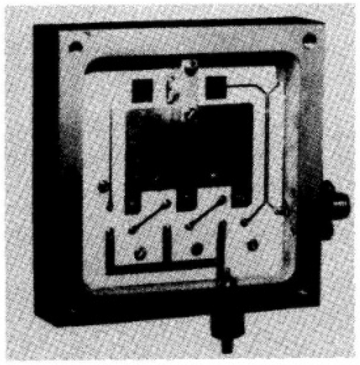


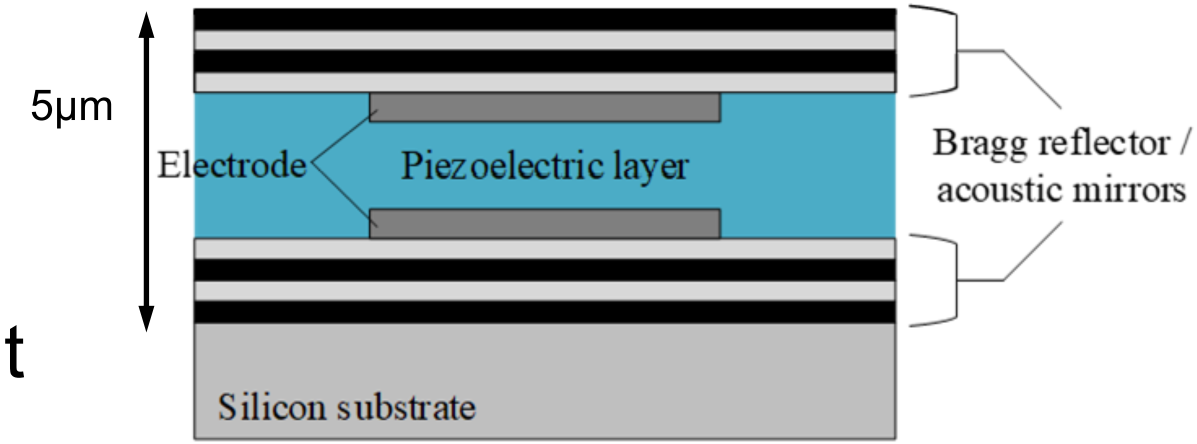
Fig. 6. Compact bulk-wave oscillator

"Behavior and Current Performances of SAW and BAW Oscillators" Schaer, 1976

Bulk Acoustic Wave (BAW) resonator

- Thin film piezoelectric Aluminum Nitride (AlN) contacted on both sides by electrodes
- Built on top of a silicon substrate
- Resonant frequency, f_R dependent on AlN thickness, t, and acoustic velocity, v_L, to first order
- Thin film manufacturing technology limits f_R to between ~1GHz and 5GHz

BAW resonator cross section

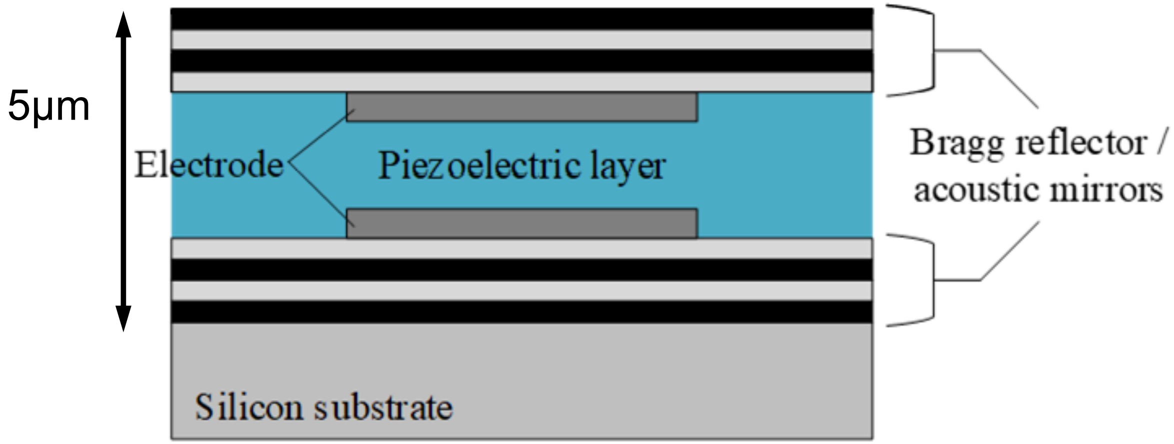


$$f_R \approx \frac{v_L}{2t}$$

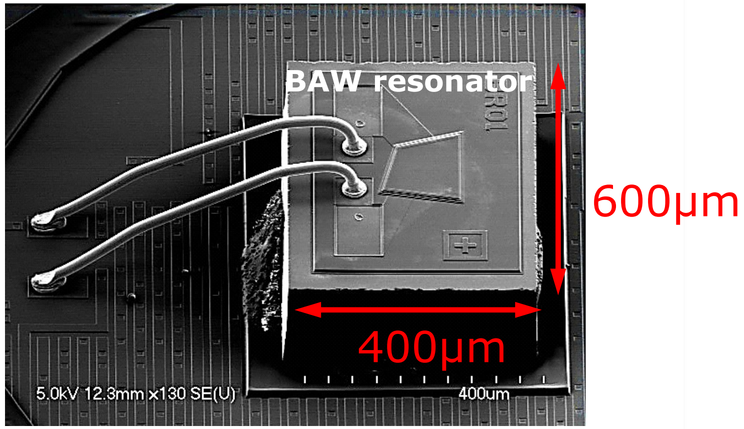
Acoustic mirrors

- AlN surrounded by high- and low-acoustic impedance layers
  - Prevents energy from leaking into substrate → Q >1000
  - Prevents energy leaking into packaging material and device contamination → low frequency drift/aging
  - Resilient to moisture and He → No hermetic packaging required
  - Shape optimized to reduce spurious modes

