Open Standards based self-powered systems for sensing and control

UCHR Team, C-DAC, Bangalore
Agenda

- Feasibility
- Technical Needs
- Wireless standards – Open / Consortium / Proprietary – End devices connectivity
  - MAC and PHY
  - Higher Layers
- C-DAC’s development efforts
  - End Devices - WSN motes
  - Self-power – Solar, Vibration, Ambient RF, Thermal Gradient
  - Access from Internet – IEEE 802.15.4 gateway
Feasibility

- Low power devices
- Low power system design / IC design
- Memory technologies and integration
- MEMS and CMOS integration
- Advancements in technology
- Power converters
- Energy storage technologies
- Energy efficient wireless communication
Technical Requirements

- Low power / Low energy
- Self-powered autonomous devices
- RF range
- Reliability
- Availability
- Safety critical
- Life Critical
- Secured systems and devices
- Environment Friendly
Standards – End Devices Connectivity

- IEEE 802.15.4 – MAC and PHY – LR-WPAN
  - Zigbee, Tiny OS, Contiki OS etc.
  - 6LowPAN
  - Wireless HART, ISA 100-11a
  - IEEE 1451 – sensor data
- IEEE 8021.15.4e
- IEEE 802.15.4a
- IEEE 802.15.1 – Bluetooth
- Bluetooth Low Energy – BTLE
- IEEE 802.15.6 – LR-WBAN
- IEEE 802.11b/g/n
- ECMA 368 / 369
Wireless Technologies – Enabling IoT
Zigbee based end devices

- Zigbee - Network and Application layers defined over IEEE802.15.4 MAC & PHY
- The maximum data rate is 250Kbps
- High battery life for devices
- CSMA/CA based MAC
- Mesh networking with multi hop
- Beacon enabled / Non beacon
- Guaranteed time slots for deterministic transfer
ZigBee Basics

- Ad-hoc Self forming network
- Star or Peer-to-Peer operation.
- Mesh and cluster tree
- Support for low latency devices.
- Dynamic device addressing.
- Fully handshake oriented protocol for transfer reliability.
- Low power consumption.
- 16 channels in the 2.4GHz ISM band, 10 channels in the 915MHz ISM band and one channel in the European 868MHz band.
- Extremely low duty-cycle (<0.1%)
802.15.4: General Characteristics
ZigBee Applications Profiles

- **ZigBee Building Automation** (Efficient commercial spaces)
- **ZigBee Remote Control** (Advanced remote controls)
- **ZigBee Smart Energy** (Home energy savings)
- **Smart Energy Profile 2** (IP-based home energy management)
- **ZigBee Health Care** (Health and fitness monitoring)
- **ZigBee Home Automation** (Smart homes)
- **ZigBee Input Device** (Easy-to-use touchpads, mice, keyboards, wands)
- **ZigBee Light Link** (LED lighting control)
- **ZigBee Retail Services** (Smarter shopping)
- **ZigBee Telecom Services** (Value-added services)
- **ZigBee Network Devices** (Assist and expand ZigBee networks)
OS for end sensing and communicating devices

- Constrained resources
- High dynamics
- Inaccessible deployment
- Architecture – monolithic (Tiny OS) / modular (Contiki)
- Execution model – events (Tiny OS) / threads / hybrid (Contiki)
- Power management
- Scheduling – real time / non-realtime
- Reprogramming
- Concurrency handling
- Memory Management

Options – Tiny OS, Contiki
WPAN over IPv6 & 6LowPAN

- IPv6 packets over wireless PAN
- Header compression
- Auto configuration of networks
- Fragmentation
- IP routing
- Unicast, multicast and broadcast support
Wireless HART

n Simple
  q Self-organizing
  q Self healing
  n Mesh Network and Multiple access points

n Reliable
  q 99.9 reliable – end – to - end
  q IEEE 802.15.4 radio – DSSS
  q Channel hopping to avoid interference
  q Coexistence with other wireless networks
  q CCA and Blacklisting frequently used channels
  q Bandwidth and radio time optimization
  q Time synchronization for on time messaging –TDMA
  q Latency Controlled communication

n Secured – message level encryption, data integrity, device authentication, always-on

n Power Management
ISA 100 11a

- IEEE 802.15.4 radio
- Process Control
- Asset Tracking and Person Identification
- Trustworthy wireless
- Class 1 – Class 5
- Coexistence
  - Channel Hopping, CCA, blacklisting etc.
- Safety Critical, Control, Monitoring
IEEE 1451

- Instrumentation and Measurement
- Network Independent communication
- TEDS
- Memory Device for a transducer
  - Identification
  - Calibration
  - Data Correction
  - Vendors Related Info.
IEEE 802.15.4e Industrial Applications of WPAN

