Design and Development of IoT Applications

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  - Wireless Sensor Networks
  - Applications
  - Challenges
- Chapter 2: Technologies and Hardware Architecture
  - Node architecture and HW platforms
  - RF Technologies and IEEE 802.15.4
  - Embedded processing and Sensing
  - Hardware reference designs

Technology Perspective

Client Tier: (desk,lap,PDA,phone)

- Interactivity, Human Interface, Form Factor, Ergonomics, Diversity of usage

Server Tier:

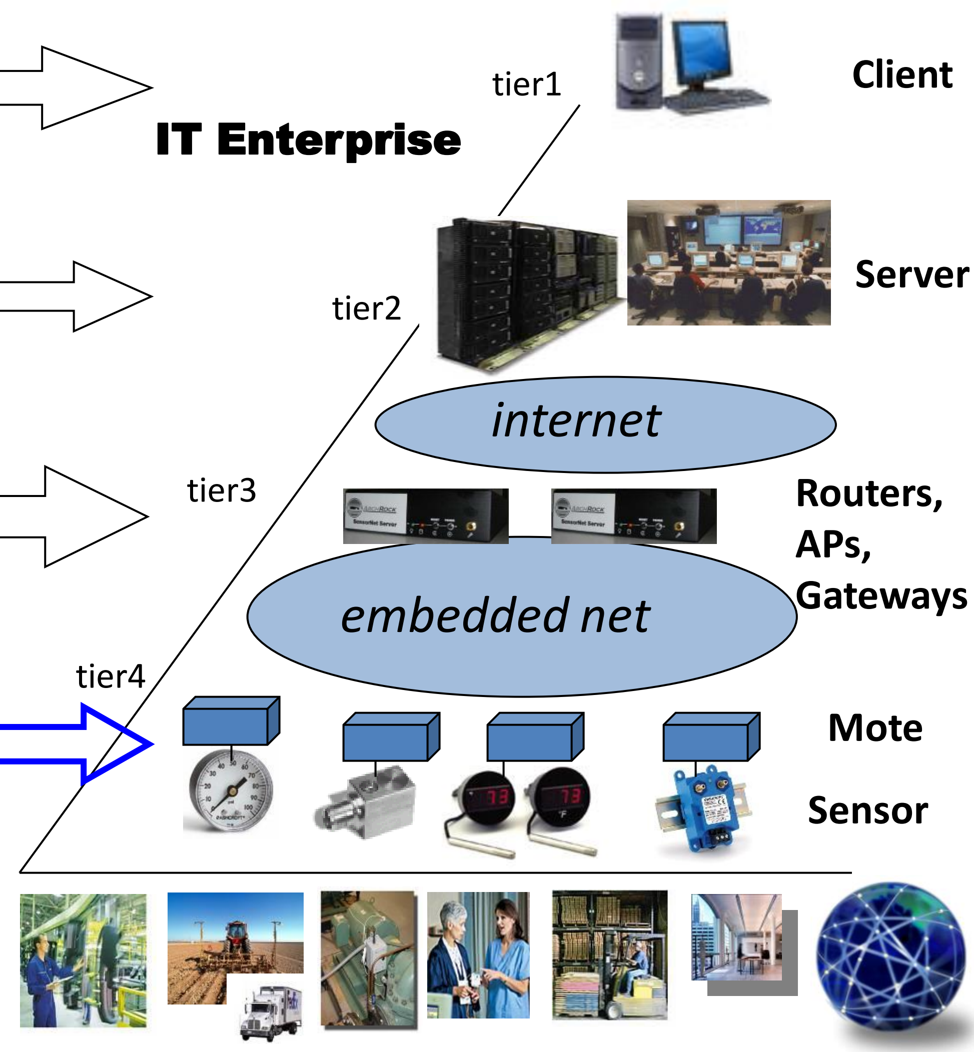
- Massive compute, storage, bandwidth
- Scalability, reliability, redundancy

Router/Gateway Tier:

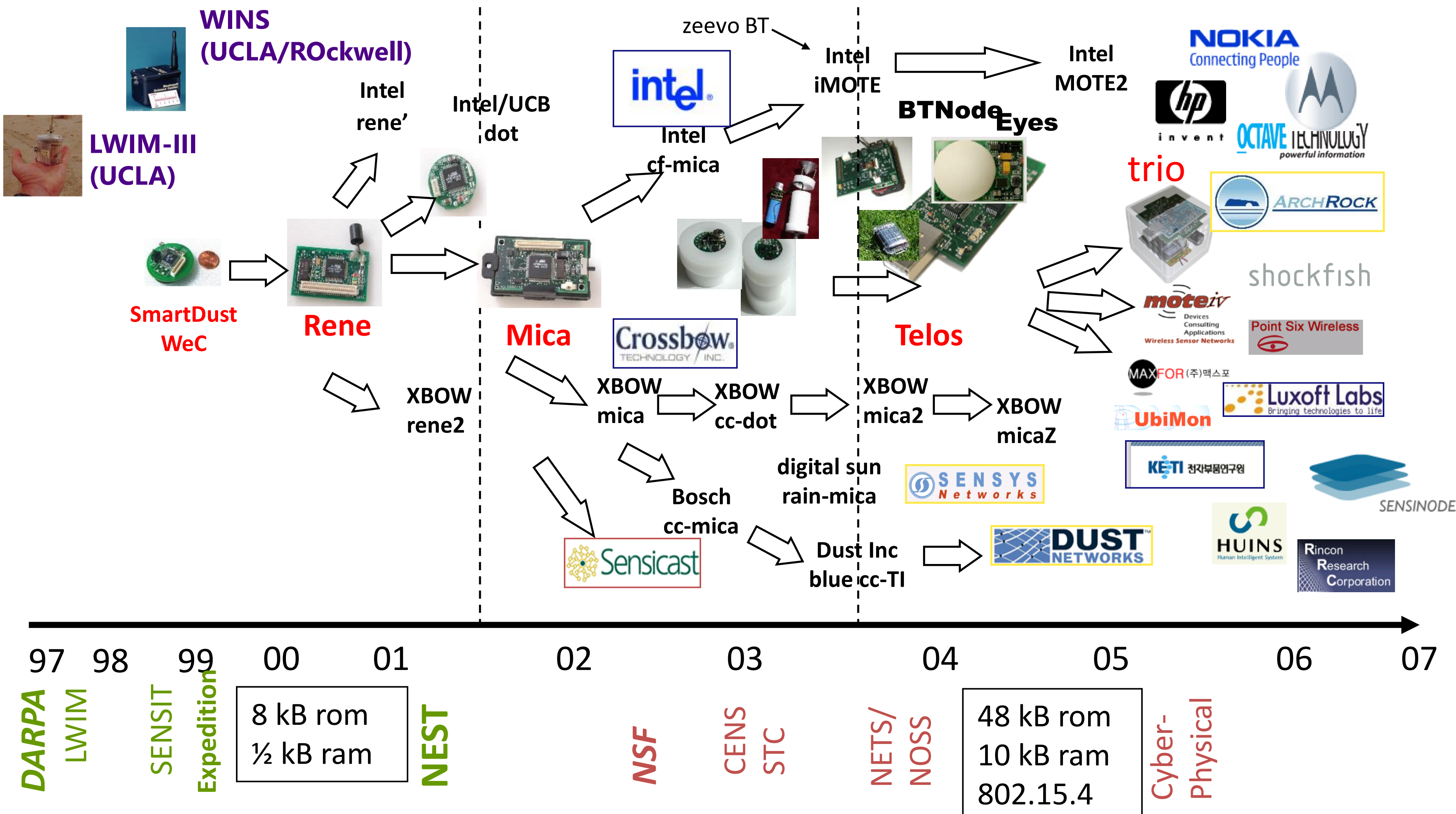
- Bridging: 802.15.4 ←→ (802.11, 802.3, GPRS)
- Routing: Embedded IP and IPv6/IPv4
- Caching, Transcoding, Logging, Gateway adapters
- Packet Processing

Embedded Tier: (mote)

- Low-power, cost-effective, robust embedded devices. Digital and analog interfaces, converters.
- Self-organized network communication



The Mote – basis for networking

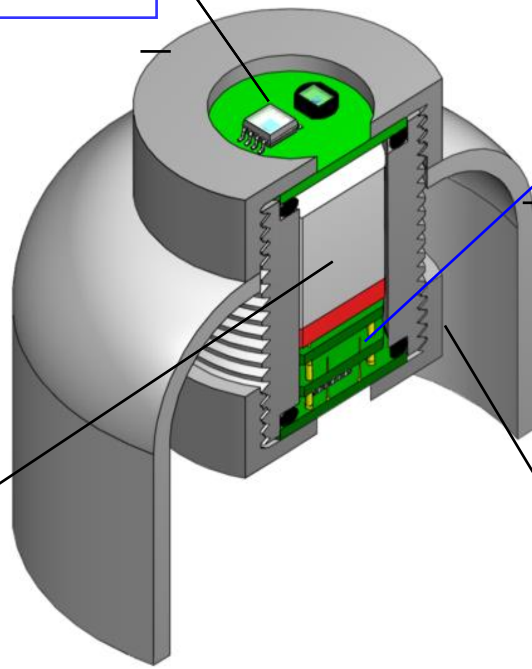


Anatomy of a Mote

Sensors/actuators*
- MEMs – Silicon/CMOS
- Mechanical/Magnetic/Electrical
- Chemical
- Biological

Processing & Storage
- 1M transistors < 1mm^2
- mW active, uW passive power

Communication
- Low bit rate
- Short distance
- CMOS RF/DSP
- Low power – ~10mwatt