BAW resonator cross section

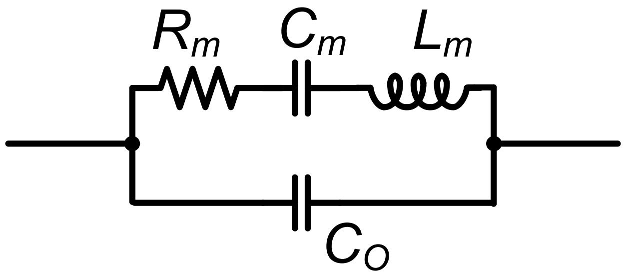


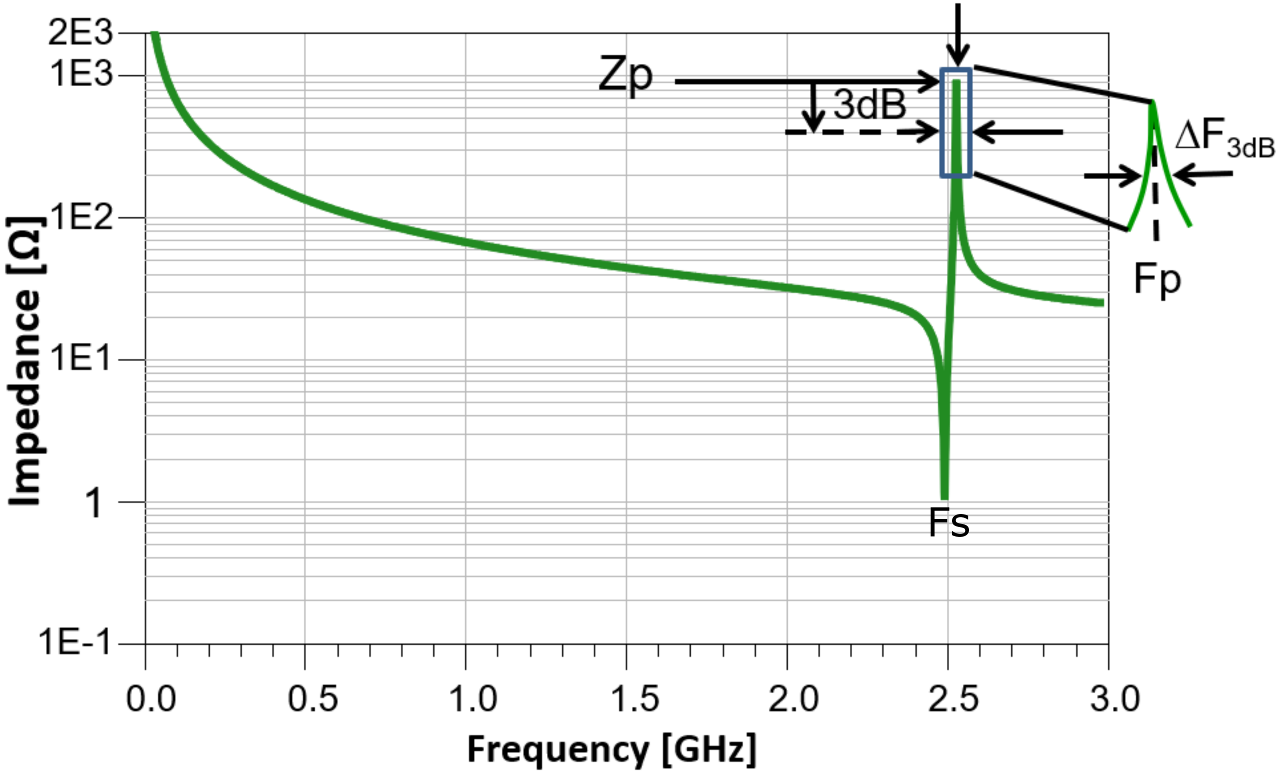
BAW stacked on CMOS die



BAW resonator model

- Same model topology as quartz crystal
  - Inductive between series and parallel resonance frequencies
  - Two pins only, no ground, no bias voltage
- Modified Butterworth Van-Dyke (MBVD) electrical model

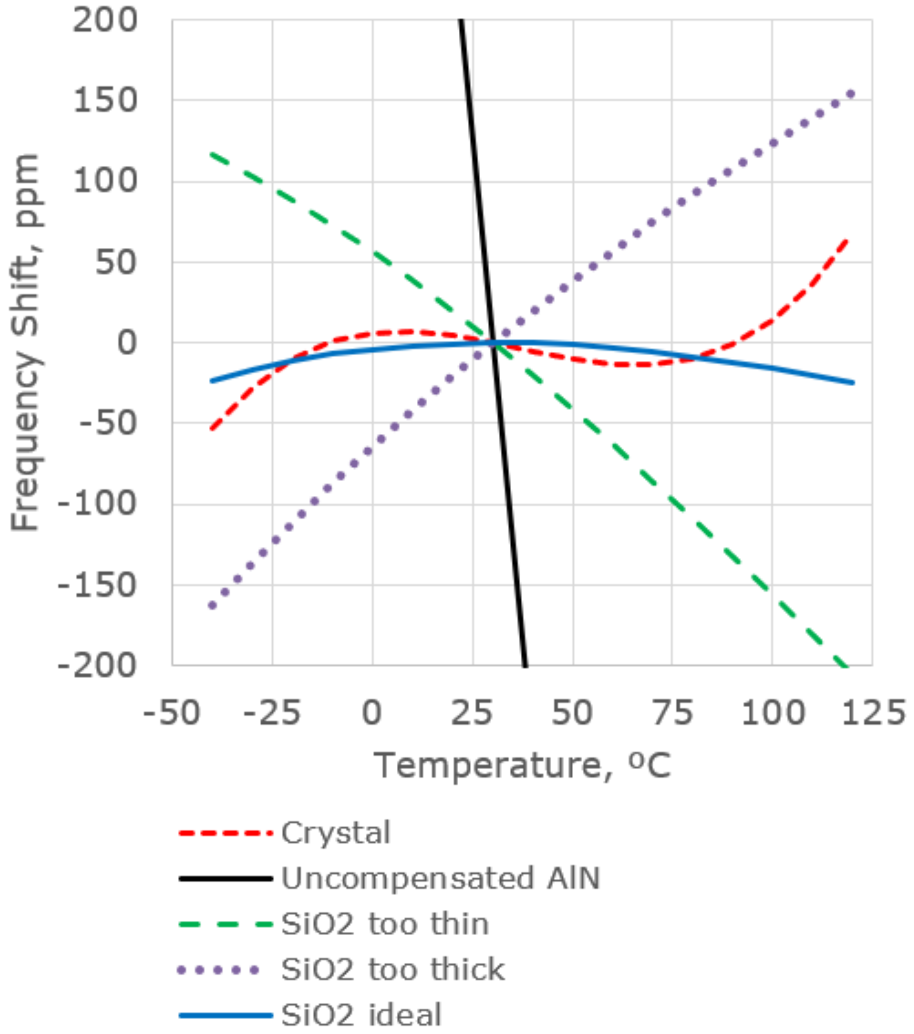




$Qp = \text{Quality Factor} = Fp/\Delta F_{3dB} > 1000$

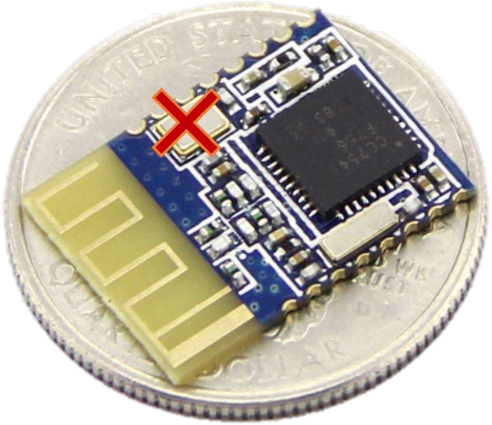
Passive temperature compensation

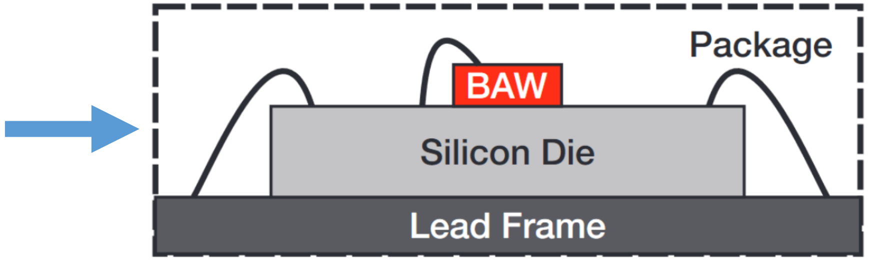
- MEMS resonator materials expand as temperature increases
  - First order temperature coefficient of frequency (TCF) for AlN is -25ppm/°C.
  - >3000ppm frequency drift
- SiO_2 has positive TCF
  - Adding a SiO_2 layer reduces effective resonator TCF to ±0.5ppm/°C
  - Manufacturing tolerances limit temperature compensation to <300ppm
  - Combine with active temperature compensation

