POLITECNICO MILANO 1863

Politecnico di Milano

Advanced Network Technologies Laboratory

Wireless Sensor Networks (aka, Active RFID)

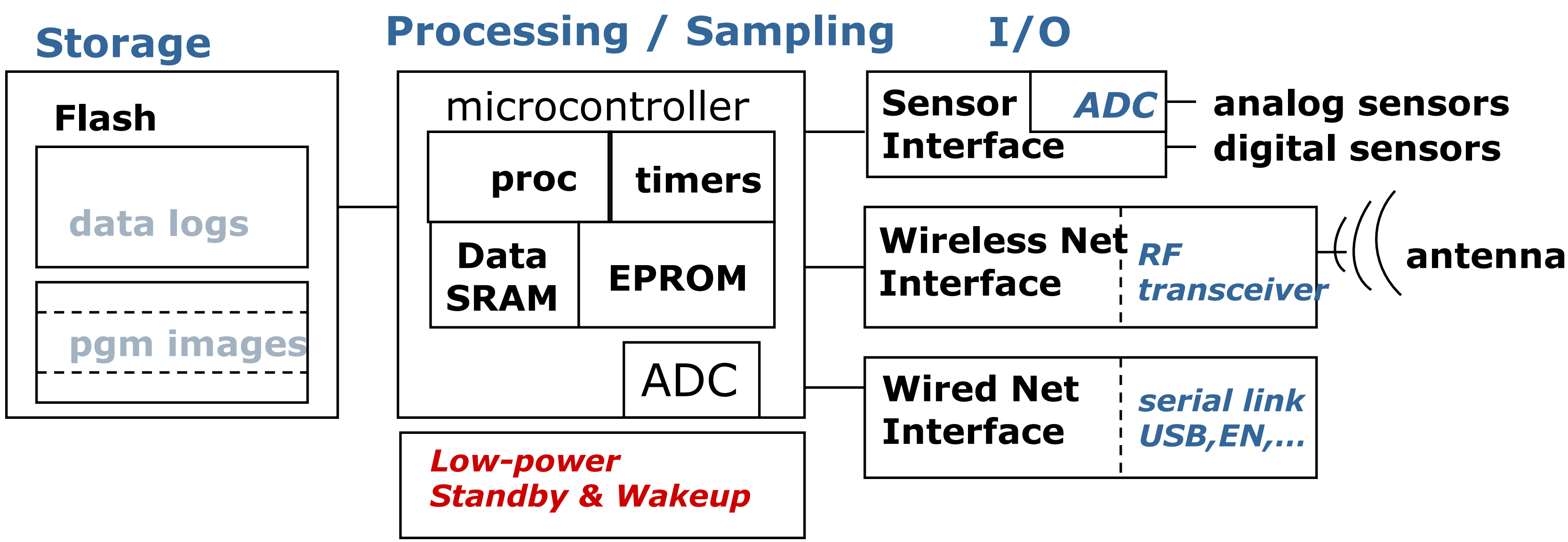
Hardware and Hardware Abstractions

Design Challenges/Guidelines/Opportunities

Let’s start From the edge..

