Wireless for the Internet of Things

— Self-Powered IIoT Wireless System —

Kuo-Ken Huang & Ricky Luna

4/19/2021
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

Environmental Tragedy
Motivation – Self-Powered System (SPS)

- Live off harvested energy to solve the battery problem

Diagram showing various energy harvesting methods including temperature gradient, light, vibration, and ambient sources. Components such as thermoelectric, photovoltaic, and piezoelectric are connected to an energy-harvesting module labeled PMU.
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
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

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor light</td>
<td>1000µW/cm²</td>
</tr>
<tr>
<td>Human motion</td>
<td>330µW/cm³</td>
</tr>
<tr>
<td>Vibration</td>
<td>200µW/cm³</td>
</tr>
<tr>
<td>Thermal</td>
<td>40µW/cm²</td>
</tr>
<tr>
<td>Indoor light</td>
<td>10µW/cm²</td>
</tr>
</tbody>
</table>

Volume Constraint

Thermoelectric

Photovoltaic

Piezoelectric

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

Proprietary Protocol EVN

Gateway
- MCU
- Cloud TRX
- Leaf TRX
- PMU
- Supply

Leaf Device
- SoC
  - Memory
  - User ADC
- MCU
- Clocks
- ULP RX
- PMU
- Main TRX
- Harvesters
- Sensors
- Supercap

Cellular

High P_OUT

Low P_OUT

sub-GHz

No wakeup received

Wakeup received & Power OK

Return to low power state

Acquire data

Process data

Transmit msg

Current Profile

ULP RX

Acquire Data

Process Data

ULP RX

Time
# Target Design Space for Wireless IIoT SPSs & ULP RX

<table>
<thead>
<tr>
<th>Target Design Space for Wireless IIoT SPS Leaf Device</th>
<th>Requirements for ULP RX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Power</td>
<td>&lt; 10µW</td>
</tr>
<tr>
<td>Wireless Range</td>
<td>250m nominal, NLoS</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-40°C to 85°C</td>
</tr>
<tr>
<td>Latency</td>
<td>&lt; 200ms</td>
</tr>
<tr>
<td>Interference Robustness</td>
<td>At least -10dB ACI selectivity</td>
</tr>
<tr>
<td>Clear Channel Assessment (CCA)</td>
<td>Support CCA/RSSI</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-70dBm</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
</tr>
<tr>
<td></td>
<td>-40°C to 85°C</td>
</tr>
<tr>
<td></td>
<td>Operation Range</td>
</tr>
<tr>
<td></td>
<td>10kbps</td>
</tr>
<tr>
<td></td>
<td>Data Rate</td>
</tr>
<tr>
<td></td>
<td>-10dB</td>
</tr>
<tr>
<td></td>
<td>ACI Selectivity</td>
</tr>
<tr>
<td></td>
<td>Support CCA/RSSI</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wakeup signal</td>
<td>In progress</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>In progress</td>
</tr>
<tr>
<td>Energy for network sync</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Mid</td>
<td>Mid</td>
</tr>
<tr>
<td>Number of devices per gateway</td>
<td>~100</td>
<td>~10,000</td>
<td>~100</td>
<td>50-100</td>
<td>20-30</td>
</tr>
<tr>
<td>Security features</td>
<td>WPA</td>
<td>3GPP, AES, ZUC</td>
<td>AES</td>
<td>AES</td>
<td>AES</td>
</tr>
<tr>
<td>End-to-end latency</td>
<td>10m-100ms</td>
<td>&lt;10s</td>
<td>1-15s</td>
<td>10m-100ms</td>
<td>&lt;3ms</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Protocol Features</th>
<th>Wi-Fi 802.11ba</th>
<th>NB-IoT</th>
<th>LoRaWAN</th>
<th>Zigbee</th>
<th>Bluetooth</th>
<th>Ethernet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wakeup signal</strong></td>
<td>In progress</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>In progress</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Energy for network association &amp; sync</strong></td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Mid</td>
<td>Mid</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Practical num of leaf devices per gateway</strong></td>
<td>~100</td>
<td>~10,000</td>
<td>~100</td>
<td>50-100</td>
<td>20-30</td>
<td>~1,000</td>
</tr>
<tr>
<td><strong>Security features</strong></td>
<td>WPA</td>
<td>SNOW 3G</td>
<td>AES</td>
<td>AES</td>
<td>AES</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>AES</td>
<td>AES</td>
<td>AES</td>
<td>AES</td>
<td></td>
</tr>
<tr>
<td><strong>Secure wakeup</strong></td>
<td>In progress</td>
<td>Addressable but no encryption</td>
<td>N/A</td>
<td>N/A</td>
<td>In progress</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>End-to-end latency</strong></td>
<td>10m-100ms</td>
<td>&lt;10s</td>
<td>1-16s</td>
<td>10m-100ms</td>
<td>&lt;3ms</td>
<td>&lt;1s</td>
</tr>
</tbody>
</table>

- **Wi-Fi 802.11ba**
- **NB-IoT**
- **LoRaWAN**
- **Zigbee**
- **Bluetooth**
- **Ethernet**
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**

![Graph showing power for beacon synchronization over beacon interval. The graph indicates a significant reduction in power with the use of an Always-on ULP RX compared to a duty-cycled TRX with clock drift.](image-url)
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

**Everactive**

» 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

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
ULP Radios – Data Rate

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

Slope = 1
10x rate = 10x power
ULP Radios – Operating Frequency

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
ULP Radios – Architecture

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
ULP Radios – Architecture

ULP RXs

Non-Coherent e.g. FSK, OOK, PPM, etc.

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
Standard-Compliant RXs

- BLE 1.1mW
- NB-IoT 20.2mW
- WLAN 11.6mW

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
Motivation – ULP RX Survey Since 2005

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
Motivation – ULP RX Survey Since 2005

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

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
Motivation – ULP RX Survey Since 2005

- Wireless standards
- Networking support
- ULP RX performance

http://www.eecs.umich.edu/wics/low_power_radio_survey.html
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
- MN
- RF ED
- BB gain
- Comparator
= Digital
- lowest power
- mid sensitivity
- bad selectivity
- no RSSI info

(b) ED-first with multi-bit ADC
- MN
- RF ED
- BB gain
- ADC
= Digital
- low power
- mid sensitivity
- mid selectivity
- RSSI

(c) LNA-first, tuned-RF
- MN
- RF LNA
- RF ED
- BB gain
- ADC
= Digital
- high power
- good sensitivity
- mid selectivity
- RSSI

(d) Mixer-first, uncertain-IF
- MN
- Mixer
- IF gain
- IF ED
- ADC
= Digital
- high power
- good selectivity
- RSSI
10µW to meet key ULP RX design targets

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

(a) ED-first with BB comparator
- lowest power
- mid sensitivity
- bad selectivity
- no RSSI info

(b) ED-first with multi-bit ADC
- low power
- mid sensitivity
- mid selectivity
- RSSI

(c) LNA-first, tuned-RF
- high power
- good sensitivity
- mid selectivity
- RSSI

(d) Mixer-first, uncertain-IF
- high power
- mid sensitivity
- good selectivity
- RSSI
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