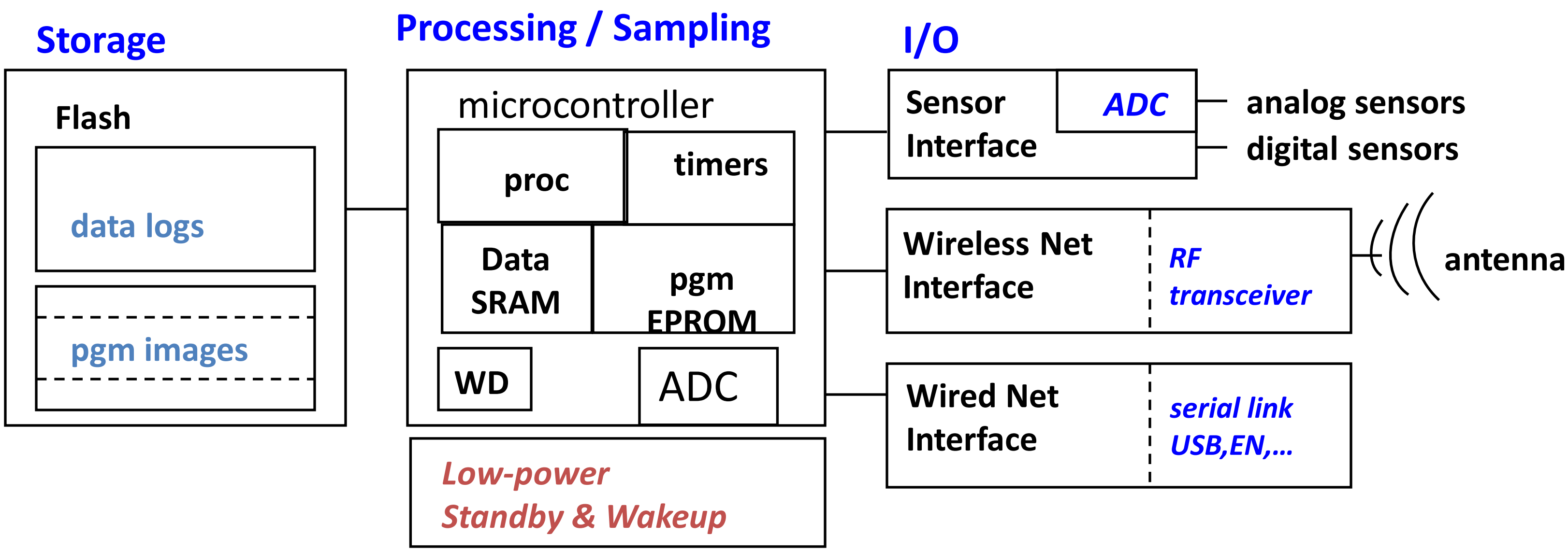


Power*
- Batteries (10mw*day/cm^3)
- Fuel cells (100mw*day/cm^3)
- Scavenging
  - Solar (10mw/cm^2 outside)
  - Vibration (~1 uw/gm)
  - Flow

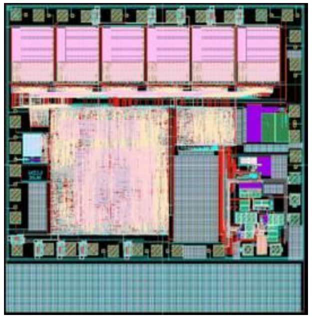
* Application Specific

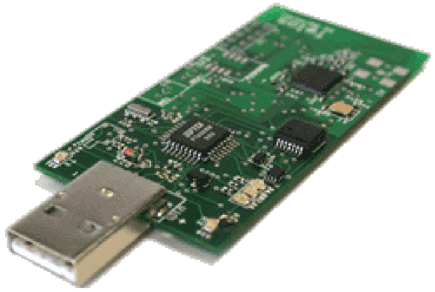
Mechanical Design*
- Enclosure
- Attachment
- Shielding & Exposure

Architecture of a Mote

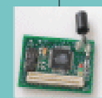
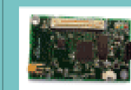
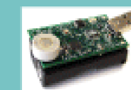


- ❑ Efficient wireless protocol *primitives*
- ❑ Flexible sensor interface
- ❑ Ultra-low power standby
- ❑ Very Fast wakeup
- ❑ Watchdog and Monitoring
- ❑ Data SRAM is critical limiting resource





Mote Platform Summary

Mote Type Year	*WeC* 1998	*René* 1999	*René 2* 2000	*Dot* 2000	*Mica* 2001	*Mica2Dot* 2002	*Mica 2* 2002	*Telos* 2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			48
RAM (KB)	0.5		1		4			10
Active Power (mW)	15		15		15		60	0.5
Sleep Power (W)	45		45		75		75	2
Wakeup Time (s)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	38.5
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

Low Power

- 2 AA => 1.5 amp hours (~4 watt hours)
- Cell => 1 amp hour (3.5 watt hours)

Cell: 500 -1000 mW => few hours active

WiFi: 300 - 500 mW => several hours

GPS: 50 – 100 mW => couple days

WSN: 50 mW active, 20 uW passive

450 uW => one year

45 uW => ~10 years

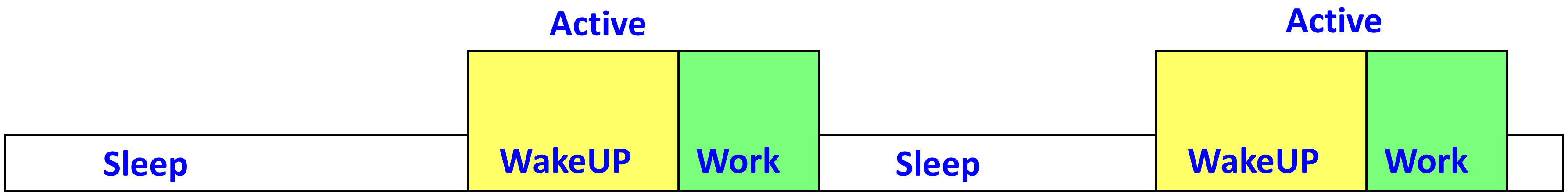
* System design

* Leakage (~RAM)

* Nobody fools mother nature

$$\text{Ave Power} = \boxed{f_{act}} * \boxed{P_{act}} + f_{sleep} * \boxed{P_{sleep}} + \boxed{f_{waking}} * P_{waking}$$

Power Model



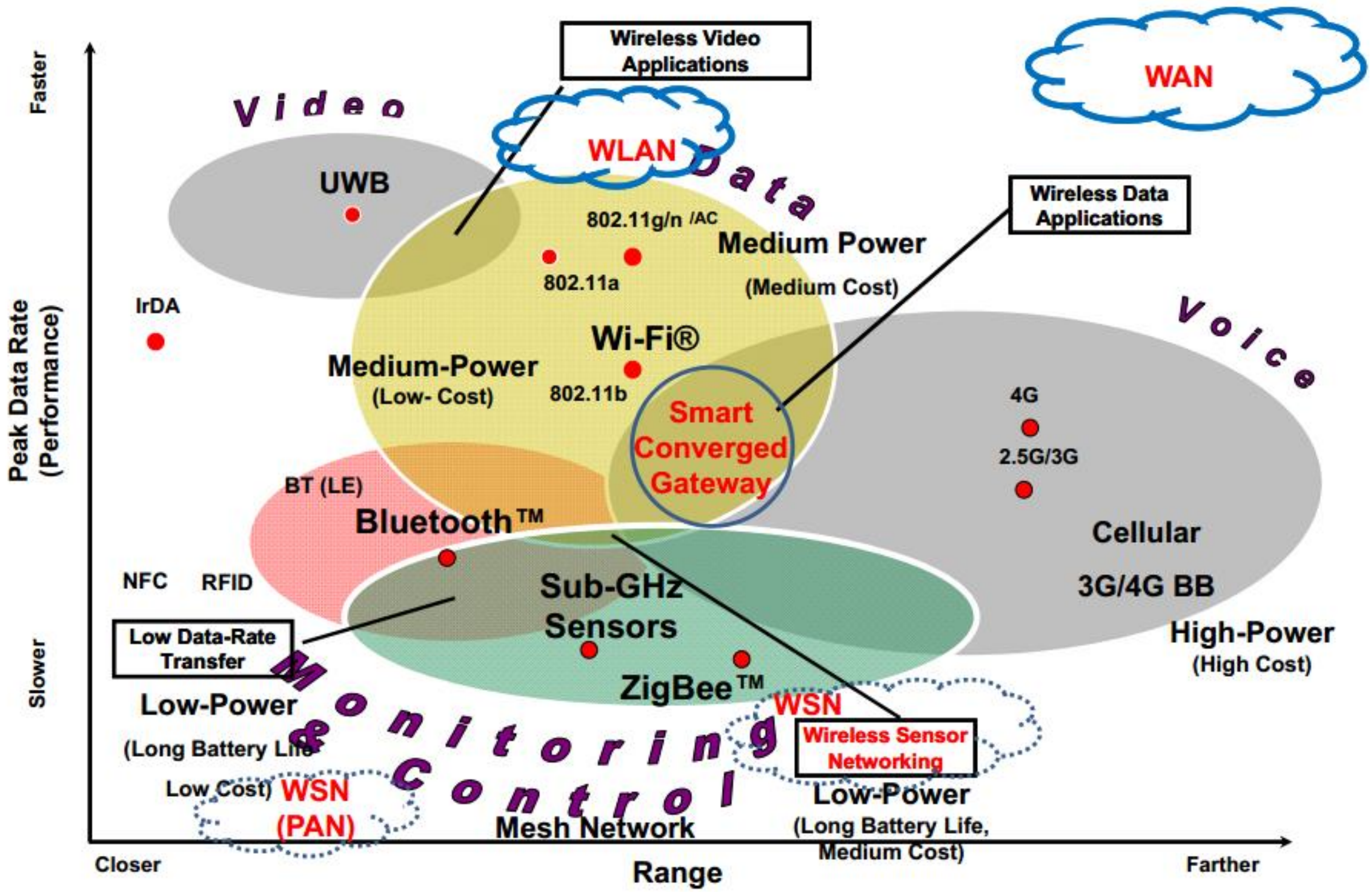
- Sleep – Active [Wakeup / Work]
- Peak Power
  - Essentially sum of subsystem components
  - MW in supercomputer, kW in server, Watts in PDA
  - milliwatts in “mote” class device
- Sleep power
  - Minimal running components + leakage
  - Microwatts in mote-class

