CMU | Portugal
Information and Communication Technologies Institute

Wireless Sensor Networks
Chapter 2: Single node architecture

António Grilo

Courtesy: Holger Karl, UPB

Goals of this chapter

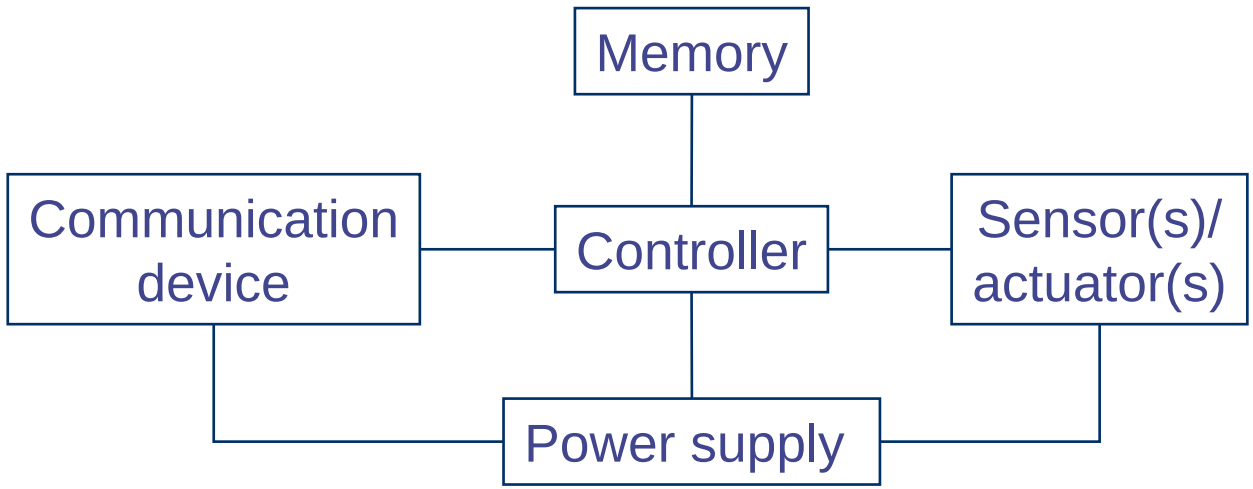
- Survey the main components of the composition of a node for a wireless sensor network
  - Controller, radio modem, sensors, batteries
- Understand energy consumption aspects for these components
  - Putting into perspective different operational modes and what different energy/power consumption means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

Outline

- ***Sensor node architecture***
- Energy supply and consumption
- Runtime environments for sensor nodes
- Case study: TinyOS

Sensor node architecture

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



Ad hoc node architecture

- Core: essentially the same
- But: 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
  - DSPs – optimized for signal processing tasks, not suitable here
  - FPGAs – may be good for testing
  - ASICs – only when peak performance is needed, no flexibility

- 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

Example Controllers

Comparison for various sensor architectures

	Btnode 3	mica2	mica2dot	micaz	telos A	tmote sky	EYES
Manufacturer	Art of Technology	Crossbow	Crossbow	Crossbow	Imote iv	Imote iv	Univ. of Twente
Microcontroller	Atmel Atmega 128L	Atmel Atmega 128L	Atmel Atmega 128L	Atmel Atmega 128L	Texas Instruments MSP430	Texas Instruments MSP430	Texas Instruments MSP430
Clock	7.37 MHz	7.37 MHz	4 MHz	7.37 MHz	8 MHz	7.37 MHz	5 MHz
RAM (KB)	64 + 180	4	4	4	2	10	2
ROM (KB)	128	128	128	128	60	48	60
Storage (KB)	4	512	512	512	256	1024	4
Radio	Chipcon CC1000 315/ 433/868/916 MHz 38.4 Kbauds	Chipcon CC1000 315/ 433/868/916 MHz 38.4 Kbauds	Chipcon CC1000 315/ 433/868/916 MHz 38.4 Kbauds	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	RFM TR1001868 MHz 57.6 Kbps
Max Range	150–300 m	150–300 m	150–300 m	75–100 m	75–100 m	75–100 m	75–100 m
Power	2 AA batteries	2 AA batteries	Coin cell	2 AA batteries	2 AA batteries	2 AA batteries	2 AA batteries
PC connector	PC-connected programming board	PC-connected programming board	PC-connected programming board	PC-connected programming board	USB	USB	Serial Port
OS	Nut/OS	TinyOS	TinyOS	TinyOS	TinyOS	TinyOS	PEEROS
Transducers	On acquisition board	On acquisition board	On acquisition board	On acquisition board	On board	On board	On acquisition board
Extras	+ Bluetooth						

In: P. Baronti et al., “Wireless sensor networks: A survey ...”

Communication device

- Which transmission medium?
  - Electromagnetic at radio frequencies? ✓
  - Electromagnetic, light?
  - Ultrasound?

- Radio transceivers transmit a bit- or byte stream as radio wave
  - Receive it, convert it back into bit-/byte stream

Transceiver characteristics

- Capabilities
  - Interface: bit, byte, packet level?
  - Supported frequency range?
    - Typically, somewhere in 433 MHz – 2.4 GHz, ISM band
  - Multiple channels?
  - Data rates?
  - Range?
- Energy characteristics
  - Power consumption to send/receive data?
  - Time and energy consumption to change between different states?
  - Transmission power control?
  - Power efficiency (which percentage of consumed power is radiated?)
- Radio performance
  - Modulation? (ASK, FSK, …?)
  - Noise figure? NF = SNR_I/SNR_O
  - Gain? (signal amplification)
  - Receiver sensitivity? (minimum S to achieve a given E_b/N_0)
  - Blocking performance (achieved BER in presence of frequency-offset interferer)
  - Out of band emissions
  - Carrier sensing & RSSI characteristics
  - Frequency stability (e.g., towards temperature changes)
  - Voltage range

Transceiver states

- Transceivers can be put into different operational ***states***, typically:
  - ***Transmit***
  - ***Receive***
  - ***Idle*** – ready to receive, but not doing so
    - Some functions in hardware can be switched off, reducing energy consumption a little
  - ***Sleep*** – significant parts of the transceiver are switched off
    - Not able to immediately receive something
    - ***Recovery time*** and ***startup energy*** to leave sleep state can be significant

- Research issue: Wakeup receivers – can be woken via radio when in sleep state (seeming contradiction!)