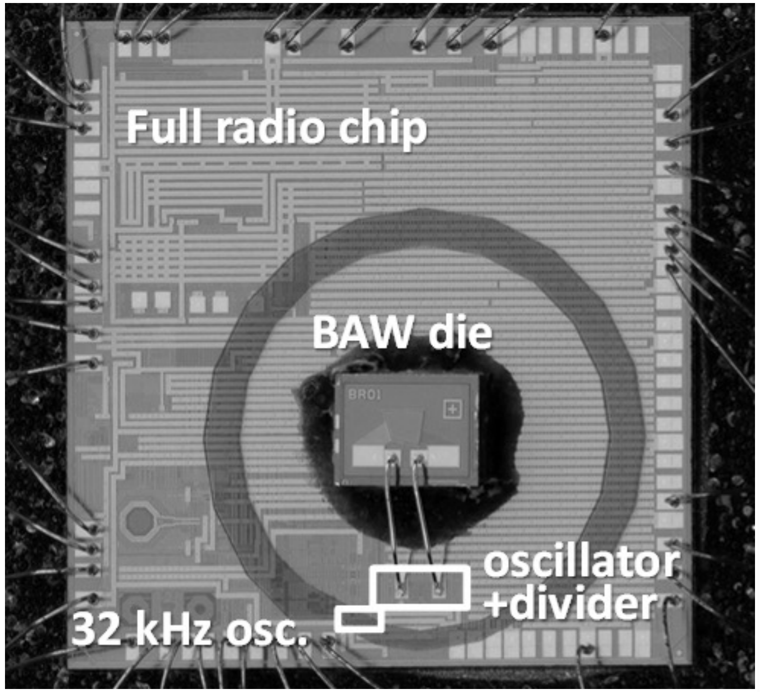


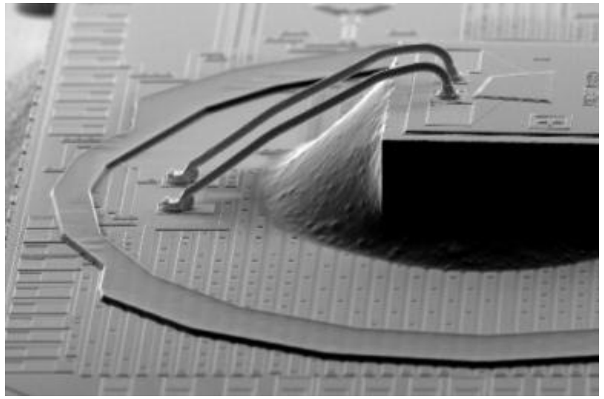
Crystal replacement

- Radio requires accurate reference clock for RF synthesizer
  - Crystal oscillator:
    - 16MHz to 64MHz, ~2.0x1.6mm^2, external to package
  - BAW-oscillator (2.5GHz) + divider
    - 0.6x0.4mm^2, integrated in the package



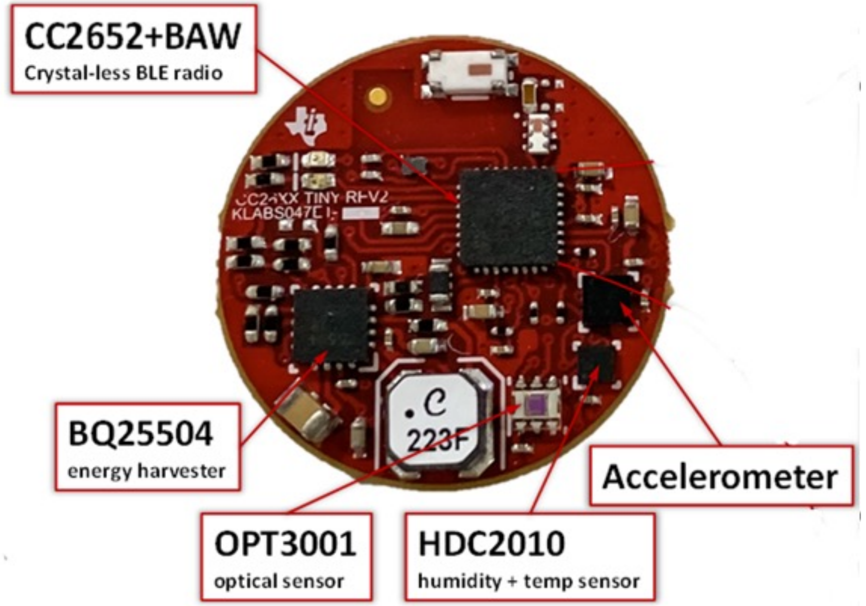


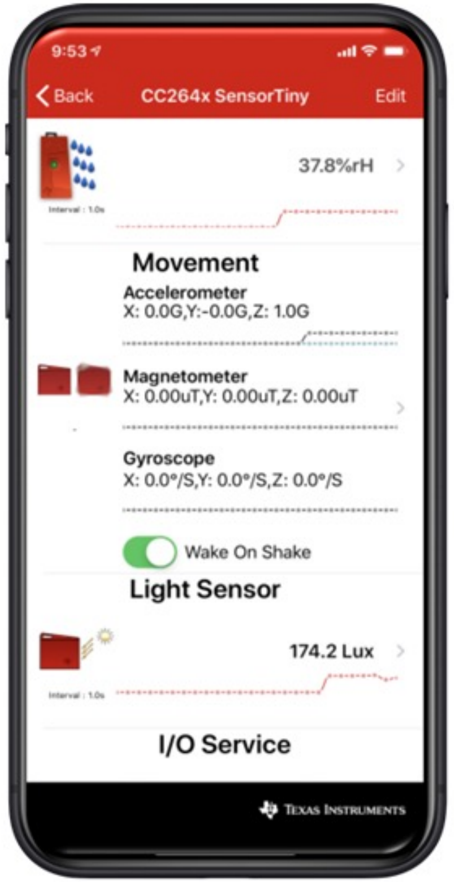




More sensors in the same footprint

- Removing crystal allows more sensors to be used in the same footprint
- Enables applications with limited space, harsh, vibration-rich environments such as power tools and factory automation





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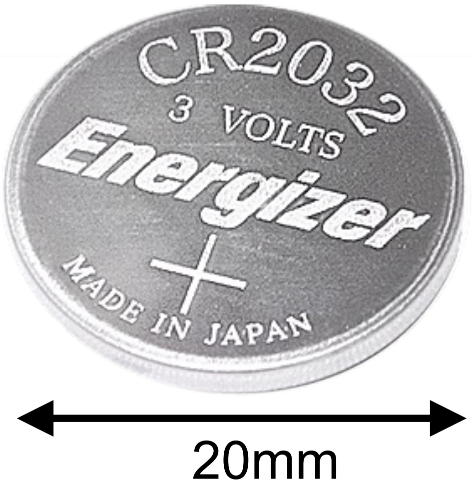
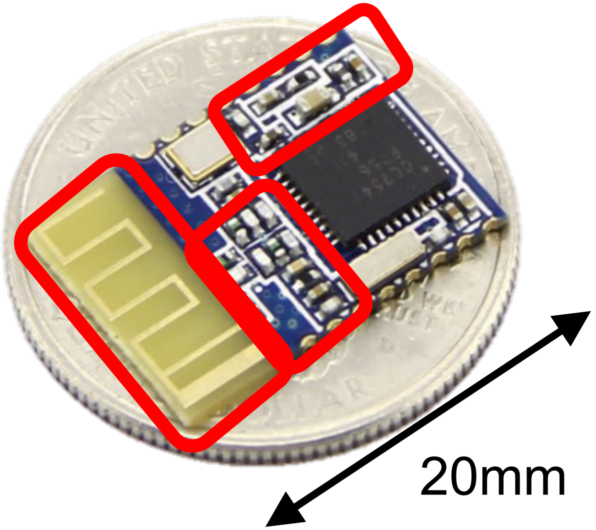
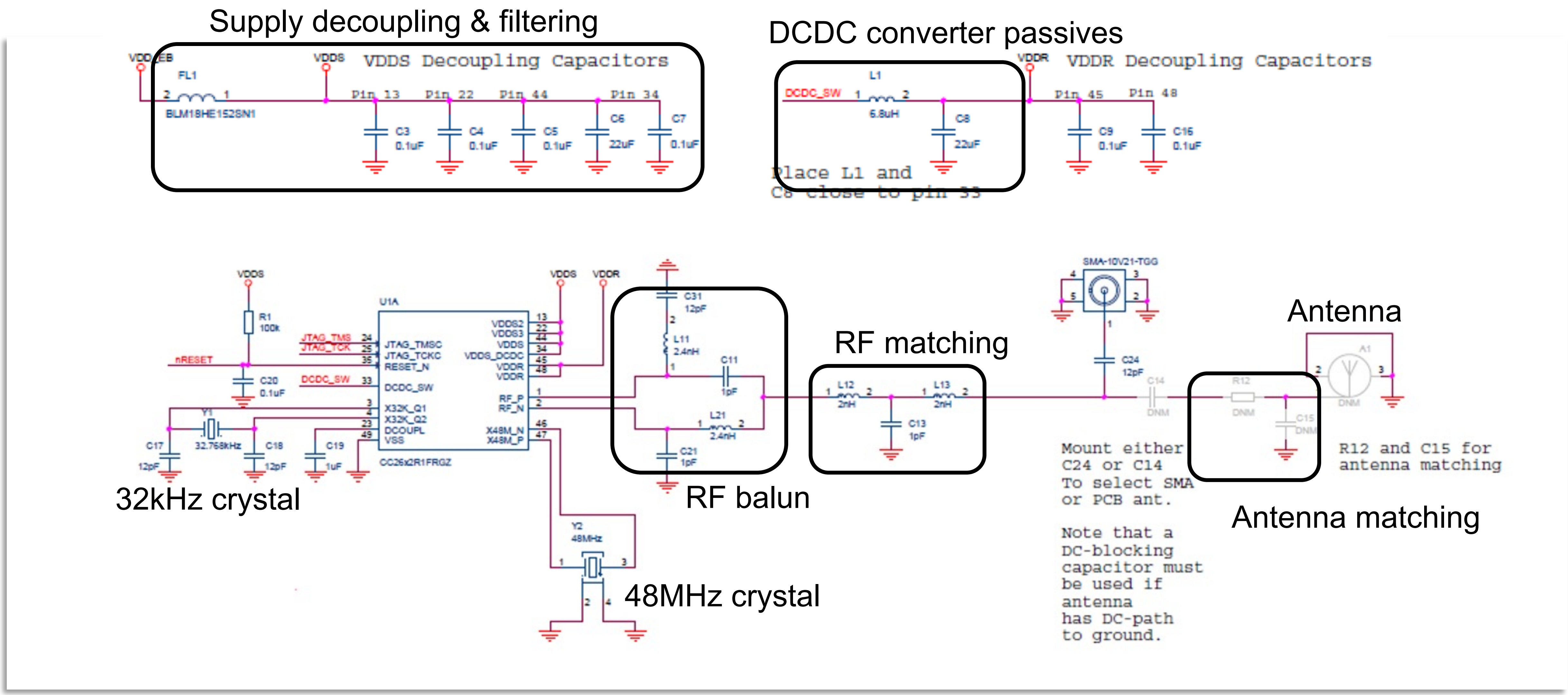