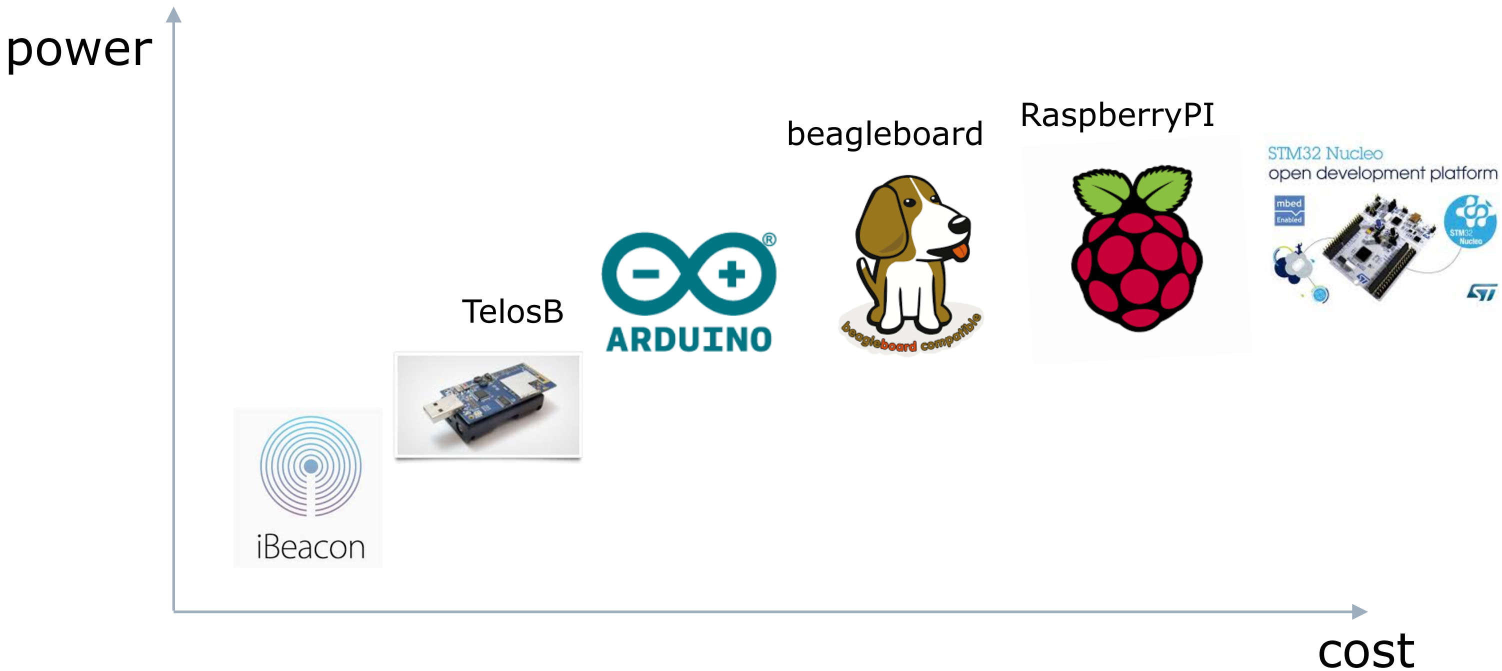
- A Sensor Node (or *mote*) is a device with the following capabilities:
  - Sensing external phenomena
  - Processing information
  - Storing information
  - Communicating with other motes or devices

Mote Architecture



IoT Hardware Breakdown

- IoT Hardware offer is vast, fragmented and heterogeneous
  - Type of CPU, connectivity, storage, sensing peripherals



Power Consumption

- Sensor node has limited power source
- Sensor node LIFETIME depends on BATTERY lifetime

- Goal: Provide as much energy as possible at smallest cost/volume/weight/recharge

- Problem: recharging and/or battery replacement may be immaterial or too expensive

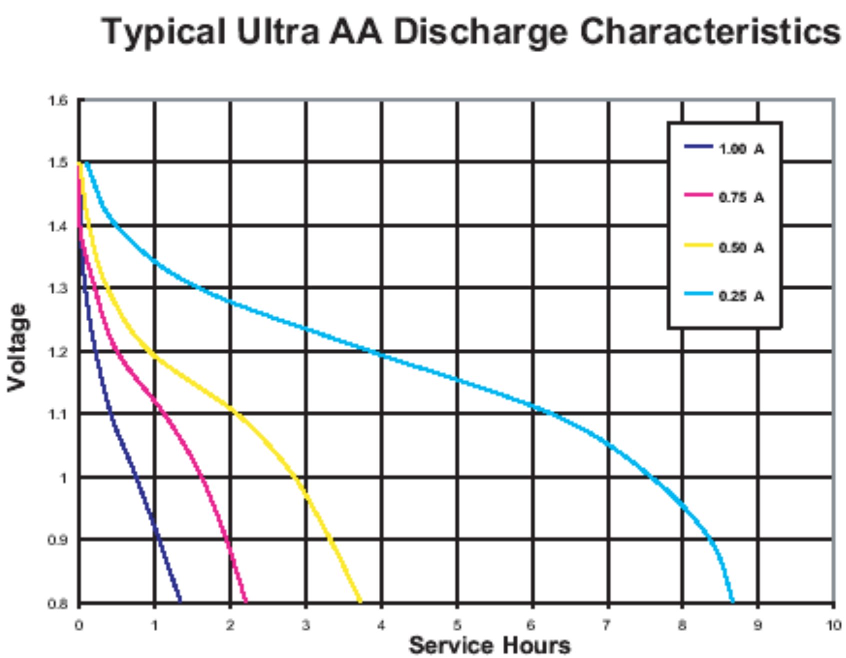
- Options
  - Primary batteries – not rechargeable
  - Secondary batteries – rechargeable, only makes sense in combination with some form of energy harvesting