Example radio transceivers

- Almost boundless variety available
- Some examples
  - RFM TR1000 family
    - 916 or 868 MHz
    - 400 kHz bandwidth
    - Up to 115,2 kbps
    - On/off keying or ASK
    - Dynamically tuneable output power
    - Maximum power about 1.4 mW
    - Low power consumption
  - Chipcon CC1000
    - Range 300 to 1000 MHz, programmable in 250 Hz steps
    - FSK modulation
    - Provides RSSI
  - Chipcon CC 2400
    - Implements 802.15.4
    - 2.4 GHz, DSSS modem
    - 250 kbps
    - Higher power consumption than above transceivers
  - Infineon TDA 525x family
    - E.g., 5250: 868 MHz
    - ASK or FSK modulation
    - RSSI, highly efficient power amplifier
    - Intelligent power down, “self-polling” mechanism
    - Excellent blocking performance

Example radio transceivers for ad hoc networks

- Ad hoc networks: Usually, higher data rates are required
- Typical: IEEE 802.11 b/g/a is considered
  - Up to 54 MBit/s
  - Relatively long distance (100s of meters possible, typical 10s of meters at higher data rates)
  - Works reasonably well (but certainly not perfect) in mobile environments
  - Problem: expensive equipment, quite power hungry
  - WLAN technology is not cost-effective in WSN applications (more about this later on)

Wakeup WSN receivers

- Major energy problem: ***RECEIVING***
  - Idling and being ready to receive consumes considerable amounts of power
- When to switch on a receiver is not clear
  - Contention-based MAC protocols: Receiver is always on
  - TDMA-based MAC protocols: Synchronization overhead and limited scalability, somewhat inflexible (more of a problem in MANETs)
- Desirable: Receiver that can (only) check for incoming messages
  - When signal detected, wake up main receiver for actual reception
  - Ideally: ***Wakeup receiver*** can already process simple addresses
  - Not clear whether they can be actually built, however

Ultra-wideband communication

- Standard radio transceivers: Modulate a signal onto a carrier wave
  - Requires relatively small amount of bandwidth
- Alternative approach: Use a large bandwidth, do not modulate, simply emit a “burst” of power
  - Forms almost rectangular pulses
  - Pulses are very short
  - Information is encoded in the presence/absence of pulses
  - Requires tight time synchronization of receiver
  - Relatively short range (typically)
- Advantages
  - Pretty resilient to multi-path propagation
  - Very good ranging capabilities
  - Good wall penetration

Sensors as such

- Main categories
  - Any energy radiated? Passive vs. active sensors
  - Sense of direction? Omidirectional?

  - Passive, omnidirectional
    - Examples: light, thermometer, microphones, hygrometer, …
  - Passive, narrow-beam
    - Example: Camera, movement IR sensor
  - Active sensors
    - Example: Radar

- Important parameter: Area of coverage
  - Which region is adequately covered by a given sensor?

Outline

- Sensor node architecture
- ***Energy supply and consumption***
- Runtime environments for sensor nodes
- Case study: TinyOS

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
- Requirements include
  - Low self-discharge
  - Long shelf live
  - Capacity under load
  - Efficient recharging at low current
  - Good relaxation properties (seeming self-recharging)
  - Voltage stability (to avoid DC-DC conversion)

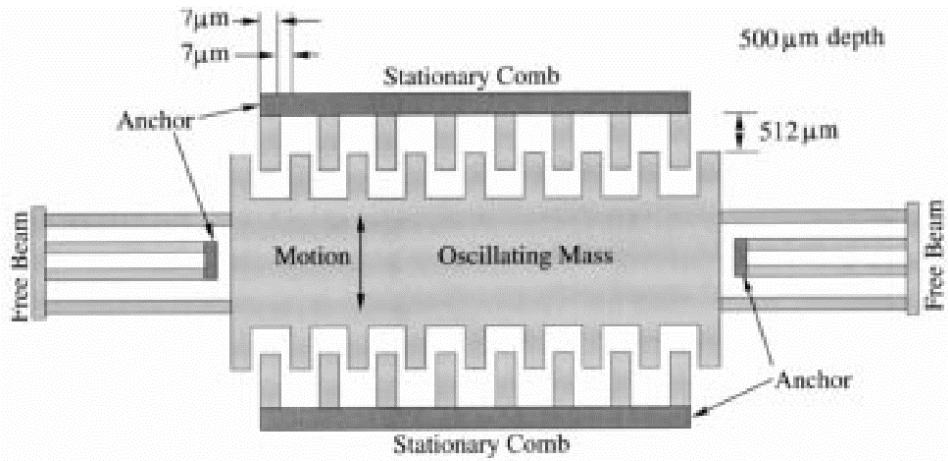
Battery examples

- Energy per volume (Joule per cubic centimeter):

Primary batteries			
Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm^3)	3780	2880	1200
Secondary batteries			
Chemistry	Lithium	NiMHd	NiCd
Energy (J/cm^3)	1080	860	650

Energy scavenging

- How to recharge a battery?
  - A laptop: easy, plug into wall socket in the evening
  - A sensor node? – Try to ***scavenge*** energy from environment
- Ambient energy sources
  - Light ! solar cells – between 10 μW/cm^2 and 15 mW/cm^2
  - Temperature gradients – 80 μ W/cm^2 @ 1 V from 5K difference
  - Vibrations – between 0.1 and 10000 μ W/cm^3
  - Pressure variation (piezo-electric) – 330 μ W/cm^2 from the heel of a shoe
  - Air/liquid flow (MEMS gas turbines)



