Wireless for the Internet of Things

— Self-Powered IIoT Wireless System —

Kuo-Ken Huang & Ricky Luna

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Everactive Overview

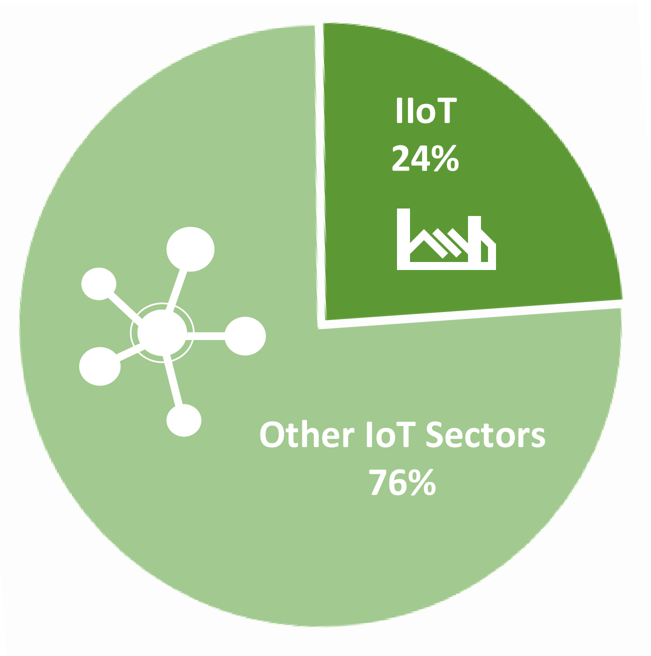
- Was founded in 2012 from UVA and UMich
- Focus on battery-less industrial IoT (IIoT) sensing platform
- It starts with chip design, and is now a system company

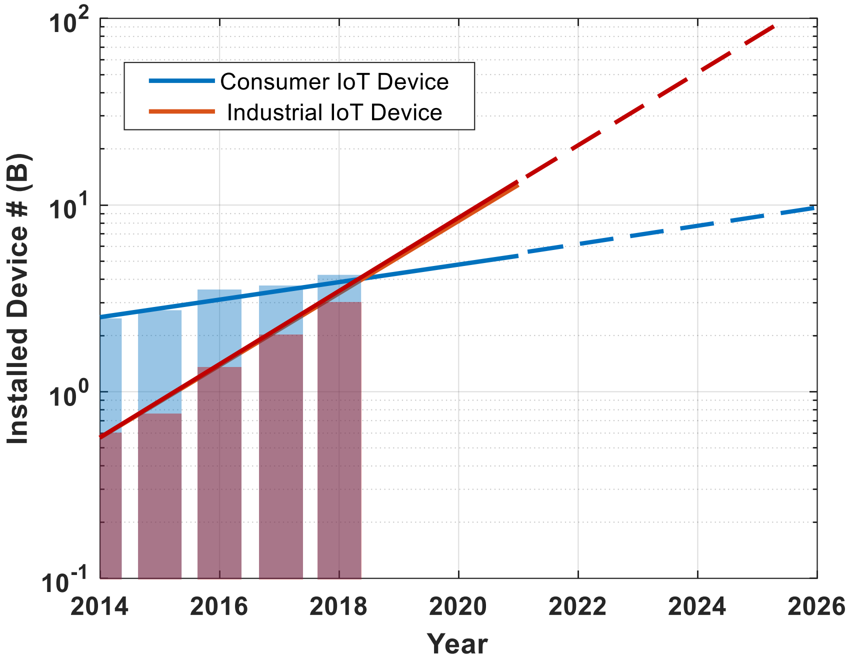
Outline

- Overview of self-powered IIoT wireless system design space
- Evernet
- Ultra-low power receiver (ULP RX)

Motivation – Industrial Internet of Things (IIoT)

- IIoT is a big and fast-growing sectors of the IoT market
- IIoT devices are predicted to be 10x of consumer IoT by 2025





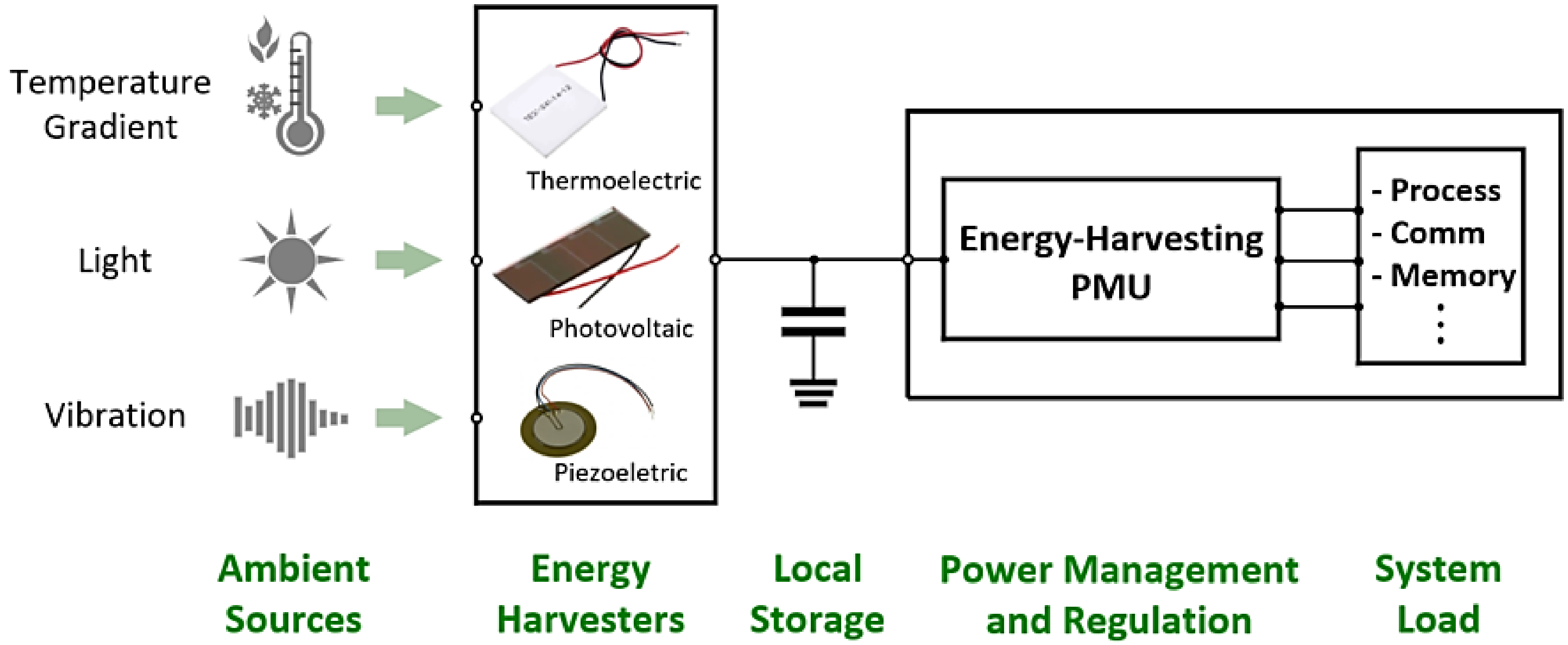
Motivation – Constraint on IIoT Scaling

- **Prohibitive cycle of battery maintenance in IIoT space**
  - » Harsh environment reduces battery lifetime and adds uncertainty
  - » Labor and logistics cost for large number of devices

1T sensors with 3-yr battery-life =
913M replacements per day

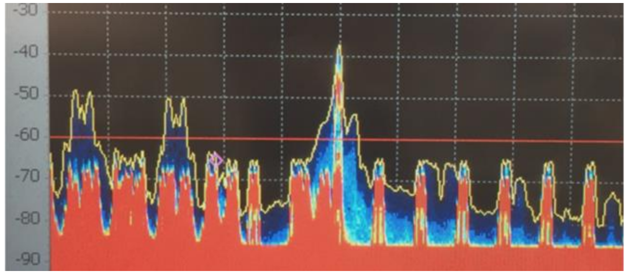
Motivation – Self-Powered System (SPS)

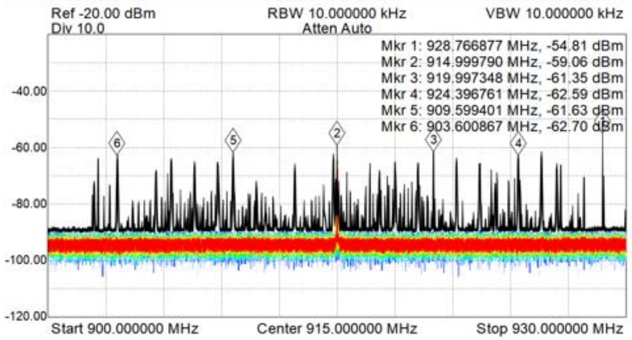
- Live off harvested energy to solve the battery problem



IIoT Wireless Environment Overview

- **Large scale device deployment**
  - » Device form factor still matters
  - » Wireless protocol should be traffic-efficient
  - » Device should be cost effective
- **Harsh wireless environment**
  - » Dense machinery
  - » Wide operating temperature range
  - » Crowded spectrum
- **Monitor data rates are generally low**
  - » But the value of the data is high





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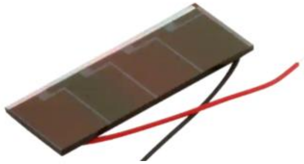
Power Budget for Wireless IIoT SPSs

- **Sensor form-factor ultimately constrains the power budget**
  - » A palm-size form-factor is generally accepted in the IIoT space

Energy Source	Power Density
Outdoor light	$1000\mu W/cm^2$
Human motion	$330\mu W/cm^3$
Vibration	$200\mu W/cm^3$
Thermal	$40\mu W/cm^2$
Indoor light	$10\mu W/cm^2$