- Real-time requirements
- MAC is enhanced
- PHY – IEEE 802.15.4
- Deterministic & Synchronous Multi-channel Extension
- Time Slotted Channel Hopping
- Low Latency Deterministic Network
  - Less MAC overhead – low latency
  - Group ACK – efficient BW utilization
- Additional Frame Formats – Reduced overhead - MAC
- Low Energy – Latency Vs Energy consumption
  - IP centric – always ON, LL, multicast capable, Sync ACK
  - Coordinated sampled listening
  - Receiver Initiated Transmission
- Enhanced Beacon behavior – additional information
IEEE 802.15.4a — Location sensing and tracking

- Precision Ranging
- Location based routing and data collection
- Physical and MAC layer changes
  - Higher data rates, range
  - Resilient to interference
- Ultra low power and High throughput
- Two PHY — IR-UWB, CSS — ISM — un-licenced
- MAC — similar to 802.15.4
  - ALOHA
  - CSMA/CA
Bluetooth Low Energy

- Less power than BT and faster transfer of data – coin cell
  - Only 3 advertising channels as against 32
  - Only 37 data channels as against 79
  - raw bandwidth – 1Mbps
  - Star – bus topology
  - Link, authenticate, send data, terminate – 3ms
  - Small packet length and low Tx/Rx power
  - GFSK modulation index – 0.35 as against 0.5
    - Low RF radio power, increased range and robustness

- Single Mode and Dual mode devices
- Frequency Hopping to reduce interference
- Blacklisting crowded frequencies
- Ultra low peak, average, and idle power
- Not always connected state
- Low volume data and infrequent transfer
- Maximized standby time, fast connection
## Bluetooth Vs Bluetooth Low Energy

<table>
<thead>
<tr>
<th>Technical specification</th>
<th>Classic Bluetooth technology</th>
<th>Bluetooth low energy technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio frequency</td>
<td>2.4GHz</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>Distance/Range</td>
<td>~10-100 meters</td>
<td>~10-100 meters</td>
</tr>
<tr>
<td>Symbol rate</td>
<td>1-3Mbps</td>
<td>1Mbps</td>
</tr>
<tr>
<td>Application throughput</td>
<td>0.7 – 2.1Mbps</td>
<td>305kbps</td>
</tr>
<tr>
<td>Nodes/Active slaves</td>
<td>7</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Security</td>
<td>56 to 128 bit</td>
<td>128-bit AES</td>
</tr>
<tr>
<td>Robustness</td>
<td>FHSS</td>
<td>FHSS</td>
</tr>
<tr>
<td>Latency (from not connected state to send data)</td>
<td>100+ ms</td>
<td>&lt;6ms</td>
</tr>
<tr>
<td>Government regulation</td>
<td>Worldwide</td>
<td>Worldwide</td>
</tr>
<tr>
<td>Certification body</td>
<td>Bluetooth SIG</td>
<td>Bluetooth SIG</td>
</tr>
<tr>
<td>Voice capable</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Network topology</td>
<td>Point-to-point, scatternet</td>
<td>Point-to-point, star</td>
</tr>
<tr>
<td>Power consumption</td>
<td>1 (reference value)</td>
<td>0.01 to 0.5 (use case dependent)</td>
</tr>
<tr>
<td>Service discover</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Profile concept</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Primary use cases</td>
<td>Mobile phones, headsets, stereo audio, automotive, PCs etc.</td>
<td>Mobile phones, gaming, PCs, sport &amp; fitness, medical, automotive, industrial, automation, home electronics etc.</td>
</tr>
</tbody>
</table>
IEEE 802.15.6 – WBAN

- MAC and PHY
- Worldwide – ISM band – 79 channels, 1MHz BW
- MAC modes – CSMA/CA OR SLOTTED ALOHA
  - Beacon mode + super frame boundary
    - High Priority Traffic – Emergency alert – EAP1 and EAP 2
    - Regular Traffic – CAP, RAP 1 and RAP 2
    - Type 1 and Type 2 – Uplink, Downlink, bi-link, delayed bi-link allocation
  - Non Beacon mode + super frame boundary
    - Either Type I or Type II access phase only
  - Non beacon mode + without super frame boundary
    - Unscheduled Type II polled allocation by hub
IEEE 802.15.6 – WBAN

Medical Applications
- Vital signs monitoring
- Respiration monitoring
- Electroencephalogram (ECG)
- pH monitor
- Glucose
- Hearing aid

Non-medical Applications
- Video streaming
- Data file transfer
- Sports
- 3D video
- Forgotten things monitor

WBAN Applications
- Disability assistance
- Muscle tension monitor
- Blind
- Speech disability
- Artificial hands