Energy scavenging – overview

Energy source	Energy density
Batteries (zinc-air)	$1050 - 1560\,\mathrm{mWh/cm^3}$
Batteries (rechargable lithium)	$300\,\mathrm{mWh/cm^3}$ (at $3 - 4\,\mathrm{V}$)
Energy source	**Power density**
Solar (outdoors)	$15\,\mathrm{mW/cm^2}$ (direct sun)
	$0.15\,\mathrm{mW/cm^2}$ (cloudy day)
Solar (indoors)	$0.006\,\mathrm{mW/cm^2}$ (standard office desk)
	$0.57\,\mathrm{mW/cm^2}$ (< 60 W desk lamp)
Vibrations	$0.01 - 0.1\,\mathrm{mW/cm^3}$
Acoustic noise	$3 \cdot 10^{-6}\mathrm{mW/cm^2}$ at 75 Db
	$9,6 \cdot 10^{-4}\mathrm{mW/cm^2}$ at 100 Db
Passive human-powered systems	1.8 mW (shoe inserts)
Nuclear reaction	$80\,\mathrm{mW/cm^3}$, $10^6\,\mathrm{mWh/cm^3}$

Energy consumption

- A “back of the envelope” estimation

- Number of instructions
  - Energy per instruction: 1 nJ
  - Small battery (“smart dust”): 1 J = 1 Ws
  - Corresponds: 10^9 instructions!

- Lifetime
  - Or: Require a single day operational lifetime = 24*60*60 =86400 s
  - 1 Ws / 86400s ¼ ***11.5 μW*** as max. sustained power consumption!

- Not feasible!

Multiple power consumption modes

- Way out: Do not run sensor node at full operation all the time
  - If nothing to do, switch to ***power safe mode***
  - Question: When to throttle down? How to wake up again?

- Typical modes
  - Controller: Active, idle, sleep
  - Radio mode: Turn on/off transmitter/receiver, both

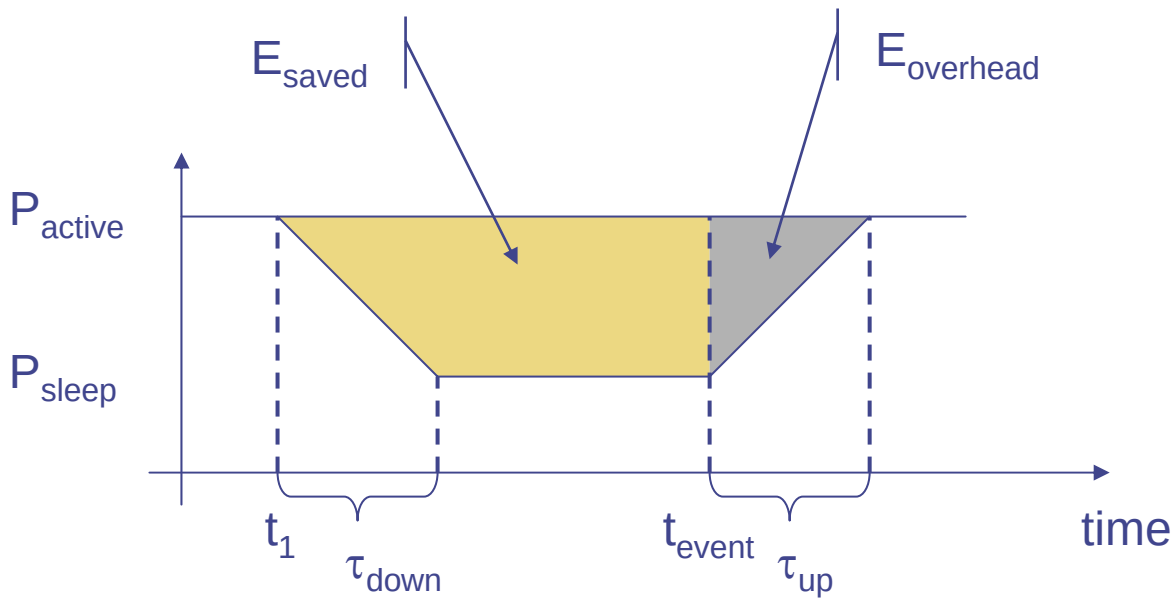
- Multiple modes possible, “deeper” sleep modes
  - Strongly depends on hardware
  - TI MSP 430, e.g.: four different sleep modes
  - Atmel ATMega: six different modes

Some energy consumption figures

- Microcontroller
  - TI MSP 430 (@ 1 MHz, 3V):
    - Fully operation 1.2 mW
    - Deepest sleep mode 0.3 μW – only woken up by external interrupts (not even timer is running any more)
  - Atmel ATMega
    - Operational mode: 15 mW active, 6 mW idle
    - Sleep mode: 75 μW

