Networks for the IoT (Internet of Things)

Hardware considerations

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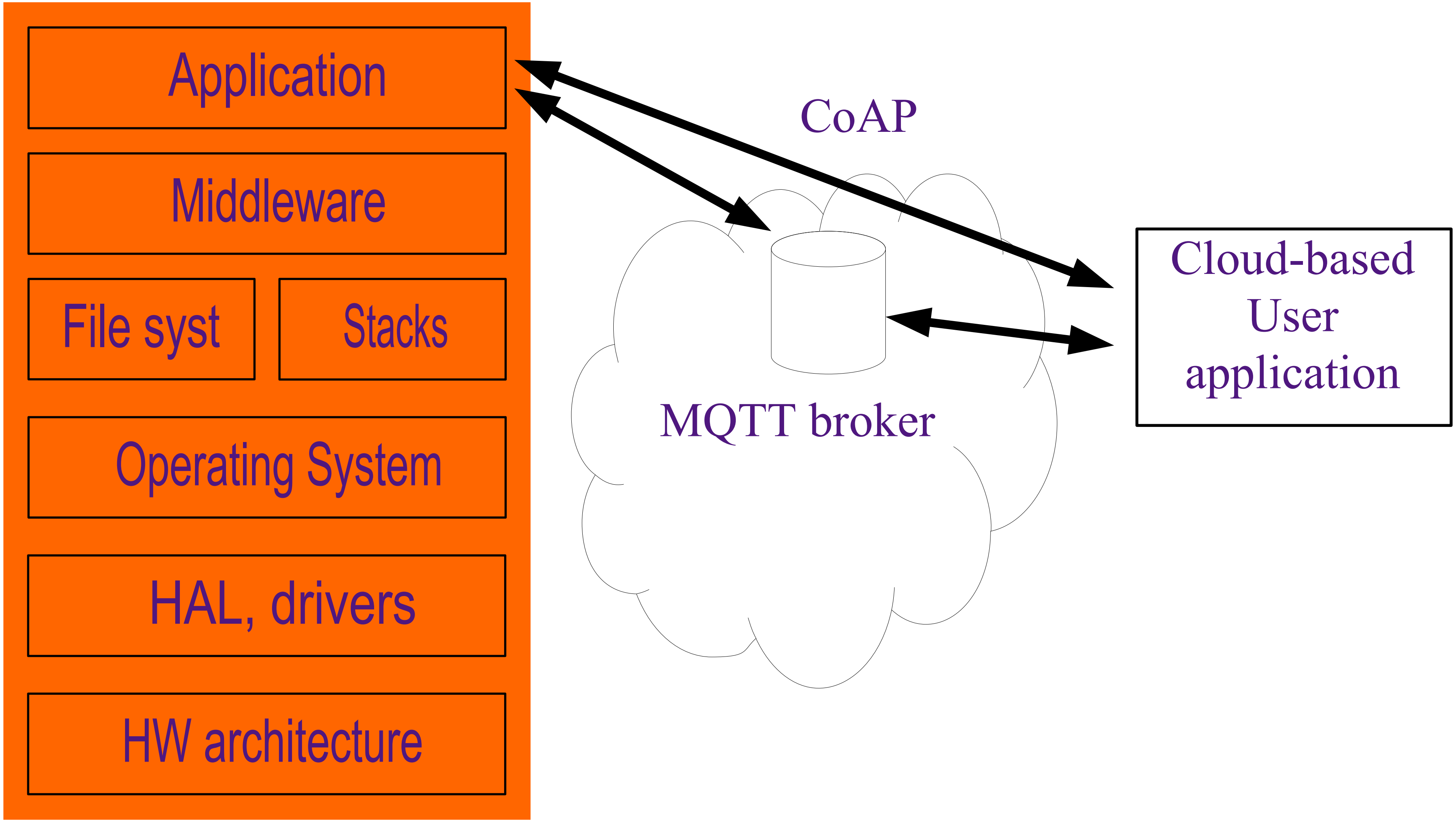
Agenda

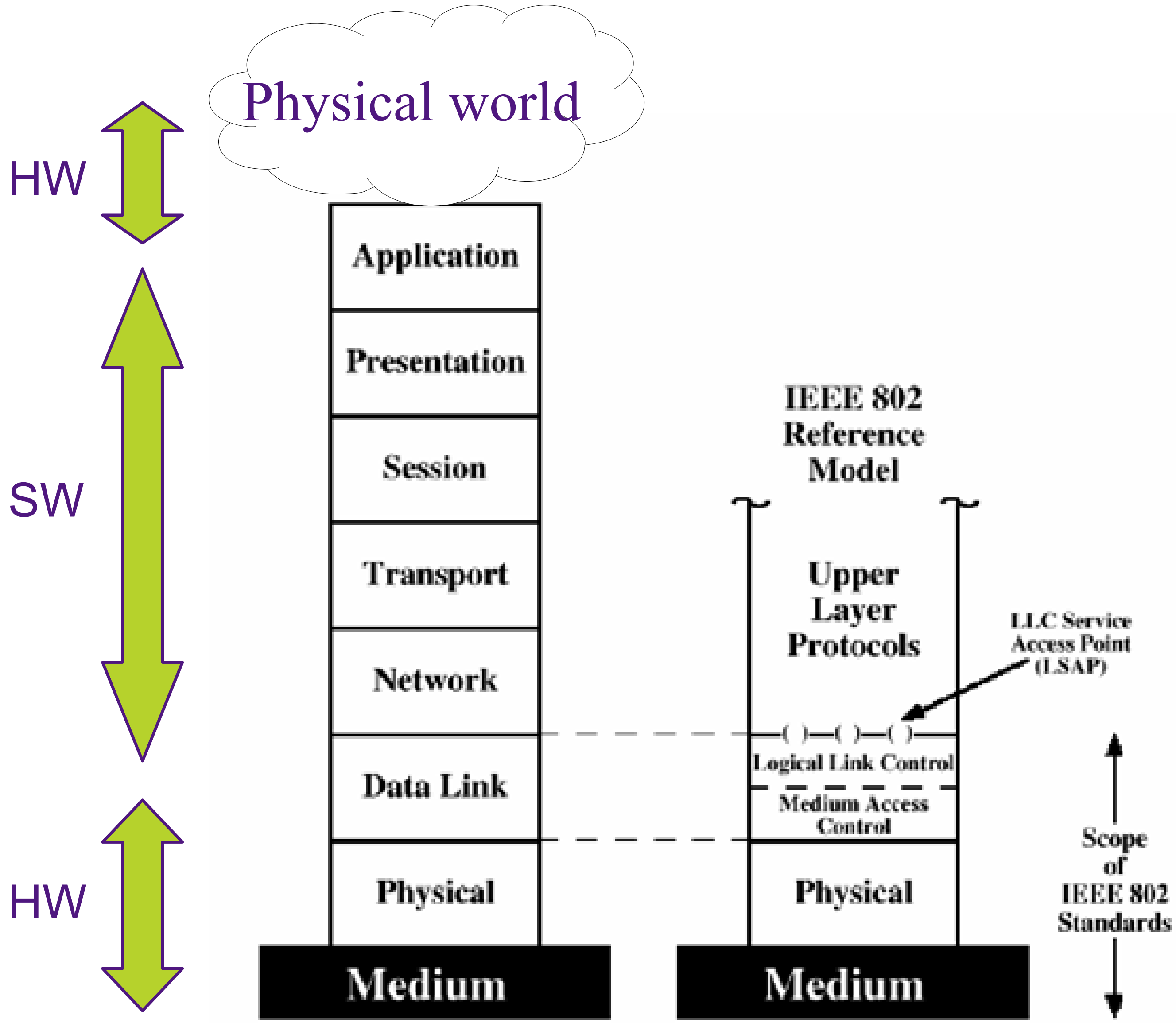
- Introduction
- Some experimentation boards and platforms
- Energy source, energy consumption
- Microcontrollers, memory
- Spectrum, PHY layer and radio chips
- Conclusions

Introduction

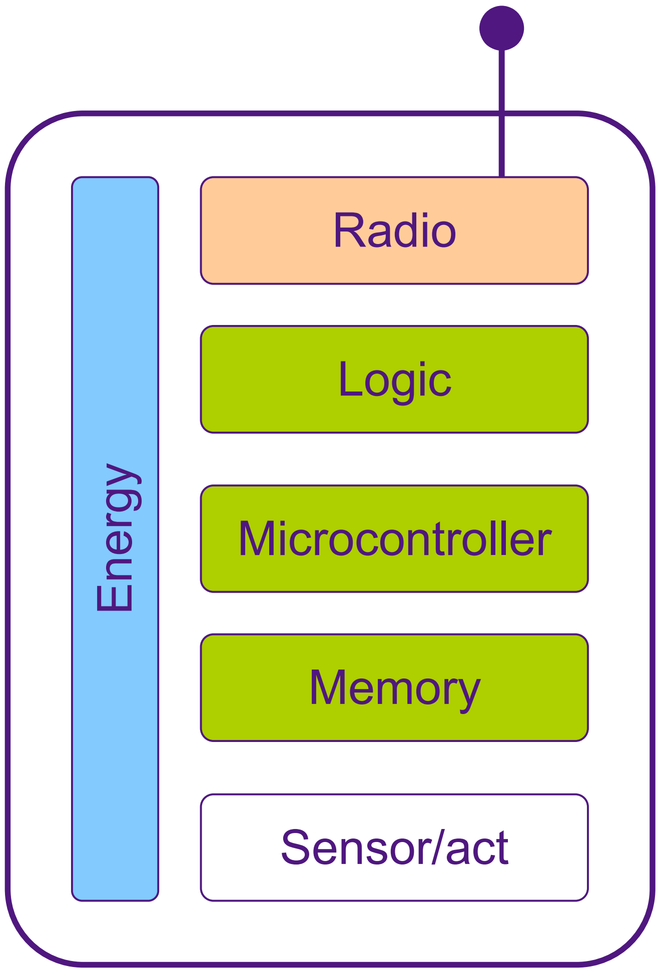
IoT not only a « software » issue



IoT device « networking » architecture



IoT device « hardware » architecture



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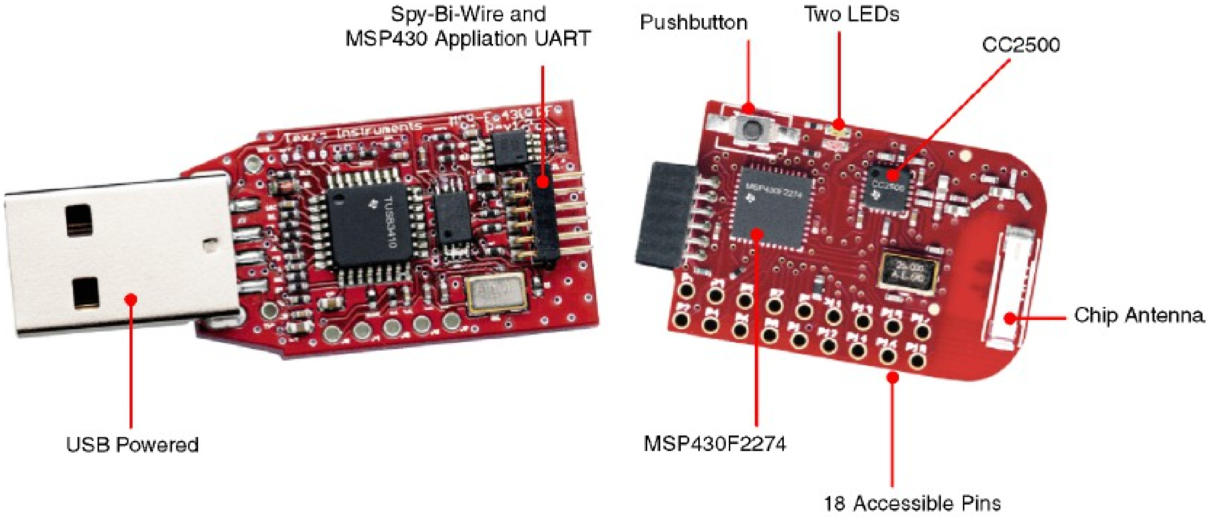
Experimentation boards and platforms