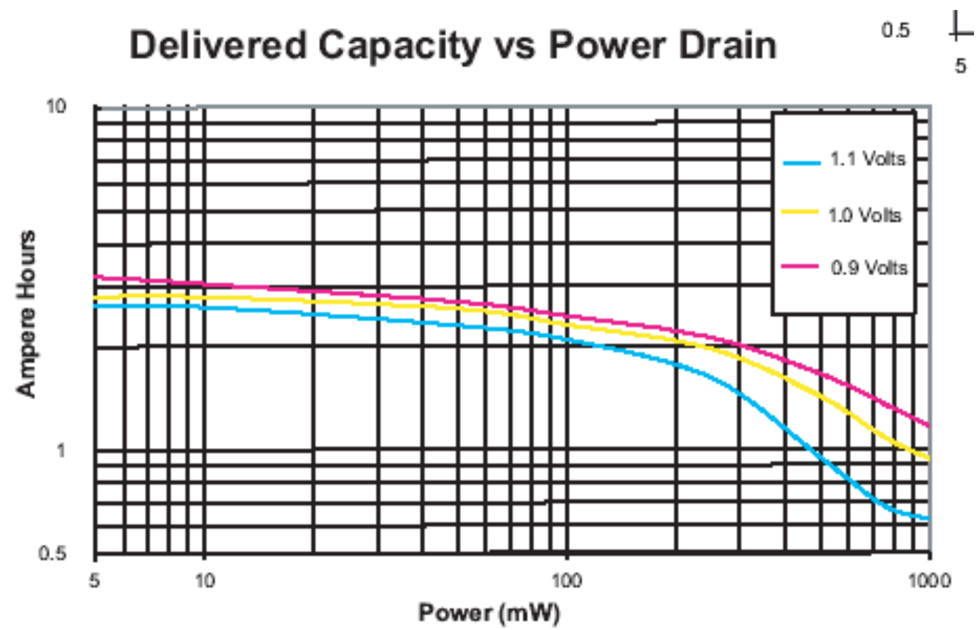
POWER CONSUMPTION

- Sensors can be a DATA ORIGINATOR or a DATA ROUTER.
- Power conservation and power management at different levels are mandatory:
  - Power-aware communication
  - Low-power processing (and processors)
  - Low-power sensing

Energy Sources

- How to Characterize a Battery
  - Voltage
  - Source current
  - Leakage
  - Voltage profile
  - Recharge
- Battery Delivered Capacity
  - Measured in Ah
  - E.g.: 1000 [mAh] means that battery is able to provide a current of 1000 [mA] for 1 hour, or of 1mA for 1000 hours (approx)