Volume Constraint


Thermoelectric


Photovoltaic

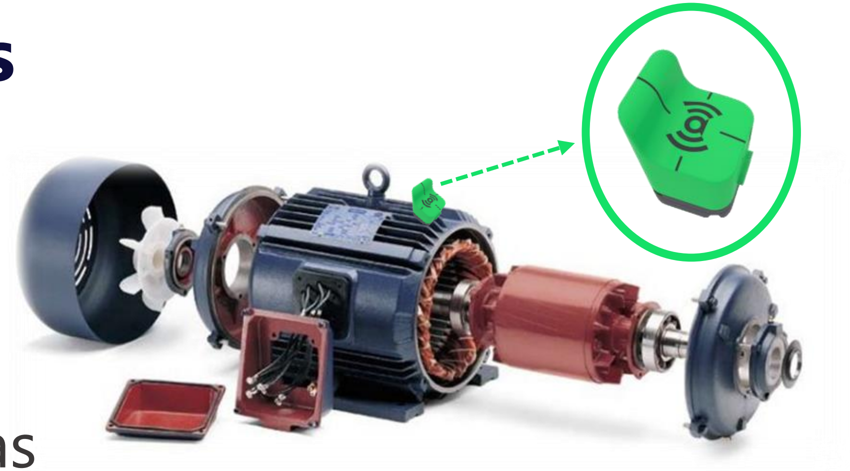

Piezoeletric

Efficiency Loss

< 10µW
Active Power

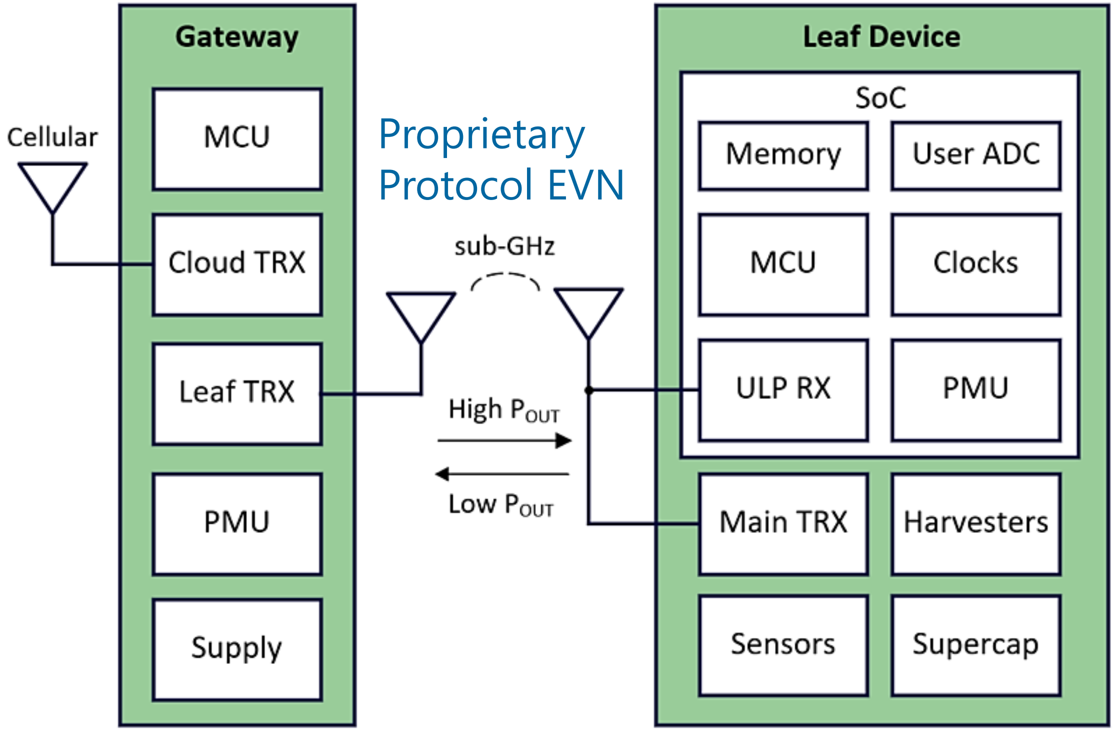
Wireless IIoT SPS Commercialized Use Case

- **Machine health monitoring system (MHM) by Everactive**
  - » Detecting failures for motors, pumps, fans, gear boxes
- **Electric motors market by the numbers**
  - » 300M electric motor installed worldwide
  - » 47% of global electricity usage
- **MHM system highlights**
  - » Harvests energy from solar and thermal deltas
  - » Utilizes a ULP RX for network synchronization
  - » Wirelessly sending vibration data to the cloud
  - » 3000+ leaf devices deployed across 30+ sites

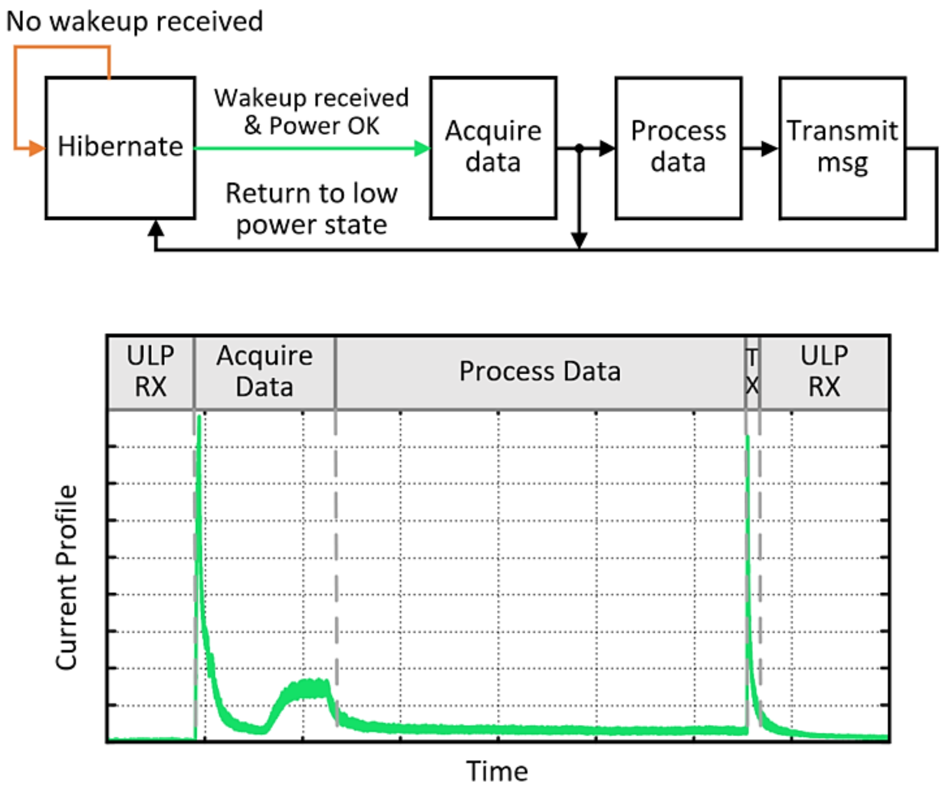


Everactive MHM System Overview

Block Diagram



System Flow Chart & Current Profile



Target Design Space for Wireless IIoT SPSs & ULP RX

Target Design Space for Wireless IIoT SPS Leaf Device	
Active Power	< 10μW
Wireless Range	250m nominal, NLoS
Temperature Range	-40°C to 85°C
Latency	< 200ms
Interference Robustness	At least -10dB ACI selectivity
Clear Channel Assessment (CCA)	Support CCA/RSSI

Requirements for ULP RX
< 10μW Power Consumption
-70dBm Sensitivity
-40°C to 85°C Operation Range
10kbps Data Rate
-10dB ACI Selectivity
Support CCA/RSSI

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Outline

- Overview of self-powered IIoT wireless system design space
- **Evernet**
- Ultra-low power receiver (ULP RX)

Wireless Standards for IIoT SPSs

- **Today's protocols are not designed for large-scale IIoT SPSs**
  - » Some have adopted a wakeup signal (WUS) for power savings, but not sufficient for SPSs
  - » System requirements have not been fully addressed, but there is progress
- **Energy overhead**
  - » Network association
  - » Synchronization
- **Security**
  - » Encryption
  - » Mutual authentication
  - » Guard against replay attacks

Wireless Protocol	Wi-Fi 802.11ba [30]	LTE CAT-NB [31]	LoRaWAN [32]	Zigbee [33]	Bluetooth [34]
Wakeup signal	In progress	Yes	No	No	In progress
Energy for network sync	High	High	High	Mid	Mid
Number of devices per gateway	~100	~10,000	~100	50-100	20-30
Security features	WPA	3GPP, AES, ZUC	AES	AES	AES
End-to-end latency	10m-100ms	<10s	1-16s	10m-100ms	<3ms

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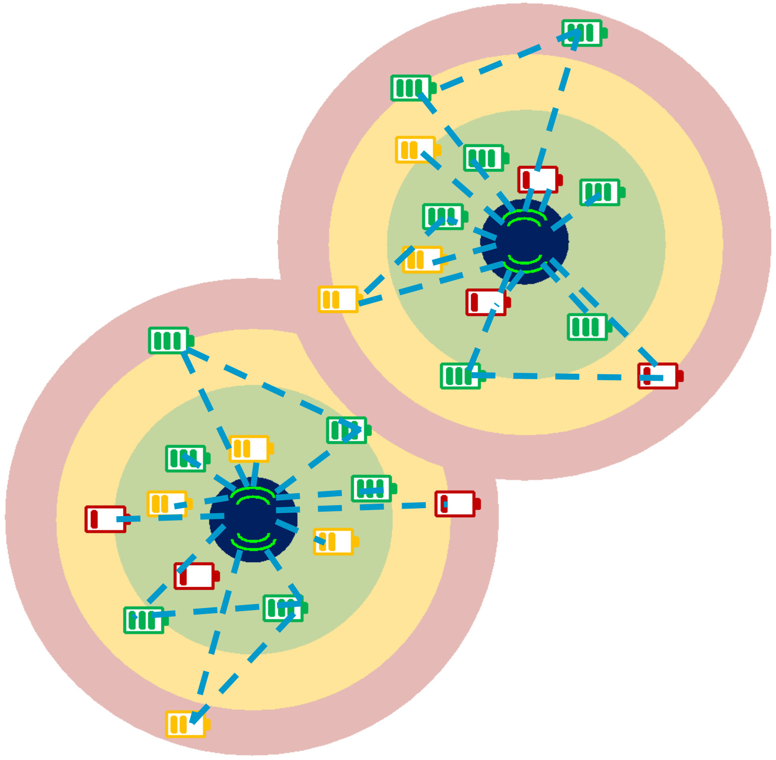
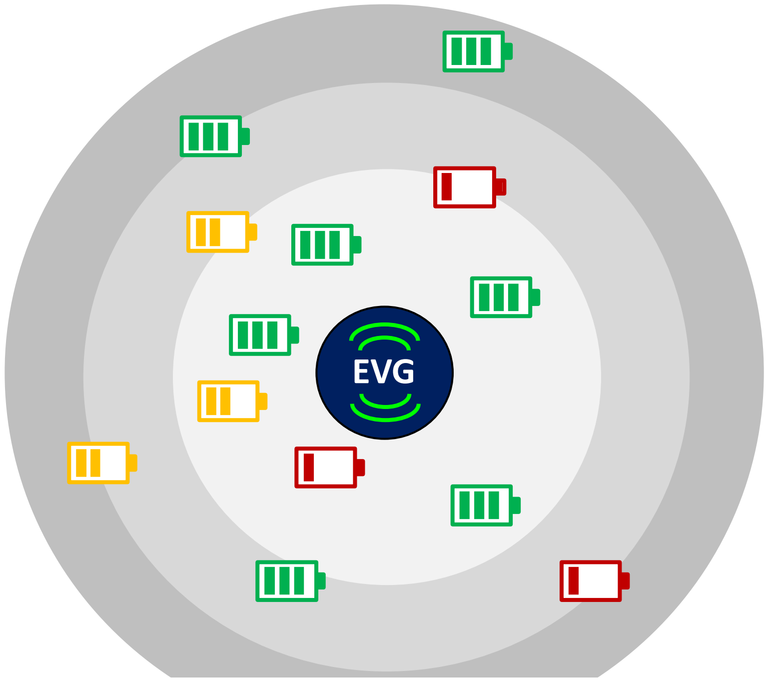
Evernet Overview