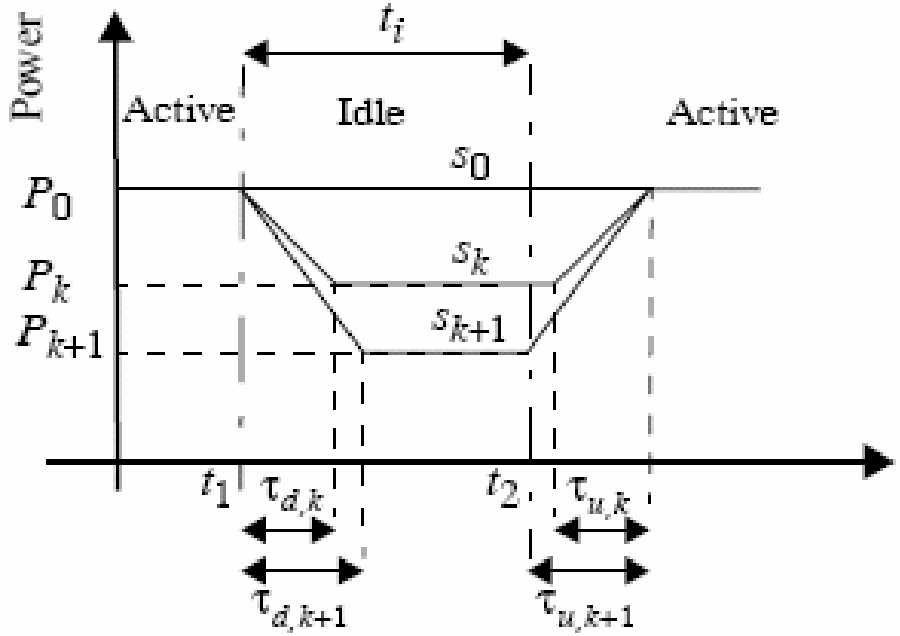
Switching between modes

- Simplest idea: Greedily switch to lower mode whenever possible
- Problem: Time and power consumption required to reach higher modes not negligible
  - Introduces overhead
  - Does switching pay off?
- Example: Event-triggered wake up from sleep mode
- Scheduling problem with uncertainty



Switching between modes: Does it pay off?

- A. Sinha et al., “Dynamic Power Management in Wireless Sensor Networks”



$$E_{save,k} = P_0 \cdot t_i - \left(\frac{P_0 + P_k}{2} \right) \cdot (\tau_{d,k} + \tau_{u,k}) - P_k \cdot (t_i - \tau_{d,k})$$

$$E_{save,k} > 0 \Leftrightarrow t_i > T_{th,k}$$

$$T_{th,k} = \frac{1}{2} \cdot \left[\tau_{d,k} + \left(\frac{P_0 + P_k}{P_0 - P_k} \right) \cdot \tau_{u,k} \right]$$

Alternative: Dynamic voltage scaling

- Switching modes complicated by uncertainty how long a sleep time is available
- Alternative: Low supply voltage & clock
  - ***Dynamic voltage scaling*** (DVS)
- Rationale:
  - Power consumption P depends on
    - Clock frequency
    - Square of supply voltage
    - $P / f V^2$
  - Lower clock allows lower supply voltage
  - Easy to switch to higher clock
  - But: execution takes longer

Memory power consumption

- Crucial part: FLASH memory
  - Power for RAM almost negligible
- FLASH writing/erasing is expensive
  - Example: FLASH on Mica motes
  - Reading: ¼ 1.1 nAh per byte
  - Writing: ¼ 83.3 nAh per byte

Transmitter power/energy consumption for n bits

- Amplifier power: $P_{amp} = \alpha_{amp} + \beta_{amp} P_{tx}$
  - P_{tx} ***radiated power***
  - α_{amp}, β_{amp} constants depending on model
  - Highest efficiency ($\eta = P_{tx} / P_{amp}$) at maximum output power
- In addition: transmitter electronics needs power P_{txElec}
- Time to transmit n bits: $n / (R * R_{code})$
  - R nominal data rate, R_{code} coding rate
- To leave sleep mode
  - Time T_{start}, average power P_{start}

$$! \; \mathbf{E_{tx} = T_{start} P_{start} + n / (R * R_{code}) (P_{txElec} + \alpha_{amp} + \beta_{amp} P_{tx})}$$

- Simplification: Modulation not considered

Receiver power/energy consumption for n bits

- Receiver also has startup costs
  - Time T_{start}, average power P_{start}
- Time for n bits is the same $n / (R * R_{code})$
- Receiver electronics needs P_{rxElec}
- Plus: energy to decode n bits $E_{decBits}$

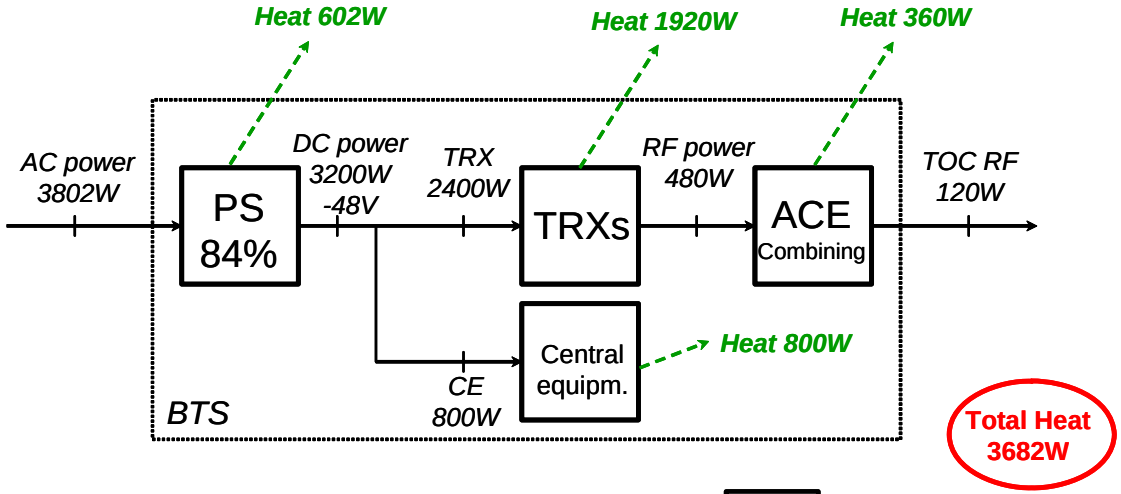
$$! E_{rx} = T_{start} P_{start} + n / (R * R_{code}) P_{rxElec} + E_{decBits}(R)$$

