Wireless Sensor Networks
Concepts, Protocols and Applications

Single Node Architecture Part 1
Goals of this chapter

• Survey the main components of the composition of a node for a wireless sensor network
  • Controller, sensors, batteries, radio modem
• Understand energy consumption aspects for these components
  • Putting into perspective different operational modes and what different energy/power consumption means for protocol design

• Note: The details of this chapter are quite specific to WSN; energy consumption principles carry over to MANET as well
Outline

- Sensor node architecture
- Energy supply (and consumption)
Node Characteristics

• Wide variety of node characteristics:
  • Volume < 1 ccm; weight < 100 g; cost < 1 $; power dissipation < 100 μW
    • Sensor Nodes for environment observation
  • Volume < 1 cmm; weight < 1 g; cost < 10 C; power dissipation ~ 0 W
    • Intelligent grains; smart dust
Smart Dust Node

Diagram showing various components of a smart dust node, including:
- Mirrors
- Interrogating Laser Beam
- Passive Transmitter with Corner-Cube Retroreflector
- Laser, Lens, Mirror
- Active Transmitter with Beam Steering
- Photodetector and Receiver
- Analog I/O, DSP, Control
- Power Capacitor
- Solar Cell
- Thick-Film Battery

Dimensions: 1-2mm
Smart Dust Node

- 16 mm³ solar-powered node
- Sensors:
  - Light sensor (CMOS ASIC)
  - Accelerometer (SOI)
- Optical receiver (downlink)
- Corner Cuber Retroreflector (passive reflector, uplink)
- Alternative uplink:
  - Laser diode with steerable mirrors
- Controller: FSM with 13 states
Sensor node architecture (minimum configuration)

- Main components of a WSN node
  - Controller
  - Communication device(s)
  - Sensors/actuators
  - Memory
  - Power supply
Sensor node architecture

- Additional components of a WSN node
  - Watchdog
    - Sensor controlled wake-up
    - Time controlled wake-up
    - Communication-controlled wake-up
  - Power Manager
    - Shut-down / reactivate power

![Sensor node architecture diagram]
Watchdog example (MSP430)

- How to reset mote remotely when it suffers from software bugs?

- Watchdog:
  Perform a controller system restart after a software problem occurs

- How it works?
  - Watchdog resets the MCU after a predefined period (e.g. 16 seconds) unless...
  - The running programs clears the active watchdog (starts the timer again)

- Application: our preamble-sampling based MAC protocols clears the watchdog on each „Listen for Transmissions”
Ad hoc node architecture

• Core: essentially the same
  • but more powerful

• And, much more additional equipment
  • Hard disk, display, keyboard, voice interface, camera, ...

• Essentially: a laptop-class device
Controller

Main options:
- Microcontroller – general purpose processor, optimized for embedded applications, low power consumption
  - Often the general purpose nature leads to inefficiencies wrt. Power consumption
- DSPs – optimized for signal processing tasks, not suitable here
  - In special cases part of the processing can be performed by embedded DSPs or specialized ALU instruction set (e.g. FFT)
- FPGAs – may be good for testing, even sufficient in some applications, as ASIC replacement e.g. if flexibility is a must (SMART-project)
- ASICs – only when peak performance is needed, no flexibility
  - The convergence between an ASIC and a specialized microcontroller for sensor node applications is sliding
- IHP run a project called “Tandem” with 2 processors/computing modules per node
Microcontrollers vs CPUs

• Why desktop-computer CPUs are not used in WSN? Because of excessive energy consumption

Energy-consumption and lifetime of desktop CPUs compared to MSP430, using standard 2xAA batteries (1.2V and 2700 mAh each)

<table>
<thead>
<tr>
<th>Processor</th>
<th>Energy consumption</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter Core i7</td>
<td>130 W</td>
<td>4 min</td>
</tr>
<tr>
<td>Intel 386</td>
<td>2 W</td>
<td>4 hours</td>
</tr>
<tr>
<td>MSP430 (active)</td>
<td>0.015 W</td>
<td>22.5 days</td>
</tr>
<tr>
<td>MSP430 (sleep)</td>
<td>0.000005 W</td>
<td>184 years</td>
</tr>
</tbody>
</table>

• Further, microcontrollers are tailored for embedded systems, and they include
  • Analog-to-digital converters included,
  • GPIO (interrupts, control of actuators, ...)
  • Common interfaces (SPI, UART, IIC)
Controller