A range of boards

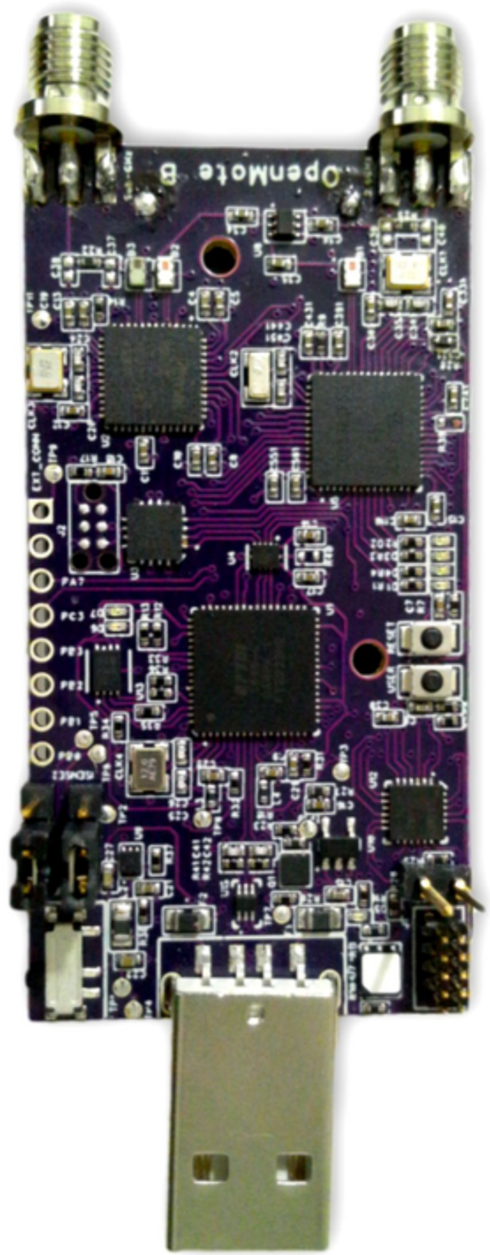
TI eZ430-RF2500

- TI starter kit
  - MSP430F2274, 16 MHz RISC
    - 32 KB flash, 1 KB RAM
  - CC2500 radio
    - IEEE 802.15.4 2.4 GHz compliant
  - Ceramic chip antenna
  - 50 m range LOS
  - Temp sensor, push button, 2 LEDs
  - Analogue and digital IOs
  - USB interface for programming and data exchange



OpenMote-B

- TI CC2538 SoC
  - ARM Cortex M3
  - 512 KiB Flash, 32 KiB RAM
  - 2.4 GHz radio, IEEE 802.15.4 compliant
- Atmel RF86RF215 radio
  - 868/915 MHz and 2.4 GHz
  - supports all IEEE 802.15.4g modulations
- Temp/humidity sensor
- User button, 4 LEDs
- Current monitoring jumpers
- Contiki, RiOT, OpenWSN support

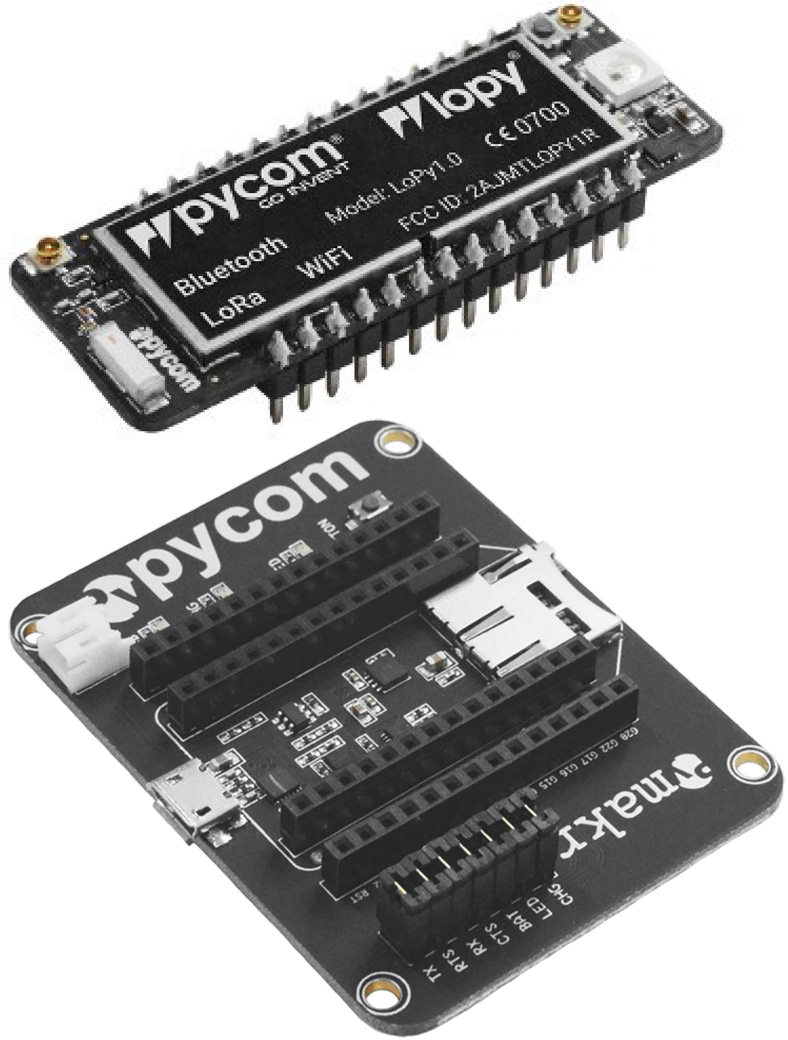


www.openmote.com

Pycom board

- ESP32 processor
- Native MicroPython interpreter
- File system, USB
- Interactive execution over serial port
- File synchronisation and detached execution
- Proprietary form factor and connector

- FiPy
  - Dual-core LX6 processor, ULP co-processor
  - 520 KB RAM, serial 8 MB Flash + 4 MB RAM
  - LTE-m/NB1 + Sigfox + LoRaWAN + BT4.2 + WiFi b/g/n

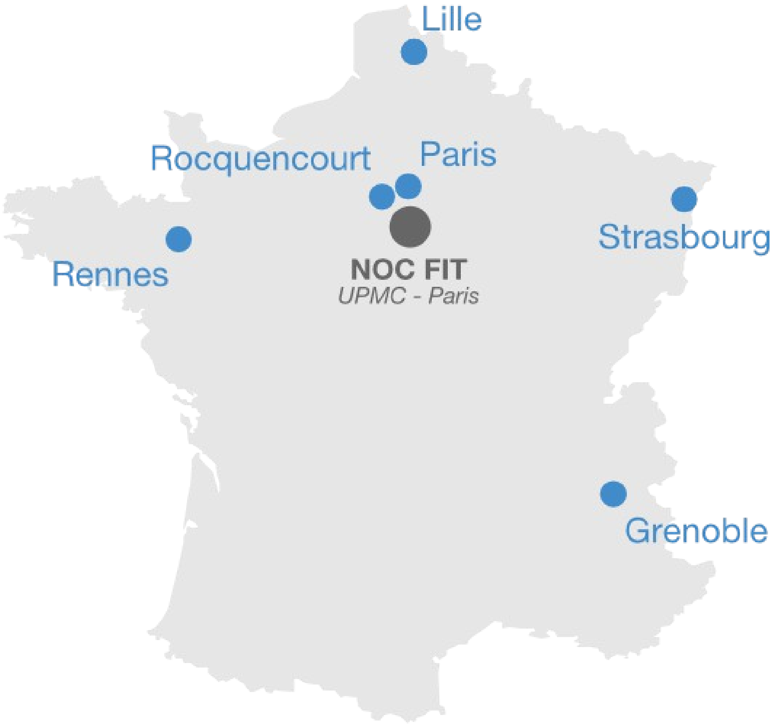


Large experimentation platforms

FIT/IoT-Lab platform

- opened Nov 2014
- 2700 nodes over 6 sites
- 4 diff. architectures
  - MSP430, Cortex M3, A8 processors
  - 868 MHz, 802.15.4 2.4 GHz radios
- some mobile nodes
  - trains, robots

www.iot-lab.info



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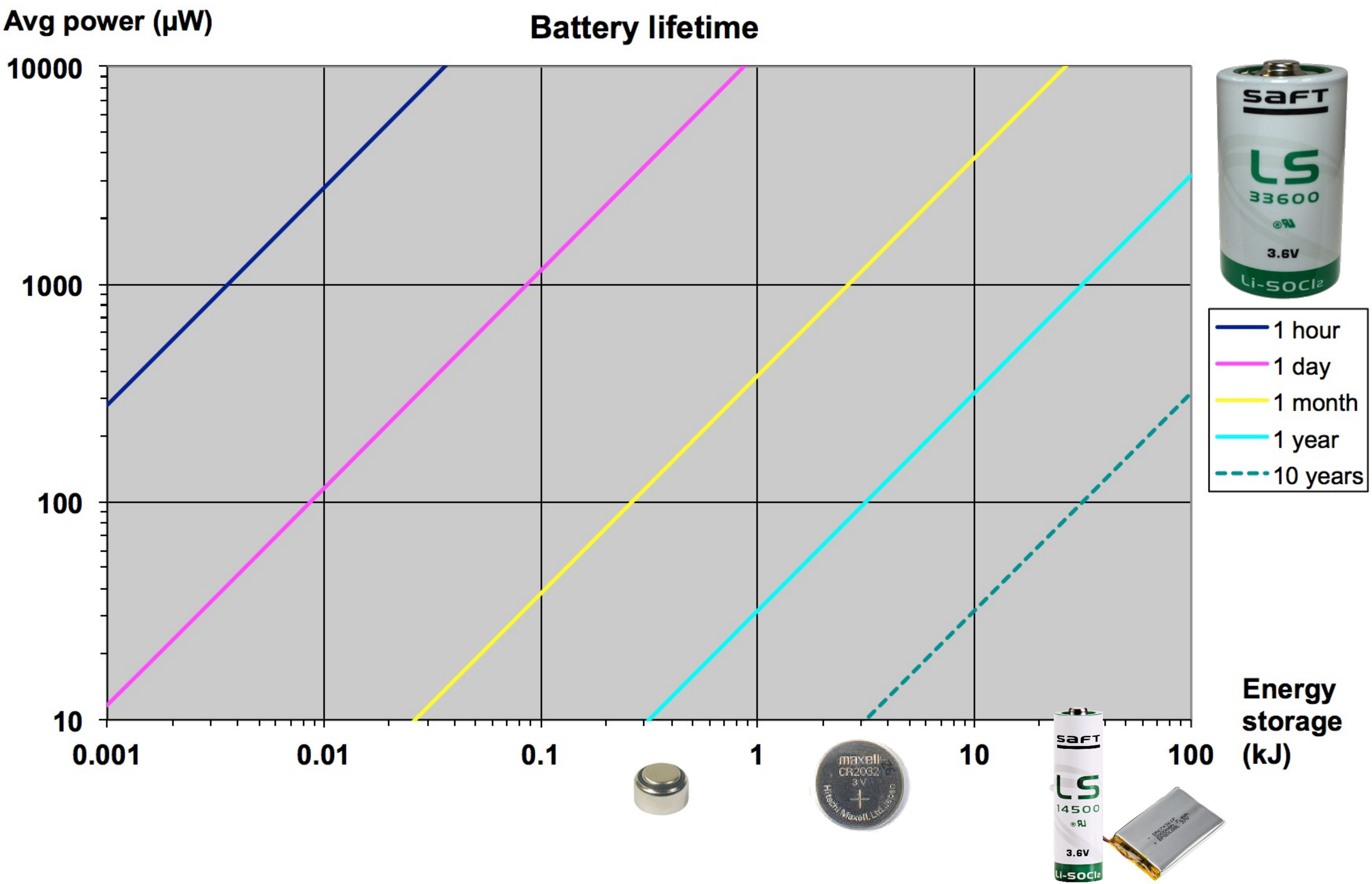
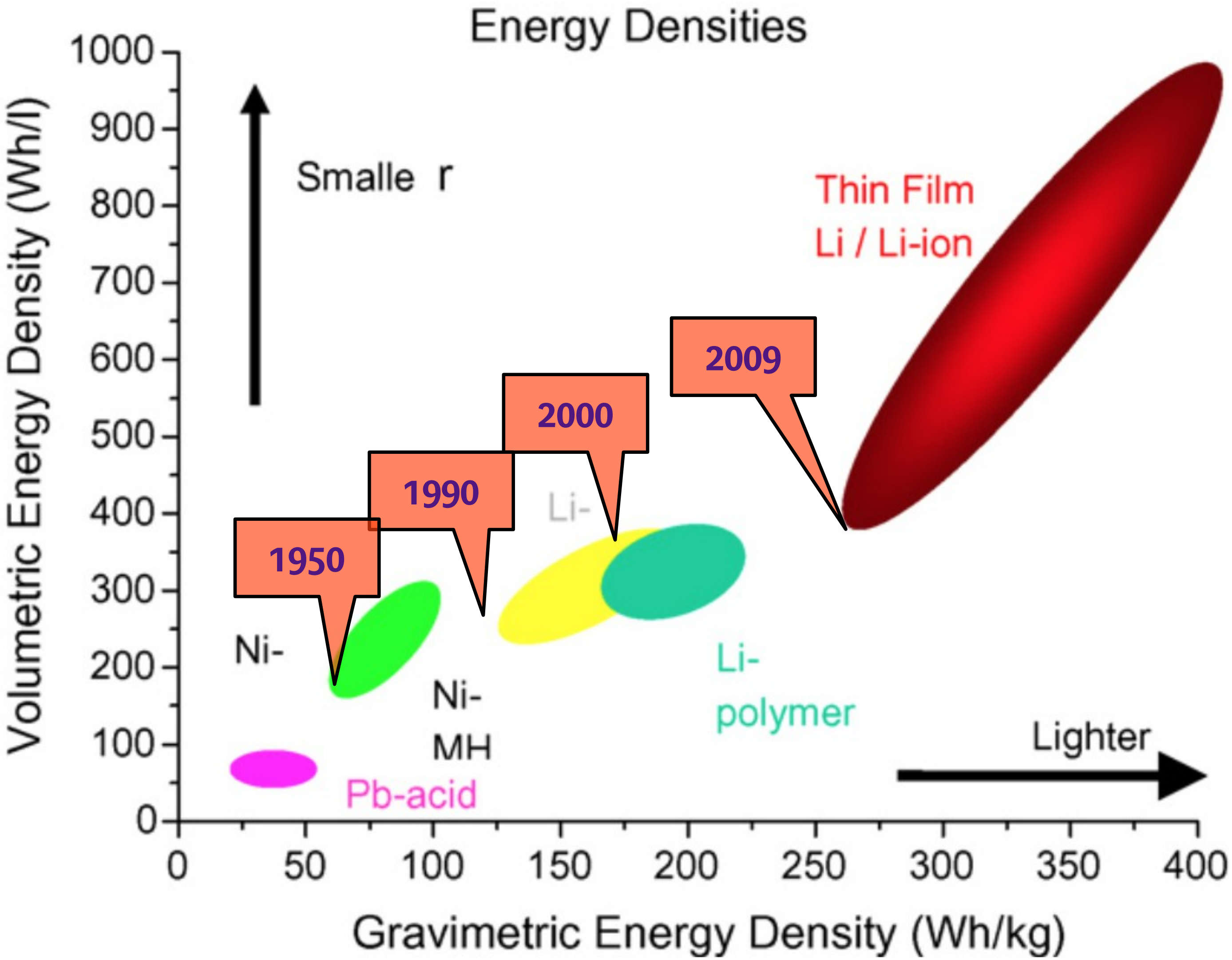
Energy source, energy consumption

