Reaching 10 Years of Battery Life for Intelligent Industrial Internet
Introduction
Challenges

End Node (uW-mW)

Sensing a complex environment
- position/motion
- material composition
- pressure
- humidity
- temperature
- chemical environment
- biosensing
- current/power
- material composition
- occupancy
- proximity
- light

Harsh Wireless Environment

Security Under Constraints

Auto Configure, Auto Join, 0 maintenance

10 years life cycle

Distributed Intelligence

TI-SimpleLink SDK/TI-RTOS/
Micro apps

Network

HMI

MCU

Processor

Wired & Wireless Connectivity

Sensors

Analog Signal Chain

Power Management

Texas Instruments

Network
I3Mote Platform

I3: Intelligent Industrial Internet

Mote: small bit of substance, such as a fleck or particle (sensor)

SenseAnywhere:

• Programming Environment
  • Connected MCU: 128KB flash, 20KB SRAM, 48MHz CM3 w/ multi-protocol radio
  • Fusion MCU: 2MB flash, 256KB SRAM, 48MHz CM4 w/ high precision AFE

• MIMO Power Management with complementary Energy Harvesting

• Multi-point, Multi-Modality Sensing: Temp, Humidity, Pressure, Ambient, Accelerometer

• Unique differentiated Ips

• 10 years battery life
**Pilots**

Factory Remote Monitoring

800 pumps/floor, 172x49 m², 10 sensors/pump, 1-10s update, 1TB/y

Motor predictive maintenance

Vrms as indication of vibration, 2kS/s, 100us sync, no wired power supply, no EH due to discharge

High-Speed Rail In-Car WSN

>50 sensos/car, GW install env., sensor types: temp, humidity, strain, current/voltage, 10-100KBps, RTD=1s, 99.999%
Path to reach 10 years battery life
Path to 10-years Battery Life

Step 1: Lowest Power and Robust Protocol (robust = low power)
  – Frequency Diversity: Channel Hopping
  – Time Diversity: Time-slotted contention free scheduling
  – Power Diversity: Tx Power
  – Space Diversity: Freq re-use, mesh

Step 2: Minimize radio wake-up overhead for duty cycled application (including wakeup radio use case)

Step 3: Improve power management efficiency

Step 4: Optimize sensor data usage (embedded analytics) and reduce radio duty cycle: 10s \(\rightarrow\) 10m

Step 5: Optimize network topology through smart Gateway

Step 6: Leverage ambient energy harvesting (if applicable)

<table>
<thead>
<tr>
<th>Sub-systems</th>
<th>Active (µA)</th>
<th>Sleep (µA)</th>
<th>Total (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectivity</td>
<td>TX: 17.68</td>
<td>2.49</td>
<td>75.96</td>
</tr>
<tr>
<td></td>
<td>RX: 55.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CPU: 0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Sensors</td>
<td>9.83</td>
<td>9.41</td>
<td>19.24</td>
</tr>
<tr>
<td>MCU Processing</td>
<td>0 (no MIPS)</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>PM</td>
<td>1.63</td>
<td>0</td>
<td>1.63</td>
</tr>
<tr>
<td>System Total</td>
<td>84.93</td>
<td>11.94</td>
<td>96.87</td>
</tr>
</tbody>
</table>
Step 1: Lowest Power and Robust Protocol
IoT Connectivity Landscape

- IoT wireless connectivity – the last mile
- Requirements:
  - Robust, low power, secure, easy to use
Time Slotted Channel Hopping

- IEEE 802.15.4e TSCH MAC
- Assigned slot: a channel offset and time
- Slotframes repeat continuously
- Each slot has a unique, globally known slot number

- 16 channel offsets
  - e.g. 33 time slots (330ms)
- WiFi – Channel 11
- one slotframe
- beacon
- shared slot
- e.g. 33 time slots (330ms)
Robustness Test – Quantification in 2.4 GHz

- Interference: Two Wi-Fi nodes in channel 1-4
  - 1470B UDP Traffic generated by jperf
  - Variable rates

- 15.4 traffic: 70B/8sec
  - ZigBee operates in channel 11
  - Uses channel hopping from chan 11 to chan 26

Channel hopping gives ~4dB gain over ZigBee/WLAN-1
Step 2: Reduce Radio Wake-up Overhead
Ultra low power & Fast Wake up – BAW MEMS Clock

- **Duty Cycled App**
  - wakeup time reduced from 500uS to 5uS
  - Duty cycle 1second (I3Mote with 6TiSCH)
  - Fig 1

- **Duty Cycled Sensors saving:**
  - HDC1080 humidity+temp sensor on I3Mote
  - wake up time reduced from 2.5ms to 0.1ms
  - Power saving: 15% - 39% (Fig 2)
Ultra Low Power and Fast Wake-up - BAW

- For radio TX and RX the system operation consists of Wake-up, “Radio Operation”, “Power Down”, and “Sleep”
- Wake-up time consumes significant time/current
- It is important to reduce the wake-up time to reduce the power consumption
- How can we optimize BAW (Bulk Acoustic Wave)
- BAW Definition: a crystal-free high-frequency (~2-3GHz), piezoelectric MEMS resonator technology targeting for high performance timing and frequency filtering applications.
- Timing Applications: Crystal replacements, oscillators, jitter cleaners, clock integration

System-in-Package Integration

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Step 3: Improve power management efficiency
Multiple Input, Multiple Output Power Management

**Energy Sources**

- USB
- Primary Cell
- Energy Harvesting
  - Solar
  - TEG
  - Vibration
  - RF
  - Electro-magnetic
- 4-20mA Loop

**Energy Storage**

- Cap/Supercap
- Rechargeable cell

**Power Management**

**Loads**

- Actuators
- Sensors
- Analog interfaces
- Drivers
- Processors
- RF Communications
- Wireline Comms
Improve Power Management Efficiency

About 60% of total power in sleep mode is consumed by analog power management functions.