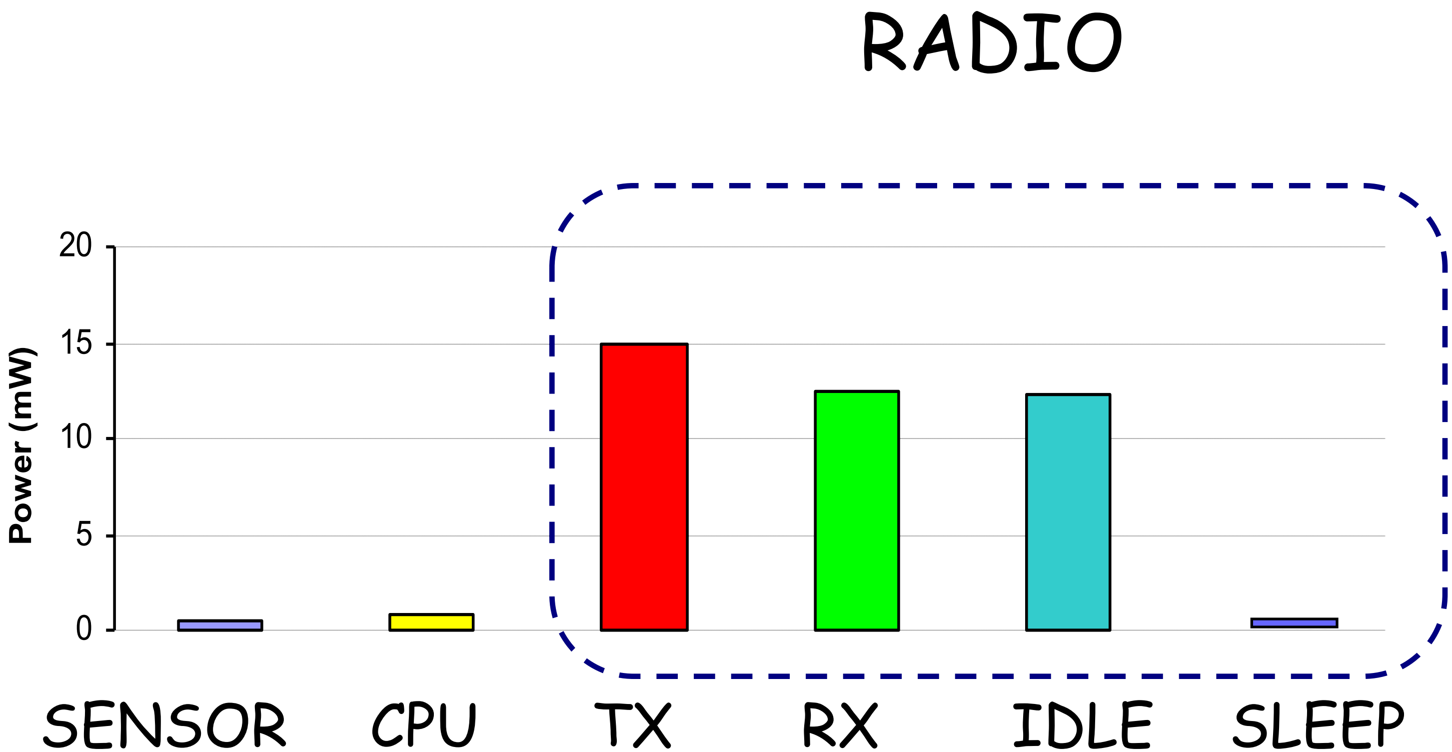
Source: Lecture slides of "Wireless Embedded Internetworking", Prof. D. Culler

Energy Scavenging

- Solar (Outdoors) – 15 mW/cm^2 (direct sun)
- Solar (Indoors) –
  - 0.006 mW/cm^2 (office desk)
  - 0.57 mW/cm^2 (<60 W desk lamp)
- Temperature Gradients – 80 mW/cm^2 at about 1V from a 5Kelvin temp. difference
- Vibrations – 0.01 and 0.1 mW/cm^3
- Acoustic Noises – $3*10^{\{-6\}}$ mW/cm^2 at 75dB - $9.6*10^{\{-4\}}$ mW/cm^2 at 100dB

Source: Lecture slides of "Sensor Networks", Prof. I. Akyildiz

Power Consumption Dissected



General Design Guideline:

To switch off the Radio (TX/RX/IDLE) "as soon as possible"

Source: Lecture slides of "Sensor Networks", Prof. I. Akyildiz

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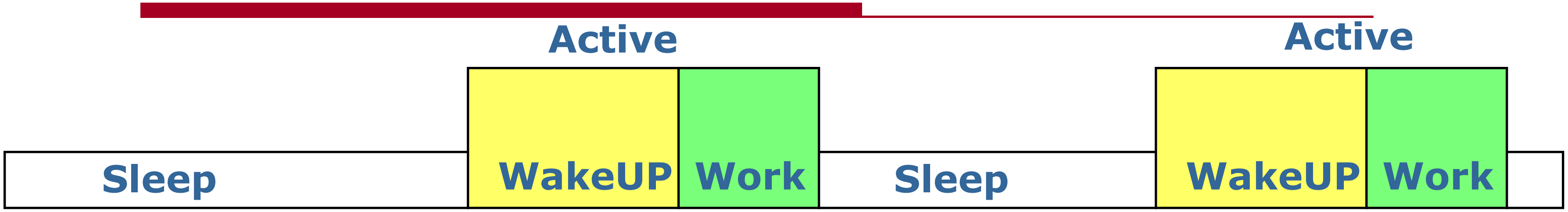
The “Idle Listening” Problem