Energy source for sensor node



Rechargeable batteries performance

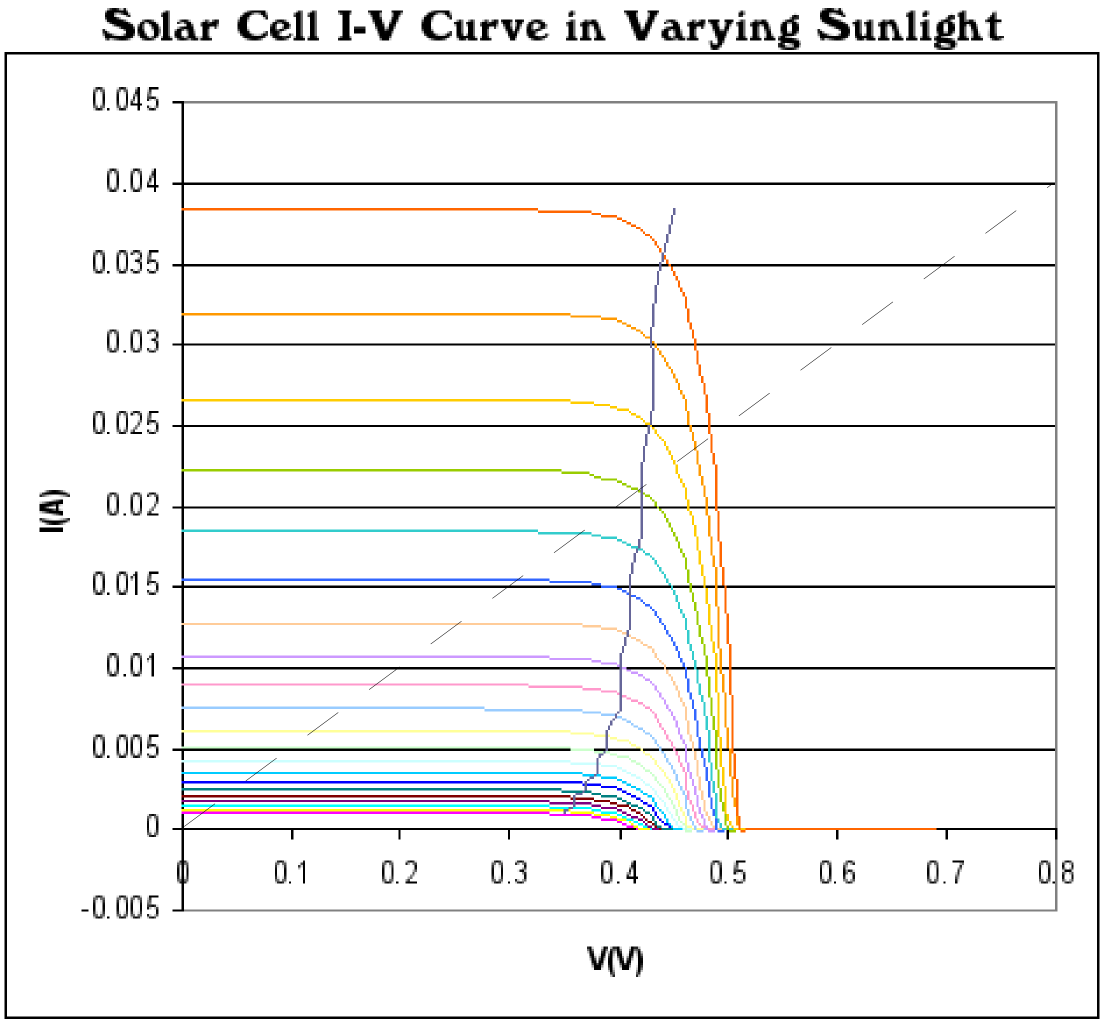
- Performance has doubled over two decades

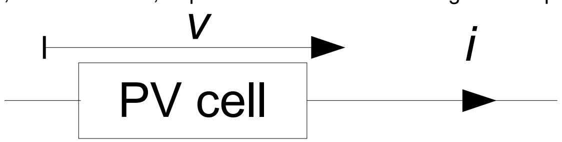


A. Patil, et al., "Issue and challenges facing rechargeable thin film lithium batteries", Materials Research Bulletin, vol. 43, 2008, 1913-1942

Solar energy harvesting

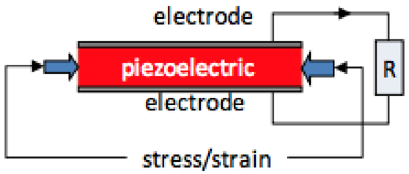
- Solar radiance
  - 1 kW/m^2 = 100 mW/cm^2
- Solar cell efficiency
  - Organic : 8-10%
    - perovskites: 20%
  - Silicon : 12-18%
  - Research: 40%
- Harvesting
  - 1 - 10 mW/cm^2 sunlight
  - 10 - 100 µW/cm^2 indoors
- Maximum Power Point ?

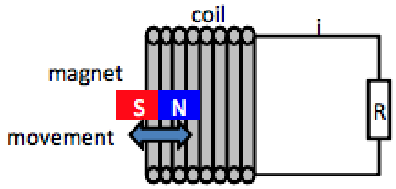




Vibration energy harvestings

Piezoelectric converters	Electromagnetic converters	Electrostatic converters
Use of piezoelectric materials	Use of Lenz's law	Use of a variable capacitor structure





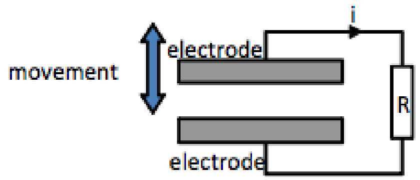


Table 5. Electret-free electrostatic vibration energy harvesters from the state of the art

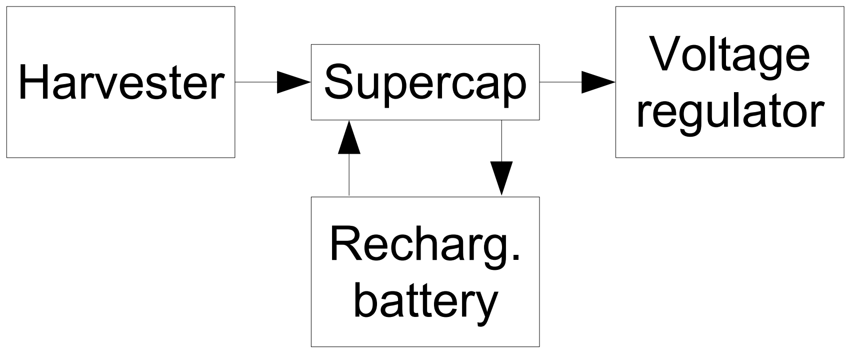
Author	Ref	Output power	Surface	Volume	Polarization voltage	Vibrations
Tashiro	[19]	36 µW		15000 mm³	45V	1,2G@6Hz
Roundy	[24]	11 µW	100 mm²	100 mm³		0.23G@100Hz
Mitcheson	[25]	24 µW	784 mm²	1568 mm³	2300 V	0.4G@10Hz
Yen	[26]	1,8 µW	4356 mm²	21780 mm³	6 V	1560Hz
Despesse	[21]	1050 µW	1800 mm²	18000 mm³	3 V	0.3G@50Hz
Hoffmann	[23]	3.5 µW	30 mm²		50 V	13G@1300-1500Hz
Basset	[22]	61nW[1]	66 mm²	61.49mm³	8 V	0.25G@250Hz

