Indoor battery-less temperature and humidity sensor for Bluetooth Low Energy
(Presented at the Wireless Congress Conference
Munich, 9th November 2011)

Dipl. Ing. Urs Beerli

Prof. Dr. Marcel Meli

Contact: Marcel.meli@zhaw.ch
Outline

- A short presentation of our activities in low power wireless
- Introduction and issues
- Hardware and software
- Tests and results
- Conclusions
- Questions
Our activities

- Institute of Embedded Systems, Winterthur, Switzerland
  - Part of Zurich University of Applied Sciences
- Involved in teaching, applied research projects
  - Wired: Industrial Real Time Communication (Ethernet, 1588...)
  - Wireless: WPAN, RFID, UWB, ...
  - Energy harvesting, very Low power applications
- Examples of Low power developments:
  - Passive, Intelligent RFID Tag
    - Battery-less: powered only by the RFID reader
    - Uses a 32-Bit microcontroller to emulate protocols
    - Successful emulation of LF, UHF, Gen2
    - Identification, sensor, security, ... (RFID sensor network)
    - Range of several meters
Our activities (New)

- Dynapic Wireless (Battery-less, wireless switch >10 million cycles)

Battery-less, wireless piezo-switch (patent filed)

- > 10 million cycles

- Silent (no unwanted clicks), thin, flat, fits on many surfaces
Introduction and motivation

- The installation and comfortable use of wireless nodes is dependant on the design of low power wireless systems.
  - This implies low power components and protocols, since they all contribute to energy consumption.

- One objective of low power design is to achieve energy autonomy for the device (systems) within an acceptable period of time.
  - Allow when possible the use of energy harvesting to power the wireless node
  - If EH not possible, allow the use of batteries
    - Reduce the frequency of battery exchange
    - If batteries, allow the use of small size batteries

- Components are important, but protocol design also plays an important role.

- In this presentation, we are especially interested in energy harvesting. We look at the new Ble protocol, and ask the question:
  - Is Ble good enough for energy harvesting? Are there limits? Where?
Introduction and motivation

• EH possible with ZigBee, EnOcean, ... etc. What about Ble?

• ZigBee: We have shown examples of wireless switches and examples of sensor powered by a small solar cell
  - ZigBee compatible frames are sent with sensor data or switch information (Demo in 2008 and 2010 at the European ZigBee Developer’s Conference)
    - The system works well. It has been improved (more about it tomorrow, during the ZigBee slot. We present an interesting improvement)

• Energy harvesting is possible with the Enocean protocol, and other proprietary protocols.

No Batteries, No maintenance
Introduction and motivation (what is Ble?)

• Some interesting aspects of Ble
  • A low power addition to the already well established Bluetooth
  • Very good base, thanks to Bluetooth
    ▪ BT is present in millions of devices (PC, phones, …)
    ▪ It is expected that the new variation (including support for Ble) will rapidly spread in phones and PCs, … etc
  • Several manufacturers of silicon. Comparable to 802.15.4
    ▪ Competition → cheap → better devices (also lower in power consumption)
  • Interesting technical aspects.
    ▪ 2.4 GHz ISM band. 40 channels (communicating parties can make a “rendez-vous” on a given channel. 3 channels dedicated for advertising
      ▪ Helps in “getting the message through” also in presence of interference
  • More about Ble in specialised sessions
  • But Is Ble good enough for Energy harvesting? Are there limits? Where?

• It is fair to ask oneself how Ble will perform with Energy Harvesting.
• This work is only a start. Lot is not covered
Design

- Choice of very simple case: monitoring non critical data in an office.
  - Sensors are T and RH devices, powered by EH (small solar cells)
  - A star configuration can easily be built, with battery-free sensors acting as slaves.
  - The host can be any device capable of scanning the channels and receiving data from the sensors.
  - In this application, data can be lost without big consequences
  - Nodes should be cheap and deliver useful data

Figure 4: Sensors and host
The main elements of the system should allow low power operation. They are shown below.

- Solar cell (as small as possible) delivering as little as 300 mv
- DC/DC converter to get the low voltage high enough for the electronics
- SHT21 T & RH sensor
- EM9301 Ble radio capable of running down to 0.8 volt
- EM6819 microcontroller capable of running down to 0.9 volt
- In this work we used a small capacitor to store the energy for 1 measurement and radio packet

As host, we used a TI Ble device (CC2540 Ble controller)
Design

• The main elements of the system.
  • EM9301 Ble controller capable of running down to 0.8 volt
    ▪ Direct connection to PCB antenna
    ▪ Optimised for low power
    ▪ 14.5 mA @ +4dBm
  • EM6819 Low power microcontroller
    ▪ Sub volt operation possible from flash
    ▪ 140\mu A @ 1 MIPS, 3volts

![Diagram of EM9301-based system]