Some transceiver numbers

Symbol	Description	Example transceiver		
		μAMPS-1 [559]	WINS [670]	MEDUSA-II [670]
α_{amp}	Eq. (2.4)	174 mW	N/A	N/A
β_{amp}	Eq. (2.4)	5.0	8.9	7.43
P_{amp}	Amplifier pwr.	179 – 674 mW	N/A	N/A
P_{rxElec}	Reception pwr.	279 mW	368.3 mW	12.48 mW
P_{rxIdle}	Receive idle	N/A	344.2 mW	12.34 mW
P_{start}	Startup pwr.	58.7 mW	N/A	N/A
P_{txElec}	Transmit pwr.	151 mW	$\approx$ 386 mW	11.61 mW
R	Transmission rate	1 Mbps	100 kbps	OOK 30 kbps ASK 115.2 kbps
T_{start}	Startup time	466 μs	N/A	N/A

Comparison: GSM base station power consumption

- Overview
- Details
- (just to put things into perspective)



Controlling transceivers

- Similar to controller, low duty cycle is necessary
  - Easy to do for transmitter – similar problem to controller: when is it worthwhile to switch off
  - Difficult for receiver: Not only time when to wake up not known, it also depends on ***remote*** partners

  Dependence between MAC protocols and power consumption is strong!

- Only limited applicability of techniques analogue to DVS
  - Dynamic Modulation Scaling (DSM): Switch to modulation best suited to communication – depends on channel gain
  - Dynamic Coding Scaling – vary coding rate according to channel gain
  - Combinations

Computation vs. communication energy cost

- Tradeoff?
  - Directly comparing computation/communication energy cost not possible
  - But: put them into perspective!
  - Energy ratio of “sending one bit” vs. “computing one instruction”: Anything between 220 and 2900 in the literature
  - To communicate (send & receive) one kilobyte = computing three million instructions!
- Hence: try to compute instead of communicate whenever possible
- Key technique in WSN – ***in-network processing!***
  - Exploit compression schemes, intelligent coding schemes, data aggregation schemes…

Outline

- Sensor node architecture
- Energy supply and consumption
- ***Runtime environments for sensor nodes***
- Case study: TinyOS

Operating system challenges in WSN

- Usual operating system goals
  - Make access to device resources abstract (virtualization)
  - Protect resources from concurrent access
- Usual means
  - Protected operation modes of the CPU – hardware access only in these modes
  - Process with separate address spaces
  - Support by a memory management unit
- Problem: These are not available in microcontrollers
  - No separate protection modes, no memory management unit
  - Would make devices more expensive, more power-hungry

! ???

Operating system challenges in WSN

- Possible options
  - Try to implement “as close to an operating system” on WSN nodes
    - In particular, try to provide a known programming interface
    - Namely: support for processes!
    - Sacrifice protection of different processes from each other

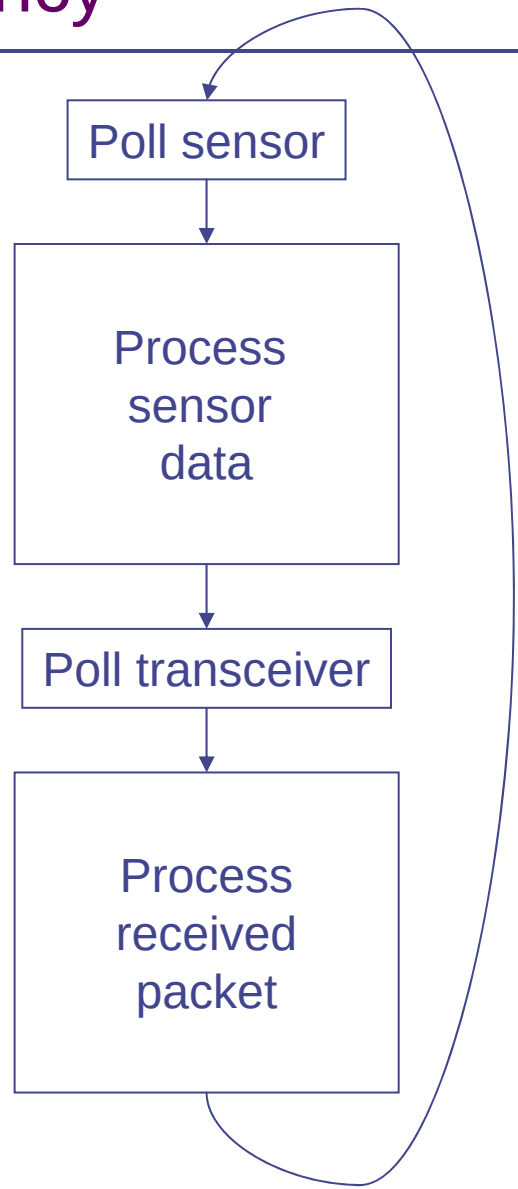
    ! Possible, but relatively high overhead
  - Do (more or less) away with operating system
    - After all, there is only a single “application” running on a WSN node
    - No need to protect malicious software parts from each other
    - Direct hardware control by application might improve efficiency
- Currently popular verdict: no OS, just a simple run-time environment
  - Enough to abstract away hardware access details
  - Biggest impact: Unusual programming model

Main issue: How to support concurrency

- Simplest option: No concurrency, sequential processing of tasks
  - Not satisfactory: Risk of missing data (e.g., from transceiver) when processing data, etc.