S. Boisseau, G. Despesse and B. Ahmed Seddik, Electrostatic Conversion for Vibration Energy Harvesting, Small-Scale Energy Harvesting, Intech, 2012

$$C = \varepsilon . S / d \; ; \qquad Q = CV \; ; \qquad dE = V . dQ$$

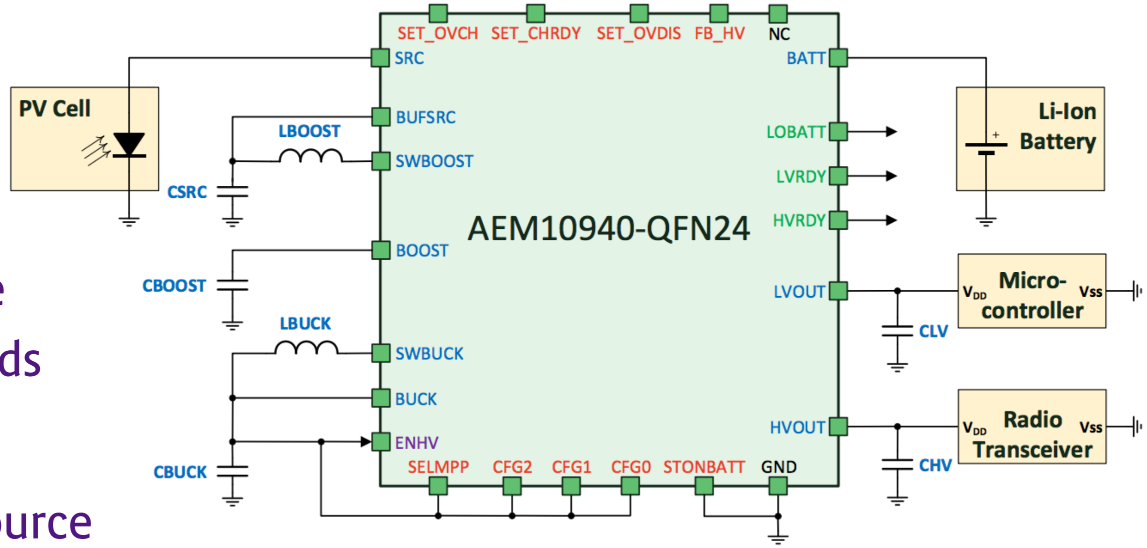
Energy storage for sensor node

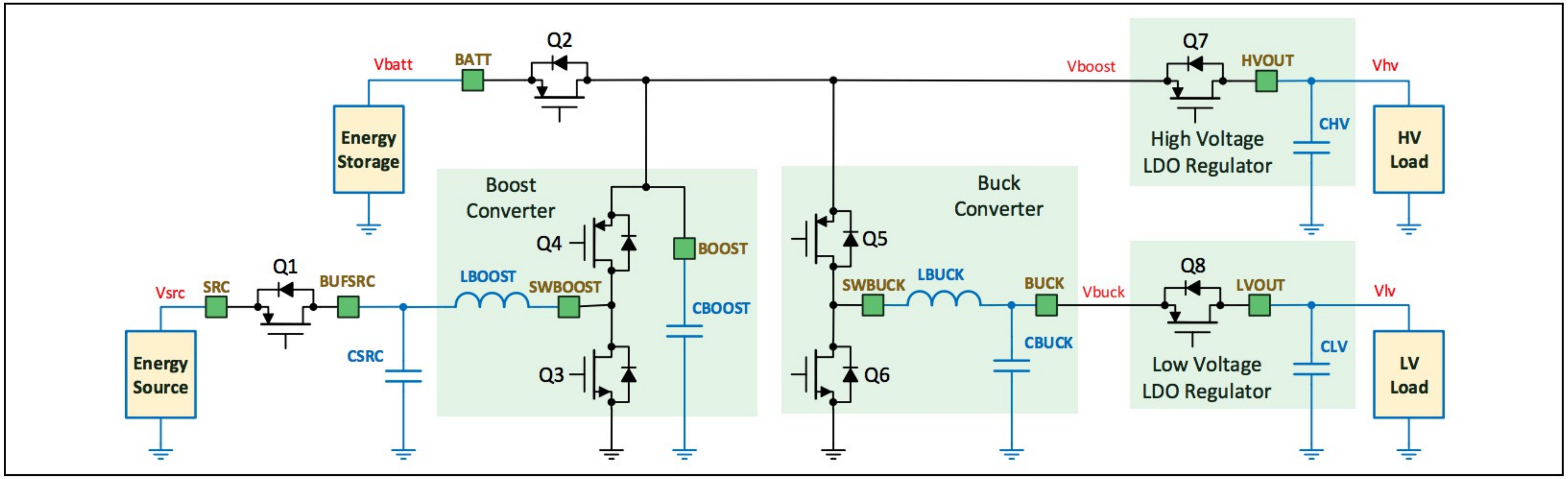
- Primary battery
  - Shelf life
  - Limited current
    - voltage drop, aging
    - requires parallel capacitor
  - Temperature
- Temporary storage
  - Rechargeable battery
    - Yield ~ 90%, limited current
    - A few A.h under 3.7 V
  - Supercap
    - high current, 95% yield,
    - a few F capacity



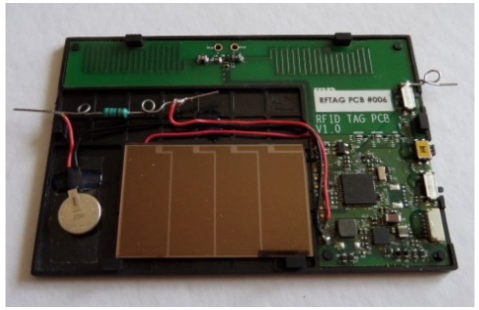
Scavenging electronics

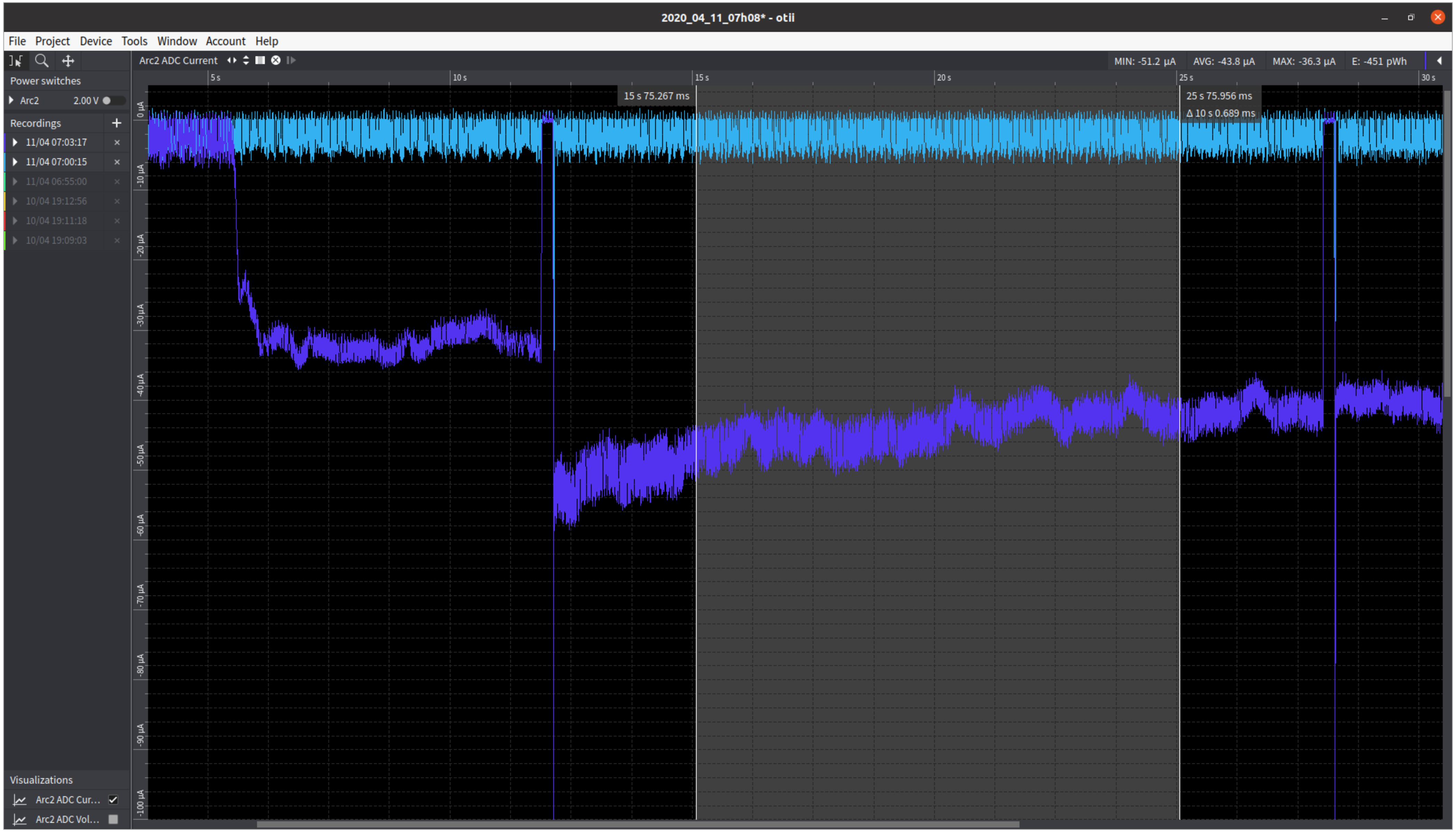
- Goals
  - Deal with variable source voltage, power
  - Control storage charge/discharge
  - Deliver regulated voltages to loads
- Example : AEM10940
  - Cold start at 0.38 V and 11 uW source
  - Sustained operation at 0.1 V source