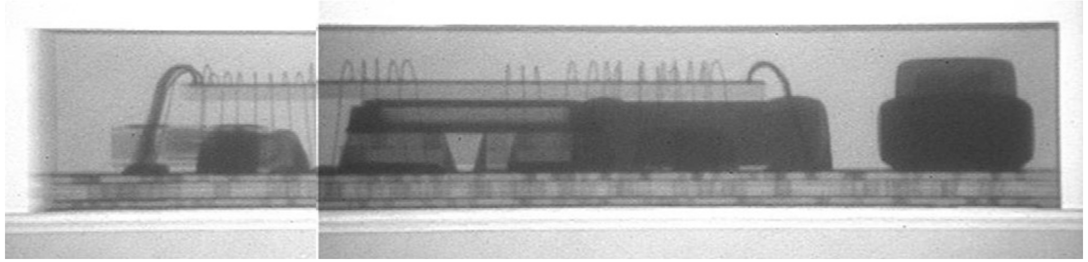


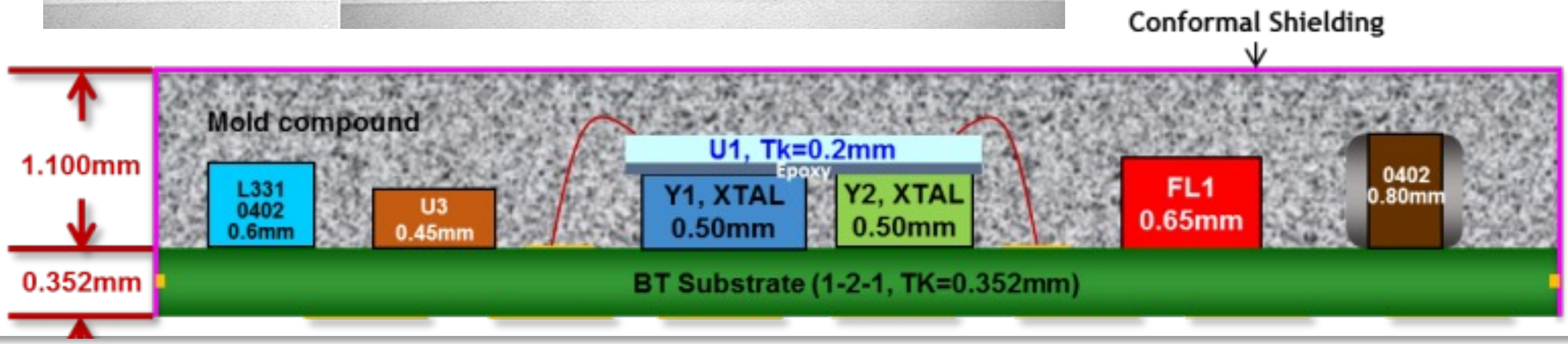
External passives

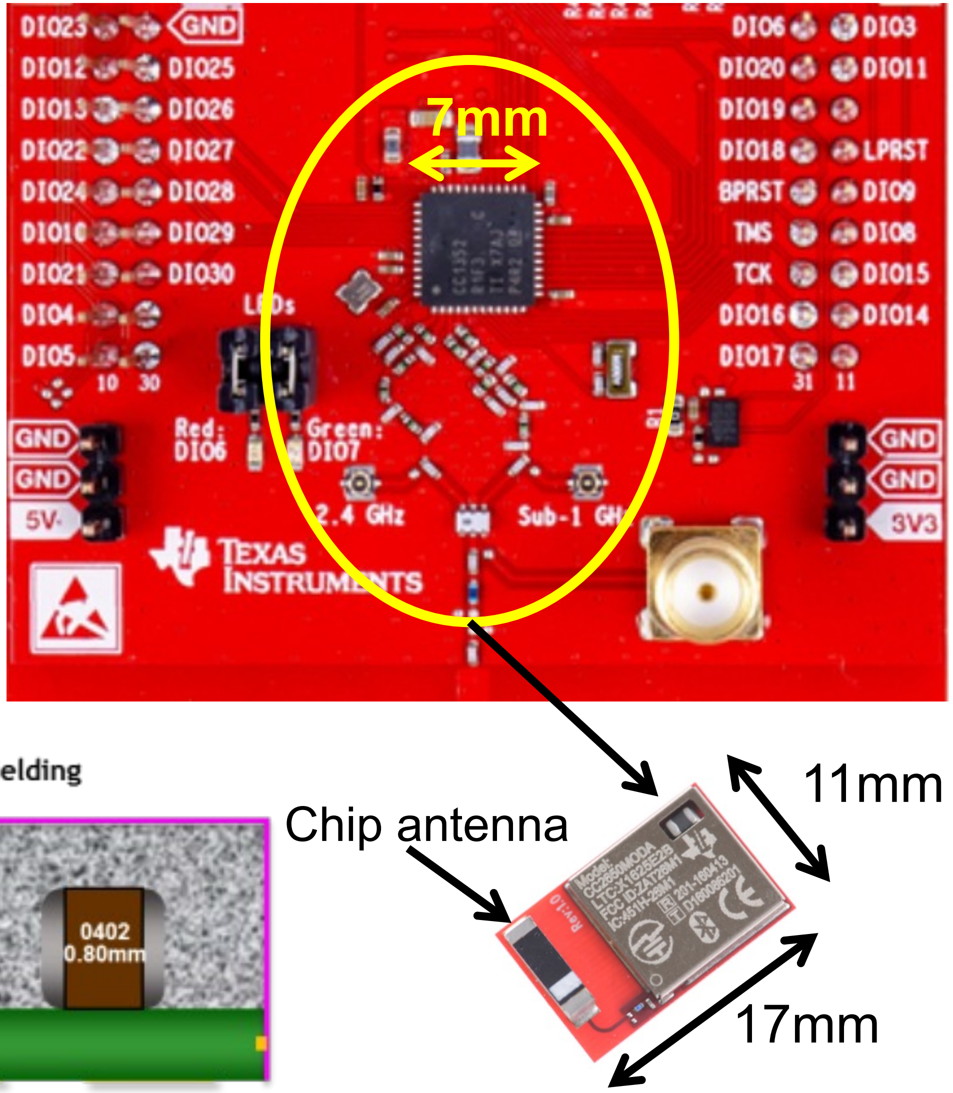


Alternative: Modules

- Certifiable package technology
  - Include all passives in one module
  - Simply end-product design
  - Remove need for customers to certify their designs with FCC ($30K cost)

