Energy Harvesting for IoT Wireless Sensor Nodes

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A Diversified Mixed-Signal Company

- **Highly diversified**
  - No product line or customer more than 20% of revenue
  - More than 14,000 customers, top 10 include leaders in their respective markets
  - Penetrated across a range of end markets

- **Powerful mixed-signal differentiation**
  - Disruptive products that rapidly gain share in established markets

2012 Revenue: $563M

- Industrial/Auto
- Consumer
- Communications
Silicon Labs’ Mixed-Signal Platform

<table>
<thead>
<tr>
<th><strong>Standard CMOS Process Technology</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analog Design</strong></td>
</tr>
<tr>
<td>Analog to Digital Conversion</td>
</tr>
<tr>
<td>Digital to Analog Conversion</td>
</tr>
<tr>
<td>Frequency Synthesis</td>
</tr>
<tr>
<td>Amplifiers and Filters</td>
</tr>
<tr>
<td>RF Design</td>
</tr>
<tr>
<td><strong>Macro Blocks</strong></td>
</tr>
<tr>
<td>Receivers and Transmitters</td>
</tr>
<tr>
<td>Modulators and Demodulators</td>
</tr>
<tr>
<td>Microcontrollers and DSP</td>
</tr>
<tr>
<td>USB, Ethernet, CAN/LIN, I2C/I2S</td>
</tr>
<tr>
<td>Sensor Interfaces</td>
</tr>
<tr>
<td><strong>Digital Design</strong></td>
</tr>
<tr>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>Algorithm Design</td>
</tr>
<tr>
<td>Digital System Design</td>
</tr>
<tr>
<td>System Level Design</td>
</tr>
<tr>
<td>Embedded Software</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Programmable and Reusable Architectures</strong></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Access</strong></th>
<th><strong>Broadcast</strong></th>
<th><strong>MCU</strong></th>
<th><strong>Sensing</strong></th>
<th><strong>Timing</strong></th>
<th><strong>Wireless</strong></th>
<th><strong>Isolation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>ProSLIC® Modems</td>
<td>AM/FM Rx/Tx</td>
<td>Connectivity</td>
<td>Prox. Sense</td>
<td>Oscillators</td>
<td>Sub-GHz Rx</td>
<td>Isolators</td>
</tr>
<tr>
<td>PoE</td>
<td>TV Tuners</td>
<td>Low-Power</td>
<td>Ambient Sense</td>
<td>Clocks</td>
<td>Tx, TRx</td>
<td>Current Sense</td>
</tr>
<tr>
<td></td>
<td>TV Demods</td>
<td>Mixed-Signal</td>
<td>Touch Sense</td>
<td>DSPLL®</td>
<td>ZigBee SoC</td>
<td>Gate Drivers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RH Sense</td>
<td>Multi-Synth™</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diversified Product Portfolio
Where is the IoT Opportunity?

- **Sensors**
  - Energy Management, Security, Monitoring

- **Motors**
  - Preventative Maintenance, Performance monitoring

- **Medical Monitoring**
  - Chronic Disease Management, On-body Wellness tracking

- **Asset/Goods Tracking**
  - Hospital Equipment, RFID “from a distance”

- **The Previously Unconnected**
  - Streetlights, Traffic Signs/Lights, Parking Meters, Vending Machines
Modern designs need a lot more software components

Many IoT MCU applications need over 64KB program memory
- Need efficient memory architecture, no paging

Low active power while processing
- To minimise drain on available power

8-bit/16-bit microcontroller might not be suitable
- Longer execution times leads to higher overall power consumption
Emerging Energy Harvesting Applications

- Wireless sensor nodes
- Industrial control systems
- Home and building automation
- Infrastructure sensing systems
- Security systems
- Agricultural monitoring systems
- Asset tracking
- Tire pressure monitoring (automotive)
When Does Energy Harvesting Make Sense?

When would it make sense to use an energy harvesting system instead of conventional batteries?

- Energy harvesting source is available
- Application is difficult to install
- Application would be difficult to service
- Wiring costs would be cost-prohibitive
- There are numerous devices
Energy is Everywhere

LIGHT

HEAT

MOTION

RF
Energy Harvesting Sources

- **RF**
  - Up to 0.1 uW/cm²
  - (1 mW/cm²)

- **Vibration**
  - Up to 1,000 uW/cm²
  - (10 mW/cm²)

- **Thermal**
  - Up to 10,000 uW/cm²
  - (100 mW/cm²)

- **Photovoltaic**
  - Up to 100,000 uW/cm²
  - (1000 mW/cm²)

Harvested Power Potential
Wireless sensor nodes are used to monitor machines that are hard to access.

Such systems are common in factories and industrial plants.
- ‘Run to failure’ is common today and downtime can be expensive.