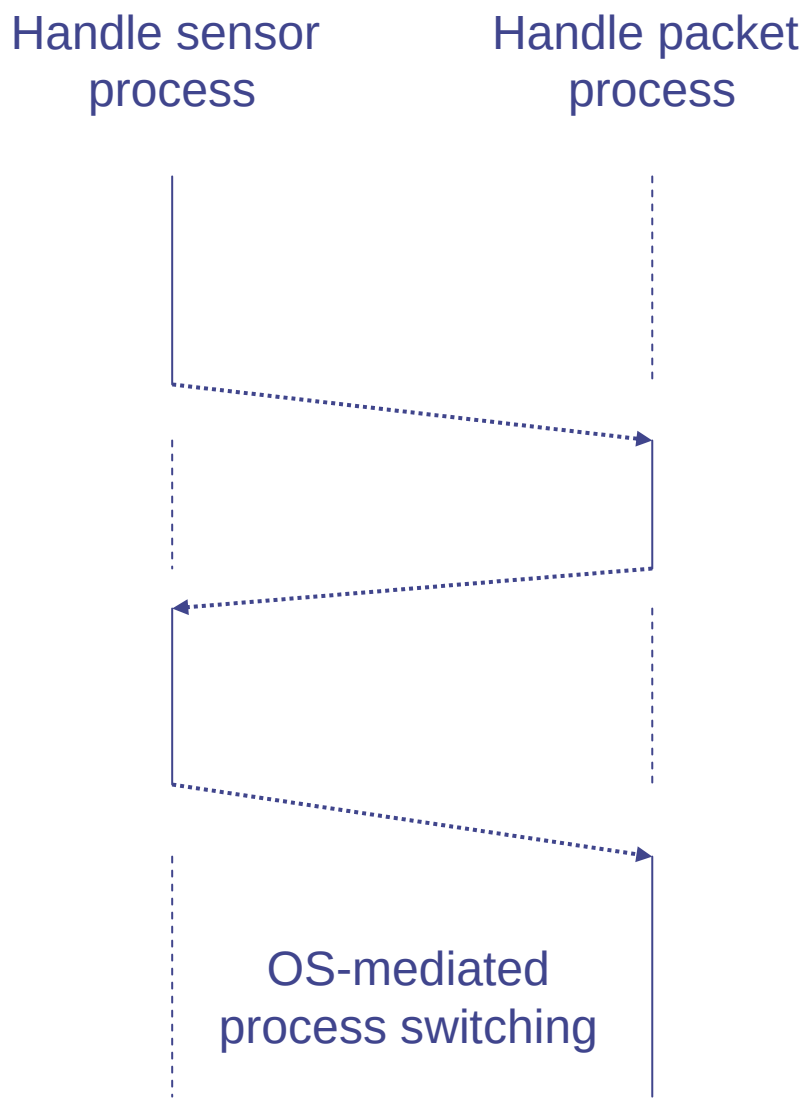
  ! Interrupts/asynchronous operation has to be supported

- Why concurrency is needed
  - Sensor node's CPU has to service the radio modem, the actual sensors, perform computation for application, execute communication protocol software, etc.



Traditional concurrency: Processes

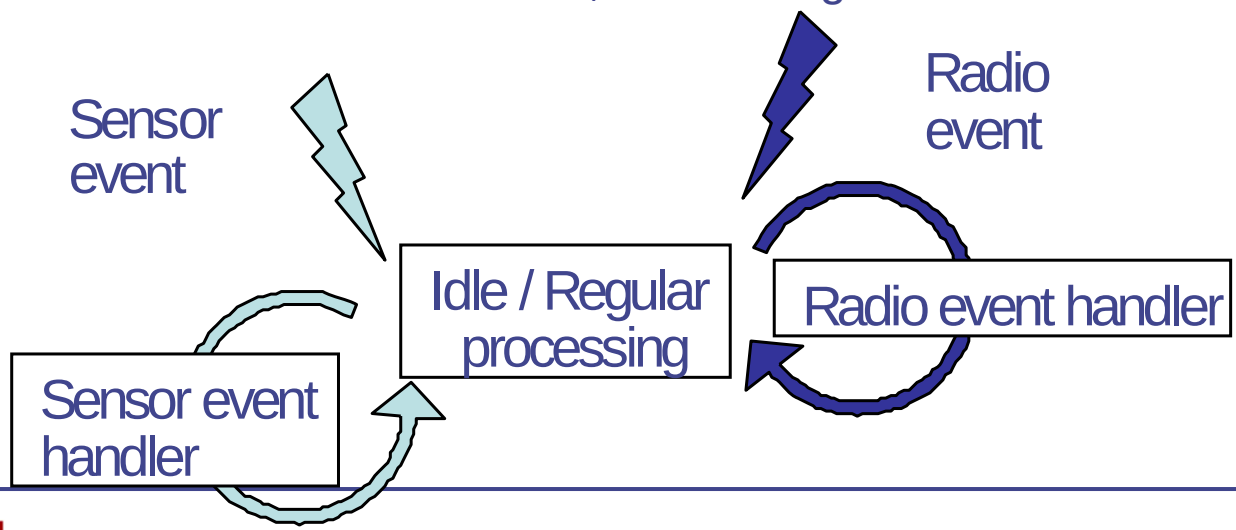
- Traditional OS: processes/threads
  - Based on interrupts, context switching
  - But: not available – memory overhead, execution overhead
- But: concurrency mismatch
  - One process per protocol entails too many context switches
  - Many tasks in WSN small with respect to context switching overhead
- And: protection between processes not needed in WSN
  - Only one application anyway



Event-based concurrency

- Alternative: Switch to ***event-based programming model***
  - Perform regular processing or be idle
  - React to events when they happen immediately
  - Basically: interrupt handler
- Problem: must not remain in interrupt handler too long
  - Danger of loosing events
  - Only save data, post information that event has happened, then return

  ! ***Run-to-completion*** principle
  - Two contexts: one for handlers, one for regular execution



Components instead of processes

- Need an abstraction to group functionality
  - Replacing “processes” for this purpose
  - E.g.: individual functions of a networking protocol

- One option: ***Components***
  - Here: In the sense of TinyOS
  - Typically fulfill only a single, well-defined function
  - Main difference to processes:
    - Component does not have an execution
    - Components access same address space, no protection against each other
  - NOT to be confused with component-based programming!