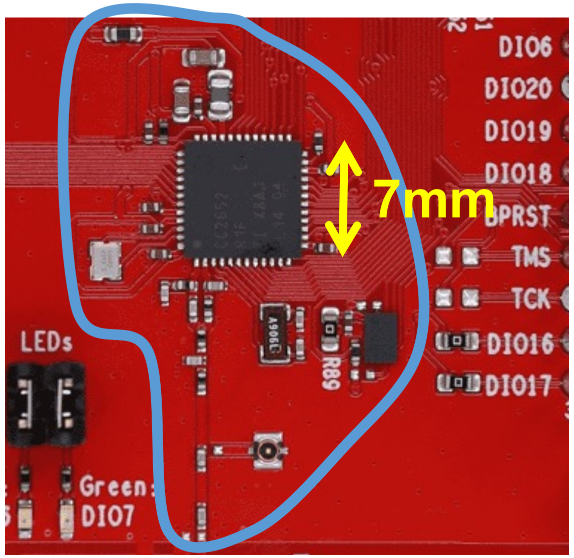


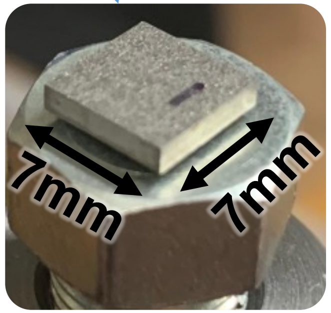




Smaller size: System-in-package

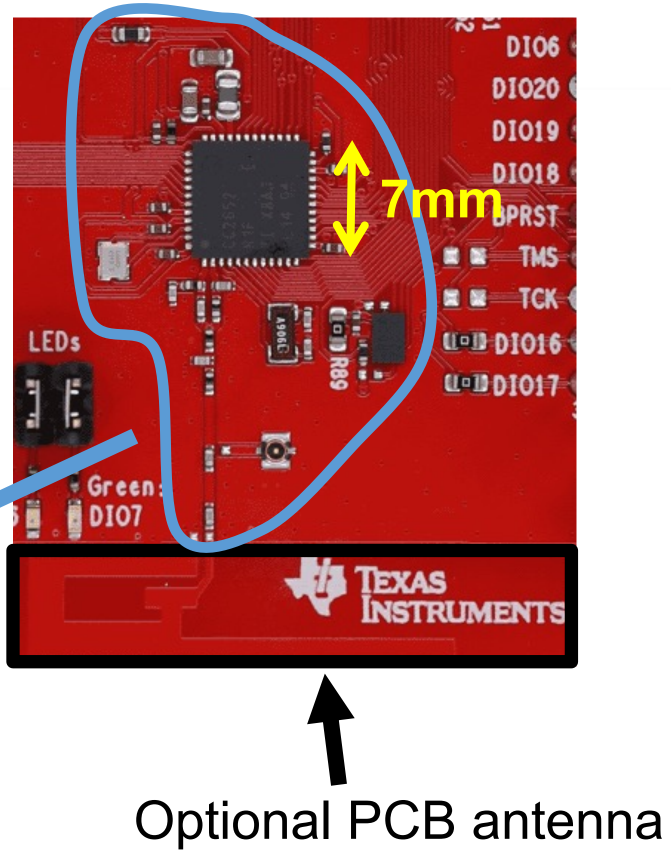
- System-in-package
  - Integrate antenna + passives + SoC into 7x7 package
  - Same X-Y dimensions as original SoC package
  - Reduce overall PCB size by 80%
  - Improved system reliability due to integrated components
  - Option to use external antenna for better performance
- Possible to add wireless connectivity to more products without RF test equipment or expertise

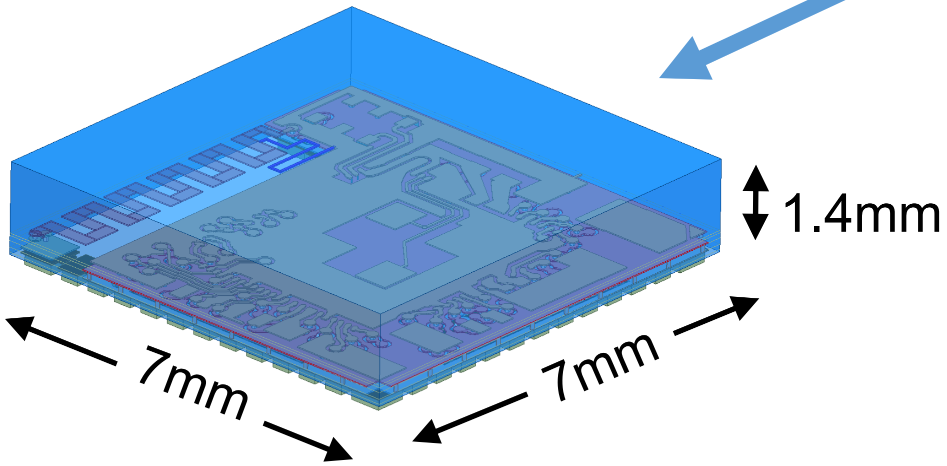




Integrated antenna option

- System-in-package
  - 49mm^2 (antenna: 5.2mm x 1.4mm)
- 2dBi integrated antenna gain
- Pin for optional external antenna
  - Printed PCB or chip antenna