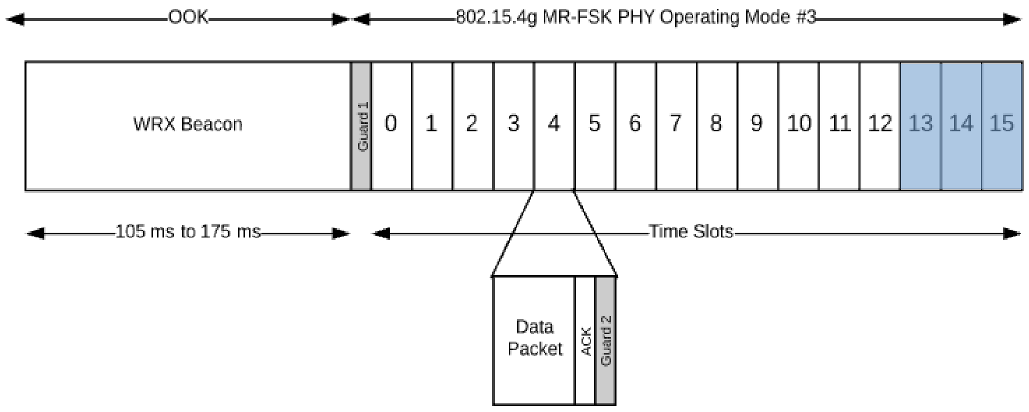
- **Inspired by slotted 802.15.4g**
  - » Star topology
  - » Gateway + leaf nodes
  - » Simple and robust
- **2 PHYs**
  - » WRX Beacon (OOK)
  - » Data (FSK)
  - » Breaks compatibility with spec
- **Asymmetric communication**
  - » High-power gateway
  - » Low-power sensors



Evernet – Synchronization & Data Traffic

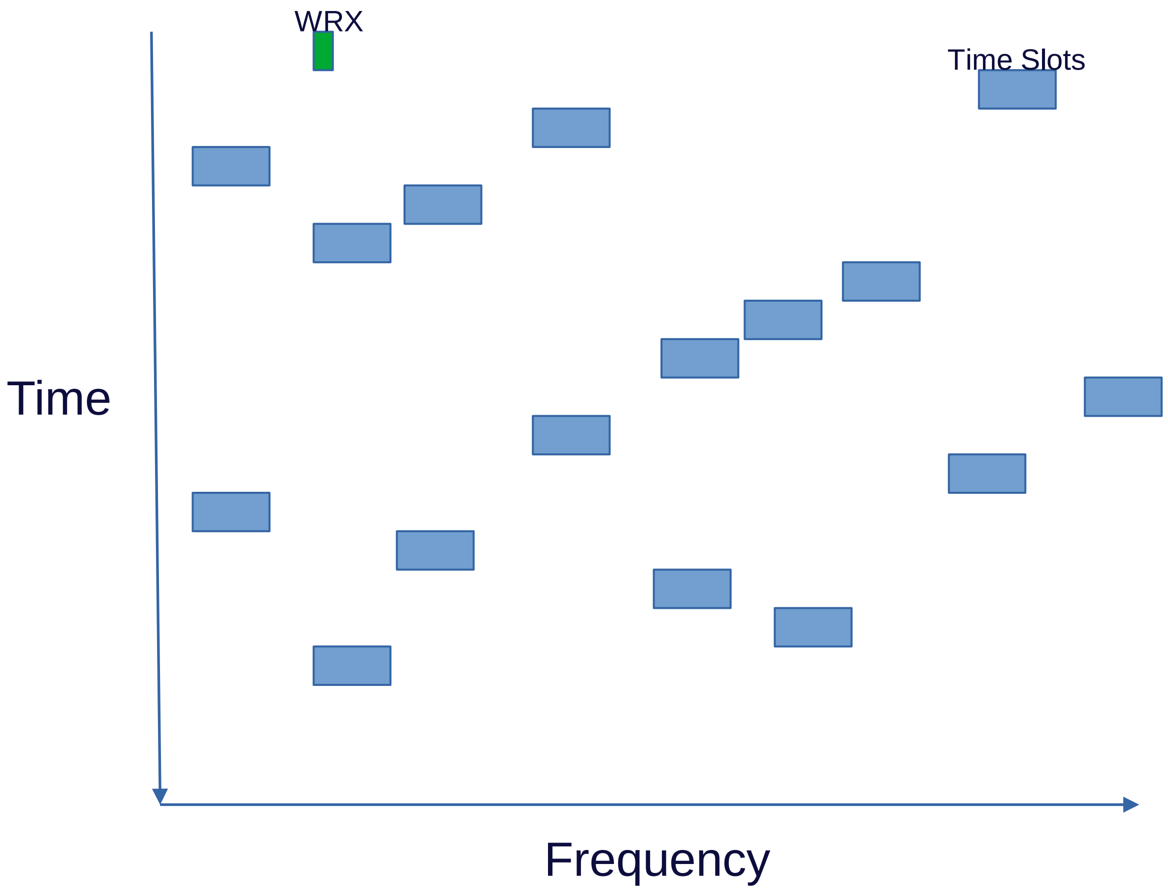
- ## Uses WRX PHY for sync
  - » Always-on and in sync with the associated network
  - » Timing, frequency hopping, security, etc.
- ## Data traffic management
  - » WRX: wideband receiver
  - » Data uplink: time-slot and channel based
  - » Data downlink: for OTA and provisioning





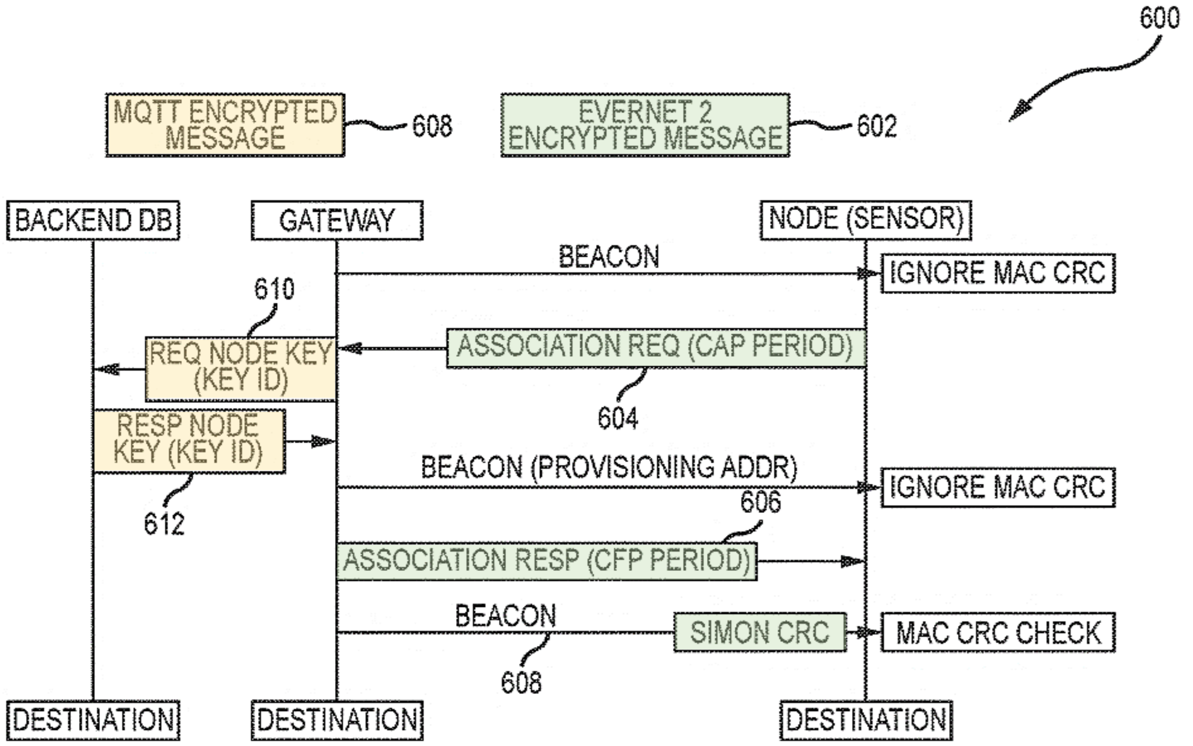
Evernet Frequency Use

- **Beacons hop**
  - FCC compliance
  - Not beneficial for interference rejection
- **Each time slot hops**
  - FCC/EU compliance
  - Rejects out of band interference



Evernet – Provisioning

- **Network association**
  - » Pick a gateway
  - » First deployment or being moved
  - » Or power-on-reset due to intermittent energy availability
- **Traditional method**
  - » **Channel scanning is required**
  - » Higher power and takes time
- **Evernet utilizes WRX**
  - » WRX is a broadband receiver
  - » Fast network scan

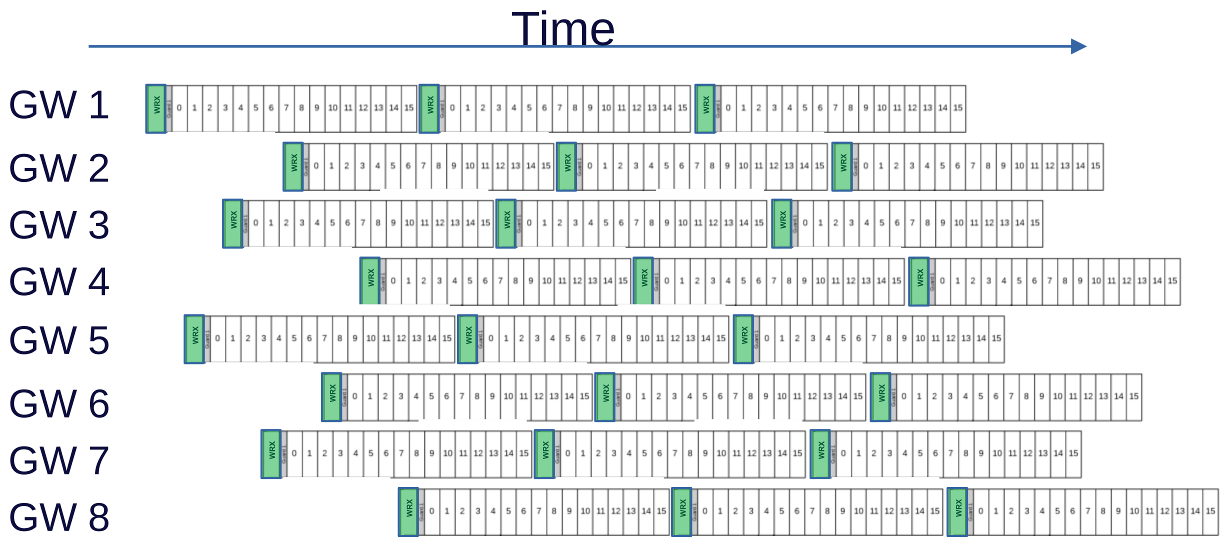


Wireless Protocol Standards

Protocol Features	Wi-Fi 802.11ba	NB-IoT	LoRaWAN	Zigbee	Bluetooth	Evernet
Wakeup signal	In progress	Yes	No	No	In progress	Yes
Energy for network association & sync	High	High	High	Mid	Mid	Low
Practical num of leaf devices per gateway	~100	~10,000	~100	50-100	20-30	~1,000
Security features	WPA	SNOW 3G AES ZUC	AES	AES	AES	• Cryptographic checksum (WRX link) • AES (Data uplink)
Secure wakeup	In progress	Addressable but no encryption	N/A	N/A	In progress	Yes
End-to-end latency	10m-100ms	<10s	1-16s	10m-100ms	<3ms	<1s