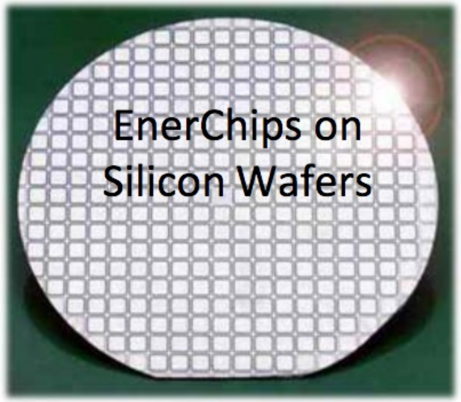


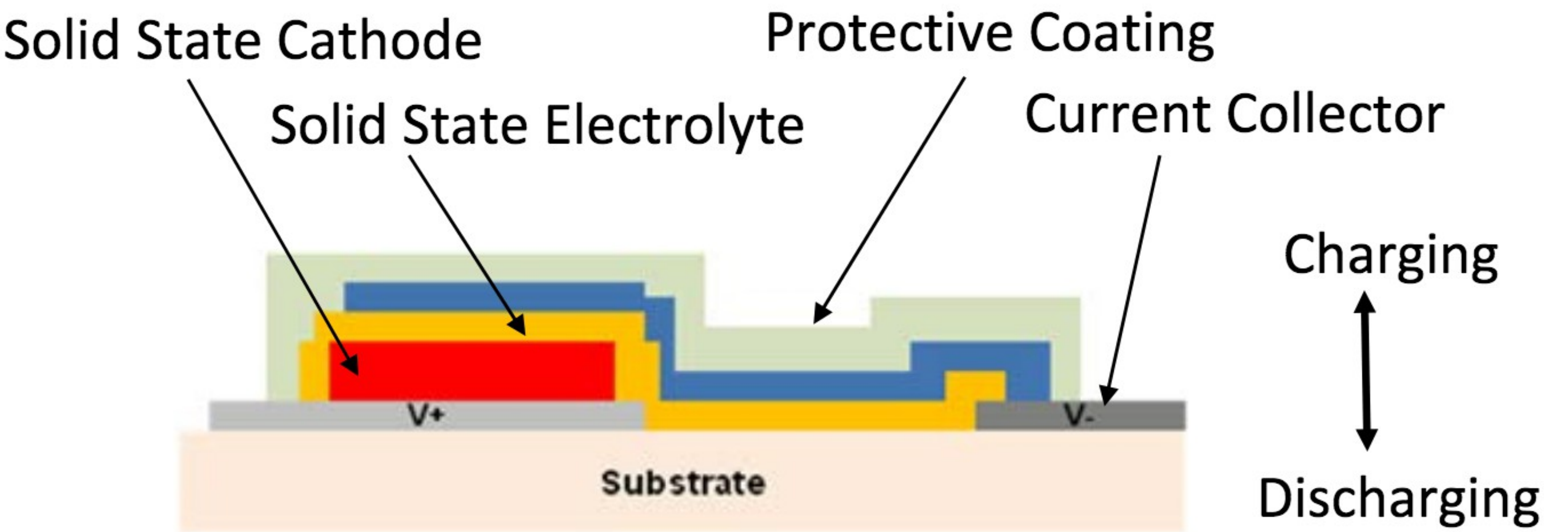
MPTT operation





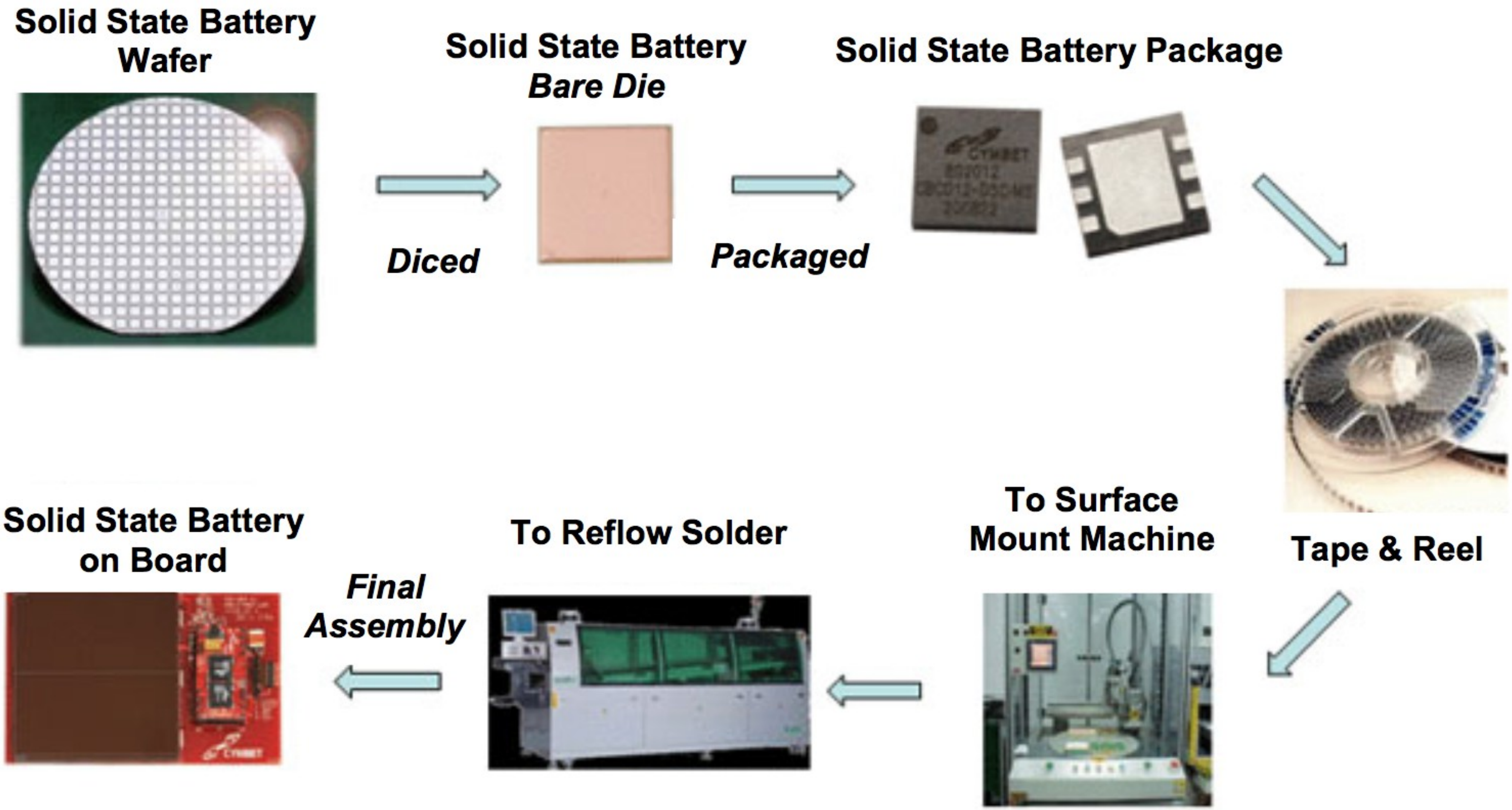
Thin Film Lithium batteries on Silicon





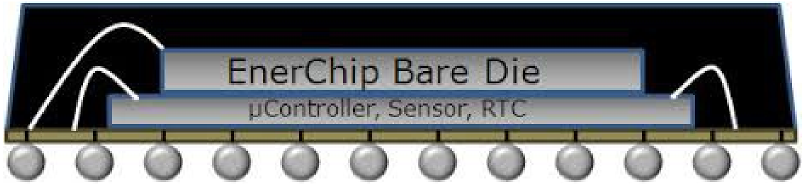
https://www.cymbet.com/wp-content/uploads/2019/02/Sensors-Expo-2013-Engineering-Ultra-low-power-SoC-sensors.pdf

Battery chips used as any other chip

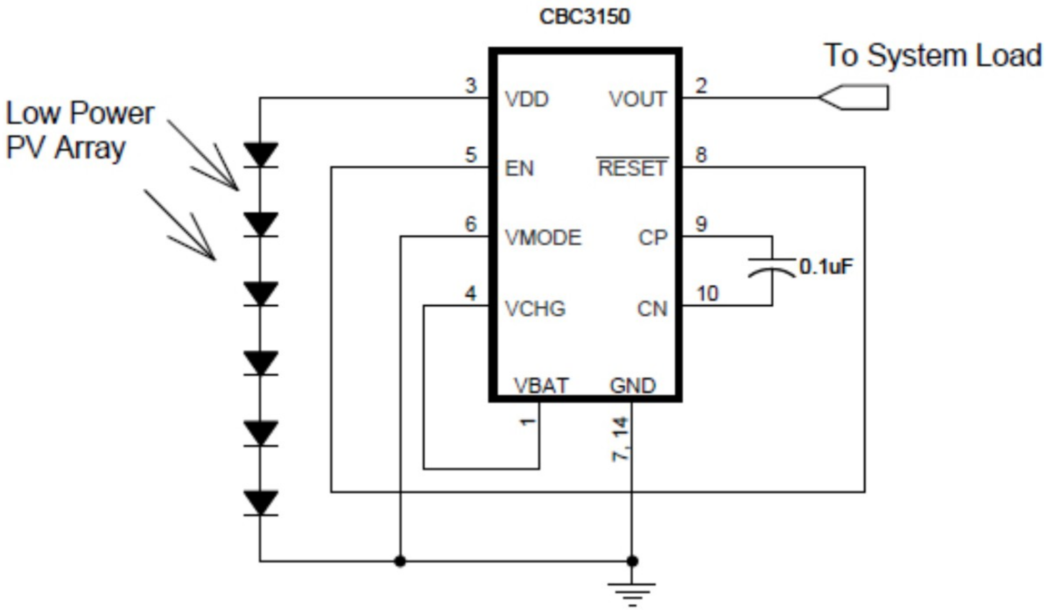


Stev Grady, Cymbet Coorporation, "Powering Wearable Technology and Internet of Everything Devices",
https:// www.cymbet.com/wp-content/uploads/2019/02/Powering-Wearable-Technology-and-the-Internet-of-Everything-WP-72-10.1.pdf

Multiple chips in package



- CBC3150
  - 0.2 J, 1 kohm Rint
  - 3.3 V, 10 uA typ output
  - 2.5 – 5.5 V input
  - 9 * 9 mm
  - $3 (2018)



- https://www.cymbet.com/wp-content/uploads/2019/02/Sensors-Expo-2013-Engineering-Ultra-low-power-SoC-sensors.pdf

Energy consumption

- Mostly dissipated into heat
  - Except actuation energy, radiation energy

- Static dissipation
  - Analogue (linear) electronics
    - Radio
    - Sensors
    - Energy management
  - Digital electronics (CMOS)
    - Leakage

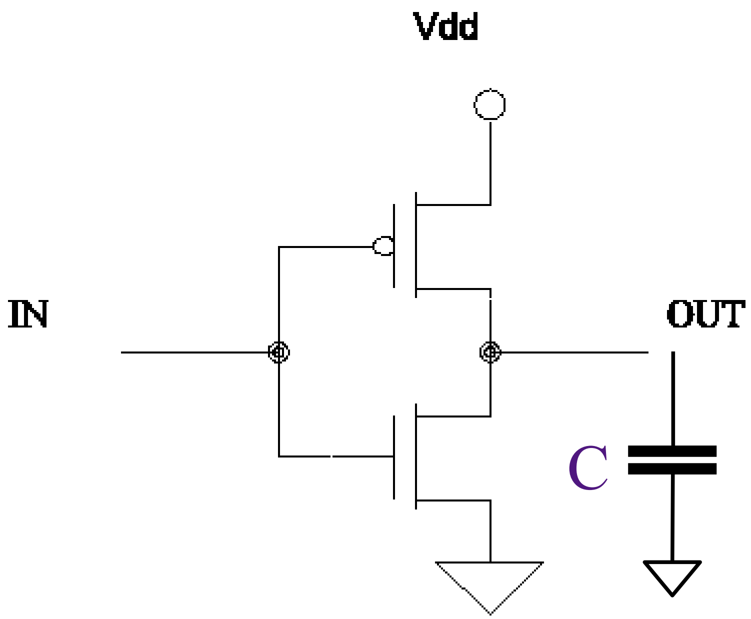
- Dynamic dissipation
  - Digital electronics (CMOS)
    - Voltage changes on digital signals : $E = ½ C V^2$

Dynamic power consumption

CMOS logic

- Voltage-based logic
  - “1” = 3.3V, “0” = 0V

- Current only needed to fill or drain output capacitance



Energy stored in capacitor

$$dQ = C\,.\,dv = i\,.\,dt$$

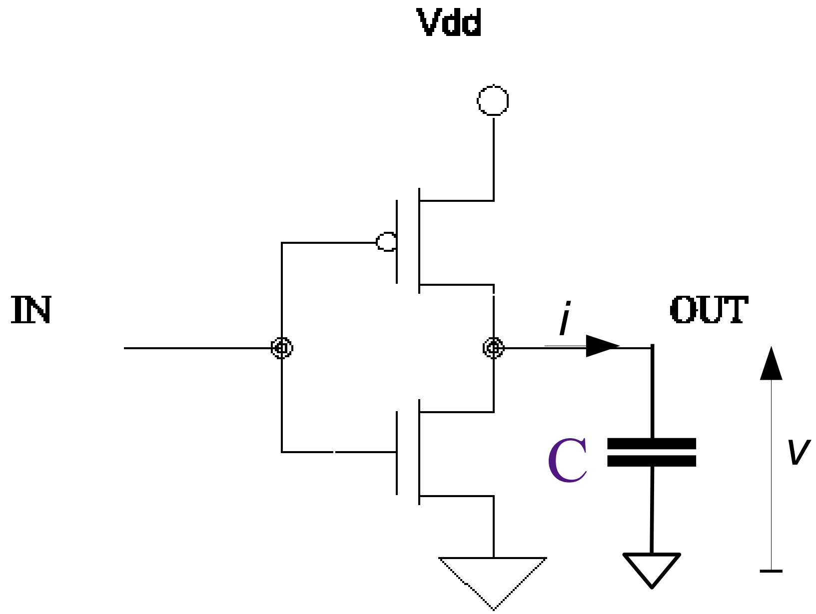
$$i = C\,.\,\frac{dv}{dt}$$

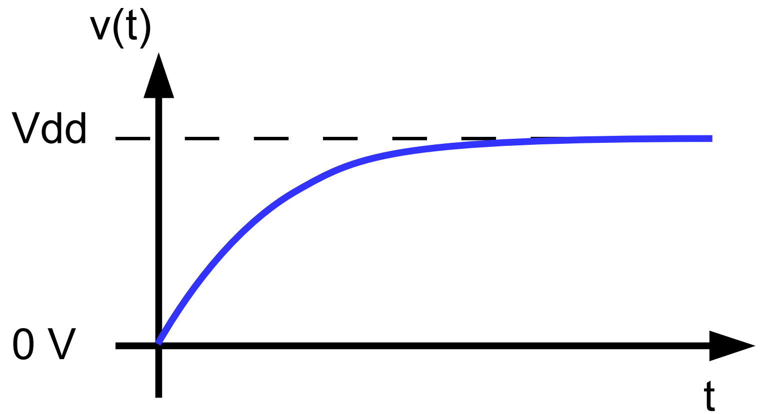
$$p_c = v.i = C\,.\,v\,.\,\frac{dv}{dt}$$