Duty Cycle

- Average power
  - $P_{ave} = = (1-f_{active})*P_{sleep} + \boxed{f_{active}}*P_{active}$
  - $P_{ave} = f_{sleep}*P_{sleep} + f_{wakeup}*P_{wakeup} + f_{work}*P_{work}$
- Lifetime
  - EnergyStore / (P_{ave} - P_{gen})

RF Technologies

RF Wireless Data Rates & Ranges



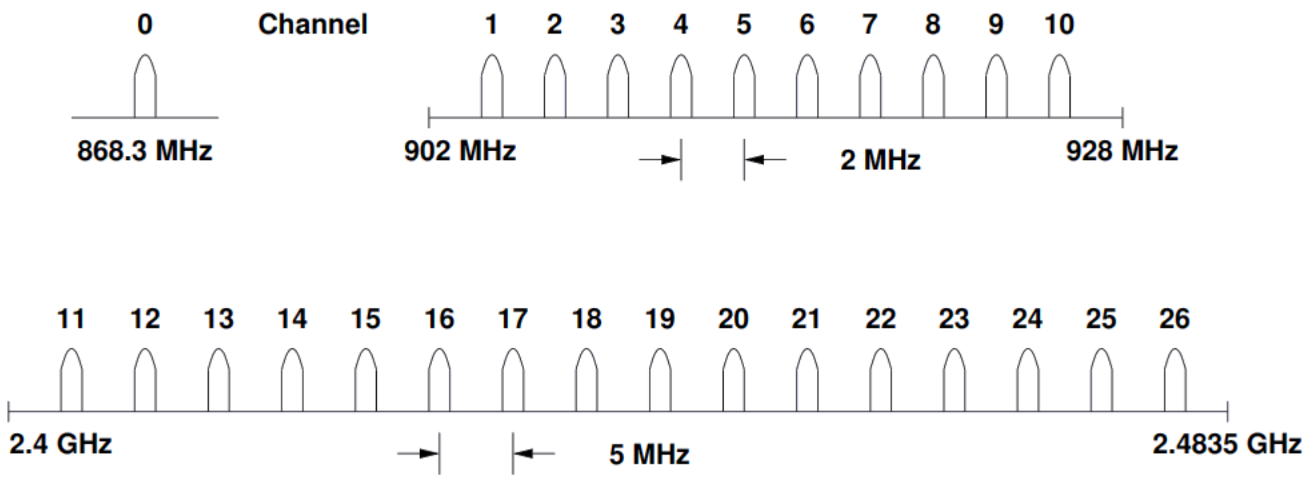
RF Radios Communication Technologies

Communication Technologies

	NFC	RFID	Blue-tooth®	Blue-tooth® LE	ANT	Proprietery (Sub-GHz & 2.4 GHz)	Wi-Fi®	ZigBee®	Z-wave	KNX	Wireless HART	6LoWPAN	WiMAX	2.5–3.5 G
Network	PAN	PAN	PAN	PAN	PAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	MAN	WAN
Topology	P2P	P2P	Star	Star	P2P, Star, Tree Mesh	Star, Mesh	Star	Mesh, Star, Tree	Mesh	Mesh, Star, Tree	Mesh, Star	Mesh, Star	Mesh	Mesh
Power	Very Low	Very Low	Low	Very Low	Very Low	Very Low to Low	Low-High	Very Low	Very Low	Very Low	Very Low	Very Low	High	High
Speed	400 Kbs	400 Kbs	700 kbs	1 Mbs	1 Mbs	250 kbs	11-100 Mbs	250 kbs	40 Kbs	1.2 Kbps	250 kbs	250 Kbs	11-100 Mbs	1.8-7.2 Mbs
Range	<10 cm	<3 m	<30 m	5-10 m	1-30 m	10-70 m	4-20 m	10-300 m	30 m	800 m	200 m	800 m (Sub-GHz)	50 km	Cellular network
Application	Pay, get access, share, initiate service, easy setup	Item tracking	Network for data exchange, headset	Health and fitness	Sports and fitness	Point to point connectivity	Internet, multimedia	Sensor networks, building and industrial automation	Residential lighting and automation	Building automation	Industrial sensing networks	Senor networks, building and industrial automation	Metro area broadband Internet connectivity	Cellular phones and telemetry
Cost Adder	Low	Low	Low	Low	Low	Medium	Medium	Medium	Low	Medium	Medium	Medium	High	High

IEEE 802.15.4

- PHY layer:
  - 868.0–868.6 MHz: Europe, allows one communication channel (2003, 2006, 2011)
  - 902–928 MHz: North America, up to ten channels (2003), extended to thirty (2006)
  - 2400–2483.5 MHz: worldwide use, up to sixteen channels (2003, 2006)



Frequency	Channels	Region	Data Rate	Baud Rate
868-868.6 MHz	0	Europe	20 kbit/s	20 kBaud
902-928 MHz	1-10	USA	40 kbit/s	40 kBaud
2400-2483.5 MHz	11-26	global	250 kbit/s	62.5 kBaud

IEEE 802.15.4: Device classes

- Full Function Device (FFD)
  - Any topology
  - PAN coordinator capable
  - Talks to any other device
  - Implements complete protocol set

- Reduced Function Device (RFD)
  - Reduced protocol set
  - Very simple implementation
  - Cannot become a PAN coordinator
  - Limited to leafs in more complex topologies

IEEE 802.15.4: Definitions

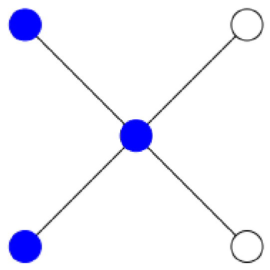
- **Network Device**: An RFD or FFD implementation containing an IEEE 802.15.4 medium access control and physical interface to the wireless medium.

- **Coordinator**: An FFD with network device functionality that provides coordination and other services to the network.

- **PAN Coordinator**: A coordinator that is the principal controller of the PAN. A network has exactly one PAN coordinator

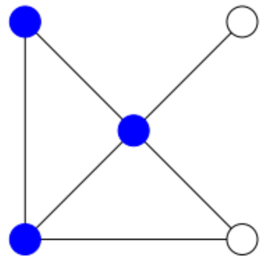
IEEE 802.15.4: Topologies

❑ Star Topology:



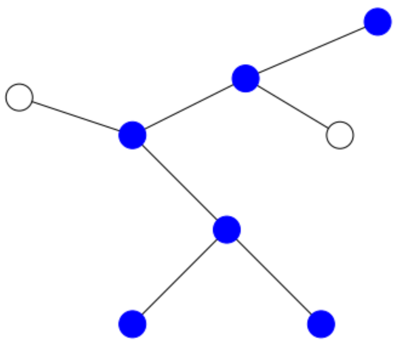
- ❖ All nodes communicate via the central PAN coordinator.
- ❖ Leafs may be any combination of FFD and RFD devices.
- ❖ PAN coordinator is usually having a reliable power source.

❑ Peer-to-Peer Topology:



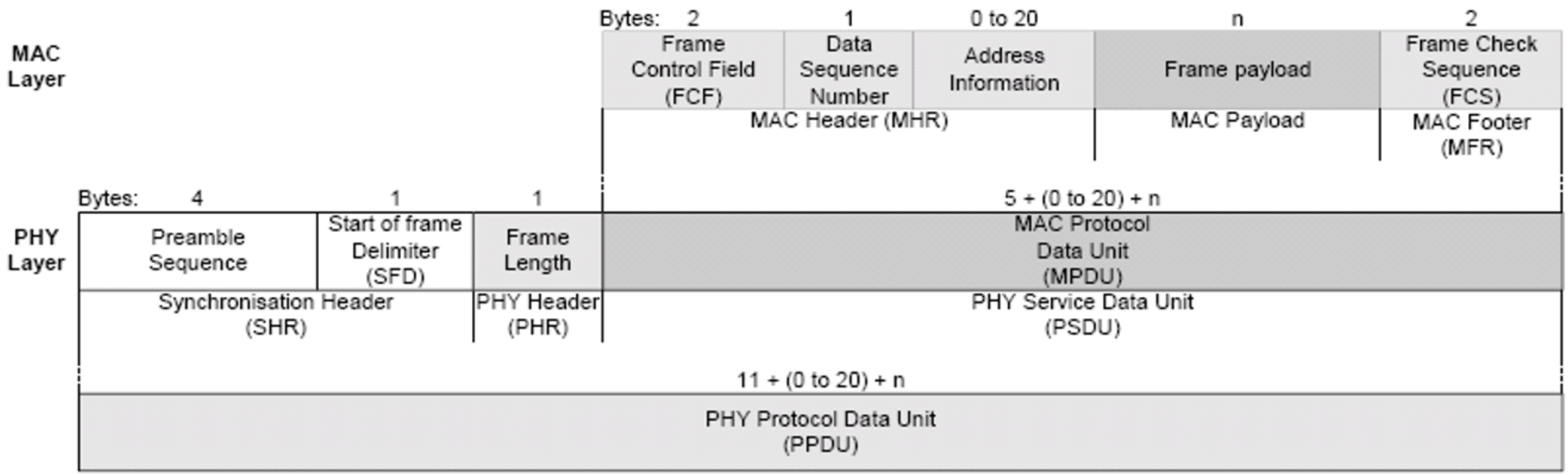
- ❖ Nodes can communicate via the central PAN coordinator and via additional point-to-point links.
- ❖ Extension of the pure star topology.