Dense Evernet Deployment

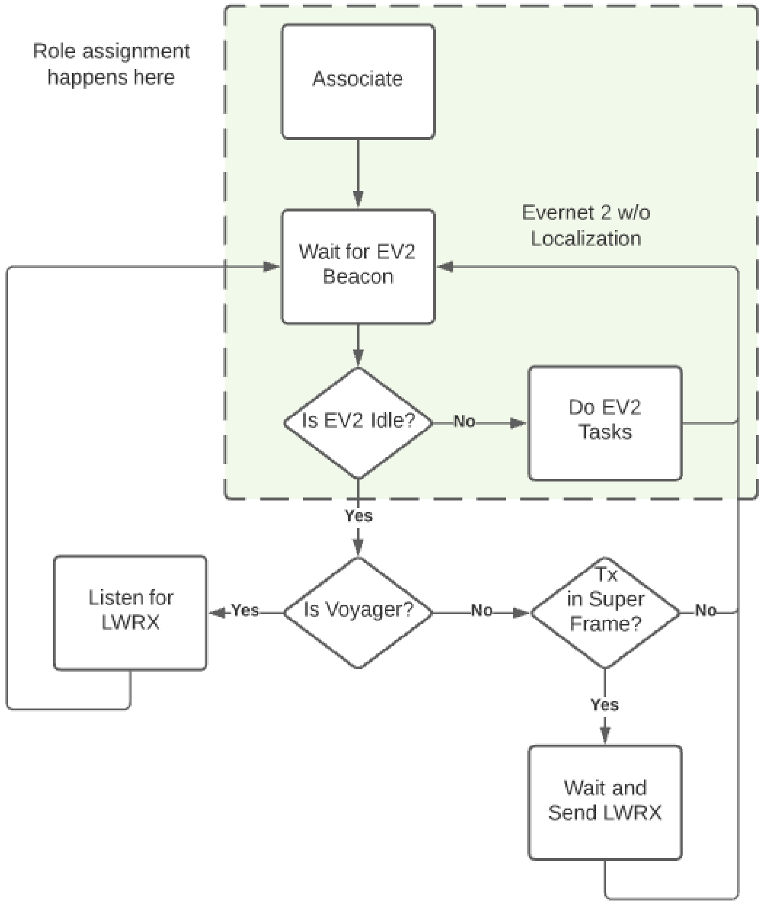
- **Every 2.085 seconds**
- **WRX ~ 120 ms**
- **Time slots = 120 ms**
- **Gateway coexistence**
  - Beacons cannot be on air at the same time
  - Time offset beacons
    - 10 GWs
    - Linux NTP clock
      - Not super accurate



Evernet – Localization

- **Dynamic role assignment**
  - Anchor or voyager
  - Anchors get an ID
  - Same FW for each
  - At association or downlink TLV

- **If no Evernet tasks**
  - Anchors check to Tx
  - Voyagers listen



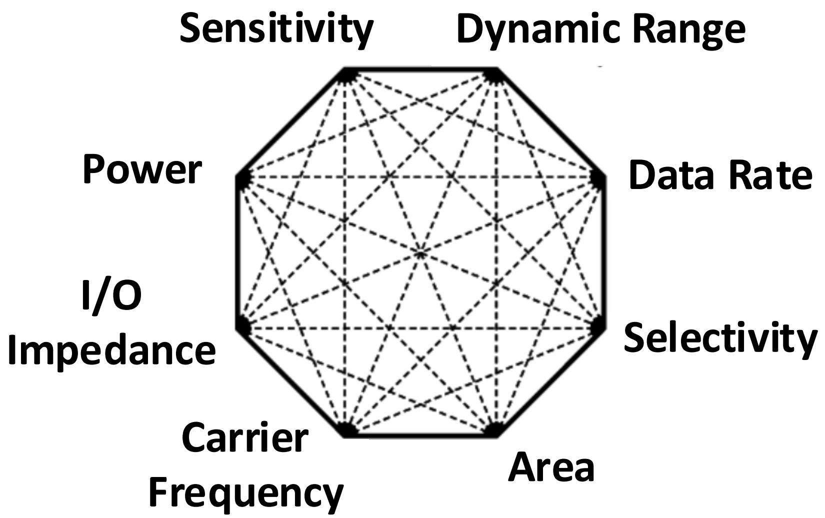
Outline

- Overview of self-powered IIoT wireless system design space
- Evernet
- **Ultra-low power receiver (ULP RX)**

Generic Radio Receiver Tradeoffs

Power/Sensitivity/Data Rate

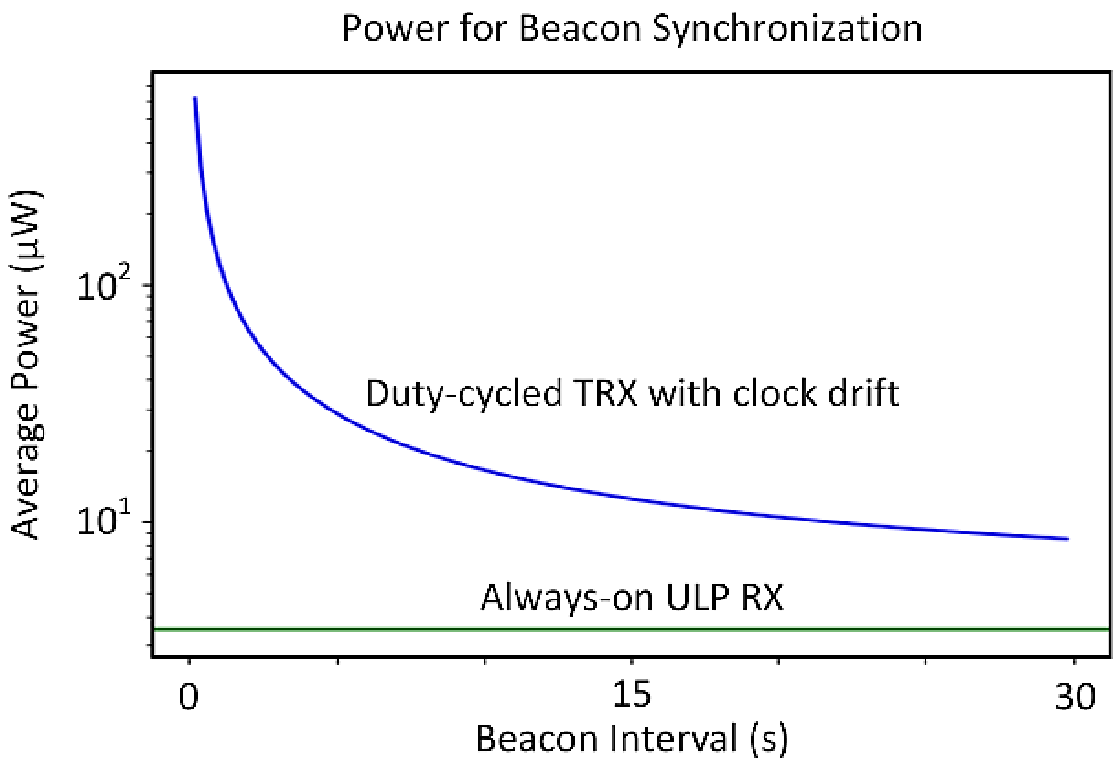
- Traditionally, you pick two
- Selectivity is crucial in dense networks, and often overlooked in ULP radio



B. Razavi, UCLA

Motivation – Ultra Low-Power Receiver (ULP RX)

- **Always-on ULP RX sets the power floor**
  - » To meet the harvested budget
- **Breaking the traditional radio power/latency tradeoff**



What Differentiates Everactive w/ ULP WRX

Conventional

- Equal POWER when RX'ing and TX'ing
- More ENERGY (= power x time) spent in RX than TX
- Therefore, maintain active network by TX on node and RX on the gateway (BLE advertising)
- Or very accurate timer is needed in order for low system average power