$$E_c = \int_0^{\infty} p_c(t)\,.\,dt = C.\int_0^{\infty} v\,.\,\frac{dv}{dt}\,.\,dt$$

$$= C.\int_0^{Vdd} v\,.\,dv = \frac{1}{2}\,.\,C.\left[v^2\right]_0^{Vdd}$$

$$= \frac{1}{2}\,.\,C.\,Vdd^2$$





Energy supplied by system

$$dQ = C\,.\,dv = i\,.\,dt$$

$$Q = \int_0^{\infty} i\,.\,dt = \int_0^{\infty} C\,.\,\frac{dv}{dt}\,.\,dt$$

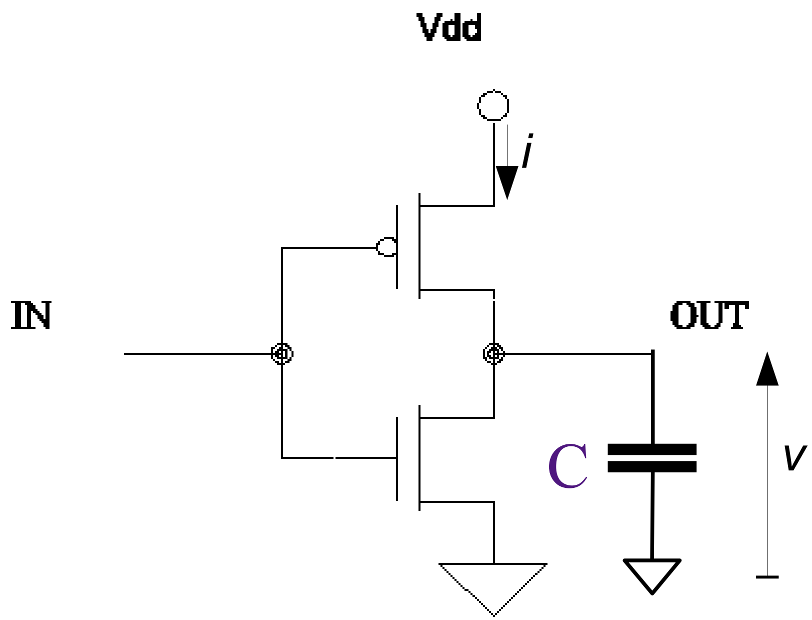
$$= C\,.\int_0^{Vdd} dv = C\,.\,Vdd$$

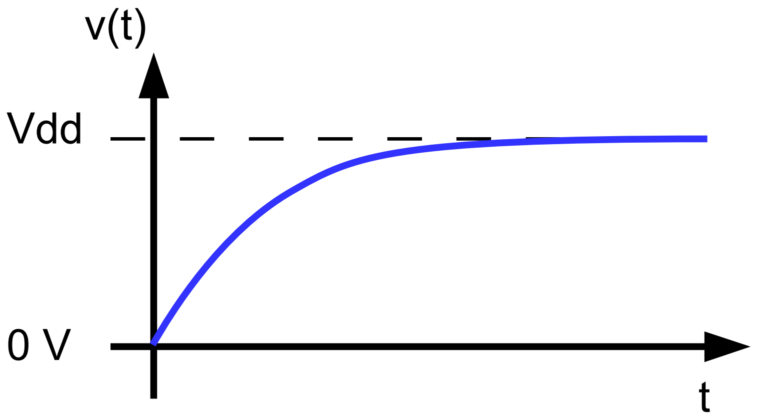
$$p_s = Vdd\,.\,i$$

$$E_s = \int_0^{\infty} p_s(t)\,.\,dt = \int_0^{\infty} Vdd\,.\,i\,.\,dt$$

$$= Vdd\,.\int_0^{\infty} i\,.\,dt$$

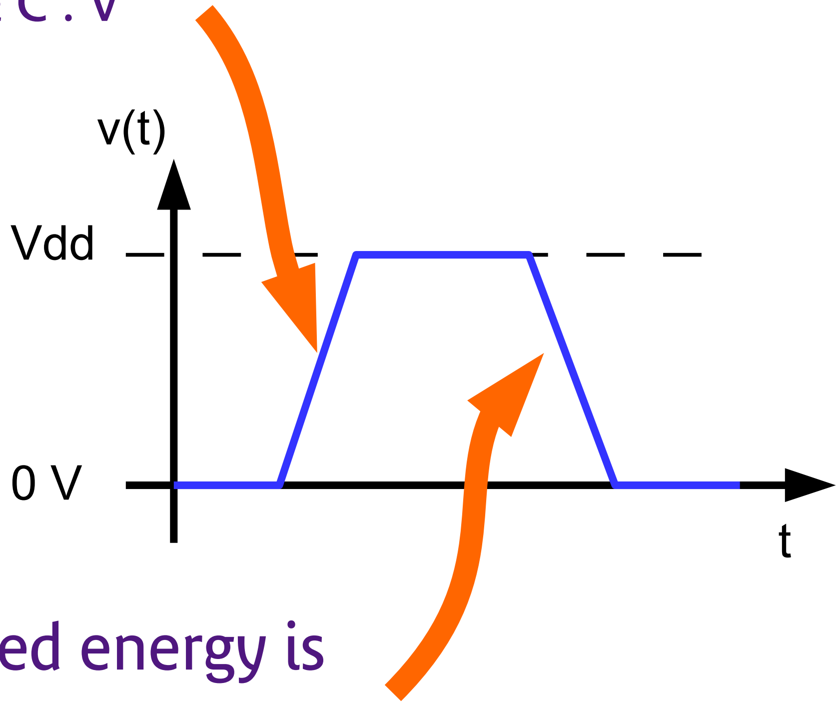
$$= C\,.\,Vdd^2$$



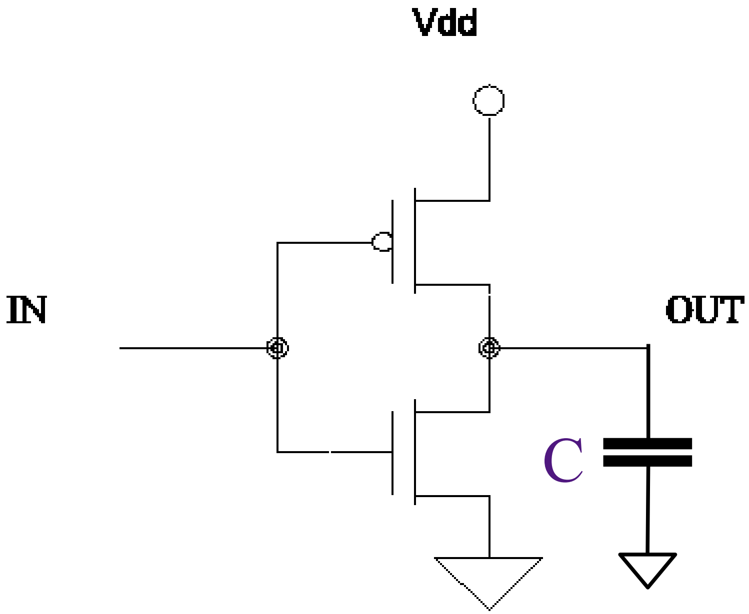


Summary

- Energy supplied on rising edge and not stored is dissipated
  - ½ C . V^2

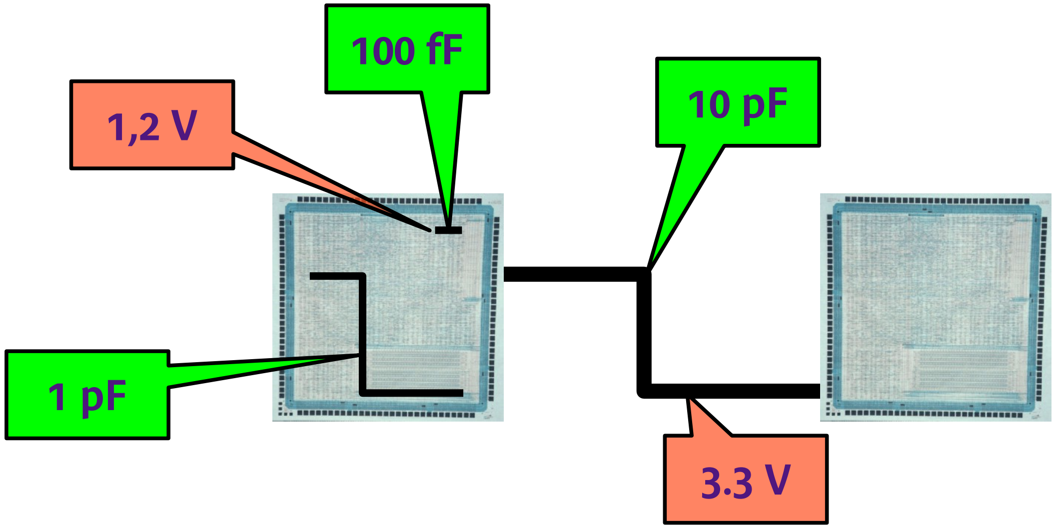


- Stored energy is dissipated on falling edge
  - ½ C . V^2



Integration, energy benefit

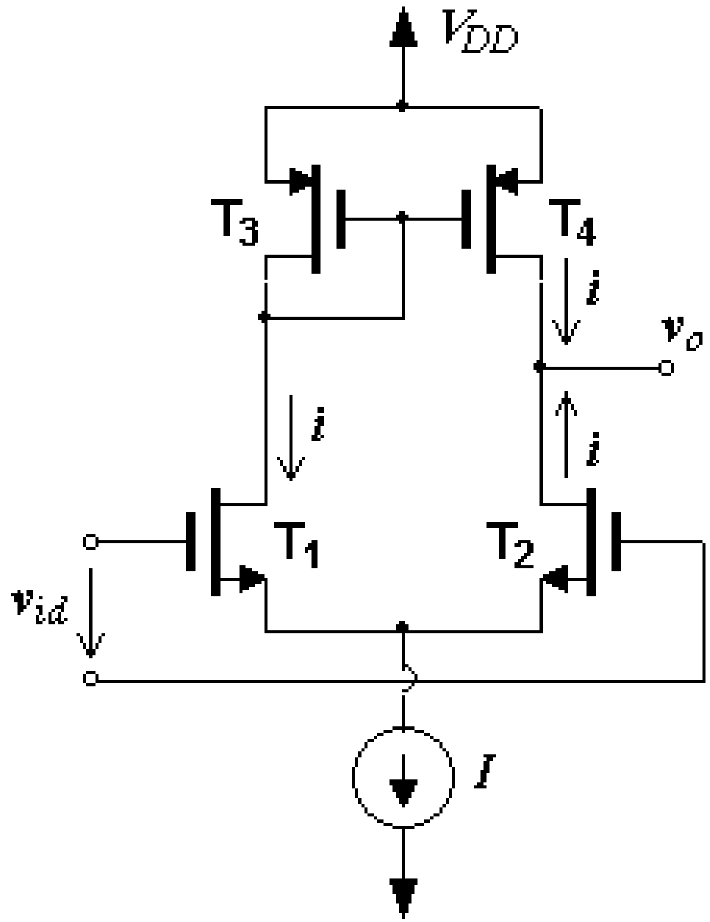
- Dynamic power consumption
  - E // C V^2
  - C from 100 fF to 10 pF
  - Standard input-output voltages
  - Lower core voltages