- Entertainment applications
- Gaming
- Social networking
<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Packet Component</th>
<th>Modulation</th>
<th>Symbol Rate (Kbps)</th>
<th>Code Rate BCH (n,k)</th>
<th>Information Data Rate (Kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>402 - 405 MHz</td>
<td>PLCP Header</td>
<td>$\pi/2$-DBPSK</td>
<td>187.5</td>
<td>(31,19)</td>
<td>57.5</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/2$-DBPSK</td>
<td>187.5</td>
<td>(63,51)</td>
<td>75.9</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/4$-DQPSK</td>
<td>187.5</td>
<td>(63,51)</td>
<td>303.6</td>
</tr>
<tr>
<td>420 - 450 MHz</td>
<td>PLCP Header</td>
<td>GMSK</td>
<td>187.5</td>
<td>(31,19)</td>
<td>57.5</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>GMSK</td>
<td>187.5</td>
<td>(63,51)</td>
<td>75.9</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>GMSK</td>
<td>187.5</td>
<td>(63,51)</td>
<td>151.8</td>
</tr>
<tr>
<td>863 - 870 MHz</td>
<td>PLCP Header</td>
<td>$\pi/2$-DBPSK</td>
<td>250</td>
<td>(31,19)</td>
<td>76.6</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/2$-DBPSK</td>
<td>250</td>
<td>(63,51)</td>
<td>101.2</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/4$-DQPSK</td>
<td>250</td>
<td>(63,51)</td>
<td>404.8</td>
</tr>
<tr>
<td>902 - 928 MHz</td>
<td>PLCP Header</td>
<td>$\pi/2$-DBPSK</td>
<td>300</td>
<td>(31,19)</td>
<td>91.9</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/2$-DBPSK</td>
<td>300</td>
<td>(63,51)</td>
<td>121.4</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/4$-DQPSK</td>
<td>300</td>
<td>(63,51)</td>
<td>485.7</td>
</tr>
<tr>
<td>950 - 956 MHz</td>
<td>PLCP Header</td>
<td>$\pi/2$-DBPSK</td>
<td>250</td>
<td>(31,19)</td>
<td>76.6</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/2$-DBPSK</td>
<td>250</td>
<td>(63,51)</td>
<td>101.2</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/4$-DQPSK</td>
<td>250</td>
<td>(63,51)</td>
<td>404.8</td>
</tr>
<tr>
<td>2360-2400 MHz</td>
<td>PLCP Header</td>
<td>$\pi/2$-DBPSK</td>
<td>600</td>
<td>(31,19)</td>
<td>91.9</td>
</tr>
<tr>
<td>2400-2483.5 MHz</td>
<td>PLCP Header</td>
<td>$\pi/2$-DBPSK</td>
<td>600</td>
<td>(63,51)</td>
<td>121.4</td>
</tr>
<tr>
<td></td>
<td>PSDU</td>
<td>$\pi/2$-DBPSK</td>
<td>600</td>
<td>(63,51)</td>
<td>485.7</td>
</tr>
<tr>
<td><strong>Topology</strong></td>
<td>Star or star mesh hybrid, bidirectional link</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Setup Time</strong></td>
<td>Insertion/De-insertion $&lt; 3s$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Devices Number</strong></td>
<td>Typically 6, Up to 256</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data Rate</strong></td>
<td>$10Kb/s – 10Mb/s$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>$&gt; 3m$ with low data rate under IEEE Channel Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PER</strong></td>
<td>$&lt; 10%$ with a link success probability of $95%$ over all channel conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>$&lt; 125ms$ (medical), $&lt; 250ms$ (non medical)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Jitter</strong></td>
<td>$&lt; 50ms$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>$&lt; 1s$ for alarm, $&lt; 10ms$ for applications with feedback</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Power Consumption</strong></td>
<td>$&gt; 1$ year (1% LDC and $500mAh$ battery), $&gt; 9$ hour (always &quot;on&quot; and $50mAh$ battery)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coexistence (Intra system)</strong></td>
<td>10 BANs in a volume of $6 \times 6 \times 6$ meters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coexistence (Inter system)</strong></td>
<td>Not defined. Environment (WiFi, Bluetooth...)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IEEE 802.11 b/g/n

- Typically high power
- PHY - Revision
  - Not feasible – interoperability
- Low Power Device
  - Low power modes of device
  - Limit the no. of connections
  - non associated data transfer
  - Shorter preamble, slot times, SIFS etc.
  - Association only when data transfer
    - Non beacon modes
- Access point is always active
RF transmitter

- Transmitter startup time
- Energy efficient modulation schemes
- Radio Circuits power efficiency
- Power consumption – not a function of data rate
- Transient energy – sleep to active mode
- Bandwidth efficiency Vs power efficiency
C-DAC Development efforts
Wireless devices and systems