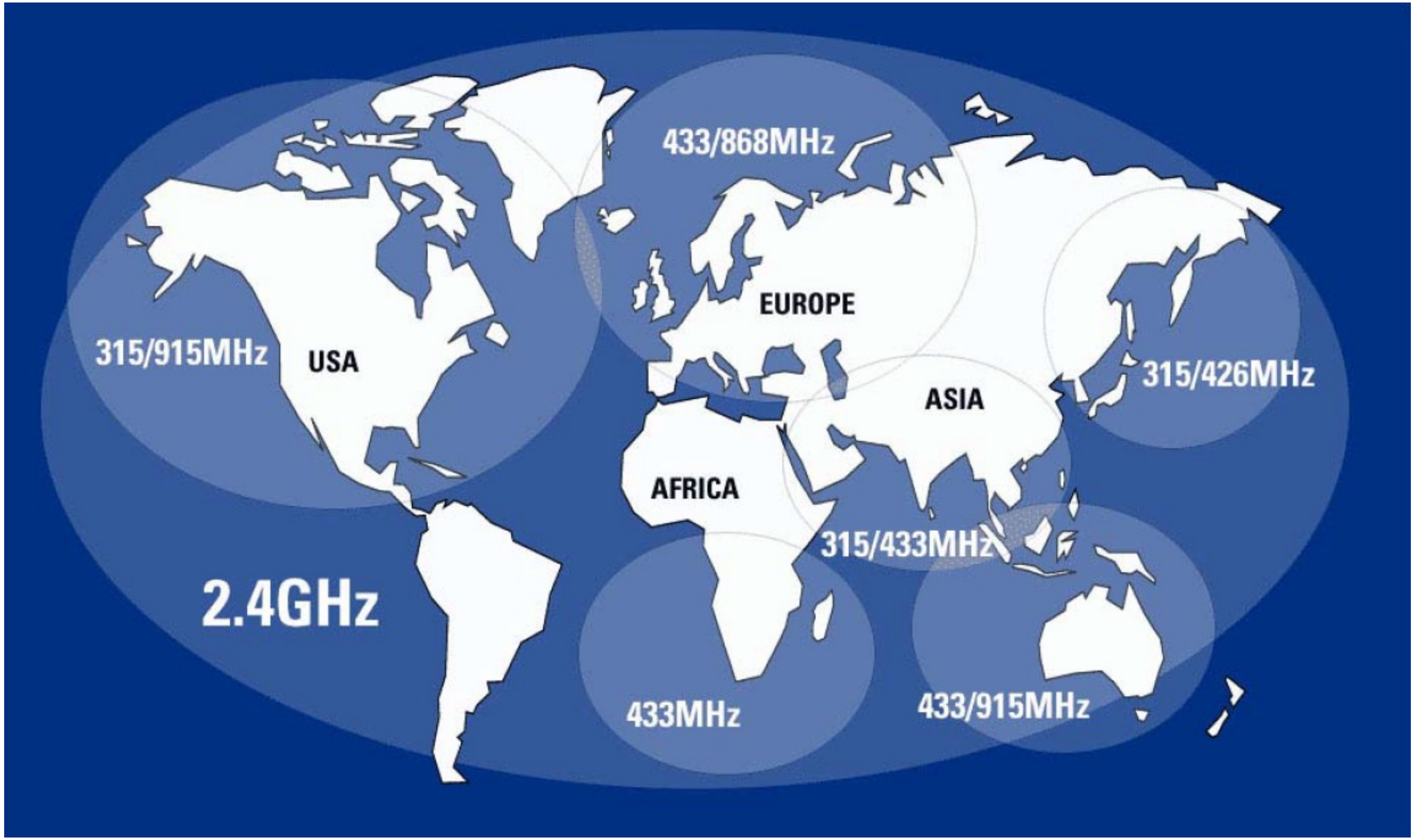


Outline

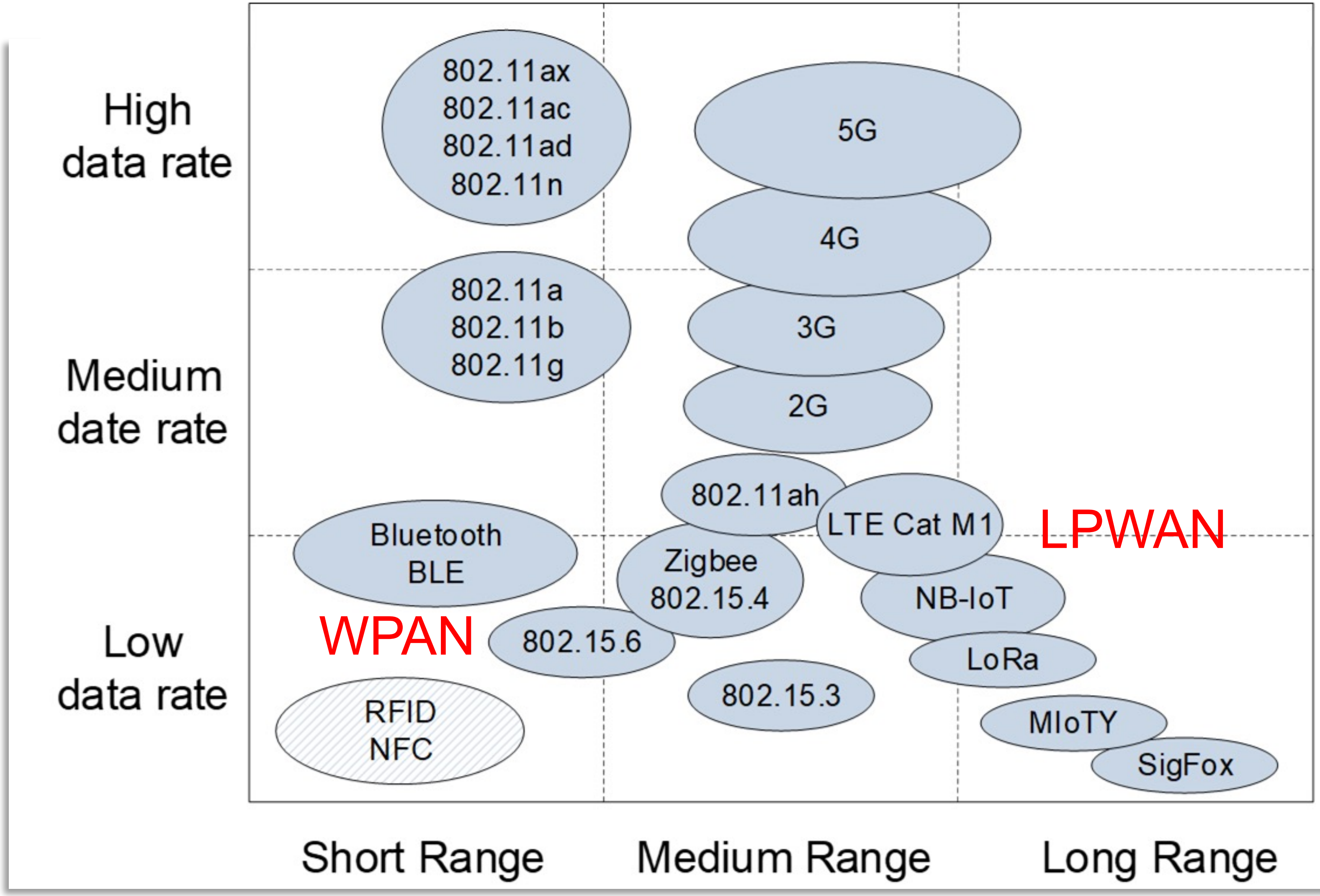
- IoT market & projections
- Innovation areas
  - Power reduction
  - Increased integration
  - Improved interoperability
- Conclusions

ISM license-free frequency bands

- Largest IoT growth is in unlicensed bands
- 2.4GHz supported worldwide
- But sub-1GHz unlicensed bands are fragmented



Connectivity landscape



- Wireless connectivity landscape is fragmented depending on range and data rates needs
- Not interoperable

Unlicensed wireless connectivity

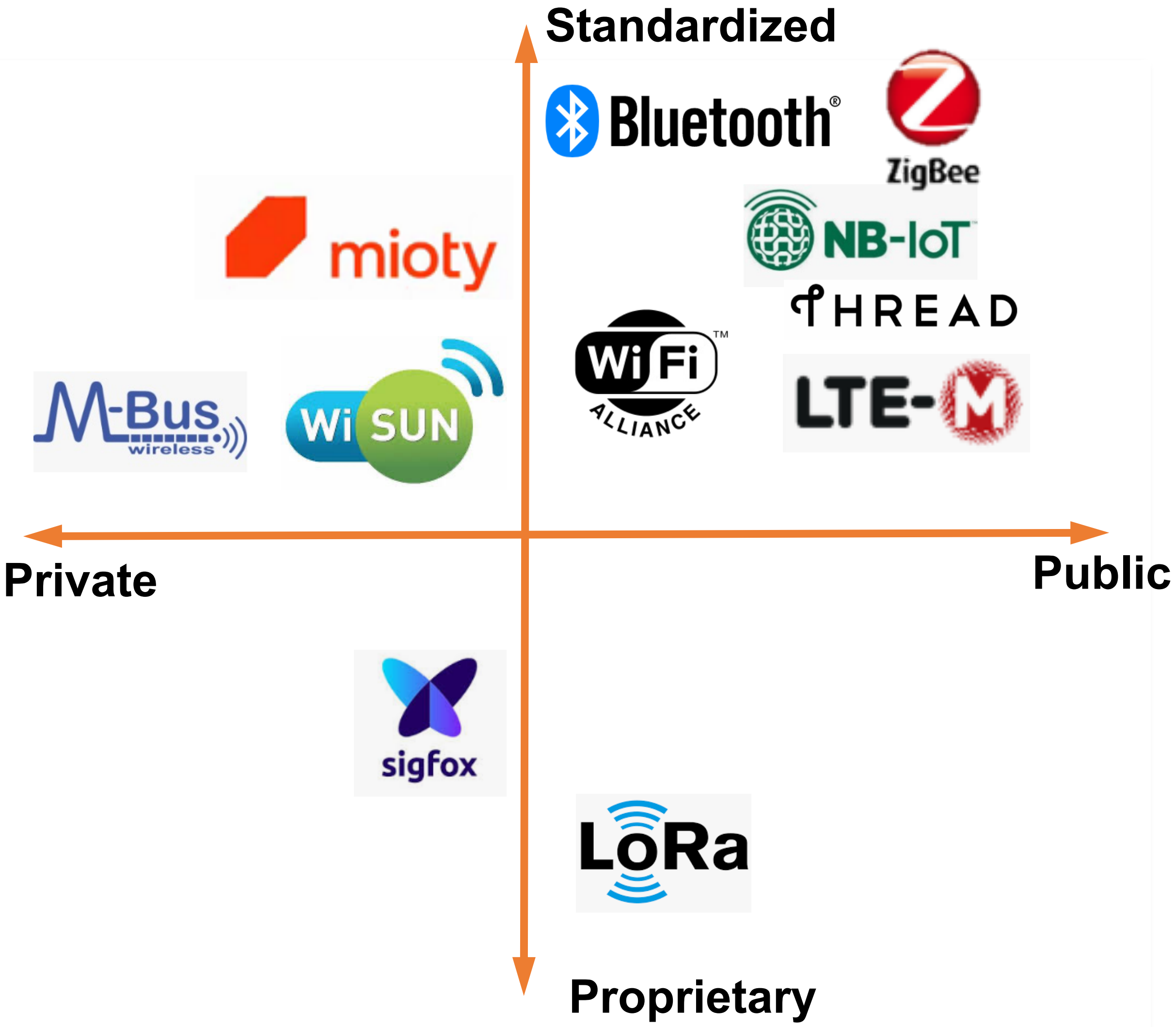
Proximity	Personal Area Networks		Local Area Networks			Neighborhood Area Networks