Energy can be harvested from the vibration or heat of the machines.
Home Security Application

- Solar powered window / glass break detectors trigger an alarm when they detect sound (or shockwave) caused by glass breaking.
- Sophisticated sensor techniques using acoustic and shock-based technology provide resistance to false alarms.
- Solar power is advantageous as battery replacement can be inconvenient.
  - Also appropriate for commercial buildings, schools, hospitals, etc.
Infrastructure Sensing Application

- Structural integrity sensors are often located in places where it is difficult to access for changing batteries
- Wireless sensor nodes can be powered by solar, vibration or RF energy
Energy Harvesting Ecosystem

- Energy Harvester
- Sensors
- Signal Conditioning
- Low Power MCU
- Energy Storage & Power Mgmt
- Battery (optional)
- Low Power Wireless
- Light Thermal Vibration RF
- Accelerometers Pressure Temperature Environmental
MCU and Wireless Design Challenges

- Must operate with extremely low standby current
  - This will maximize the potential of the energy harvesting circuit

- Must consume lowest possible amount of power when active

- Must be able to turn on and off extremely quickly
  - This minimizes the amount of wasted power during these transition states

- Must offer analog capabilities to interface with sensors and take measurements

- Must be able to operate at extremely low voltage levels
EFM32 – Perfect for more demanding applications

- Compatible MCU’s from 4K to 1MB of on board flash
- Industry leading low power performance
- Highly flexible LESENSE peripheral for interfacing with sensors
Si446x – Next Generation EZRadioPRO®

**Features**
- Frequency bands from 119 to 1050 MHz
  - Si4464: 119-960 MHz
  - Si4460/1/3: 142-175, 284-350, 425-525, 850-1050 MHz
- Up to +20dBm output power
- -126dBm sensitivity (GFSK @ 500bps)
- Antenna diversity
- (G)FSK / 4(G)FSK / (G)MSK / OOK / ASK modulation
- Low current consumption
  - Standby Current = 50nA
  - Tx Active Current = 85mA (@+20dBm)
  - Rx Active Current = 10mA
- Max Data Rate = 1Mbps
- Advanced modem features

**Benefits**
- Low current consumption (long battery life)
- High sensitivity (long range)
- High output power (long range)
- Small size, low external BOM
Which RF Software Stack to use?

- Power budget available for RF transmission?
- Direct connection to Internet?
- Proprietary link into a data collector?
EFM32 – Ultra Low Power MCU

CPU and Memory
- ARM Cortex-M4 processor
- Flash Program Memory
- RAM Memory
- Debug Interface
- Embedded Trace Macrocell
- DMA

Clock Management
- High Freq Crystal Osc
- Low Freq Crystal Osc
- Ultra Low Freq RC Osc
- Low Freq RC Osc
- Auxiliary RC Osc

Energy Management
- Voltage Regulator
- Brown-out Detector
- Power-on Reset
- Back-up Power Domain

Serial Interfaces
- USART
- UART
- Low Energy UART
- I2C
- USB

I/O Ports
- External Bus Interface
- TFT Driver
- General Purpose I/O
- External Interrupt
- Pin Reset
- GPIO Wake-up
- Backup RTC

Timers and Triggers
- Timer/Counter
- Low Energy Sensor IF
- Low Energy Timer
- Real Time Counter
- Pulse Counter
- Watchdog Timer
- Backup RTC

Analog Modules
- ADC
- DAC
- LCD Controller
- Operational Amplifier
- Analog Comparator

Security
- AES Accelerator

Available down to:
- EM0 (Run Mode)
- EM1 (Sleep)
- EM2 (Deep Sleep)
- EM3 (Stop Mode)
- EM4 (Shutoff Mode)
**Energy Efficient Processing**

- Very low active power consumption
  - $\mu$A/MHz @3V @1 MHz: 210
  - $\mu$A/MHz @3V @25 MHz: 150
  - $\mu$A/MHz @3V @32 MHz: 150

- Reduced processing time
  - Cortex-M3 DMIPS/MHz: 1.25 @25 MHz

- Very fast wake-up time
  - Wake-up time from sleep modes: 2 $\mu$s

- Energy Efficient Processing
  - VDD=3V
  - Required area in cm$^2$ (direct drive)
    - **Active Mode**
      - Energy Mode EM0 (1MHz): 0.63 mW, 0.0063 Solar, 0.063 Thermal, 0.63 Piezo
      - Energy Mode EM0 (32MHz): 14.4 mW, 0.14 Solar, 1.44 Thermal, 14.4 Piezo
Benefits of local Digital Signal Processing

- **Example: Kalmann-Filter** (e.g. for noise detection and elimination in sensor data)

- 10x10 matrix calculation with floating point (f32) and fix point operations (q15) on ARM Cortex M3 vs. M4F

- 4x better energy consumption with ARM Cortex M4F vs. M3
  Example: average current consumption was reduced from 550 µA to 170 µA (Wonder Gecko)
Energy Efficient Peripherals