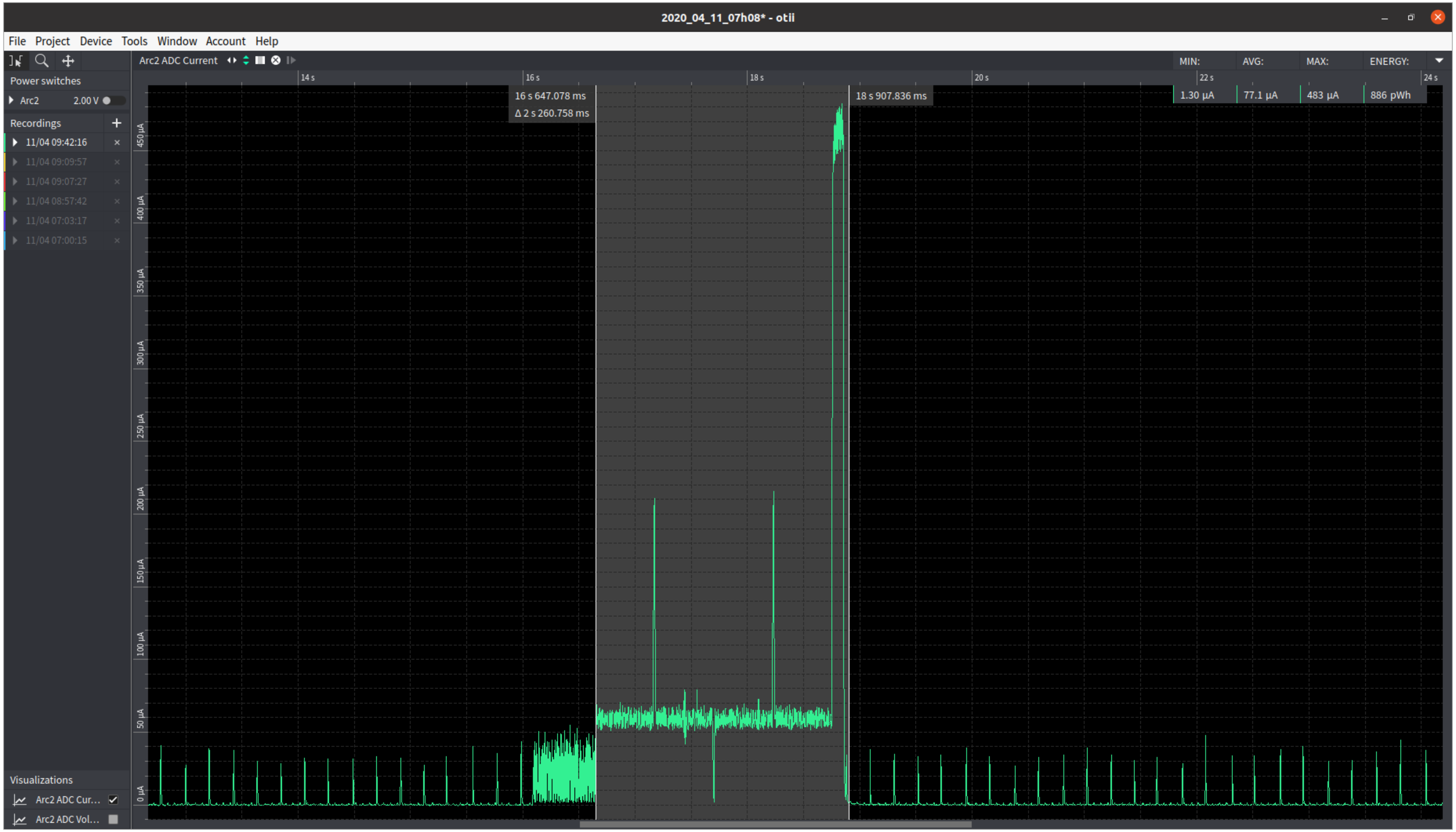
Static power consumption

Steady current flow

- Analogue electronics
  - Current is constant by design
- Digital electronics
  - Leaks at junctions, channels
- Only cure is to turn power off



Typical supply current measurement



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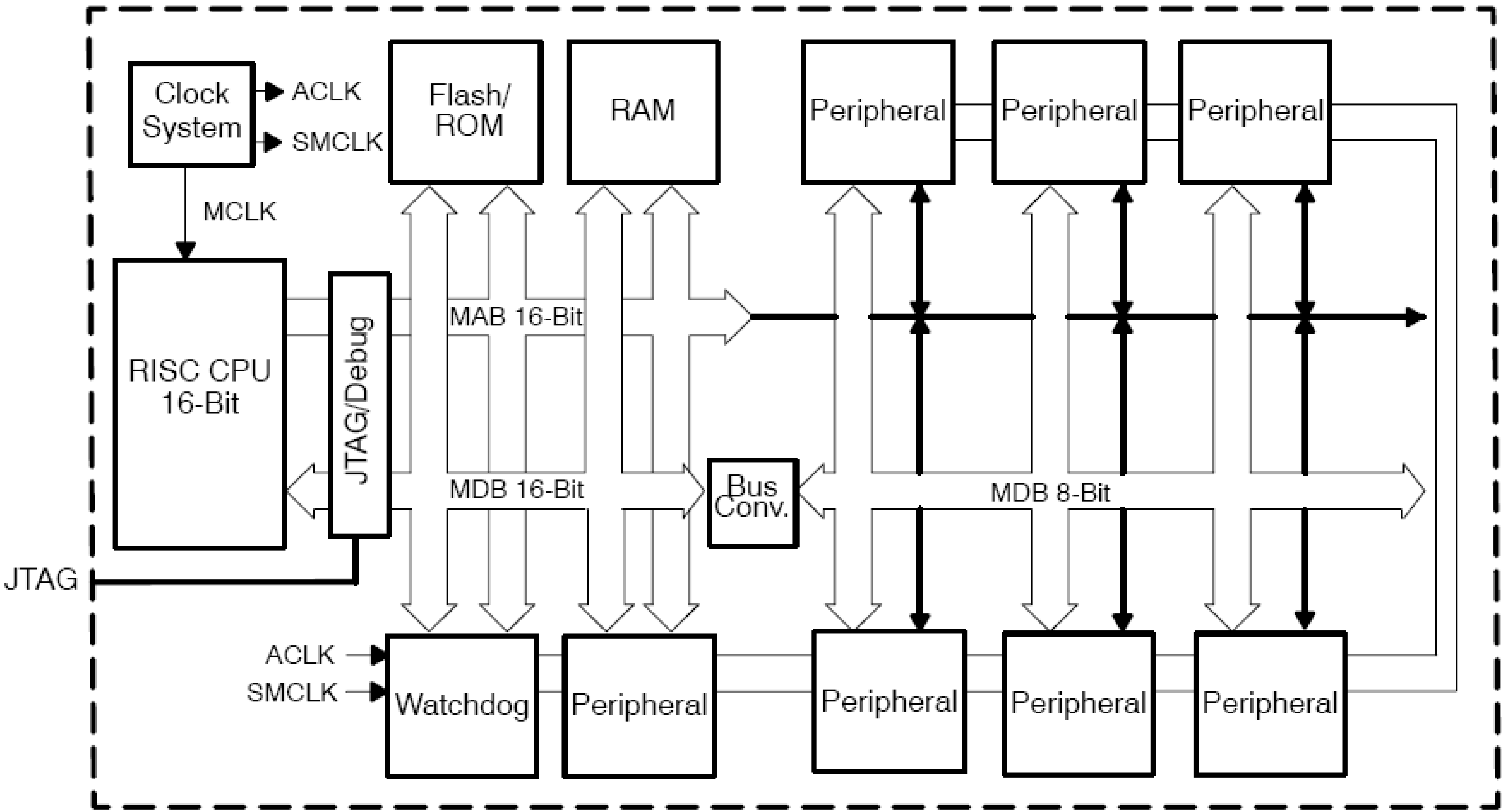
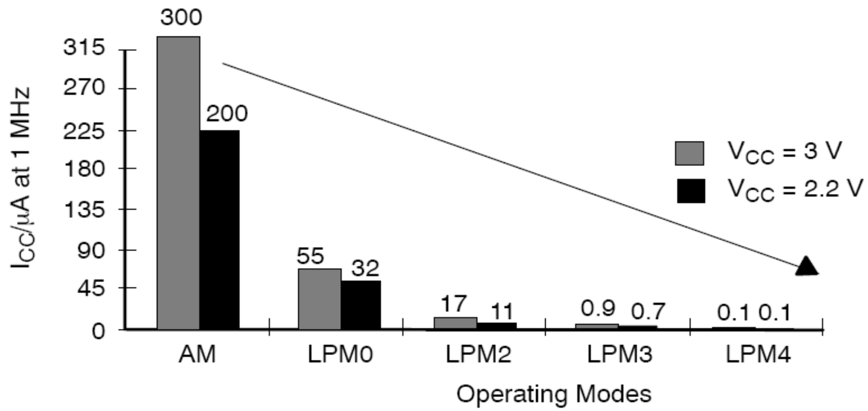
Microcontrollers