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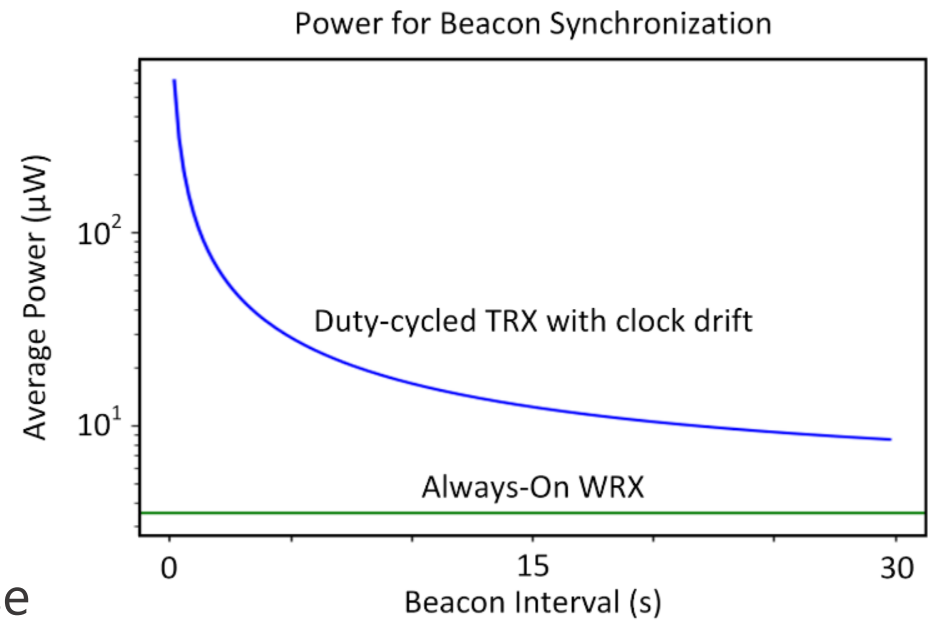
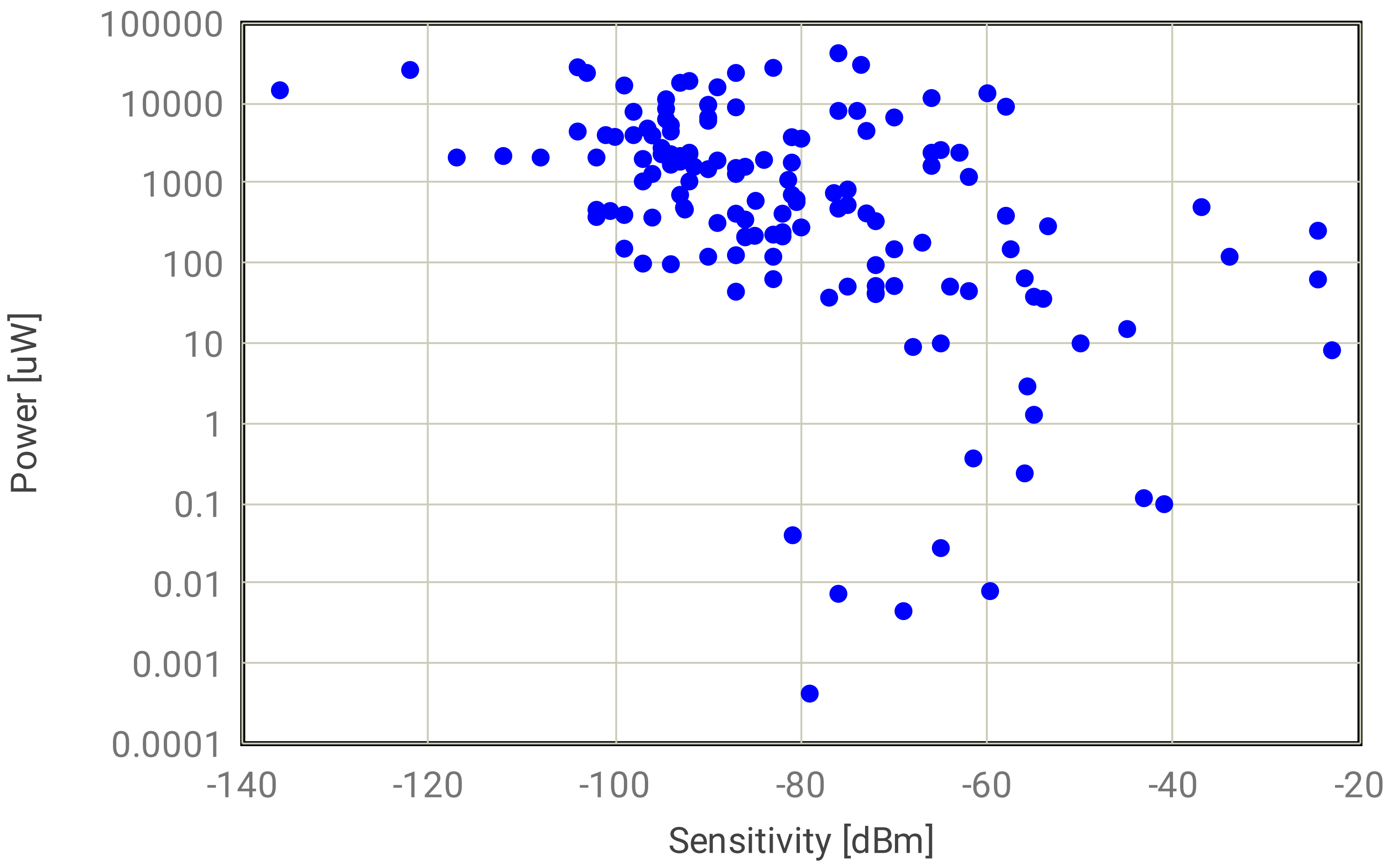
- Assist WRX is 1/1000th the POWER of Tx
- "Invert" the network to Tx on gateway, Rx on node leveraging WRXs
- Overall power is lower on the node, no compromise on rate
- Remove the need for advertising on every node

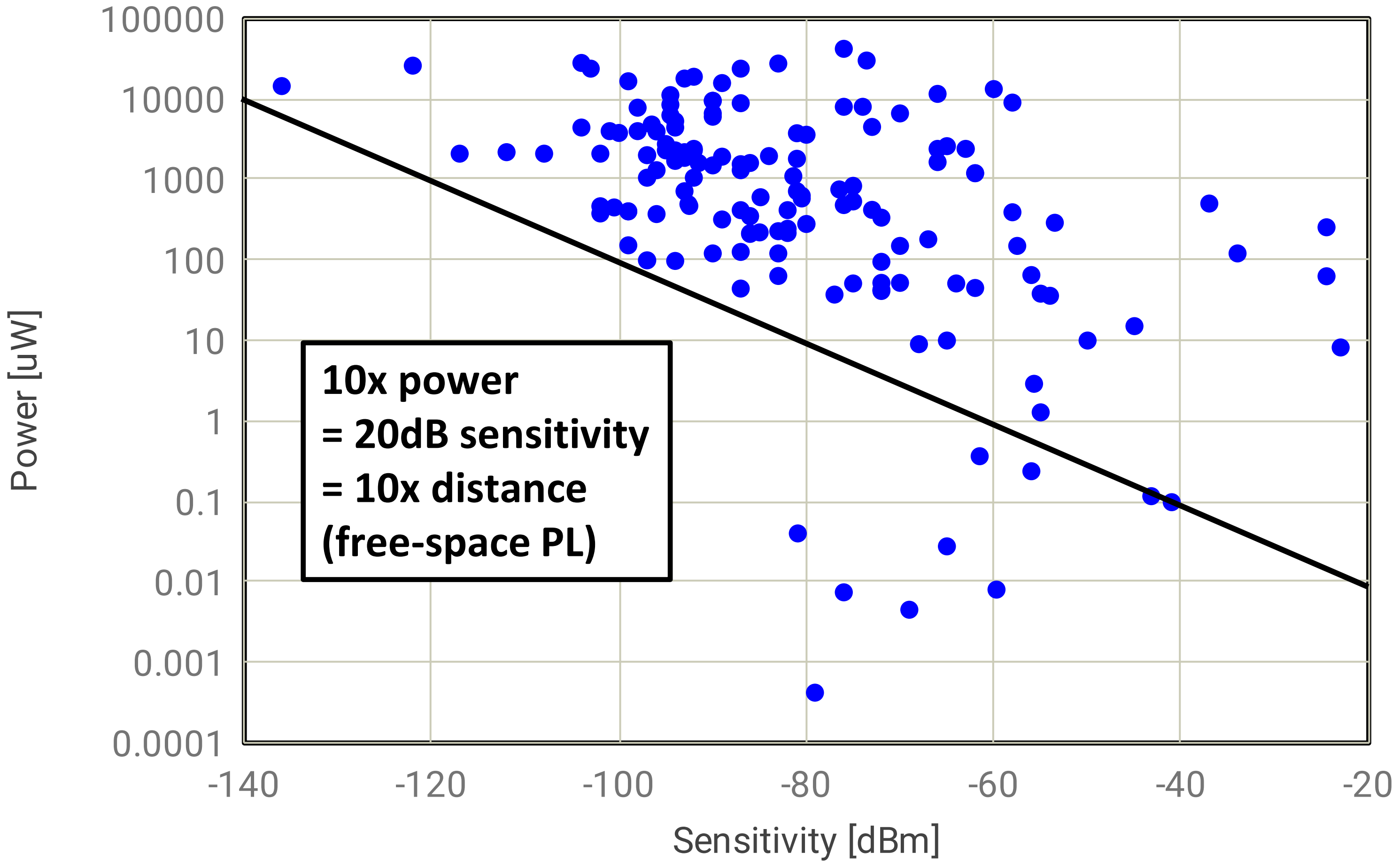


Motivation – ULP RX Survey Since 2005



http://www.eecs.umich.edu/wics/low_power_radio_survey.html

ULP Radios – Range



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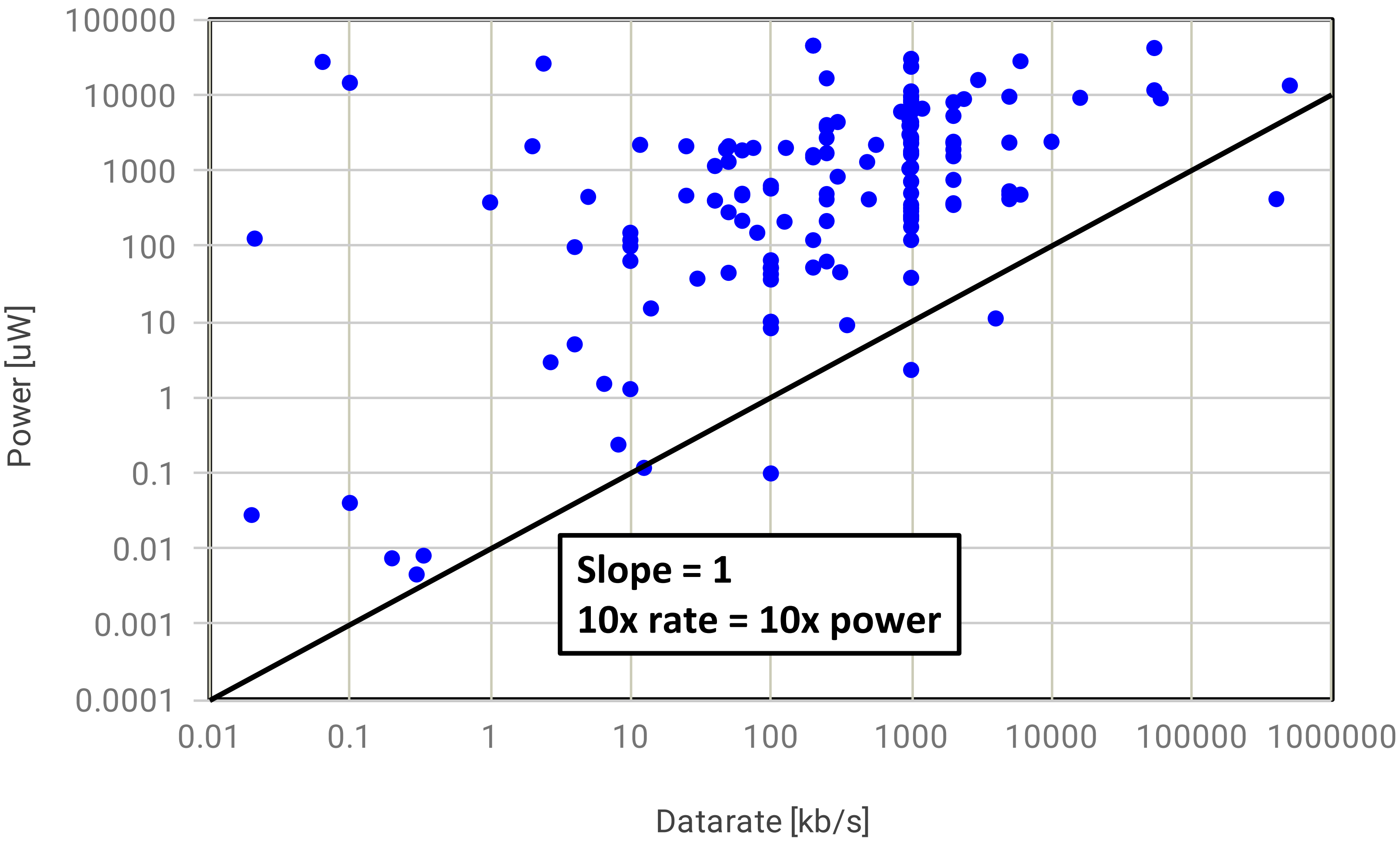
ULP Radios – Data Rate