❑ Cluster Tree Topology:



- ❖ Leafs connect to a network of coordinators (FFDs)
- ❖ One of the coordinators serves as the PAN coordinator
- ❖ Clustered star topologies are an important case (e.g., each hotel room forms a star in a HVAC system)

IEEE 802.15.4: Frame format



IEEE 802.15.4: Frame format

octets: 2	1	0/2	0/2/8	0/2	0/2/8	variable	2
Frame control	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source address	Frame payload	Frame sequence check

bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame type	Security enabled	Frame pending	Ack. requested	Intra PAN	Reserved	Dst addr mode	Reserved	Src addr mode

- IEEE 64-bit extended addresses (globally unique)
- 16-bit "short" addresses (unique within a PAN)
- Optional 16-bit source / destination PAN identifiers
- max. frame size 127 octets; max. frame header 25 octets

IEEE 802.15.4: Frame format

- Beacon Frames:
  - Broadcasted by the coordinator to organize the network.
- Command Frames
  - Used for association, disassociation, data and beacon requests, conflict notification, . . .
- Data Frames
  - Carrying user data — this is what we are interested in
- Acknowledgement Frames
  - Acknowledges successful data transmission (if requested)

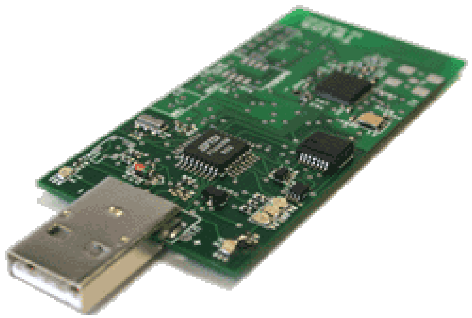
IEEE 802.15.4 Media Access Control

- Carrier Sense Multiple Access/Collision Avoidance. Basic idea of the CSMA/CA algorithm:
  - First wait until the channel is idle.
  - Once the channel is free, start sending the data frame after some random back-off interval.
  - Receiver acknowledges the correct reception of a data frame.
  - If the sender does not receive an acknowledgement, retry the data transmission

Initial 802.15.4 Mote Platforms

- Focused on low power
- Sleep - Majority of the time
  - Telos: 2.4mA
  - MicaZ: 30mA
- Wakeup
  - As quickly as possible to process and return to sleep
  - Telos: 290ns typical, 6ms max
  - MicaZ: 60ms max internal oscillator, 4ms external
- Process
  - Get your work done and get back to sleep
  - Telos: 4MHz 16-bit
  - MicaZ: 8MHz 8-bit
- TI MSP430
  - Ultra low power
    - 1.6mA sleep
    - 460mA active
    - 1.8V operation

- Standards Based
  - IEEE 802.15.4, USB
- IEEE 802.15.4
  - CC2420 radio
  - 250kbps
  - 2.4GHz ISM band
- TinyOS support
  - New suite of radio stacks
  - Pushing hardware abstraction
  - Must conform to std link
- Ease of development and Test
  - Program over USB
  - Std connector header
- Interoperability
  - Telos / MicaZ / ChipCon dev



UCB Telos

Xbow MicaZ

Microcontrollers

- Memory starved
  - Far from Amdahl-Case 3M rule
  - 2005 => 4x improvement
- Fairly uniform active inst per nJ
  - Faster MCUs generally a bit better
  - Improving with feature size
- Min operating voltage
  - 1.8 volts => most of battery energy
  - 2.7 volts => lose half of battery energy
- Standby power
  - Recently a 10x improvement
  - Probably due to design focus
  - Fundamentally SRAM leakage
  - Wake-up time is key
- Trade sleep power for wake-up time
  - Memory restore
- DMA Support
  - permits ADC sampling while processor is sleeping

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

2004: Microcontroller market responded substantially to WSN requirements

2005/6: Radio integration

2006/7: Proliferation and solidification

? - Complete SoC

Radio

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.

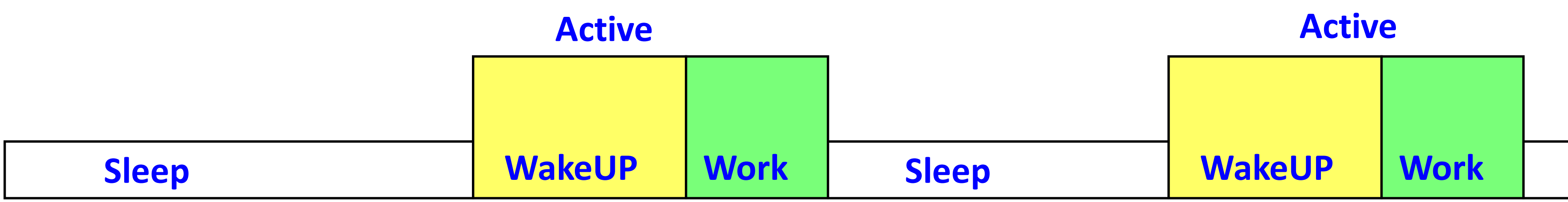
- Trade-offs:
  - resilience / performance => slow wake up
  - Wakeup vs interface level
  - Ability to optimize vs dedicated support

CMOS

- CMOS radios now widely available
  - 1 mW transmit power
  - Consume 10s mW transmitting, receiving, or listening
  - Nominal range 10’s of meters
    - Power grows as R3 or worse
- Substantial improvements in link coding
  - On/Off => Amplitude Shift => Frequency Shift narrow band
  - => Frequency tunable spread spectrum (802.15.4)
- 802.15.4 radio has gained wide adoption
  - IEEE only standardizes PHY to MAC
  - Many competing higher level protocols
    - ZIGBEE, several TinyOS Stacks, Ember, Dust, Sensicast, Millennial, … , IPv6
- Higher level hardware interfaces reduce processor load, but limit power optimizations
- Reliability must be addressed at higher levels too

Power States at Node Level

Operation	Telos	Mica2	MicaZ
Minimum Voltage	1.8V	2.7V	2.7V
Module Standby	5.1 μA	19.0 μA	27.0 μA
MCU Idle	54.5 μA	3.2 mA	3.2 mA
MCU Active	1.8 mA	8.0 mA	8.0 mA
MCU + Radio RX	21.8 mA	15.1 mA	23.3 mA
MCU + Radio TX (0dBm)	19.5 mA	25.4 mA	21.0 mA
MCU + Flash Read	4.1 mA	9.4 mA	9.4 mA
MCU + Flash Write	15.1 mA	21.6 mA	21.6 mA
MCU Wakeup	6 μs	180 μs	180 μs
Radio Wakeup	580 μs	1800 μs	860 μs



Telos: Enabling Ultra-Low Power Wireless Research, Polastre, Szewczyk, Culler, IPSN/SPOTS 2005

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, Z-Wwave, 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. Reception α Transmit x Density
  - Listening (potentially) happens all the time
- Total energy consumption dominated by idle listening