Range: cm — Up to 100m — km

NFC RFID	*Bluetooth® Bluetooth® LE*	Proprietary 2.4GHz	ZigBee®, RF4CE, Thread	Wi-Fi®	6LoWPAN	Sub-1 GHz
Identification	*Connection to smart devices*	*Customizable*	*Mesh*	*Universal – Cloud connection*	*IP Mesh*	*Long range*
Key Differences						
Throughput: ✓ **Data up to 848 kbps**	**Throughput:** ✓ Data or voice up to 3 Mbps	**Throughput:** ✓ Data up to 1 Mbps	**Throughput:** ✓ Data up to 256 kbps	**Throughput:** ✓ Voice or video from 10 -100 Mbps	**Throughput:** ✓ Data up to 256 kbps	**Throughput:** ✓ Data up to 1 Mbps
Power Required: No battery to coin cell	**Power Required:** Coin cell to AAA	**Power Required:** Coin cell	**Power Required:** Energy harvesting to AAA	**Power Required:** AA to Lithium Ion	**Power Required:** Energy harvesting to AAA	**Power Required:** Coin cell
Key Attributes						
• Passive operation & data storage • Dedicated multi-tag read zone • In portable devices	• Interoperable with other Bluetooth devices • Large install base • In mobile devices • Ultra Low Power	• Customizable to application • Robust RF	• Standards based • Self-healing mesh • Ultra low power • Large area coverage	• Existing infrastructure • Power optimized • Built-in security • Wi-Fi certified • Connection to the cloud	• IPv6 stack • Ultra low power • IoT platform	• Longest range • Ultra low power • Customizable to application • Robust RF

IoT: Not a single standard

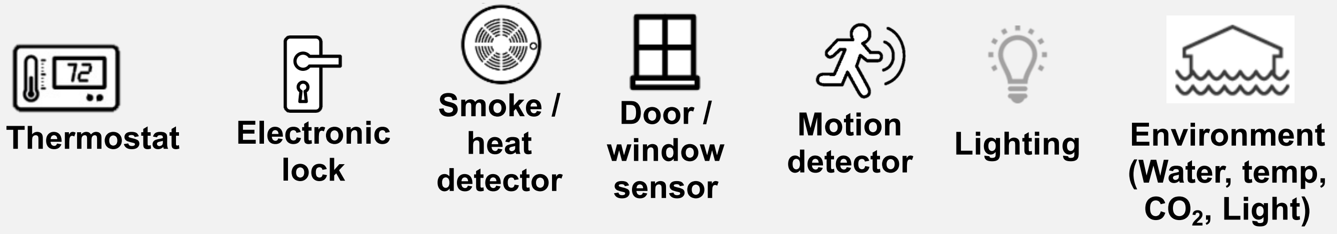
- Can be an open standard or proprietary
- Networks can be public or private
  - Possible to have both public and private implementations of some protocols
- Other considerations
  - Star vs mesh
  - Network capacity
  - Licensed vs unlicensed bands
  - Security



Matter: Unified approach to IoT

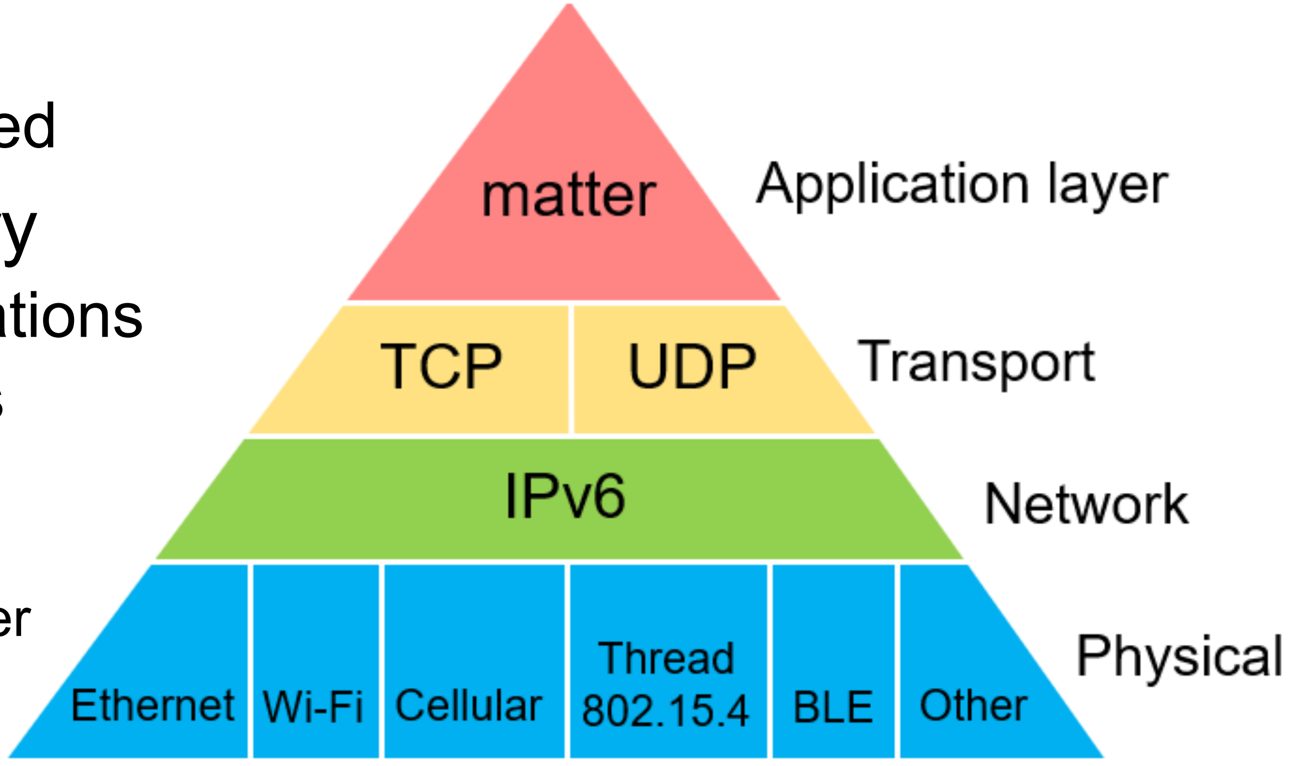
- Smart home ecosystems are fragmented
- Solution: Matter
  - Unified application layer protocol which allows communication across smart home devices and mobile apps
  - Simplify development for manufacturers and increase compatibility for consumers
  - Open source development
  - Built on IPv6
  - Focus on security
  - Optional cloud connectivity