Light load efficiency in low load current down to mA.
## Requirements for New Power Module

<table>
<thead>
<tr>
<th>Features</th>
<th>Target</th>
<th>Now</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power efficiency</td>
<td>&gt; 90%</td>
<td>~75 %</td>
</tr>
<tr>
<td>Integration</td>
<td>High (single chip)</td>
<td>Low (4 chips)</td>
</tr>
<tr>
<td>Ultra low-power metering</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Iq (Quiescent Current)</td>
<td>&lt; 100 nA</td>
<td>1.5 uA</td>
</tr>
<tr>
<td>Reverse voltage protection</td>
<td>Internal</td>
<td>External diode (reduces the efficiency)</td>
</tr>
<tr>
<td>Number of required external inductors</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Automatic power source detection</td>
<td>Yes (with the specific power ordering)</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Step 4: Optimize Sensor Data Usage (Embedded Analytics) and Reduce Radio Duty Cycle
Motivation of Data Analytics: Remote Monitoring

- A factory has 1000 pumps + equipment for monitoring on the factory floor
- More than 10 different kinds of sensor data monitored needs to be read every 1-10s
- In one year, total over-the-air data size is about \( \sim 1 \text{ TB} \), which consumes \( \sim 1.2 \text{ MJ} \) system energy
- \( \sim 1\% \) of 1 TB carries “useful” info
  - Energy consumption number can be reduced
  - Supported number of nodes can be increased by upto \( \sim 100x \)

- **Send necessary information from the sensor nodes to the central controller**
Data Duty Cycle Reduction Concept
Data Duty Cycle Reduction Concept

- **IP-based Industrial 4.0 Gateway**
  - **IP-based Industrial real-time wireless networks**
  - Environment sensing

  Compressed data w/ low duty cycling

  Data Decompression Module

  Compressed data w/ low duty cycling

  IBM Bluemix
  IBM Watson IoT
  Other Cloud Services

  Mobile Alerting
  Real-Time Visualization

  Advanced Analytics

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Data Compression

- Slowly varying data example:
  - Temp, humidity, pressure ... data duty cycle of read/10s can be reduced to ~20 mins with compression recovery accuracy of 99.5-99.9%
- Data recipient (GW) needs to obtain data variation pattern over time of 1% of the original duty cycle

Data Compression Performance

<table>
<thead>
<tr>
<th>Sensor Data</th>
<th>Compression ratio (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity</td>
<td>99.9</td>
<td>99.5</td>
</tr>
<tr>
<td>Temperature (Ambient)</td>
<td>99.9</td>
<td>99.9</td>
</tr>
<tr>
<td>Vibration (1 Hz signal)</td>
<td>99.9</td>
<td>99.7</td>
</tr>
<tr>
<td>Vibration (1 kHz signal)</td>
<td>99</td>
<td>99.8</td>
</tr>
<tr>
<td>Pressure</td>
<td>99.9</td>
<td>99.95</td>
</tr>
<tr>
<td>Temperature (Oven, low frequency sine wave)</td>
<td>99.67</td>
<td>99.96</td>
</tr>
<tr>
<td>Temperature (Oven, high frequency sine wave)</td>
<td>99.3</td>
<td>99.97</td>
</tr>
<tr>
<td>Temperature (Oven, square wave)</td>
<td>99.25</td>
<td>99.9</td>
</tr>
</tbody>
</table>
Power saving through “Smart Sensing”

~2x current consumption reduction

Star topology

Mesh topology
Step 5: Optimize Network Topology through Smart Gateway
Step 6: Energy Harvesting
Application on I3Mote

- Rechargeable battery used as the secondary battery
  - Whenever the energy from the secondary battery is available, use the energy from it. Otherwise, use the energy from the primary battery
- Solar panel used to charge the secondary battery
Experiment Results (Under “Normal” Office Light Strength)

- Office light on during the day (~250 lux) and off during the night
- Average ambient light strength: 120 lux
- Average efficiency: 38.8%
- Battery life increase: 160%

Average EH Efficiency
Experiment Results (Location Close to Window)

- Node close to window
- Average ambient light strength: 319 lux
- Average efficiency: 100% ⇒ No battery required

![Graph showing EH efficiency and ambient light over time, with very sunny and very cloudy days indicated.]

Very sunny days 😊

Very cloudy days 😌
Network Topology

Conference rooms
Office and lab spaces
Nodes close to the windows (sunlight)
Dark area

Nodes close to the windows (sunlight)

Graphs showing light levels and efficiency.

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Summary

1. Power performance is one of the key challenges for WSN “motes”

2. A methodology proposed to reach 10 years battery life

<table>
<thead>
<tr>
<th>Protocol Description</th>
<th>AA Battery Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZigBee (Fully Functionally Device Mode)</td>
<td>4.4 years</td>
</tr>
<tr>
<td>TSCH</td>
<td>5.70 years</td>
</tr>
<tr>
<td>TSCH + fast wakeup</td>
<td>6.06 years</td>
</tr>
<tr>
<td>TSCH+ fast wakeup + improved PM with higher efficiency and low Iq</td>
<td>7.2 years</td>
</tr>
<tr>
<td>TSCH + fast wakeup + improved PM + smart sensing with higher efficiency and low Iq</td>
<td>13.12 years</td>
</tr>
</tbody>
</table>

3. It is a system wide optimization which contains
   - Ultra-Low-Power and Robust protocol
   - Fast wake-up clock and low leakage
   - Power management circuits efficiency
   - Smart sensing to reduce duty cycle of radio
   - Energy harvesting as complimentary power supply