Sensors

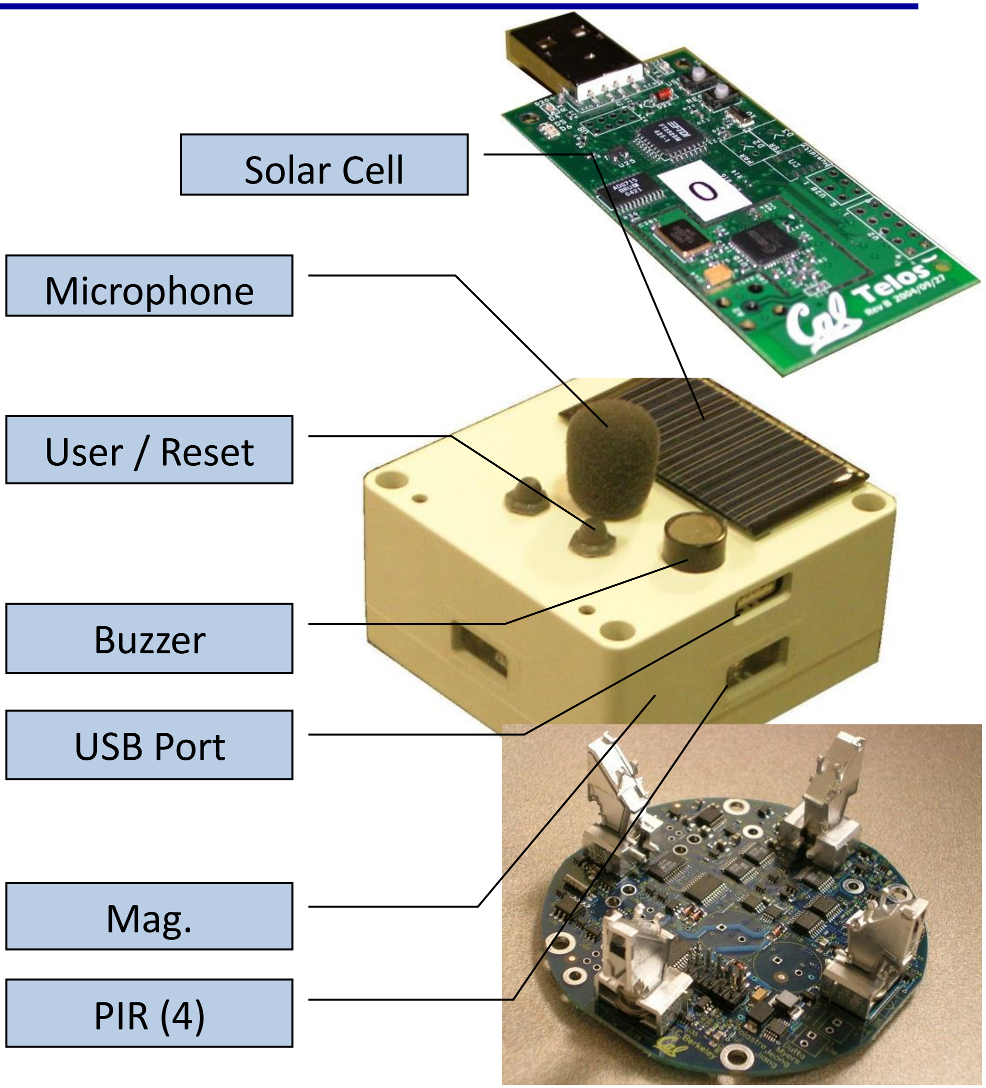
- ❑ Wide array of low-power micro sensors available
  - ❖ Temp, Light, Humidity, Acceleration, Mag, Pressure, …
- ❑ Several digital interfaces
  - ❖ RS232, SPI, I2C, …
- ❑ Too many analog interfaces
- ❑ Conventional external sensor very diverse
  - ❖ Excitation voltage
  - ❖ Bandpass, Op Amps, sensitivity, range, …
- ❑ In all cases, mechanical design is critical
  - ❖ Expose sensors, protect electronics

⇒ Hassle for node developers

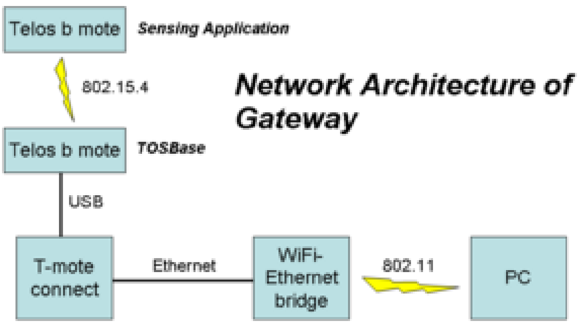
⇒ Vastly easier to integrate wireless (or wired) sensor modules than the sensors themselves

Trio Node

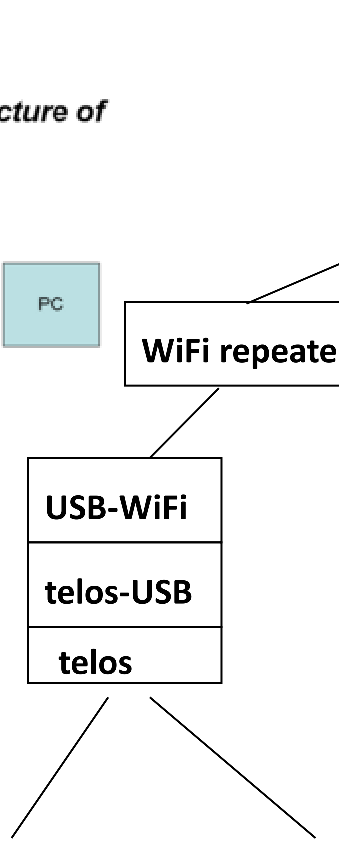
- Platform Goals
  - Permanent deployment
  - Weather resistance
  - Research-friendly
- Features
  - Telos (MCU, radio, flash)
  - Rich sensor-board
    - Solar Harvesting
    - Passive Infrared
    - Microphone
    - Magnetometer
    - Grenade Timer
- Improved Usability
  - Pushbuttons
  - Integrated Antenna
  - Exposed USB Connector



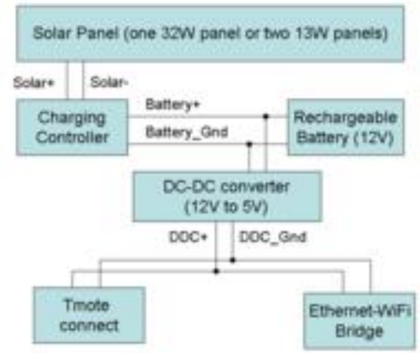
Self-powered Multi-Tier Network



COTS components



Tier2 node power supply schematic



The New Power Point

- Microcontrollers:
  - 1-10 mW active, 1 uW passive => 10-100 uW average
- Micro-sensors (MEMS, Materials, Circuits)
  - acceleration, vibration, gyroscope, tilt, magnetic, heat, motion, pressure, temp, light, moisture, humidity, barometric
  - chemical (CO, CO2, radon), biological, microradar, ...
  - actuators too (mirrors, motors, smart surfaces, micro-robots)
- Micro-Radios
  - CMOS, short range (10 m), low bit-rate (200 kbps), 10 mW
- Micro-Power
  - Batteries: 1,000 mW*s/mm3, fuel cells
  - solar (10 mW/cm2, 0.1 mW indoors), vibration (~uW/gm), flow
- 1 cm3 battery => 1 year at 1 msgs/sec

Passive Vigilance

- Sense only when there is something useful to detect
- Listen only when there is something useful to hear
- How do you know?
  - By arrangement
  - By cascade of lower power triggers

Trends and issues

- 2006-7 integrate 802.15.4 radio with microcontroller
  - 8051 or XAP2 1-address arch. with poor compilers
- Rapid migration of RISC cores
  - ARM and XSCALE moving down
- Improved system support

- MCU + Radio + Flash is universal
- Sensor suite, power subsystem, mechanical design are application specific
- *Mote will be manufactured in to end devices and building fixtures (or materials)*
- *Solution integrated through software*

Recent Developments

- ATMEL 1281 – more data RAM
- ATMEL RF230 – more TX and RX
  - Crossbow IRIS, Meshnetics Zigbit
- CC2530 – integrated 8051
  - Sensinode
- EM250 / EM260 – integrated XAP + zigbee stack
- Jennic – 32-bit processor + MB
- ARM Cortex – 32-bit Processor (e.g. CC2538)

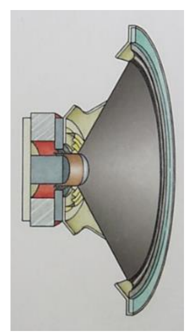
Microcontroller Analysis

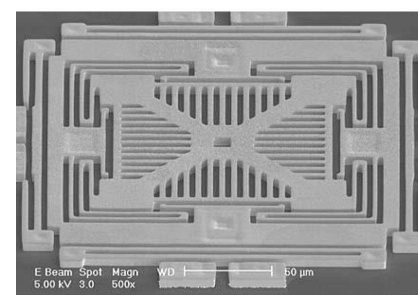
Mfg	Device	Year	Arch	GCC (y/n)	VCC (V)	RAM (kB)	Flash (kB)	Active (mA)	Sleep (μA)	Wake (μs)	Timer (bits)	DMA (y/n)	Area (mm^2)
Atmel	ATmega128L	2002	RISC/8	yes	2.7-5.5	4	128	5.5	10	1	8	no	81
	ATmega1281	2005	RISC/8	yes	1.8-5.5	8	128	3.2	1	8.4	8	no	81
	ATmega2561	2005	RISC/8	yes	1.8-5.5	8	256	3.2	1	8.4	8	no	81
Ember	EM250	2006	XAP2b/16	no	2.1-3.6	5	128	8	1.5	> 1000	16	yes	49
Freescale	HC05	1988	8-bit	no	3.0-5.5	0.3	0	1	1	> 2000	16	no	180
	HC08	1993	8-bit	no	4.5-5.5	1	32	1	20	4	16	yes	305
	HCS08	2003	8-bit	no	2.7-5.5	4	60	7.4	1	10	16	yes	144
	MC13213	2007	HCS08	no	2.0-3.4	4	60	6.5	35	10	16	yes	81
Jennic	JN5121	2005	RISC/32	yes	2.2-3.6	96	128	4.2	3.5	0.2	16	yes	64
	JN5139	2007	RISC/32	yes	2.2-3.6	96	128	2.7	1.3	0.2	16	yes	64
TI	MSP430F14xx	2000	RISC/16	yes	1.8-3.6	2	60	1.5	1	6	16	no	81
	MSP430F16xx	2004	RISC/16	yes	1.8-3.6	10	48	2	1	6	16	yes	81
	MSP430F2618	2007	RISC/16	yes	1.8-3.6	8	116	0.5	0.5	1	16	yes	144
	CC2430	2007	8051	no	2.0-3.6	8	128	5.1	0.5	4	8/16	yes	49
ZiLOG	eZ80F91	2004	ez80/16	no	3.0-3.6	8	256	50	50	3200	16	yes	169

- Low active current
- Low Sleep Current / Fast Wake up
- 16-bit Sleep timer
- Large RAM
- DMA
- Operating Range