• Example microcontrollers
  • Texas Instruments MSP430
    • 16-bit RISC core, up to 4 MHz, versions with 2-10 kbytes RAM, several DACs, RT clock, prices start at 0.49 US$
  • Atmel ATMega
    • 8-bit controller, larger memory than MSP430, slower

• FPGAs – may be good for testing before fabricating ASIC
  Example: TandemStack has a board with FPGA to perform complex math. operations (encryption / decryption)
FPGA for WSN example

- IHPStack provide many PCBs that can be stacked onto each other

- With the FPGA board, motes can carry out complex math. operations, mainly encryption/decryption, faster and more energy-efficient than on MCU
MSP430

- 16-bit microcontroller, CPU speed up to 8 MHz
- Memory:
  - Up to 60 kB Flash
  - UP to 10 kB SRAM
  - Direct Memory Access (DMA) Controller
- Features
  - UART / SPI
  - Up to 48 GPIO
  - 12-bit analog-to-digital converter
  - JTAG for debugging
  - 2x 16-bit timers (each with 7 capture/compare registers)
  - Watchdog timer
MSP430 F5xx (next gen)

- 16-bit microcontroller, CPU speed up to 25 MHz
- Memory:
  - Up to 512 kB Flash (20-bit address bus)
  - UP to 66 kB SRAM
  - Direct Memory Access (DMA) Controller
- Features
  - UART / SPI / I2C / IRDA / USB
  - Up to 87 GPIO
  - ADC and DAC
  - JTAG for debugging
  - 4x 16-bit timers (each with 7 capture/compare registers)
  - Watchdog timer
Secure Sensor Node

- MIPS Processor Core
  - I-Cache (16 kB)
  - D-SPRAM (8 kB)
- EJTAG (Debug)
- Memory Controller (AHB Slave)
  - Registers & Control
  - Check Sum
  - ECC
  - Internal SRAM (32 kB)
  - AES / MD5
- UART
- EPP
- Data I/O
- AMBA AHB Bus
  - Bridge (Master)
- CardBus
  - (Linux/Windows Host)
  - UART 0 (Master)
- CardBus (Master)
  - Bridge (Master)
  - UART
  - GPIO
- Data I/O Control (Master)
  - Packet Filter / Checksum
- CPU Control Bus
- SRAM
- Flash
- EJTAG (Debug)
Memory

• Different types of memory possible:
  • RAM: to store data and interim results
    • Registers for fast access to results in computations
    • NVR (Non Volatile Ram) to store results also during power down
    • Dynamic RAM to save space in embedded applications
  • ROM: to store programs
    • PROM: For programs and fixed configuration data
    • Flash: For programs and data
    • EEPROM: For programs and fixed configuration data
    • EPROM: see above
• Research today:
  • Have an “All in One” approach based on NVR with high speed read time and fast write time. Increase the number of programming cycles to last for the total lifetime of the node
  • Reduce power consumption by changing the power supply voltage dynamically
  • Store all state carrying information in NVM before power down
What Is MRAM?

- **Operation**
  - Cell is 1 MTJ + 1 Transistor
  - Electric current switches the magnetic polarity
  - Change in magnetic polarity sensed as resistance change

- **Attributes**
  - Non-Volatile
  - High Density
  - Non Destructive Read
  - Low Voltage & Low Power
  - Write = Read Speed, < 50 nsec
  - Unlimited R/W Endurance
  - Material compatibility with CMOS a key challenge
Sensors as such

- Main categories
  - Any energy radiated? Passive vs. active sensors
    - Has measurement method impact on the measured object?
  - Sense of direction? Omnidirectional?
  - Passive, omnidirectional
    - Examples: light, thermometer, microphones, hygrometer, ...
  - Passive, narrow-beam
    - Example: Camera
  - Active sensors (without impact on object)
    - Example: Radar
  - Active sensor (with impact)
    - Chemical sensors that analyze some molecules
- Important parameter: Area of coverage
  - Which region is adequately covered by a given sensor?
Sensor examples

Wind direction

- Movable flag points to the wind direction
- The sensor usually provides an analog output (e.g. 0-2 Volt) based on the „flag direction”
- Must be placed 10 meters above objects that affect the wind direction

- Example:
  - We placed such a sensor 2.5 m above ground on a glade surrounded by trees (about 30 meters away from the sensor)
  - Sensor readings every 15 mins provided rather random results

- Solutions:
  - install sensor on a mast above trees
  - Perform several readings, discard outliers, etc.
Dendrometer

- Measures changes in the circumference of plant stems
- The sensor changes its resistance when three trees grow/shrink
- In a short-term, a tree may shrink -> it depends on water absorption

What it is used for?