Key Applications



Layers

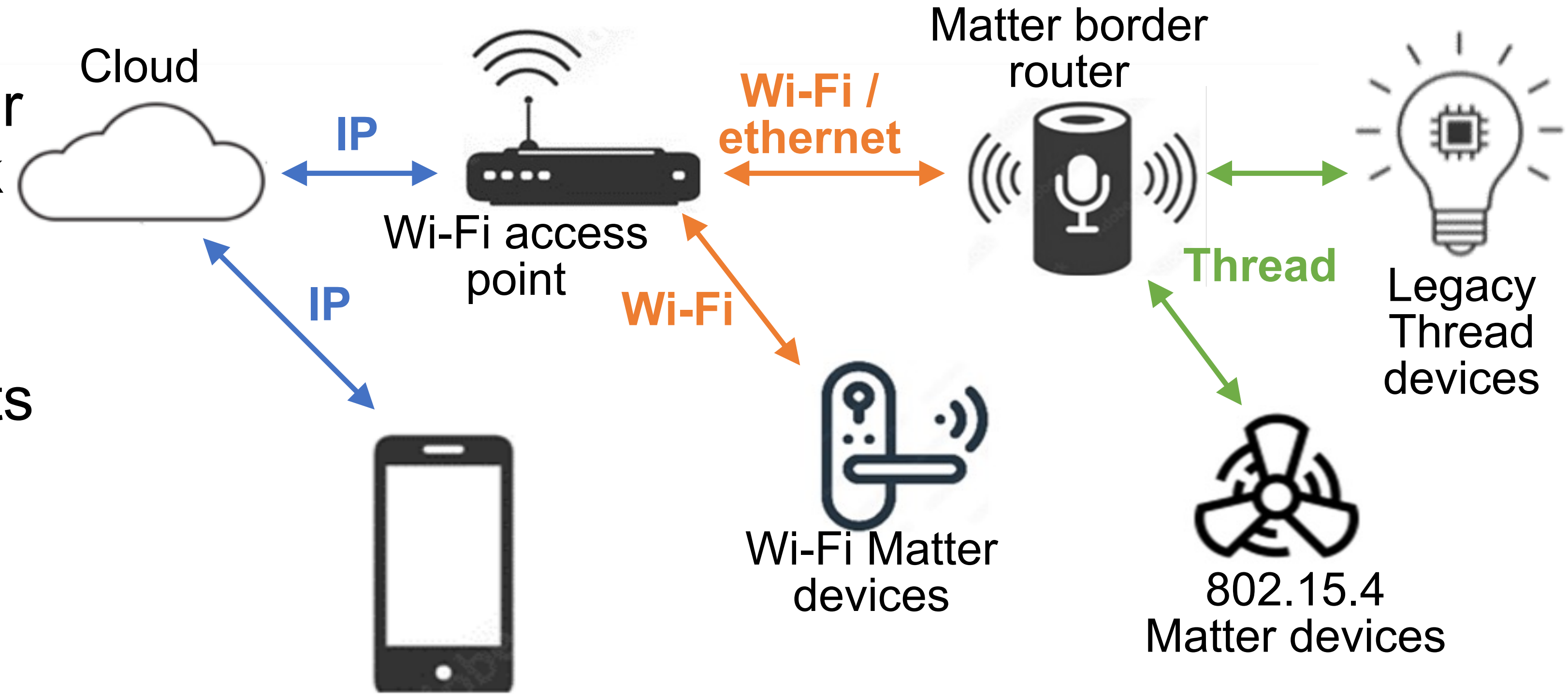
- At launch, Matter runs on top of Thread, Wi-Fi, and Ethernet
  - Support for more PHYs to be added
- Thread/Wi-Fi are complementary
  - Wi-Fi for higher bandwidth applications
  - Thread for battery powered nodes
    - Uses IPv6 (6LoWPAN)
    - Secure mesh networks
    - Supports 100s – 1000s of devices per network
- BLE used for commissioning



Matter Protocol

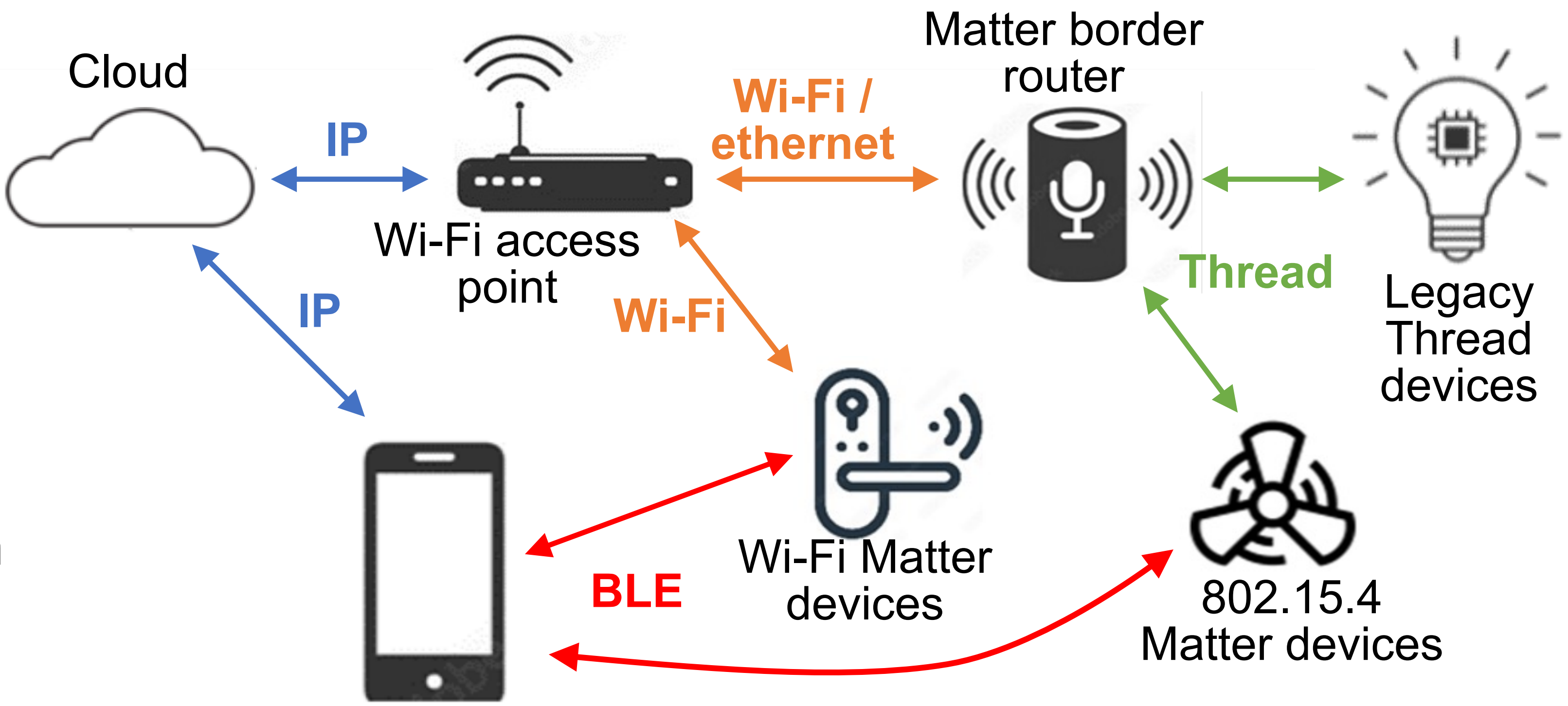
Matter network topology

- Wi-Fi and Thread Matter devices on one network with optional cloud connectivity
- Matter border router acts as a bridge to include non-Matter devices into a network
- Hardware impact:
  - Border router (Thread) support added to future Wi-Fi access points
  - Increased need for low-power Thread/802.15.4 nodes



Matter commissioning

- Bluetooth LE used for commissioning
  - Transferring network credentials to a new device so it can join an existing network
  - BLE not used for device-to-device communication after commissioning.



- Hardware impact:
  - Matter nodes require enough memory to support Thread protocol stack + BLE protocol stack + application layer
  - Matter nodes must have PHY that supports Thread + BLE or Wi-Fi + BLE.

Outline

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Conclusions

- The IoT market has grown tremendously over the last 20 years
  - Growth has been fueled by innovation
- IoT market growth projections of 20%/year will not be met with today's technology
  - Number of batteries is unsustainable / not environmentally friendly
  - Some markets saturating
  - Adding wireless connectivity can be a barrier to entry
  - Fragmented market with many standards, bands, and regulations

Conclusions

- Innovations needed to for IoT 2.0
  - Lower power
    - Battery must last the lifetime of the device
    - Both low leakage and low active power are critical
    - Room for innovation in process technology and wireless protocols
  - Smaller form factor: higher integration
    - Battery can be largest component
      - Energy harvesting size/power tradeoff
    - Replace crystals with silicon MEMS resonators
    - Integrate passives and antenna into package
  - Interoperability
    - Matter: standardized application layer for connected devices
    - Increased need for multiprotocol, low power wireless nodes


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