An Analog World

- ❑ Everything in the physical world is an analog signal
  - ❖ Sound, light, temperature, gravitational force
- ❑ Need to convert into electrical signals
  - ❖ Transducers: converts one type of energy to another
    - Electro-mechanical, Photonic, Electrical, …
  - ❖ Examples
    - Microphone/speaker
    - Thermocouples
    - Accelerometers
- ❑ And digitize
- ❑ Then manipulate

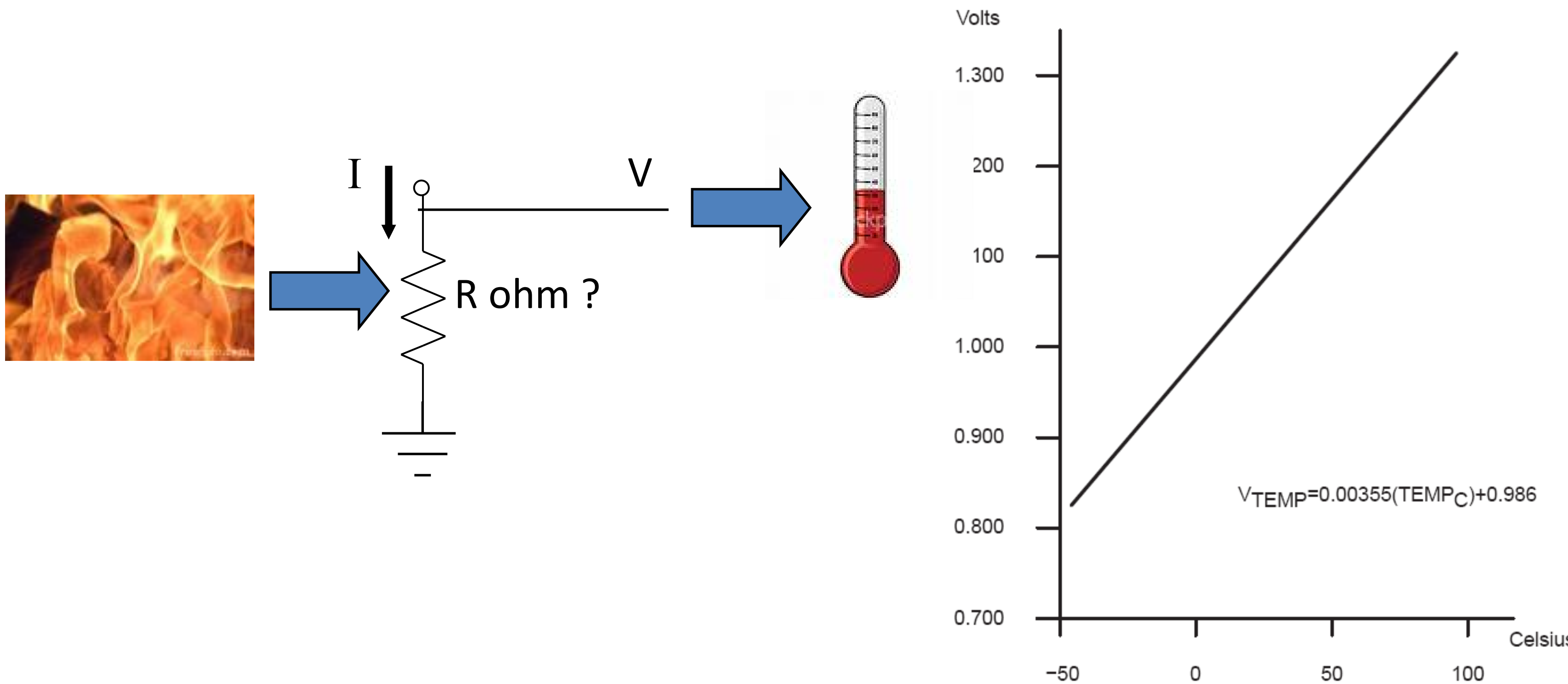




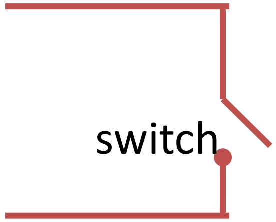
An Analog World

❑Transducers

❖Allow us to convert physical phenomena to a voltage potential in a well-defined way.

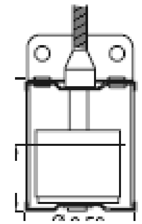


Simplest Analog Device



- ❑ Often think of it as an actuator, rather than a sensor
  - ❖ But that's because of the circuit we put it in
- ❑ It is binary (two states) but why is it not digital?