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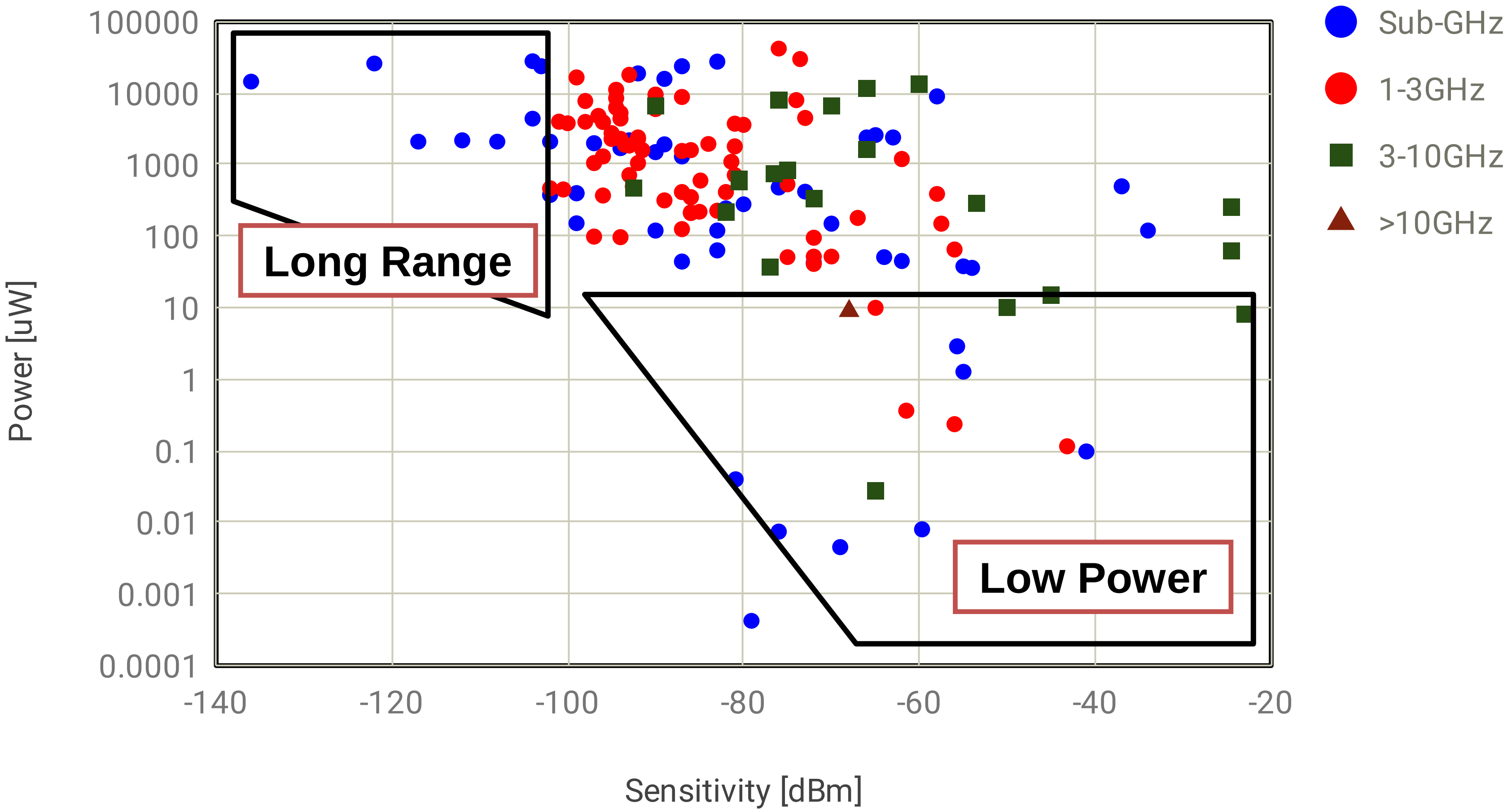
ULP Radios – Operating Frequency



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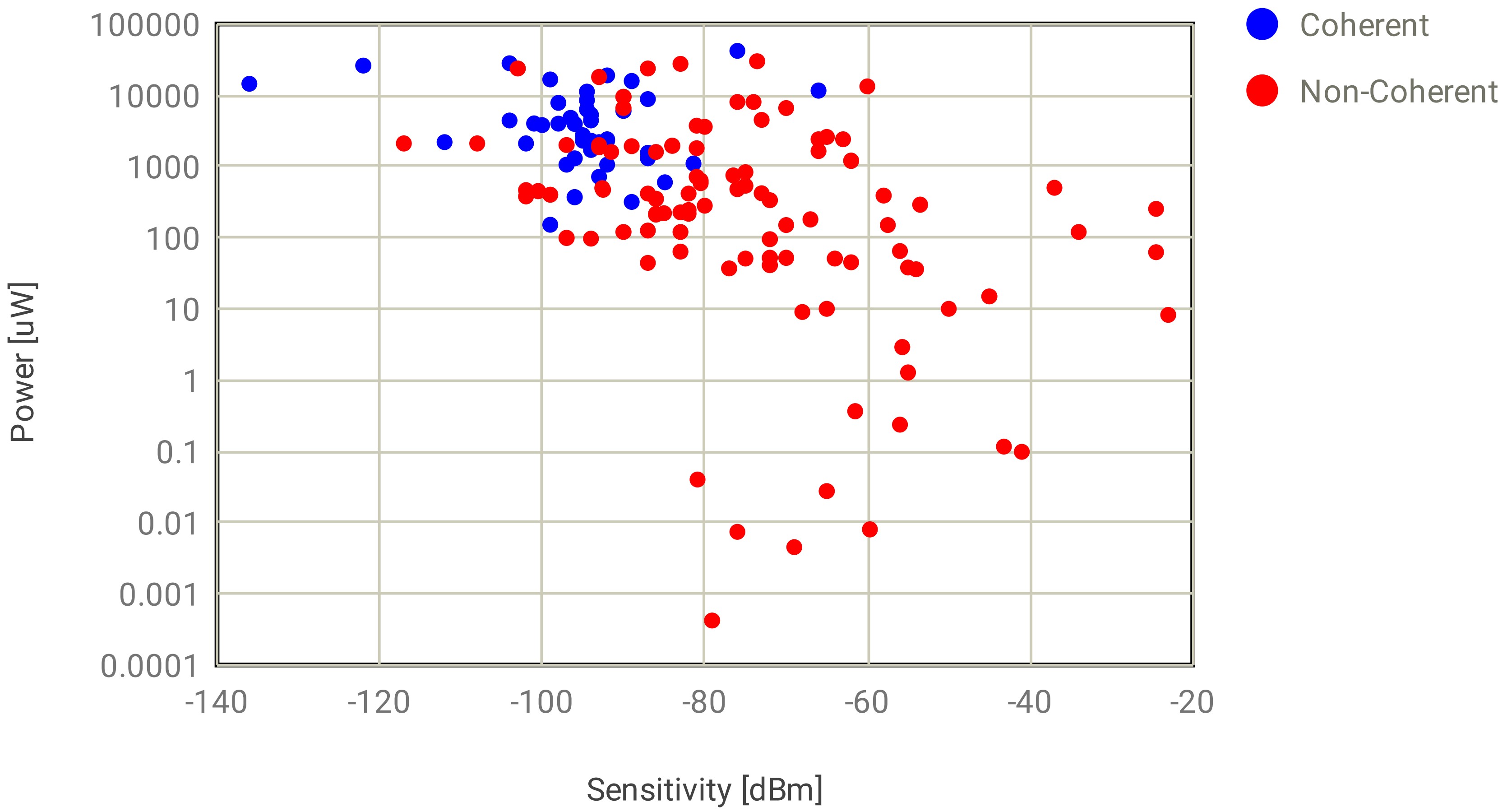
ULP Radios – Architecture



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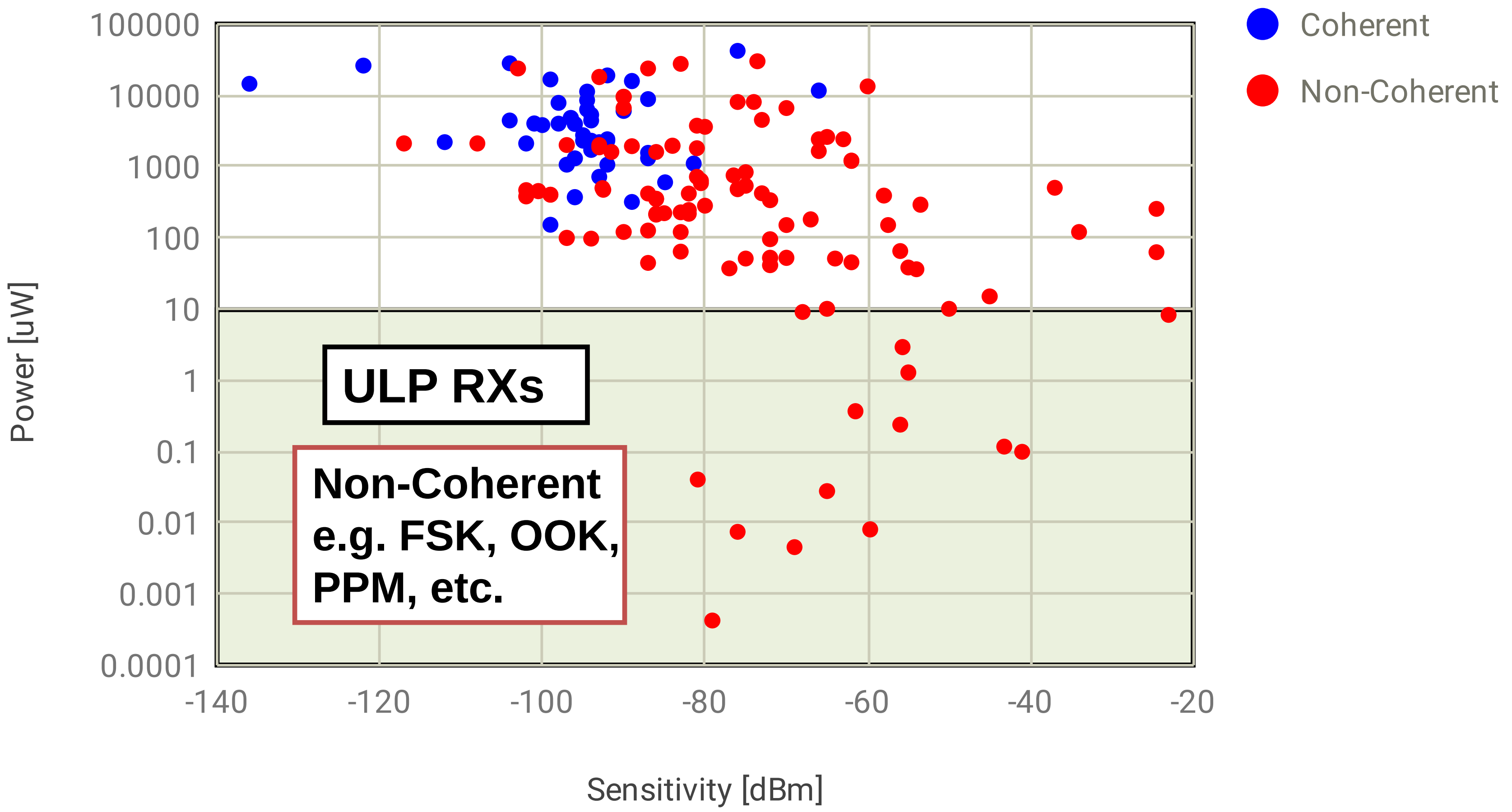
ULP Radios – Architecture