API to an event-based protocol stack

- Usual networking API: sockets
  - Issue: blocking calls to receive data
  - Ill-matched to event-based OS
  - Also: networking semantics in WSNs not necessarily well matched to/by socket semantics

- API is therefore also event-based
  - E.g.: Tell some component that some other component wants to be informed if and when data has arrived
  - Component will be posted an event once this condition is met
  - Details: see TinyOS example discussion below

Dynamic power management

- Exploiting multiple operation modes is promising
- Question: When to switch in power-safe mode?
  - Problem: Time & energy overhead associated with wakeup; greedy sleeping is not beneficial (see exercise)
  - Scheduling approach
- Question: How to control dynamic voltage scaling?
  - More aggressive; stepping up voltage/frequency is easier
  - Deadlines usually bound to the required speed from below
- Or: Trading off fidelity vs. energy consumption!
  - If more energy is available, compute more accurate results
  - Example: Polynomial approximation
    - Start from high or low exponents depending where the polynomial is to be evaluated

Outline

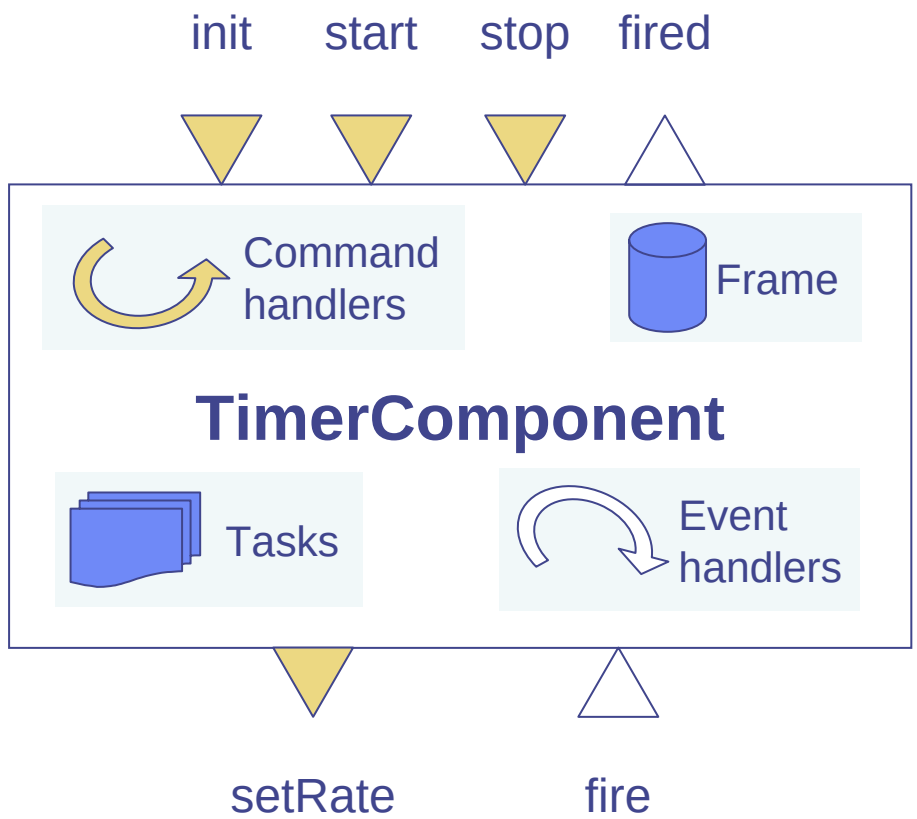
- Sensor node architecture
- Energy supply and consumption
- Runtime environments for sensor nodes
- ***Case study: TinyOS***

Case study embedded OS: TinyOS & nesC

- TinyOS developed by UC Berkely as runtime environment for their “motes”
- nesC as adjunct “programming language”
- Goal: Small memory footprint
  - Sacrifices made e.g. in ease of use, portability
  - Portability somewhat improved in newer version
- Most important design aspects
  - Component-based system
  - Components interact by exchanging asynchronous events
  - Components form a program by ***wiring*** them together (akin to VHDL – hardware description language)

TinyOS components

- Components
  - Frame – state information
  - Tasks – normal execution program
  - Command handlers
  - Event handlers
- Handlers
  - Must run to completion
  - Form a component's interface
  - Understand and emits commands & events
- Hierarchically arranged
  - Events pass upward from hardware to higher-level components
  - Commands are passed downward



Handlers versus tasks

- Command handlers and events must run to completion
  - Must not wait an indeterminate amount of time
  - Only a ***request*** to perform some action
- Tasks, on the other hand, can perform arbitrary, long computation
  - Also have to be run to completion since no non-cooperative multi-tasking is implemented
  - But can be interrupted by handlers

! No need for stack management, tasks are atomic with respect to each other

Split-phase programming

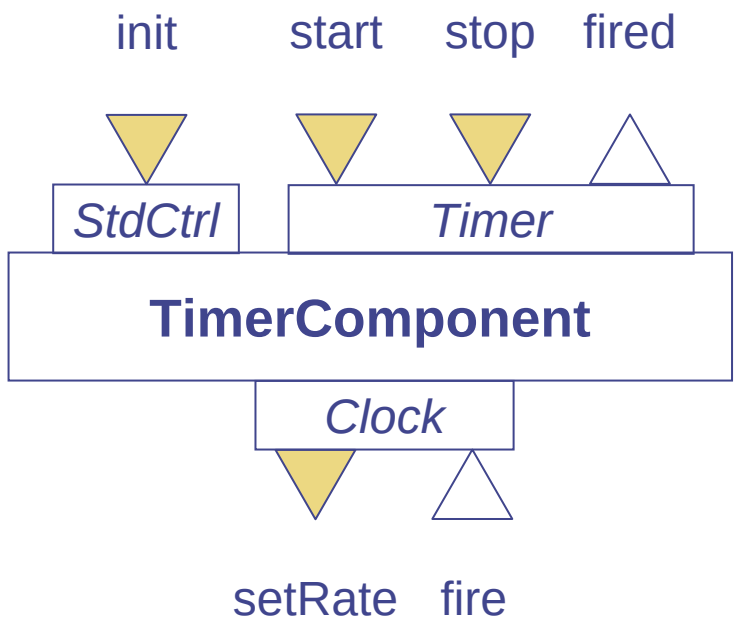
- Handler/task characteristics and separation has consequences on programming model
  - How to implement a blocking call to another component?
  - Example: Order another component to send a packet
  - Blocking function calls are not an option