- The power consumption of “short range” (i.e., low-power) wireless communications devices is roughly the same whether the radio is transmitting, receiving, or simply ON, “listening” for potential reception
  - includes IEEE 802.15.4, Zwave, Bluetooth, and the many variants
  - WiFi too!
  - Circuit power dominated by core, rather than large amplifiers
- Radio must be ON (listening) in order receive anything.
  - Transmission is infrequent.
  - Listening (potentially) happens all the time

⇒ Total energy consumption dominated by *idle listening*

Power: Model of operation



- Sleep – Active [Wakeup / Work]
- Peak Power
  - MW in supercomputer, kW in server, Watts in PDA
  - milliwatts in “mote” class device
- Sleep power
  - Minimal running components + leakage
  - Microwatts in mote-class
- Average power
  - $P_{ave} = = (1-f_{active})*P_{sleep} + f_{active}*P_{active}$ (Duty Cycle: f_{active})
  - $P_{ave} = f_{sleep}*P_{sleep} + f_{wakeup}*P_{wakeup} + f_{work}*P_{work}$
- Lifetime
  - EnergyStore / (P_{ave} - P_{gen})

Source: Lecture slides of “Wireless Embedded Internetworking”, Prof. D. Culler

Power Consumption for Communication

$$P_c = N_T\,[P_{te}(T_{on} + T_{wu}) + P_O(T_{on})] + N_R[P_{re}(R_{on} + R_{wu})]$$

where

P_{te} is power consumed by transmitter

P_{re} is power consumed by receiver

P_O is output power of transmitter

T_{on} is transmitter "on" time

R_{on} is receiver "on" time

T_{wu} is start-up time for transmitter

R_{wu} is start-up time for receiver

N_T is the number of times transmitter is switched "on" per unit of time

N_R is the number of times receiver is switched "on" per unit of time

[1] *E. Shih et al.,"Physical Layer Driven Protocols and Algorithm Design for Energy-Efficient Wireless Sensor Networks", ACM MobiCom, Rome, July 2001*

On the emitted power

- The emitted power is often a tunable parameter
- Good practice is to set it to the lowest value which allows for “good reception”
- The quality of the reception process is “measured” in terms of
  - Bit Error Rate (BER): fraction of bit not correctly received (“1” for a “0” or viceversa)
  - Packet Error Rate (PER): fraction of packet not correctly received
  - PER/BER relation (packet of length *l*, independent errors):

$$PER = 1 - (1 - BER)^l$$

Signal to noise and Interference Ratio

- BER (and PER in turn) depends on the "level of noise" in the TX/RX channel, which, in turn, depends on the transmitted/received power

$$\mathrm{SINR} = 10\log_{10}\left(\frac{P_{\mathrm{recv}}}{N_0 + \sum_{i=1}^{k} I_i}\right)$$

Thermal noise: *KTB*

- BER can be computed once given the specific TX/RX channel (modulation) and the specific SINR

Receiver Sensitivity

- Each receiver is characterized by a *sensitivity* parameter (e.g. P_{min}=-95dBm),
  - The minimum input signal power needed at receiver input to provide adequate SNR at receiver output to do data demodulation
- Example: IEEE 802.15.4
  - Receiver sensitivity (packet error rate < 1%)
    - $P_{min} > -85$ dBm @ 2.4 GHz band
    - $P_{min} > -92$ dBm @ 868/915 MHz band
- Knowing such parameter, one can find the required emitted power at the transmitter by inverting the propagation law of the channel to get to required emitted power

Emitted power - Example

- A wireless receiver is characterized by a sensitivity P_r=-0.1[uW]; the transmitter is d=10[m] from the receiver; the TX-RX is performed at a carrier frequency f=2.4GHz; the propagation on the channel is characterized by the following model

$$^{*}P_r = P_t g_t g_r (\frac{\lambda}{4\pi d})^2$$

- Further assuming the antenna gains equal to 1, we get a required emitted power

$$P_t = P_r (\frac{4\pi d}{\lambda})^2 \approx 100[mW]$$

*If you have no clue on where this model comes from you may want to have a look at the primer on wireless propagation available at the course web site