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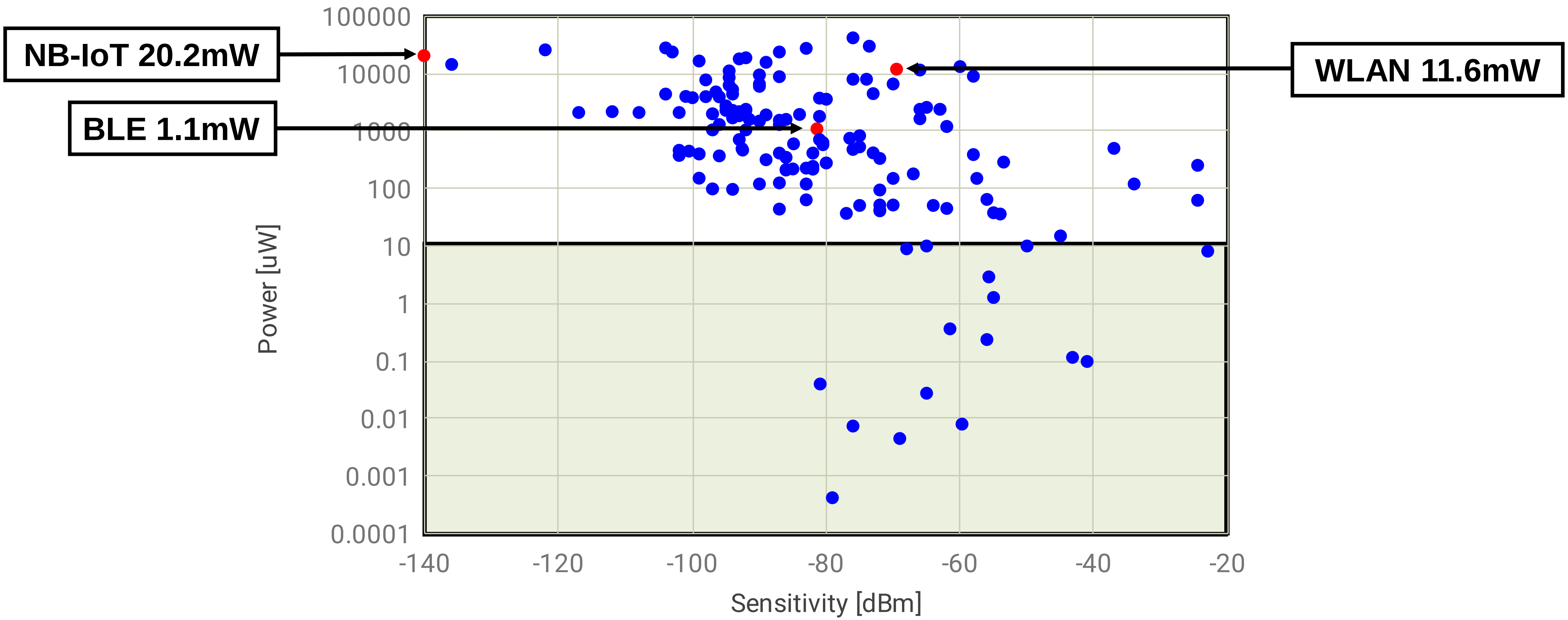
Standard-Compliant RXs



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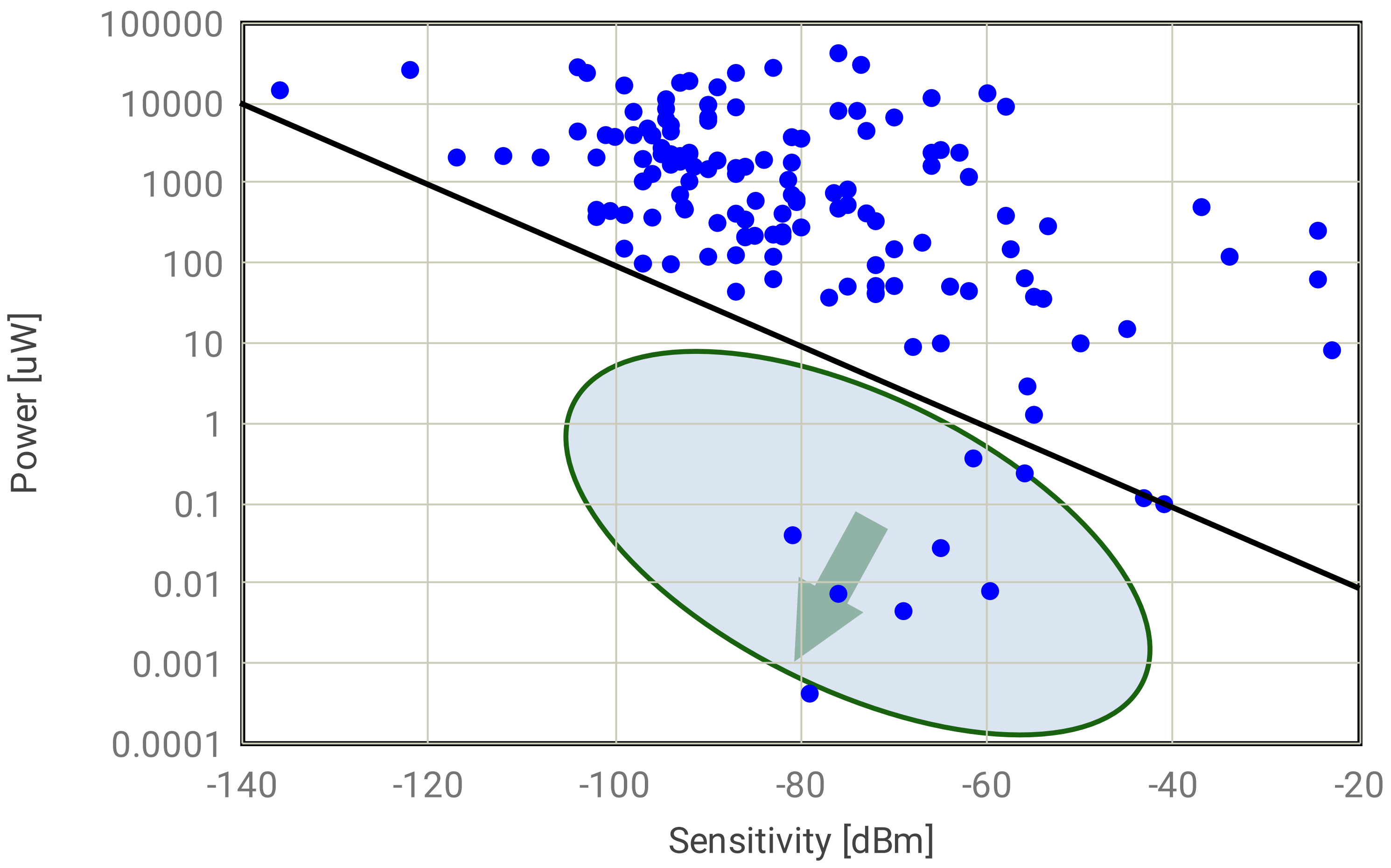
Motivation – ULP RX Survey Since 2005



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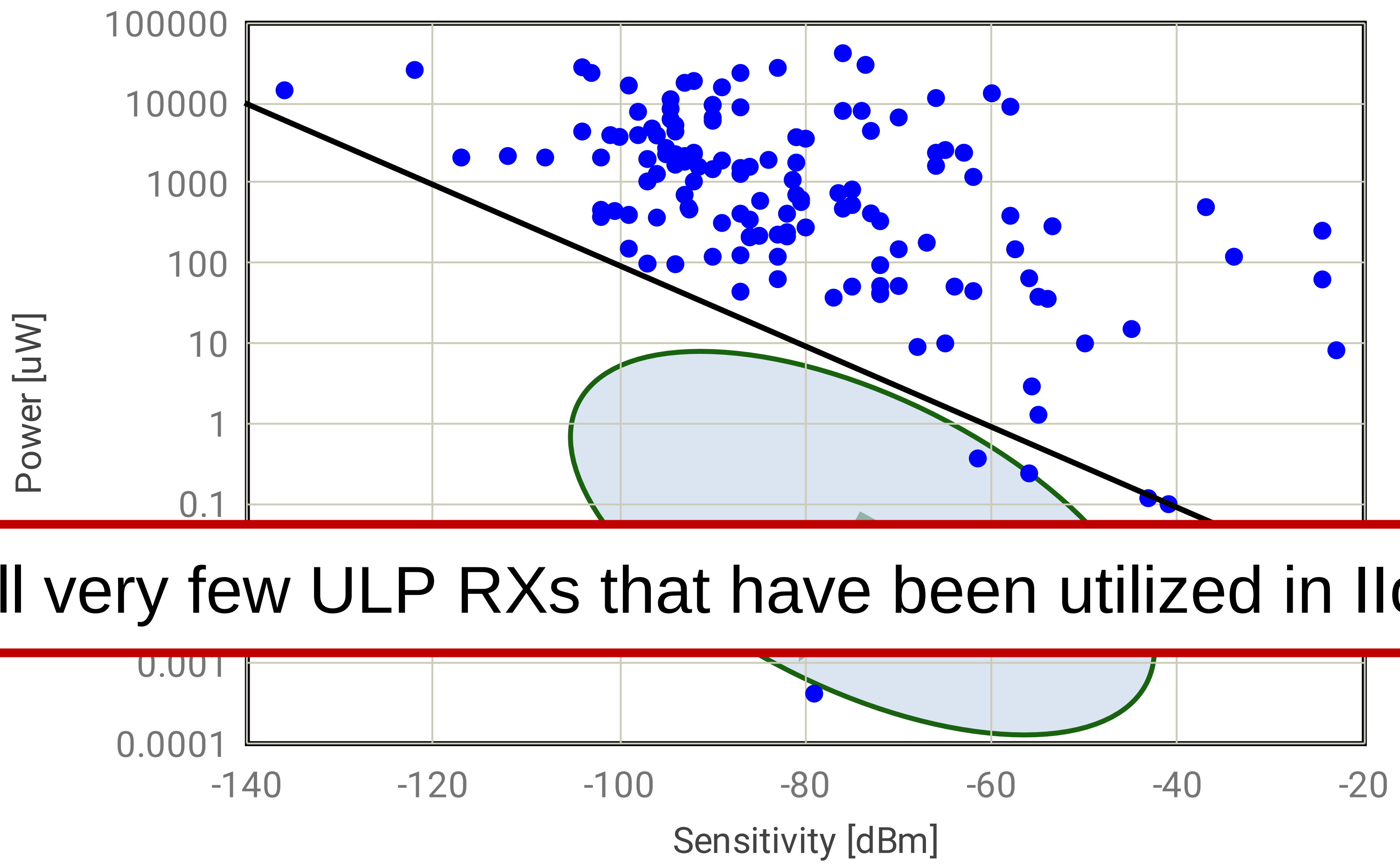