Figure 2: EM9301-based system
Design

• The main elements of the system.
  • SHT21 T & RH sensor. Extremely small, fully calibrated T/RH sensor
    ▪ I2C Serial link for communication with host
    ▪ Low power. Consumes max of 300\(\mu\)A @ 3.6 volts while converting
    ▪ 0.4 \(\mu\)A in sleep mode
    ▪ RH max \(\rightarrow\) 12-bit, T \(\rightarrow\) max 14-bit (influences conversion time \(\rightarrow\) energy)
  • Indy2050 Solar cell
    ▪ good in office environment
    ▪ 35mm x 50mm

<table>
<thead>
<tr>
<th>Resolution</th>
<th>RH typ</th>
<th>RH max</th>
<th>T typ</th>
<th>T max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 bit</td>
<td></td>
<td></td>
<td>66</td>
<td>85</td>
<td>ms</td>
</tr>
<tr>
<td>13 bit</td>
<td></td>
<td></td>
<td>33</td>
<td>43</td>
<td>ms</td>
</tr>
<tr>
<td>12 Bit</td>
<td>22</td>
<td>29</td>
<td>17</td>
<td>43</td>
<td>ms</td>
</tr>
<tr>
<td>11 bit</td>
<td>12</td>
<td>15</td>
<td>11</td>
<td>22</td>
<td>ms</td>
</tr>
<tr>
<td>10 bit</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>11</td>
<td>ms</td>
</tr>
<tr>
<td>8 bit</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
</tbody>
</table>

Table 1: Measurement time against resolution
Frame format and contents

- Communication can occur
  - In connected mode $\rightarrow$ more energy needed
    - More data exchange for “agreement” between parties
  - In advertisement mode $\rightarrow$ less energy, data in Adv frame.

- Format of the frame used to send data
  - In case the Adv. frame with Data is used, the different fields are as shown below.

<table>
<thead>
<tr>
<th>Field</th>
<th>Lsb</th>
<th>msb</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL packet format</td>
<td>Preamble</td>
<td>Access address</td>
</tr>
<tr>
<td></td>
<td>(1 octet)</td>
<td>(4 octets)</td>
</tr>
<tr>
<td></td>
<td>PDU</td>
<td>CRC</td>
</tr>
<tr>
<td></td>
<td>(2 to 39 octets)</td>
<td>(3 octets)</td>
</tr>
<tr>
<td>Access address</td>
<td>1000111010001001101111011010110b (0x8E89BED6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(this is the access address of all adv. Packets)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Field</th>
<th>Lsb</th>
<th>msb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adv. PDU format</td>
<td>Header</td>
<td>Pload</td>
</tr>
<tr>
<td></td>
<td>(16-Bit)</td>
<td>(length in header)</td>
</tr>
<tr>
<td>Header of ADV PDU</td>
<td>PDU type</td>
<td>RFU</td>
</tr>
<tr>
<td></td>
<td>(4 bits)</td>
<td>(2 bits)</td>
</tr>
<tr>
<td></td>
<td>TxAdd</td>
<td>RxAdd</td>
</tr>
<tr>
<td></td>
<td>(1 bit)</td>
<td>(1 bit)</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>RFU</td>
</tr>
<tr>
<td></td>
<td>(6 bits)</td>
<td>(2 bits)</td>
</tr>
<tr>
<td>PDU type ADV_NONCONN_IND</td>
<td>0100 (b0 ... b3)</td>
<td></td>
</tr>
<tr>
<td>Payload ADV_NONCONN_IND</td>
<td>ADVA</td>
<td>ADV Data</td>
</tr>
<tr>
<td></td>
<td>(6 octets)</td>
<td>(0-31 octets)</td>
</tr>
</tbody>
</table>
Frame format and contents

- Format of the frame used to send data
  - When enough energy is accumulated, the system will start up. T and RH will be measured. Data will be processed, then transmitted.
  - Broadcasted data can be read by host, provided it is monitoring that channel at the time the data is sent.
  - 2 bytes are used to code temperature, and 2 bytes are used to code relative humidity.
  - 20 octets are enough.

<table>
<thead>
<tr>
<th>Format of frame used to send data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamble</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>1 octet</td>
</tr>
<tr>
<td>(0x8E89BED6)</td>
</tr>
</tbody>
</table>

- Software was written to be energy efficient
  - After start, radio initialised, sensors initialised
  - Sensor starts T conversion (micro sleeps)
  - Micro wakes up and read T data, starts RH measurement, sleeps
  - Micro wakes up, reads RH data, processing, loads data in radio, Tx order
Tests and results

• Several tests were carried out to evaluate various aspects of the system
  • The current profile of the system while processing and sending a typical frame was recorded and analysed.
  • The effect of the luminosity on the time interval between measurements was observed.