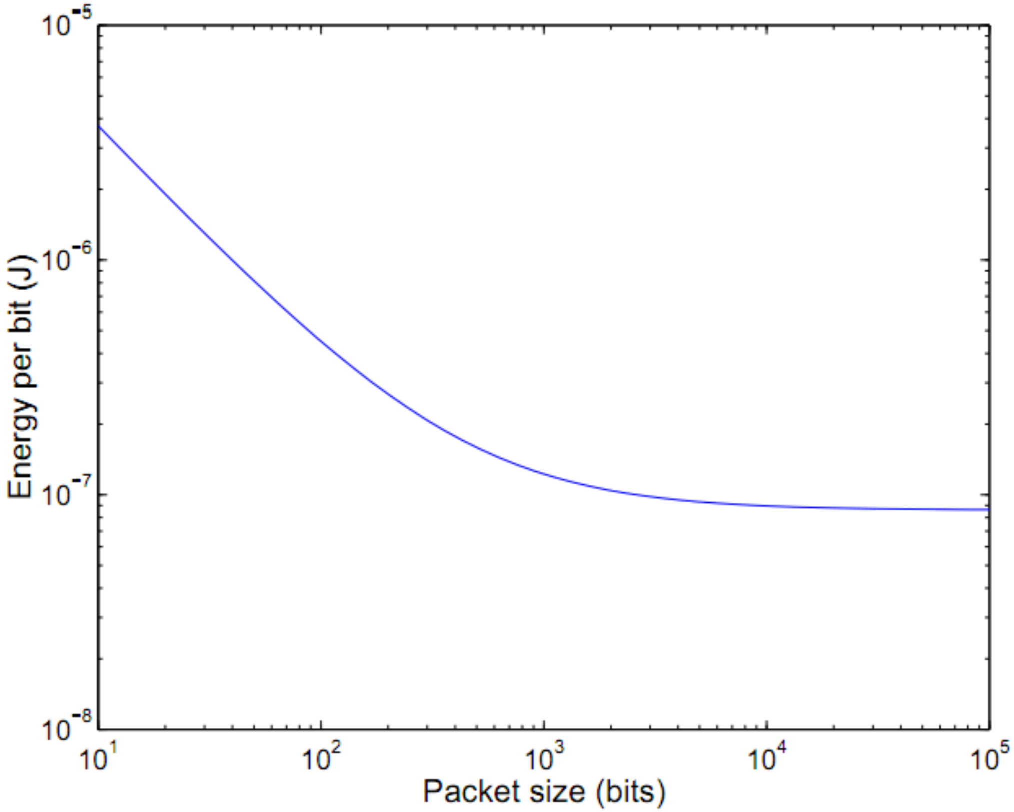
Wake-Up Overhead

- Wake-Up comes with "energy overhead"

- Question:
  - What is the consumed energy per bit for transmitting a packet of *L* [bits]?
  - Energy spent in transmission: $E_o=P_oT_L$
  - Energy spent during wake-up: $E_{wu}=P_{te}T_{wu}$
  - Energy spent for TX circuitry: $E_{tx}=P_{tx}(T_{wu}+T_L)$
  - Energy per bit: $(E_{wu}+E_o+E_{tx})/L$