Still very few ULP RXs that have been utilized in IIoT SPSs

http://www.eecs.umich.edu/wics/low_power_radio_survey.html

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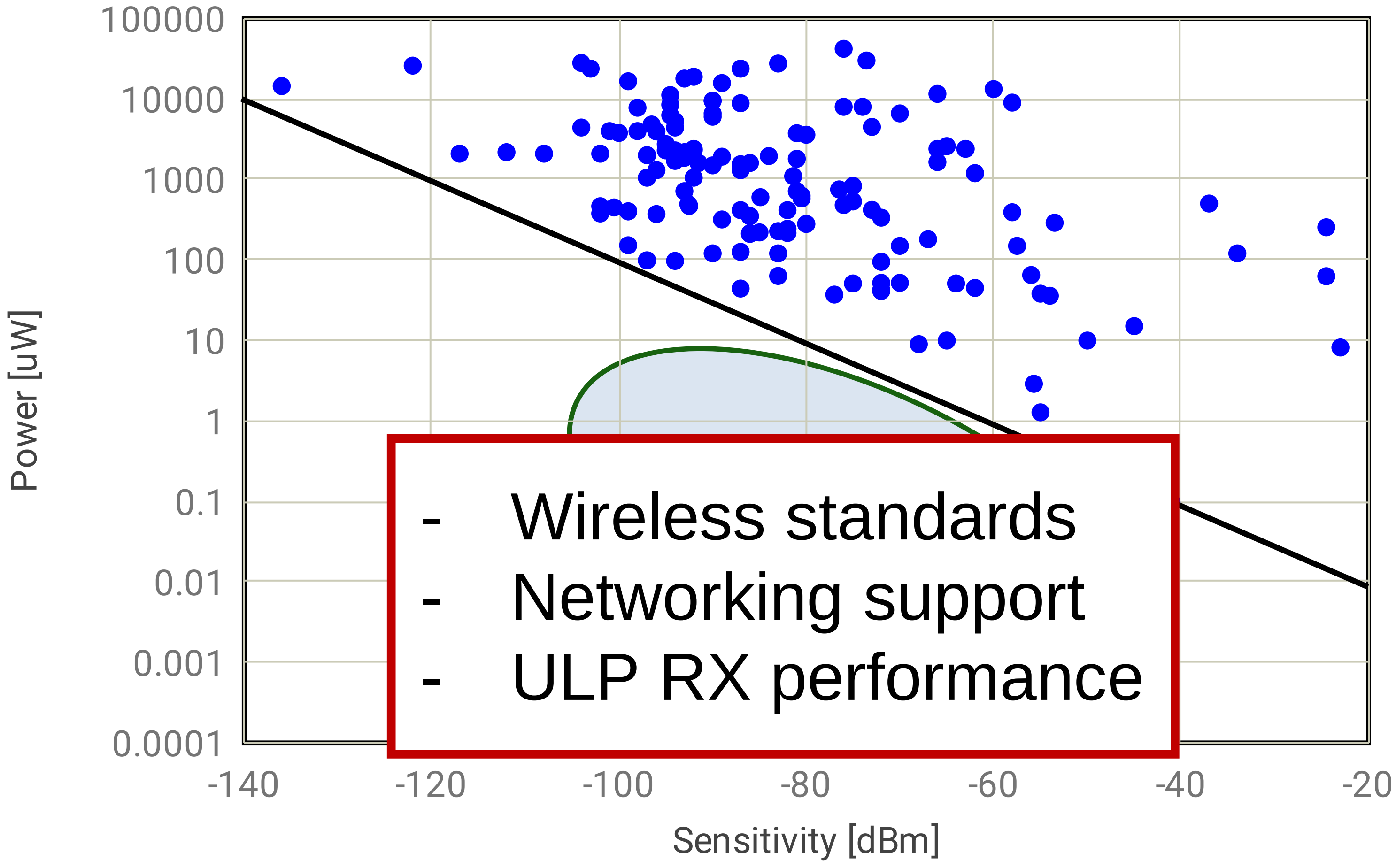

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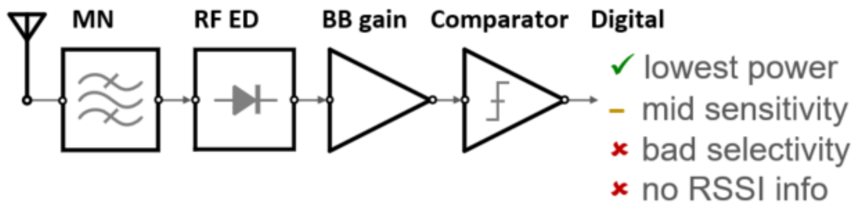
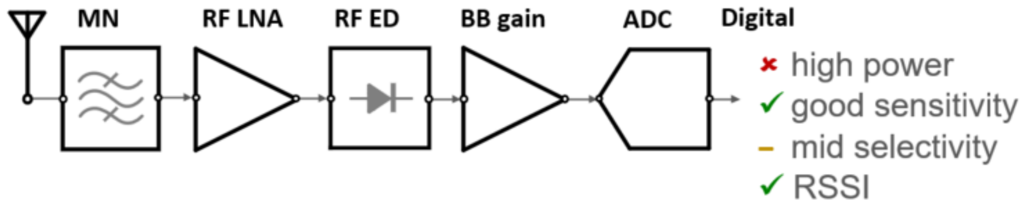
Architecture for Limited Harvested Power Budget

10µW to meet key ULP RX design targets

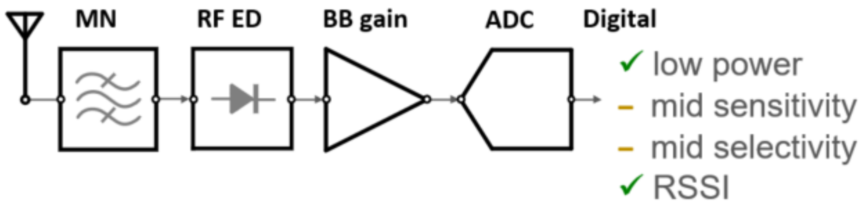
» Energy asymmetric approach, which determines the ULP RX architecture/modulation



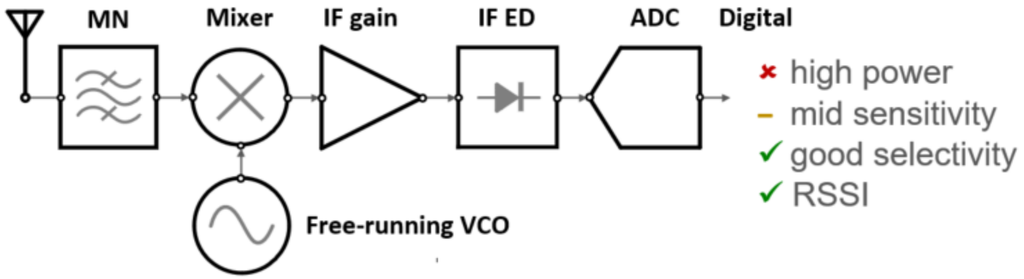
(a) ED-first with BB comparator



(c) LNA-first, tuned-RF



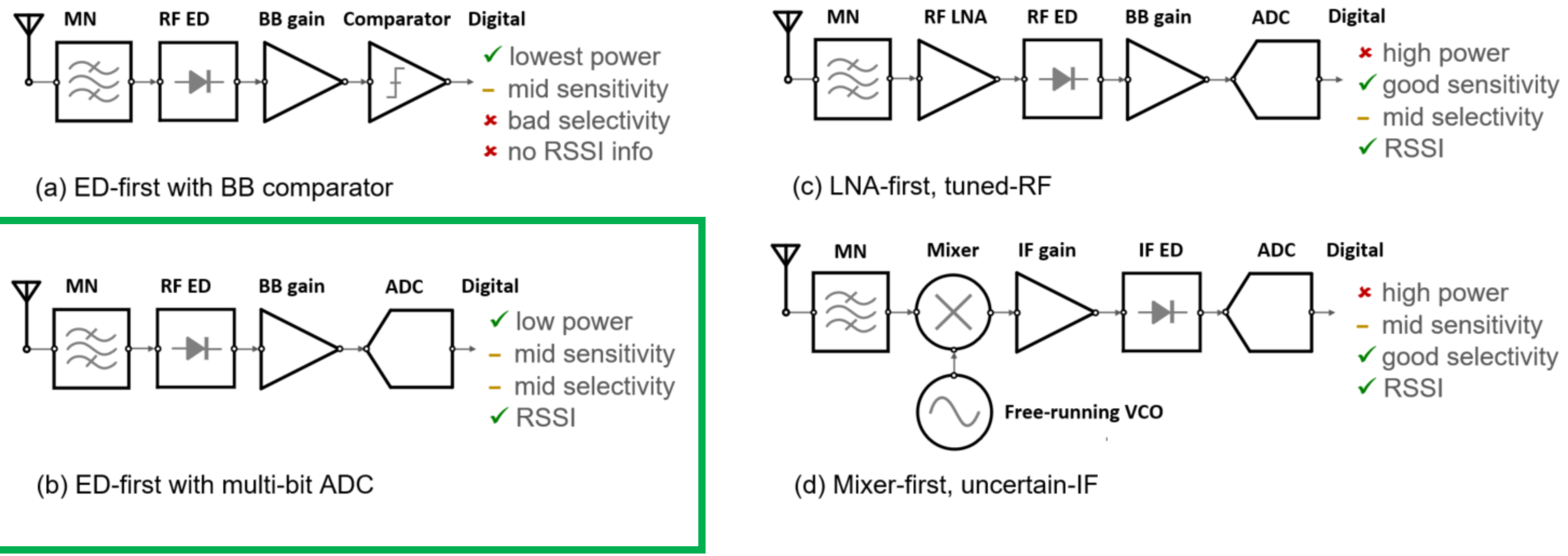
(b) ED-first with multi-bit ADC



(d) Mixer-first, uncertain-IF

Architecture for Limited Harvested Power Budget

- **10µW to meet key ULP RX design targets**
  - » Energy asymmetric approach, which determines the ULP RX architecture/modulation



Summary

- **ULP Wakeup Rx is one of the keys to IIoT SPS device scaling**
  - To enable self-powered operation for massive deployments
- **Evernet is designed for SPS, and wireless standards are catching up**
  - Start to consider SPS use cases
  - Doing more to capitalize on the ULP RX to offload frequent network-level tasks

Ultimate goal: Deliver **seamless data streams** from **batteryless sensors** as **frictionless services** to unlock end-user value and enable solution-partner innovation