- Self-powered power aware Wireless Modules – IEEE 802.15.4
  - Ubimotes and Smartmotes
- Wireless IP network gateway for Zigbee
- Power Over Ethernet for Zigbee router / coordinator
- Self-powering of wireless modules – Energy Harvesting
  - Solar
  - Vibration
  - Ambient RF
  - Thermal gradient
  - Pressure / Motion (Linear / Rotary)
- Signal conditioning, data storage
## Energy Harvesting Techniques

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Characteristics</th>
<th>Efficiency</th>
<th>Harvested Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Outdoor Indoor</td>
<td>10~24%</td>
<td>100 mW/cm², 100 µW/cm²</td>
</tr>
<tr>
<td>Thermal</td>
<td>Human Industrial</td>
<td>~0.1%~3%</td>
<td>60 µW/cm², ~1-10 mW/cm²</td>
</tr>
<tr>
<td>Vibration</td>
<td>~Hz–human, ~kHz–machines</td>
<td>25~50%</td>
<td>~4 µW/cm³, ~800 µW/cm³</td>
</tr>
<tr>
<td>RF</td>
<td>GSM 900 MHz WiFi</td>
<td>~50%</td>
<td>0.1 µW/cm², 0.001 µW/cm²</td>
</tr>
</tbody>
</table>

Courtesy of Texas Instruments
Vibration Based Energy Harvesting

- Electromagnetic.
- Electrostatic.
- Piezo Electric.
Inductive.

- Power Results From Relative Motion of a conductor in Magnetic Field
- Typically Conductor will be a wound coil.
- Voltage on the coil is determined by Faraday's law.

Limitations.

- Produced voltage Depends on Vibration Frequency.
- Difficult to integrate this device with standard Microelectronics.
Electrostatic Power Conversion

- Capacitive.
  - Relative motion b/w two conductors separated by dielectric changes the energy stored b/w them.
  - Significant advantage is it can be integrated with standard Microelectronics.

- Limitations.
  - It requires a separate voltage source to initiate the conversion.
  - Mechanical limit tops must be provided.
Piezo Electric power Conversion`H.

- Piezo Electric Effect.
  - Piezoelectric materials produce an electric field when subjected to mechanical deformation.
  - As in Electrostatic method no separate voltage source is required.
  - Highest energy Density.

- Limitations.
  - Micro fabrication process is not compatible with standard CMOS process.
Piezoelectric Converter Design
Off-the-shelf energy processor

- Nanopower, High efficiency, Synchronous Buck converter.
- Uses a Hysteretic voltage Algorithm.
- Low quiescent current in no load and UVLO.
- Selectable output voltages.
DC/DC control method.

- Voltage Control Method.
- Current Control Method.
- Hysteretic Control Method.
DC-DC boost converter.

**BQ25504.**
- Suited well for Solar and Thermal Energy Harvesting.
- Along with LTC3588 can be used in Vibrations based energy Harvesting also.

**CBC915.**
- Use any type of Energy Harvesting transducer: Light, Vibration, Thermal, RF, etc
- EH Transducer to System Load Impedance matching
RF energy harvesting

Matching Network → RF-DC Converter → DC-DC Boost Converter → Battery Management → Battery
Detectors

Forward Characteristics

O/P Voltage Vs Input power
General Architecture of WSN based monitoring and control system

- Sensor Networks
- Ethernet
- GSM
- CDMA
- Gateway
Wireless Motes based on other standards

- **Wi-Fi mote**
  - High throughput for vision sensing

- **BTLE mote**
  - Mote based on IEEE802.15.4 and Bluetooth smart standard
  - For Body area network systems
Internet of “Things” – “Systems”

- Industrial Systems
- Transportation Systems
- Home and Building Systems
- Body Area Devices
- Systems for Agriculture
- Environmental Monitoring
- Power Systems control
- Asset Management and Tracking
**Wireless sensor network development kit (WSNDK1)**

- Ubimote – 2 Nos
- UbimoteHR – 2 Nos
- Smartmote – 2 Nos
- Smartmote C – 2 Nos
- Sensor boards – 2 Nos
- Data Acquisition Card – 2 Nos
- CC debugger – 1 No
- MSP430FET – 1 No

**WSNDK – MSP430**

- Smartmote – 2 Nos
- SmartmoteC – 2 Nos
- Sensor Board – 1 No
- Data Acquisition Card – 1 No
- MSP430FET – 1 No
WSNDK – CC2430
- Ubimote -- 2 Nos
- UbimoteHR – 2 Nos
- Sensor Board – 1 No
- Data Acquisition card – 1 No
- CC debugger – 1 No

Applications
- To encourage industry, universities and other educational institutions in India to participate in wireless sensor network research and applications development
Some of the experiments possible with WSNDK

- Embedded System Programming
  - Interfaces
  - Low Power modes of processor
- Energy Aware System design – Protocols, OS
- Sensor Network Applications
Thank you