Rain Sensor



Water Level Float Sensor

Temperature Switch

Flow Sensor

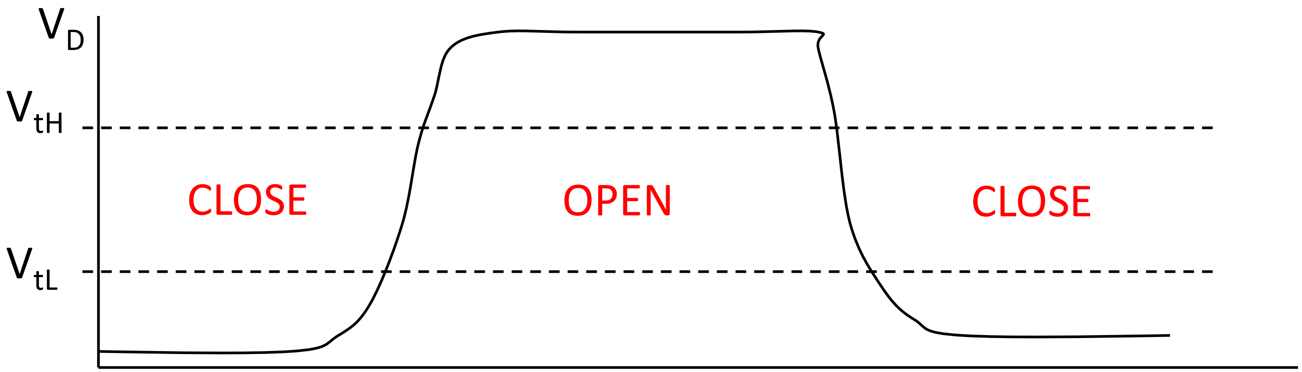
Pressure Switch

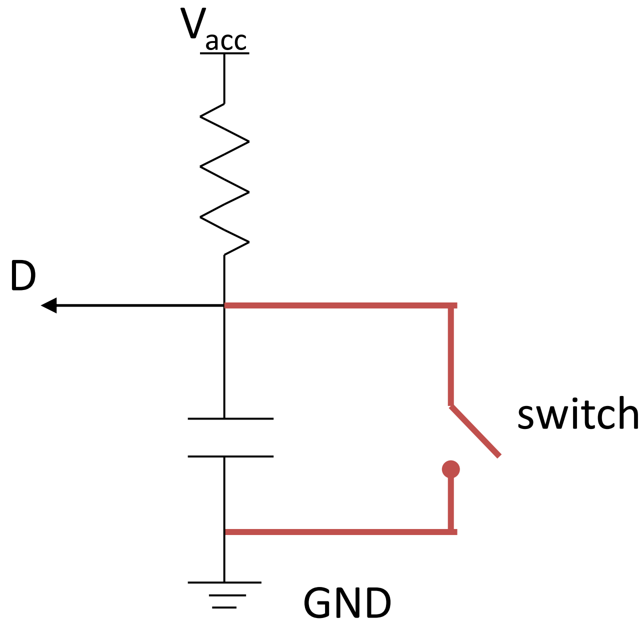
Magnetic Reed Contact Switch

Tilt Sensor

PhotoInterrupter

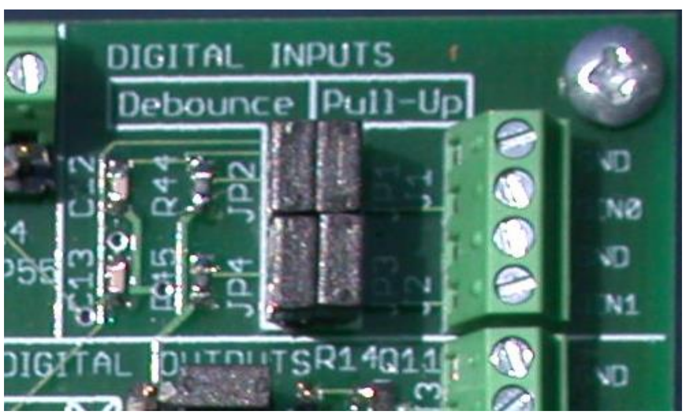
To Sample a switch, make it digital

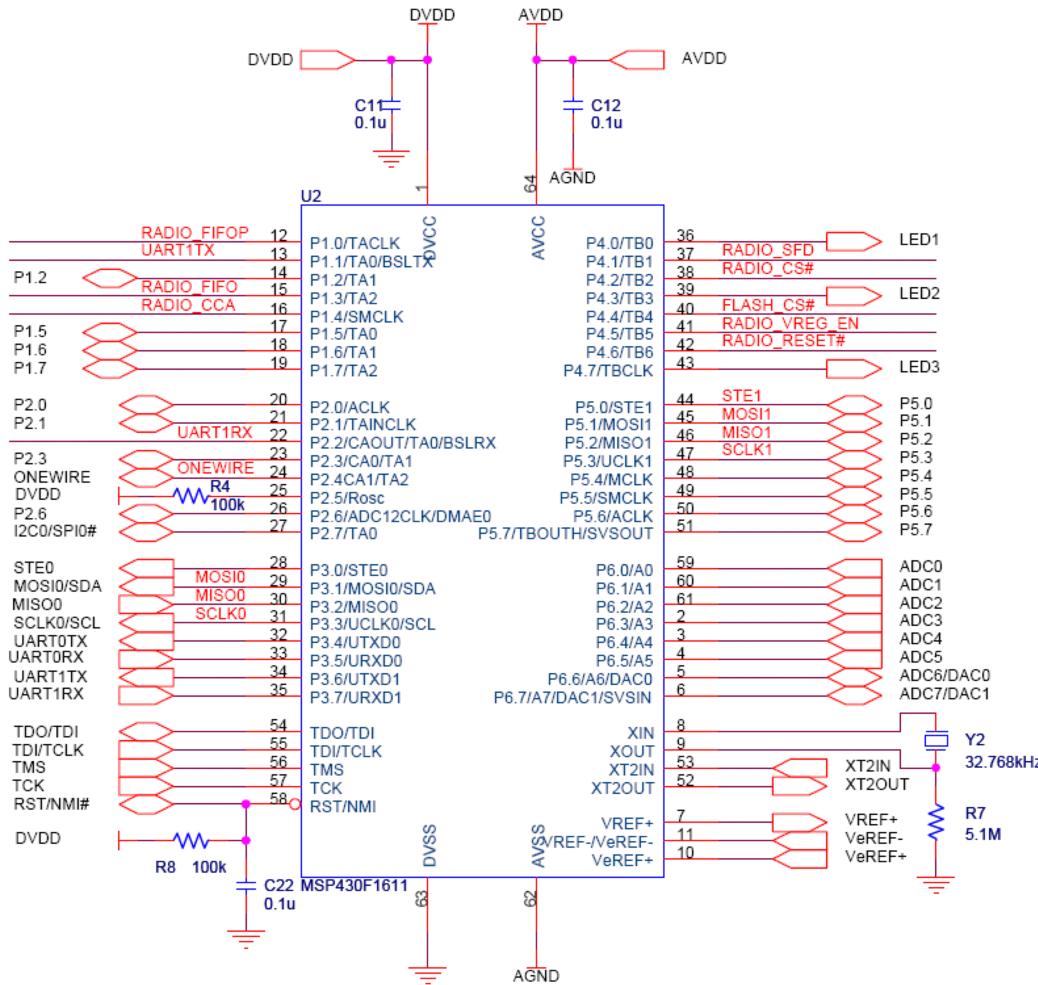




- Many sensor are switches
- Two “states” but not digital
  - Open => no current
  - Closed => no voltage drop
- Capacitor charges to $\mathbf{V_{acc}}$ when open
- Capacitor discharges to GND when closed

Getting Input into the MCU



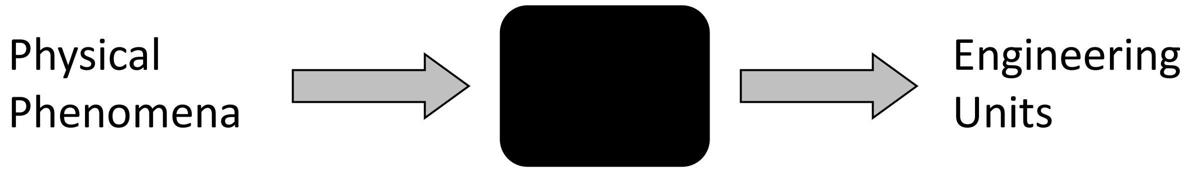


Making Sense of Physical Information

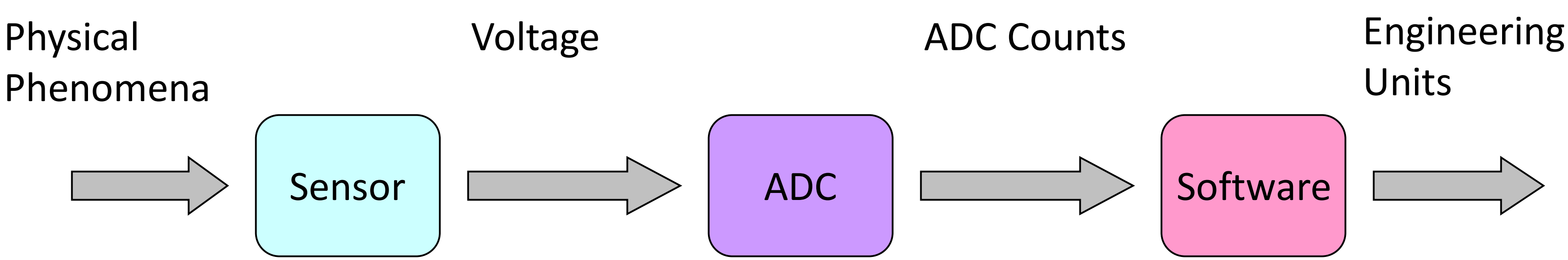
- Digital representation of physical phenomenon
  - Transducer => Signal Conditioning => ADC =>
  - Conversion to physical units
  - Calibration and correction
  - Here: 0 / 1, True / False
- Associating meaning to the reading
  - Open / Closed
  - Empty / Full
  - In Position / Not
- Depends on the specific device taking the reading
- The Context of the device

Analog to Digital

- What we want



- How we have to get there

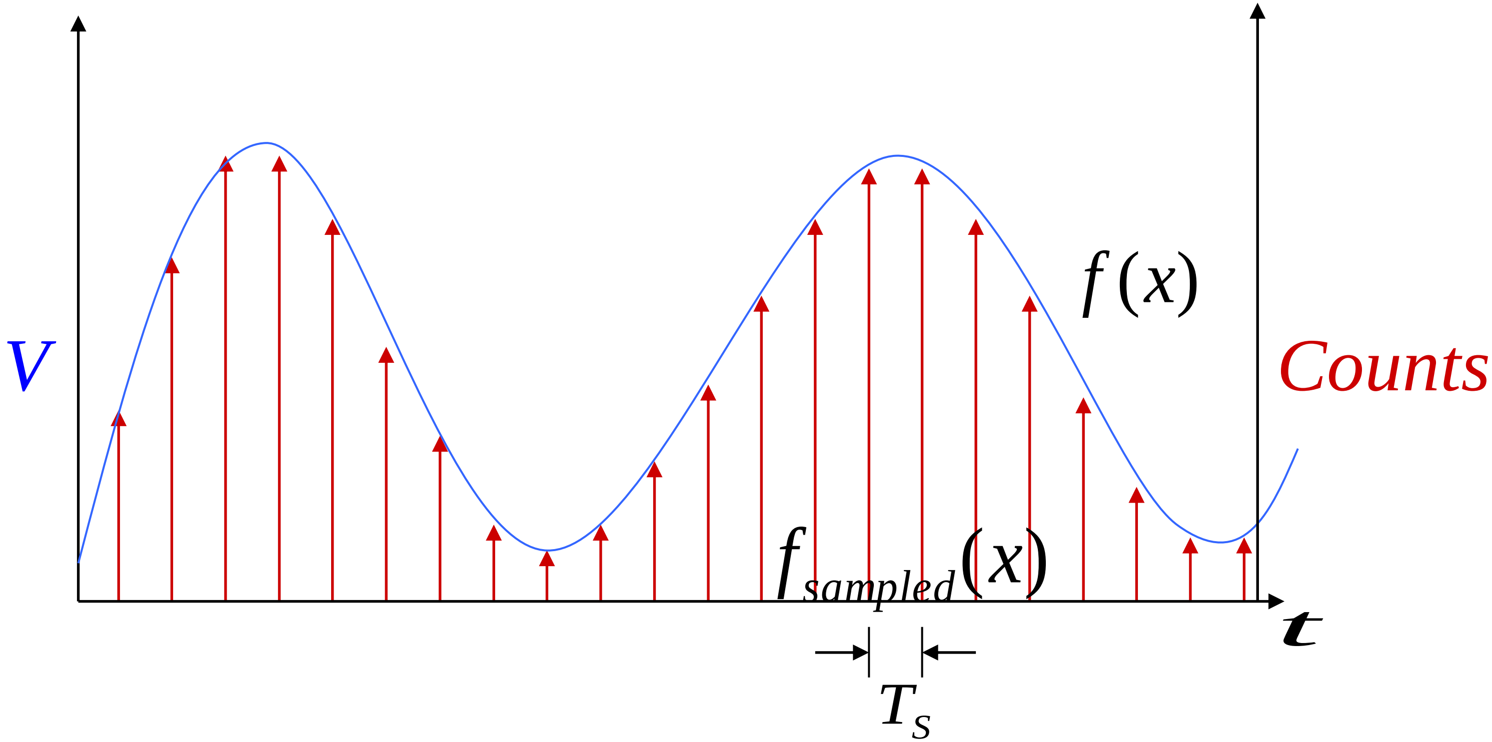


Sampling Basics

❑ How do we represent an analog signal?