Wasted Energy

- Parameters: R=1 Mbps; T_{WU} ~ 450 msec, P_{te}~81mW; P_{out} = 0 dBm



Sample Radio Data sheets

Type	Narrowband				Wideband		
Vendor Part no.	RFM TR1000	Chipcon CC1000	Chipcon CC2400	Nordic nRF2401	Chipcon CC2420	Motorola MC13191/92	Zeevo ZV4002
Max Data rate (kbps)	115.2	76.8	1000	1000	250	250	723.2
RX power (mA)	3.8	9.6	24	18 (25)	19.7	37(42)	65
TX power (mA/dBm)	12 / 1.5	16.5 / 10	19 / 0	13 / 0	17.4 / 0	34(30)/ 0	65 / 0
Powerdown power (μA)	1	1	1.5	0.4	1	1	140
Turn on time (ms)	0.02	2	1.13	3	0.58	20	*
Modulation	OOK/ASK	FSK	FSK,GFSK	GFSK	DSSS-O-QPSK	DSSS-O-QPSK	FHSS-GFSK
Packet detection	no	no	programmable	yes	yes	yes	yes
Address decoding	no	no	no	yes	yes	yes	yes
Encryption support	no	no	no	no	128-bit AES	no	128-bit SC
Error detection	no	no	yes	yes	yes	yes	yes
Error correction	no	no	no	no	yes	yes	yes
Acknowledgments	no	no	no	no	yes	yes	yes
Interface	bit	byte	packet/byte	packet/byte	packet/byte	packet/byte	packet
Buffering (bytes)	no	1	32	16	128	133	yes *
Time-sync	bit	SFD/byte	SFD/packet	packet	SFD	SFD	Bluetooth
Localization	RSSI	RSSI	RSSI	no	RSSI/LQI	RSSI/LQI	RSSI

* Manufacturer's documentation does not include additional information.

Processing Power Consumption

- CPU power dissipation due to:

$$P_p = P_{dyn} + P_{sc} + P_{leak}$$

Job done → P_{dyn}; Short circuits → P_{sc}; leakage → P_{leak}

- Where

$$P_{dyn} = CfV^2$$

- C: capacitance (~ 0.67nF)
- f: frequency
- V: voltage

Processing Power Consumptions

- Rough Comparison:
  - Energy cost of transmitting 1 KB a distance of 100 m is approx. equal to executing 3 Million instructions by a 100 million instructions per second processor.

- Local data processing (if possible) is crucial in minimizing power consumption in a multi-hop network

Source: Lecture slides of "Sensor Networks", Prof. I. Akyildiz

Multiple Power Consumption Modes

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

Source: Lecture slides of "Sensor Networks", Prof. I. Akyildiz

Optimize Power Consumption

- Power aware computing
  - Ultra-low power microcontrollers
  - Dynamic power management HW
  - Dynamic voltage scaling (e.g Intel's PXA, Transmeta's Crusoe)
  - Components that switch off after some idle time

Manufacturer	Device	RAM (kB)	Flash (kB)	Active (mA)	Sleep (μA)	Release
Atmel	AT90LS8535	0.5	8	5	15	1998
	Mega128	4	128	8	20	2001
	Mega165/325/645	4	64	2.5	2	2004
General Instruments	PIC	0.025	0.5	19	1	1975
Microchip	PIC Modem	4	128	2.2	1	2002
Intel	4004	0.625	4	??	??	1971
	8051 Classic	0.5	32	30	5	1995
	8051 16-bit	1	16	45	10	1996
Philips	80C51 16-bit	2	60	15	3	2000
Motorola	HC05	0.5	32	6.6	90	1988
	HC08	2	32	8	100	1993
	HCS08	4	60	6.5	1	2003
Texas Instruments	TSS400 4-bit	0.03	1	15	??	1974
	MSP430F14x 16-bit	2	60	1.5	1	2000
	MSP430F16x 16-bit	10	48	2	1	2004
Atmel	AT91 ARM Thumb	256	1024	38	160	2004
Intel	XScale PXA27X	256	N/A	39	574	2004

Memory Power Consumption

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

Source: Lecture slides of "Sensor Networks", Prof. I. Akyildiz

Design Guidelines

- Do not run motes 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

Source: Lecture slides of "Sensor Networks", Prof. I. Akyildiz

Optimize Power Consumption

- Energy aware software
  - Power aware OS: dim displays, sleep on idle times, power aware scheduling
- Energy aware packet forwarding
  - Radio automatically forwards packets at a lower level, while the rest of the node is asleep
- Energy aware wireless communication
  - Exploit performance energy tradeoffs of the communication subsystem, better neighbor coordination, choice of modulation schemes

What About Sensing?

- A unifying framework is missing:
  - Wide array of low-power micro sensors available (Temp, Light, Humidity, Acceleration, Mag, Pressure, …)
  - Several digital interfaces (RS232, SPI, I2C, …)
  - Several Analog Interfaces
- Design and integration with other components are critical