• Different solar cells were tried
  ▪ Sensors work also with very small cells

• The number of frames received (frames lost) was measured in a time range for 2 cases:
  ▪ Host works only on 1 channel
  ▪ Host scans all 3 Advertisement channels
## Tests and results

### Light mostly from Neon tubes

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Quantity</th>
<th>Architecture</th>
<th>Luminosity (Lux)</th>
<th>Time between 2 frames (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IXYS Triple Cell</td>
<td>4</td>
<td>Parallel</td>
<td>1000-1100</td>
<td>10.1-10.4</td>
</tr>
<tr>
<td>IXYS Single Cell</td>
<td>4</td>
<td>Series</td>
<td>1000-1100</td>
<td>9.1-9.4</td>
</tr>
<tr>
<td>IXYS Single Cell</td>
<td>1</td>
<td>-</td>
<td>1000-1100</td>
<td>15.9-16.3</td>
</tr>
<tr>
<td>G24i Indy2050</td>
<td>1</td>
<td>-</td>
<td>1000-1100</td>
<td>5.4</td>
</tr>
</tbody>
</table>

### Light mostly from the sun

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Quantity</th>
<th>Architecture</th>
<th>Luminosity (Lux)</th>
<th>Time between 2 successive frames (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IXYS Triple Cell</td>
<td>4</td>
<td>Parallel</td>
<td>2300-2500</td>
<td>0.98</td>
</tr>
<tr>
<td>IXYS Single Cell</td>
<td>4</td>
<td>Series</td>
<td>2300-2500</td>
<td>0.95</td>
</tr>
<tr>
<td>IXYS Single Cell</td>
<td>1</td>
<td>-</td>
<td>2300-2500</td>
<td>6-6.3</td>
</tr>
<tr>
<td>G24i Indy2050</td>
<td>1</td>
<td>-</td>
<td>2300-2500</td>
<td>1.8-2</td>
</tr>
</tbody>
</table>

Measurements during 169 Mins (2.8h), 1 frame sent every 11.3s. Adv on 1 channel

| Frames received by Sniffer on correct channel | 900 |
| Frames received by scanner (scanning 3 Adv channels) | 278 |

30.89% received frames

69.11% lost frames
Tests and results

- Data was sent to a TI Ble receiver (captured here in sniffer mode)
- Temperature and humidity data can be seen in AdvData Field

<table>
<thead>
<tr>
<th>P.rbr.</th>
<th>Time (us)</th>
<th>Channel</th>
<th>Access Address</th>
<th>Adv PDU Type</th>
<th>Adv PDU Header</th>
<th>AdvA</th>
<th>AdvData</th>
<th>CRC</th>
<th>RSSI (dBm)</th>
<th>FCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+0</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>+11162933</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>+30113242</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>+50083880</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>+7005755</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>+9949559</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>+9856517</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>+10469565</td>
<td>0x26</td>
<td>0xBE89BED6</td>
<td>ADV_NON_CONN_IND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tests and results

- The dynamic profile of the current shows how energy is used
  - Less than 150 uJ is enough to measure and send the data. Far from optimised.
Conclusions

• It is possible to power Ble (Bluetooth Low Energy) nodes with energy harvested from the surroundings.
  • A low-cost sensor node with temperature and humidity measurements has been build.
  • The node can be powered with a small solar cell designed for office environment.
  • Less than 150 μJ are needed to carry out precise measurements, process the results and send them to a host station.
  • Advertisement mode was used in other to limit the energy requirements
  • Working on different channels helps to improve the quality (reduce interference problems)
  • However, data packets can be lost if the host is serving another channel when they are sent → energy loss.
    ▪ Sending data on all 3 advertisement channels is possible also with a solar cell.
      → need to wait longer to collect enough energy + no guarantee that you get through.
  • A small and cheap solar cell is good enough for this type of application.
Thanks, more information

- Thanks to the following firms for their help and support.
  - Sensirion A.G. in Stäfa, Switzerland
  - EM Microelectronics SA in Marin, Switzerland
  - G24i in Wales
  - The Texas Instruments team in Switzerland

- For more information:
  - Marcel Da Silva, Bsc in Computing Sciences
  - Prof. Dr. Marcel Meli, Head of Wireless Systems Group

- Zurich University of Applied Sciences (ZHAW)
  Institute of Embedded Systems (InES)
  Technikumstr. 9
  CH-8401 Winterthur
  Phone: +41 58 934 75 25
Question time

??????
Our activities

- Wireless automation with different energy harvesting sources

  The sender can use different power sources
  Works with 802.15.4/Zigbee and other wireless protocols

The receiver controls a lamp

Electro-dynamic  Seebeck  Solar
Our activities

- 6WLoPAN-Ethernet Bridge

- Cortex M3 with 1588 PTP support
- USB
- CAN, JTAG
- PoE HW
- 802.15.4 module
- Ethernet 100 Mb/S