! Split-phase programming

- First phase: Issue the command to another component
  - Receiving command handler will only receive the command, post it to a task for actual execution and returns immediately
  - Returning from a command invocation does not mean that the command has been executed!
- Second phase: Invoked component notifies invoker by event that command has been executed
- Consequences e.g. for buffer handling
  - Buffers can only be freed when completion event is received

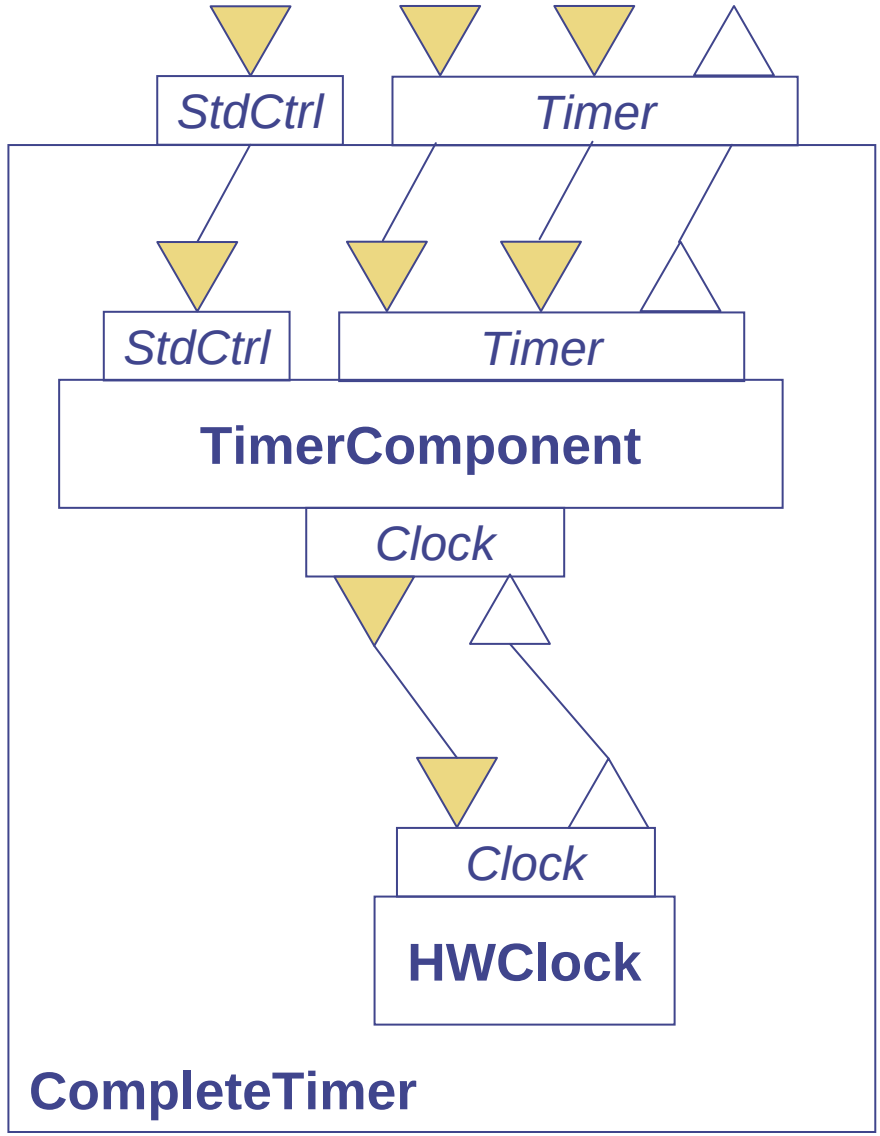
Structuring commands/events into interfaces

- Many commands/events can add up
- nesC solution: Structure corresponding commands/events into ***interface types***
- Example: Structure timer into three interfaces
  - StdCtrl
  - Timer
  - Clock
- Build configurations by wiring together corresponding interfaces



Building components out of simpler ones

- Wire together components to form more complex components out of simpler ones
- New interfaces for the complex component



Defining modules and components in nesC

```
interface StdCtrl {
  command result_t init();
}

interface Timer {
  command result_t start (char type, uint32_t interval);
  command result_t stop ();
  event result_t fired();
}

interface Clock {
  command result_t setRate (char interval, char scale);
  event result_t  fire ();
}

module TimerComponent {
  provides {
    interface StdCtrl;
    interface Timer;
  }
  uses interface Clock as Clk;
}
```

Wiring components to form a configuration

```
configuration CompleteTimer {
  provides {
    interface StdCtrl;
    interface Timer;
  }
  implementation {
    components TimerComponent, HWClock;
    StdCtrl = TimerComponent.HWClock;
    Timer = TimerComponent.Timer;
    TimerComponent.Clk = HWClock.Clock;
  }
}
```

Summary

- For WSN, the need to build cheap, low-energy, (small) devices has various consequences for system design
  - Radio frontends and controllers are much simpler than in conventional mobile networks
  - Energy supply and scavenging are still (and for the foreseeable future) a premium resource
  - Power management (switching off or throttling down devices) crucial
- Unique programming challenges of embedded systems
  - Concurrency without support, protection
  - De facto standard: TinyOS