Well architectured Energy Modes

- EM0 “Run Mode”: 150 µA/MHz
- EM1 “Sleep Mode”: 45 µA/MHz
- EM2 “Deep Sleep Mode”: 900 nA
  RTC, Brown-Out Detection, RAM and CPU retained

Ultra energy efficient peripherals

- Analog to Digital Converter
  12-bit @ 1 MSamples/s: 350 µA
  6-bit @ 1 kSamples/s: 500 nA

- Low Energy UART
  Full UART with 32 kHz clock
  150 nA @ 9600 baud/s

Low Energy Sensor Interface

- Autonomous sensor monitoring in deep sleep
- Up to 16 sensors simultaneously
- Highly configurable
  Resistive, Capacitive, Inductive

<table>
<thead>
<tr>
<th>Function in Deep Sleep Mode</th>
<th>VDD=3V</th>
<th>Required area in mm² (direct drive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 4x40 LCD Display</td>
<td>4.35</td>
<td>0.00435 0.0435 0.435</td>
</tr>
<tr>
<td>Communicate with 9000Baud/s</td>
<td>3.15</td>
<td>0.00315 0.0315 0.315</td>
</tr>
<tr>
<td>A/D conversion (12Bit,10ksps,int ref)</td>
<td>384</td>
<td>0.384 3.84 38.4</td>
</tr>
</tbody>
</table>

RTC + 512-byte backup memory : 400 nA
LESENSE – Low Energy Sensor Interface

Analog events
Capacitive, inductive or resistive sensors

Generic MCU
Wake-up periodically to detect the events
LESENSE – Low Energy Sensor Interface

**Analog events**
Capacitive, inductive or resistive sensors

**Generic MCU**
Wake-up periodically to detect the events

**Gecko MCU**
Wake-up only on the events
Analog events
Capacitive, inductive or resistive sensors

Generic MCU
Wake-up periodically to detect the events

Gecko MCU
Wake-up only on the events

Gecko MCU
Conditional wake-up (e.g. on every 2nd event)
Example 1: Capacitive Measurement

<2 μA
Example 2: Resistive/General Measurement

- EFM32
- CPU
- LESEN SE
- Input
- Sensor
- Power supply

Sample Sample Sample

ACMP

<1.5 µA
Example 3: Inductive Measurement

<2 μA

No metal

Metal
Example 3: Counting propulsions in Deep Sleep

EFM32

LESENS

CH0

CH1

<1.5 μA

Flow
LESENSE Demo
Low Power ADC strategies on EFM32

Three possible approaches:

1. Standard approach, ADC + PRS + DMA
   - Average: 165 µA @ 1 ksamples/s
   - 350 µA @ 32 ksamples/s

2. New approach, EM2 + interrupt
   - Average: 60 µA @ 1 ksamples/s
   - 32 ksamples/s not possible

3. Optimized new approach, EM2 + wait for event, no interrupt latency
   - Average: 20 µA @ 1 ksamples/s
   - 550 µA @ 32 ksamples/s
Low Power ADC strategies on EFM32

Optimized approach:
- 20 kHz sample rate
- Break even

Interrupt approach:
- 4 kHz sample rate
- Break even

12Bit @ 1ksps: 14µA

See Energy Silicon Labs Application Note AN0021
Energy Efficient Signal Processing/Capture

- Signal monitoring can be realized at about 1.5µA
- Signal acquisition is possible from 14µA (12Bit, 1ksps) to maximum 350µA (12Bit, 1Mmps)
- Integrated DSP command set helps applications with digital signal processing functions like FFT or Kalman-Filter decreasing their average current consumption to about 100µA

Energy consumption for signal processing can be reduced to:

1. Gain battery life times up to 4x higher or
2. Avoid using batteries at all (energy harvesting)
Energy Harvesting Kit

- Energy Harvesting Experiments made easy!
- Uses Wonder Geko Starter Kit and Energy Harvesting Add-on
  - Piezo
  - Diode
  - Solar
  - TEG
EFM32 + EZRadioPro IoT Sensor Node

- Under Development Now!

- Reference Implementation
  - Wireless Sensor Node

- Small Form Factor
  - 25 x 45 mm

- Expansion Headers
  - ADC connected to headers

- LEDs + Buttons
  - Simple application function built in

- RF Stack ready to use
  - EZMacPro
  - WMBus (Steinbus)
There is a growing interest in energy harvesting solutions
- Fuelled in part by the IoT segment

Silicon Labs has a complete reference design for wireless sensor nodes including networking software, RF hardware design and USB interface

The Silicon Labs solutions are the lowest power implementation on the market
- 8-bit Wireless MCU Single Chip
- 32-bit MCU + RF Two Chip
Silicon Labs Energy Harvesting

www.silabs.com/EHRD

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