- Mainly to examine the impact of various factors (soil quality, rainfall, temperature) on tree growth
Sensor examples

Tensiometer

• Measures the soil water tension: suction that plants’ root must exert to extract water from the soil (= availability of water to a plant)

• Help to aid irrigation decisions
  • Important when the water requirements of plants are the highest ones (the need of daily measurements)

• Examination of the impact of water tension on tree’s growth
Sensor examples

Rainfall Sensor

- The bucket tips when it is full (e.g. 0.20 mm of rain/snow)
- When used with a MCU, it rises an interrupt
- Some models have an integrated heater for operation in cold temperatures
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Sensor examples

Water flow, total volume, level and velocity

- Measurement in open channels and man-made pipes

- Uses acoustic Doppler instrument with 5 beams
Actuators

• From the point of view of the sensor node actuators are seen via I/O operations. These output operations may:
  • Output digital signals (on/off, digital value etc.)
  • Output analog values
  • Receive response back from actuator

• Good design practice:
  • Never trust an actuator -> always pair actuator/sensor such that the actuator action can be independently observed and reported
Outline

- Sensor node architecture
- *Energy supply and consumption*
Energy supply of mobile/sensor nodes

- Goal: provide as much energy as possible at smallest cost/volume/weight/recharge time/longevity
  - In WSN, recharging may or may not be an option
- Options
  - Primary batteries – not rechargeable
  - Secondary batteries – rechargeable, only makes sense in combination with some form of energy harvesting (or recharge systems)
Energy supply of mobile/sensor nodes

- Requirements include
  - Low self-discharge
  - Long shelf live (similar to above)
  - Capacity under load (the method of loading can make a big difference on the accessible capacity)
    - Important for WSN? Depends on sensors & transceivers
  - Efficient recharging at low current
  - Good relaxation properties (seeming self-recharging)
  - Voltage stability (to avoid DC-DC conversion)
Battery examples

- Motes needs high-capacity, small, light and low-price batteries
- Preferred are batteries with high energy per volume rates:
  - Thus, primary batteries often preferred
- However, other metrics must be considered as well:
  - Zinc-air batteries have attractive energy density, but very short lifetime (in the order of weeks) due to self-discharge

<table>
<thead>
<tr>
<th>Primary batteries</th>
<th>Chemistry</th>
<th>Zinc-air</th>
<th>Lithium</th>
<th>Alkaline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (J/cm$^3$)</td>
<td></td>
<td>3780</td>
<td>2880</td>
<td>1200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary batteries</th>
<th>Chemistry</th>
<th>Lithium</th>
<th>NiMHd</th>
<th>NiCd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (J/cm$^3$)</td>
<td></td>
<td>1080</td>
<td>860</td>
<td>650</td>
</tr>
</tbody>
</table>
Battery examples

- Problem with batteries: Reduction of battery’s voltage as the capacity drops
- Example:
  - Tmote Sky needs voltage > 2.1 V, and > 2.7 V for programming
  - 2x AA eneloops: >90% of capacity @ > 2.1V
Battery examples

- Self-discharge problem

- Tmote sky with 2xAA and schedule-based MAC (DLDC-MAC)
  - Beacon period: 1 minute
  - Beacon length: 128 bytes (4.1 ms)
  - Beacon rx time: 11 ms (clock drift compensated)
  - Number of neighbours: 4

<table>
<thead>
<tr>
<th>Sleep mode</th>
<th>0.24</th>
<th>mAh / day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beacons (tx, rx)</td>
<td>0.49</td>
<td>mAh / day</td>
</tr>
<tr>
<td><strong>Self discharge</strong></td>
<td>0.82</td>
<td>mAh / day</td>
</tr>
<tr>
<td><strong>total:</strong></td>
<td><strong>1.55</strong></td>
<td><strong>mAh / day</strong></td>
</tr>
</tbody>
</table>

Lifetime: more than 3 years

Self discharge is the major „energy consumer”
• HeadWay 38120 (secondary battery)
  • Lithium iron phosphate (LiFePO$_4$) battery
  • Capacity: 10 000 mAh
  • Nominal Voltage: 3.2V
  • Energy density (LiFePO$_4$) 220 Wh/ L (792 J/cm$^3$)
  • Self-discharge rate <2% monthly
  • Very constant discharge voltage (close to 3.2V until exhausted)
Single node architecture, part 2

- Communication devices
- Energy consumption
- Energy scavenging
- Energy saving
Thanks for your attention!