❖ As a time series of discrete values

- On the MCU: read the ADC data register periodically

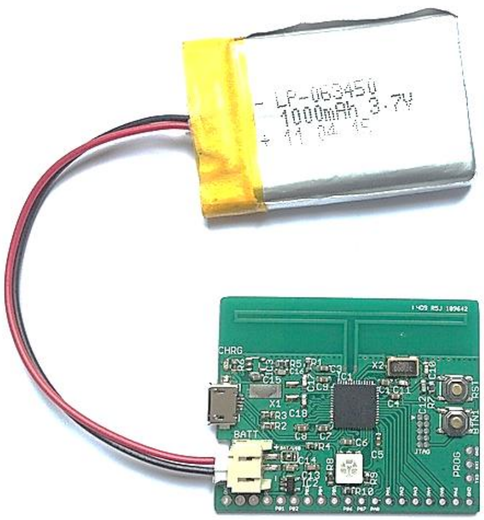


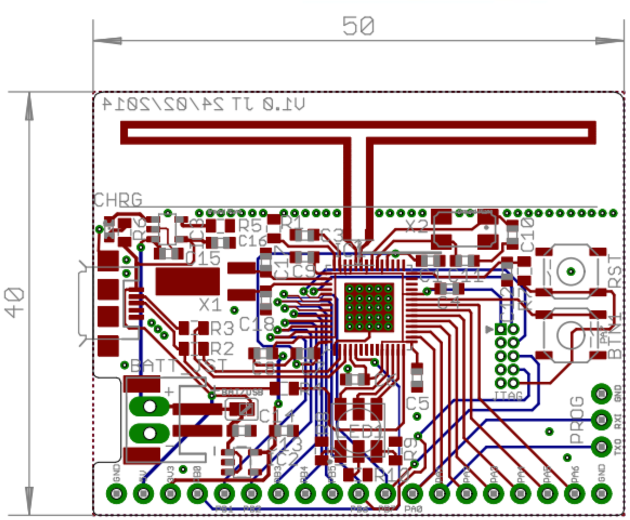
Analog-to-Digital Basics

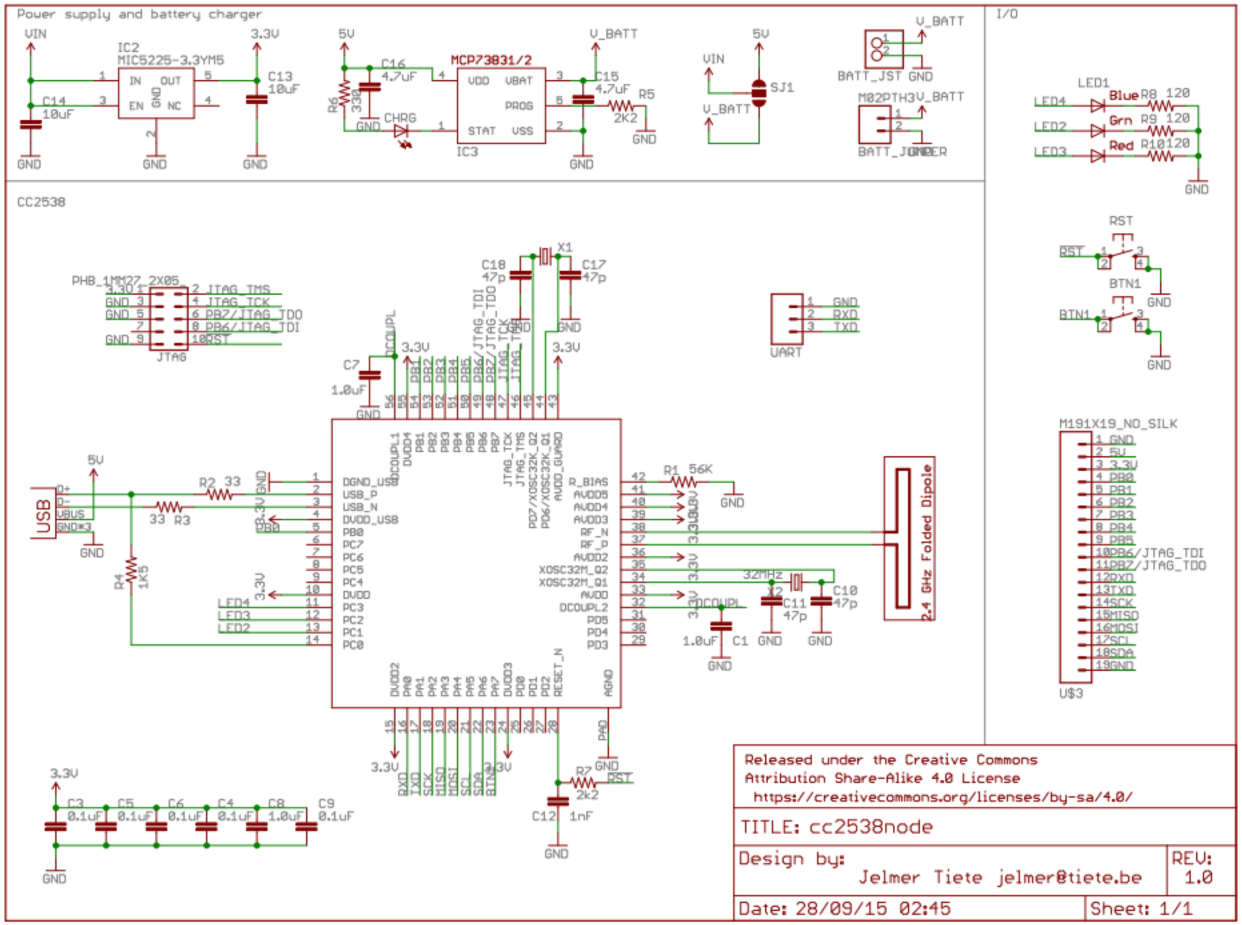
- So, how do you convert analog signals to a discrete values?

- A software view:
  1. Set some control registers :
     - Specify where the input is coming from (which pin)
     - Specify the range (min and max)
     - Specify characteristics of the input signal (settling time)
  2. Enable interrupt and set a bit to start a conversion
  3. When interrupt occurs, read sample from data register
  4. Wait for a sample period
  5. Repeat step 1

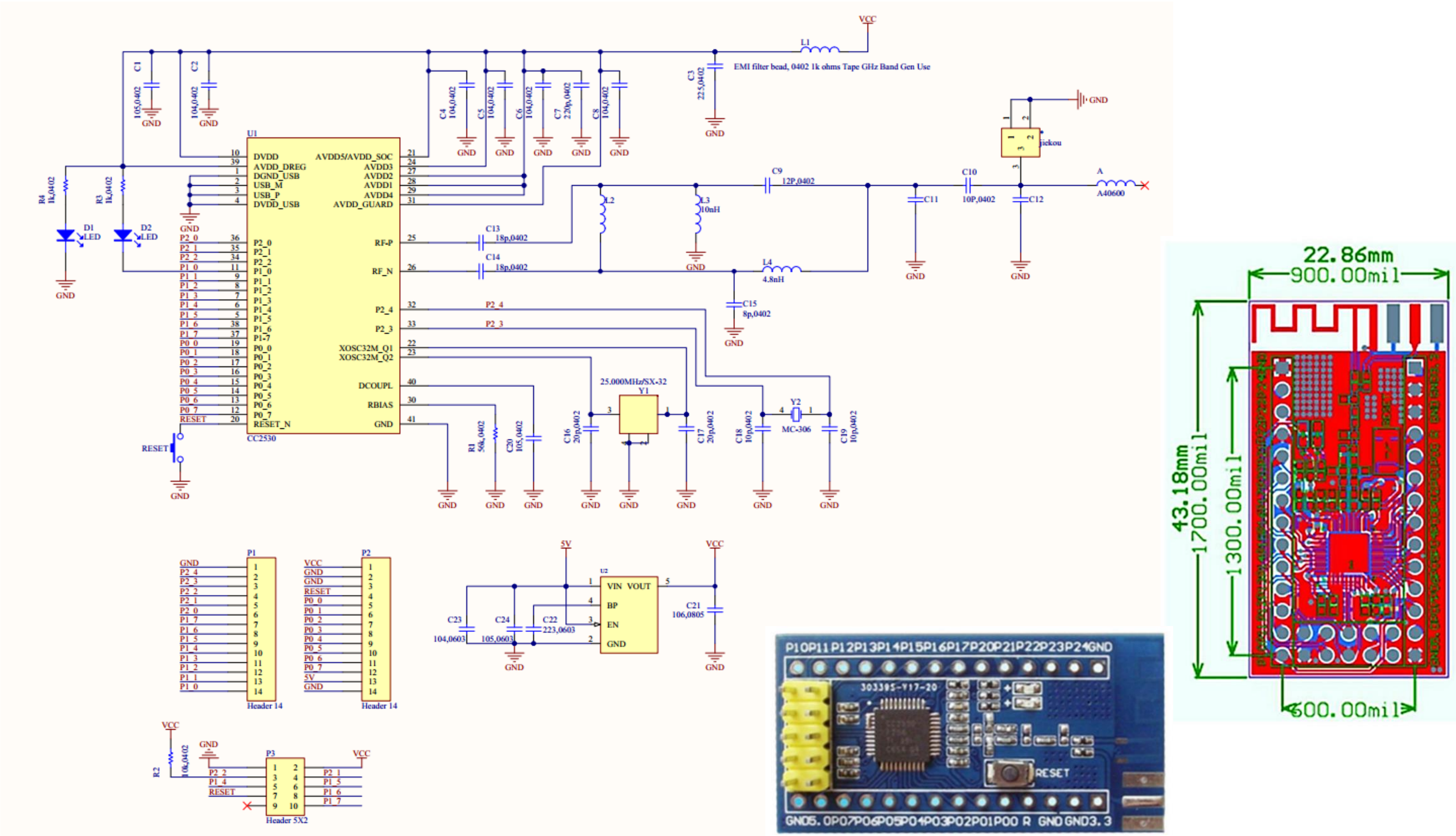
CC2538 Reference design







CC2530 Reference design



Interfaces

- ❑ I/O pins
- ❑ UART
- ❑ SPI
- ❑ I2C
- ❑ Others