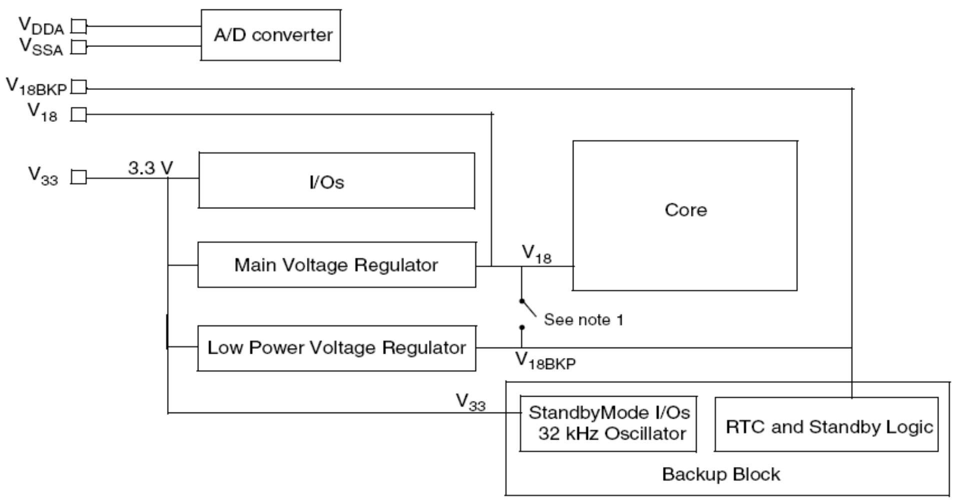
Microcontroller typical block diagram



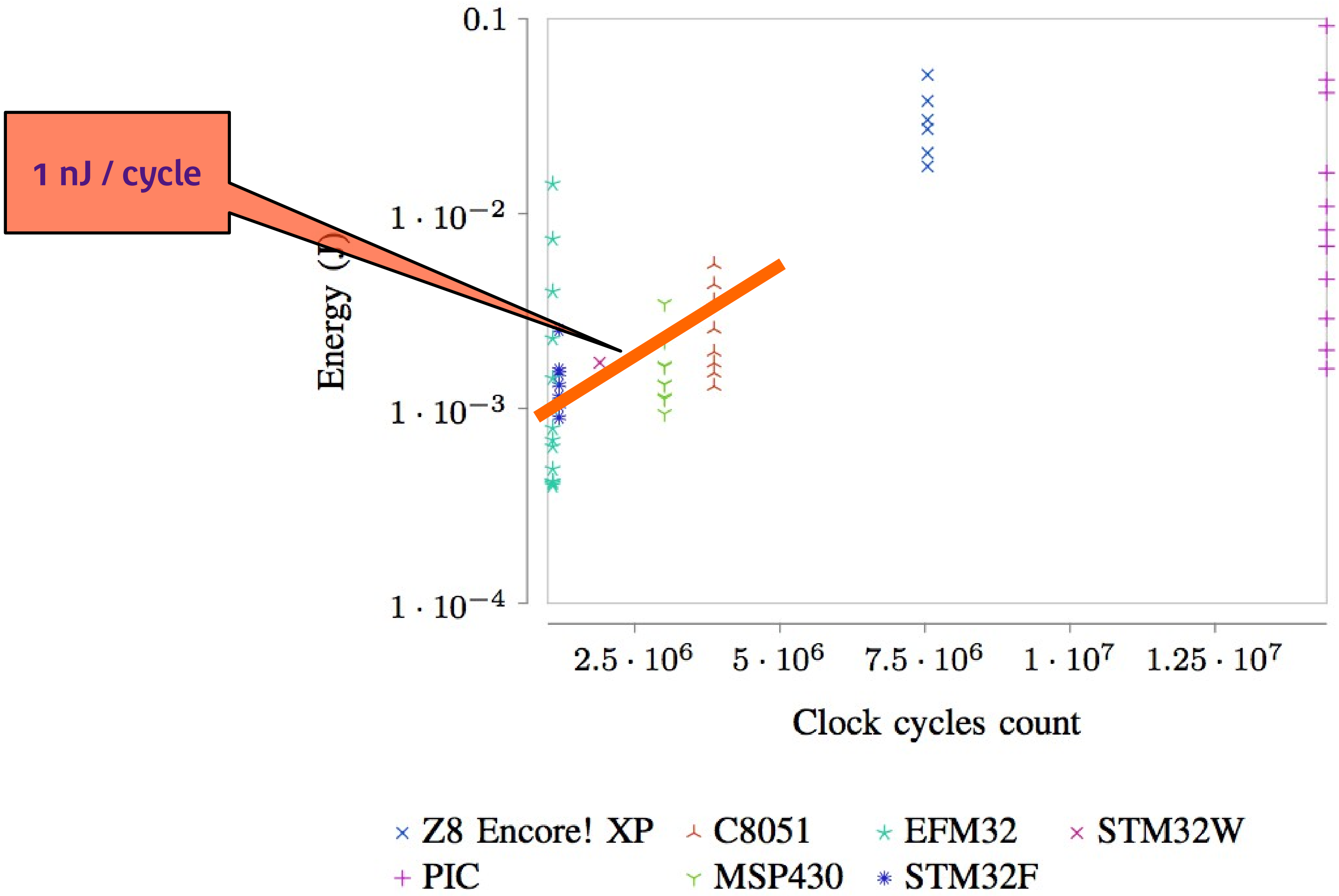
Microcontroller low-power features

- Instruction word size
  - Compact instruction set
    - Native 8 bit (x86, AVR)
    - Compact 16 bit (ARM Thumb, MSP430)
- Selective disabling of functions
  - Clock gating, power gating
  - Low-power vs startup time tradeoff
- Several oscillators
  - Ext. crystal, 32 kHz, internal RC
- Several voltage regulators





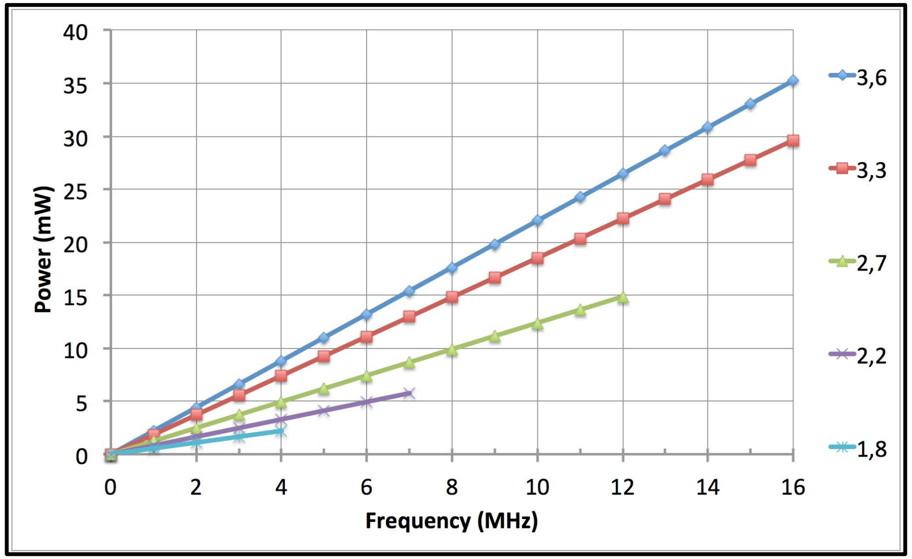
Microcontroller energy consumption



- I. Tsekoura et al., "An evaluation of energy efficient microcontrollers," 2014 9th International Symposium on Reconfigurable and Communication-Centric Systems-on-Chip (ReCoSoC), Montpellier, 2014, pp. 1-5. doi: 10.1109/ReCoSoC. 2014.6861368

Low power operation

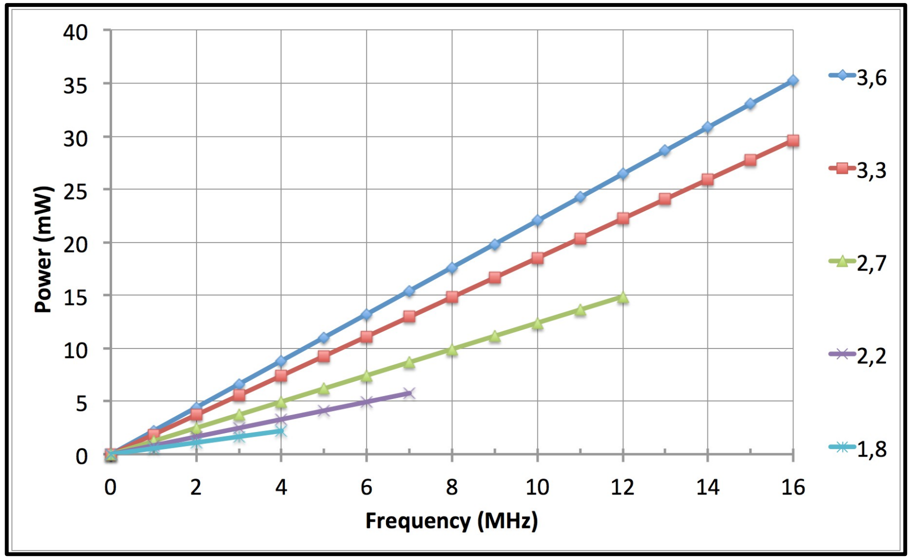
- Dynamic power consumed
  - $P \propto V^2 . f$
- Fixed approach
  - Pick required frequency
  - Pick required voltage
    - Pick voltage regulator
  - Design for worst case
- Variable frequency, fixed voltage
  - On-Off clock?
  - Continuously variable frequency?



Min energy operation

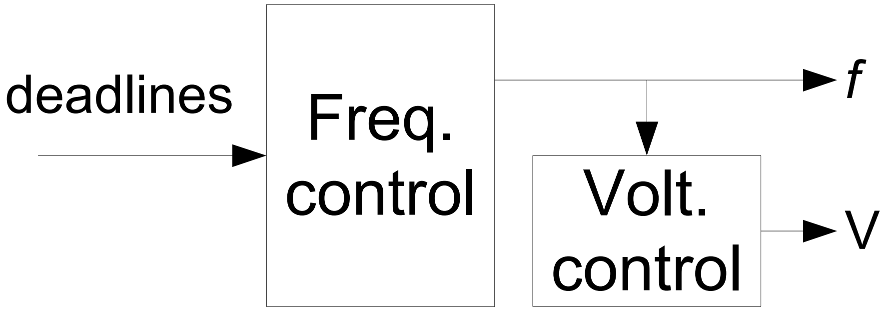
- Dynamic power consumed
  - $P \propto V^2.f$
- Task Duration = n. $1/f$
- Energy = P * Duration

  $\propto n V^2$

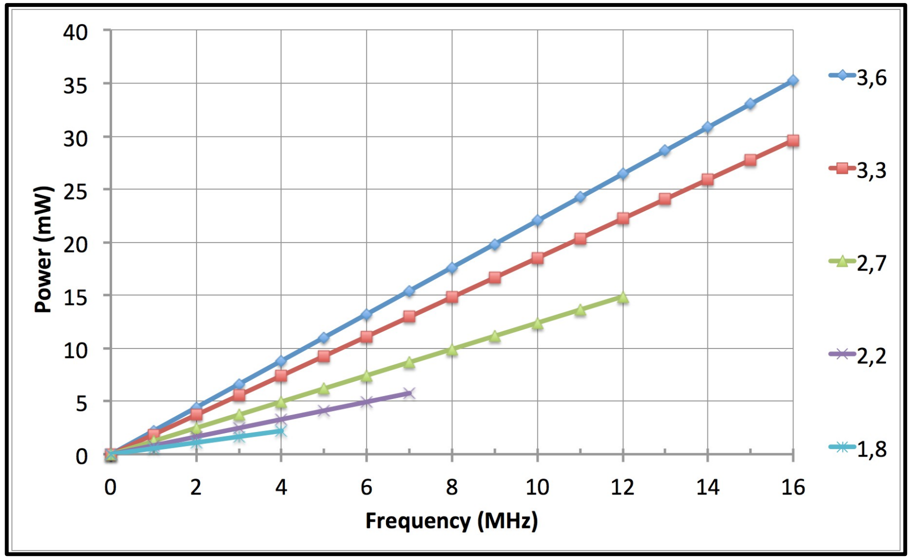


Min energy operation

- Dynamic power consumed
  - P // $V^2.f$
- Task Duration = n. 1/f
- Energy = P * Duration
  // n V^2
- Operate as slowly as possible
- Control voltage accordingly

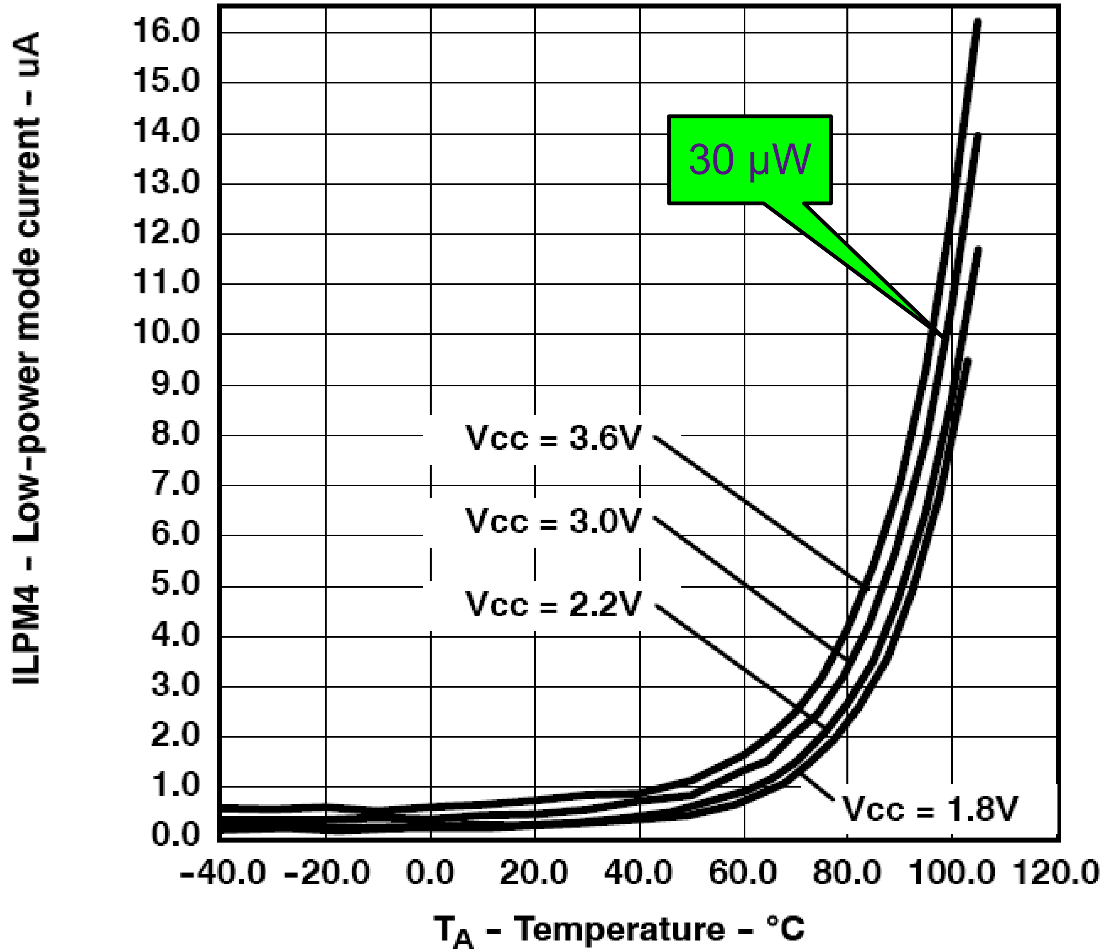


- Leakage/steady current not accounted for



Microcontroller leakage current

- In standby mode, just a giant diode
- Don't buy more memory than you really need



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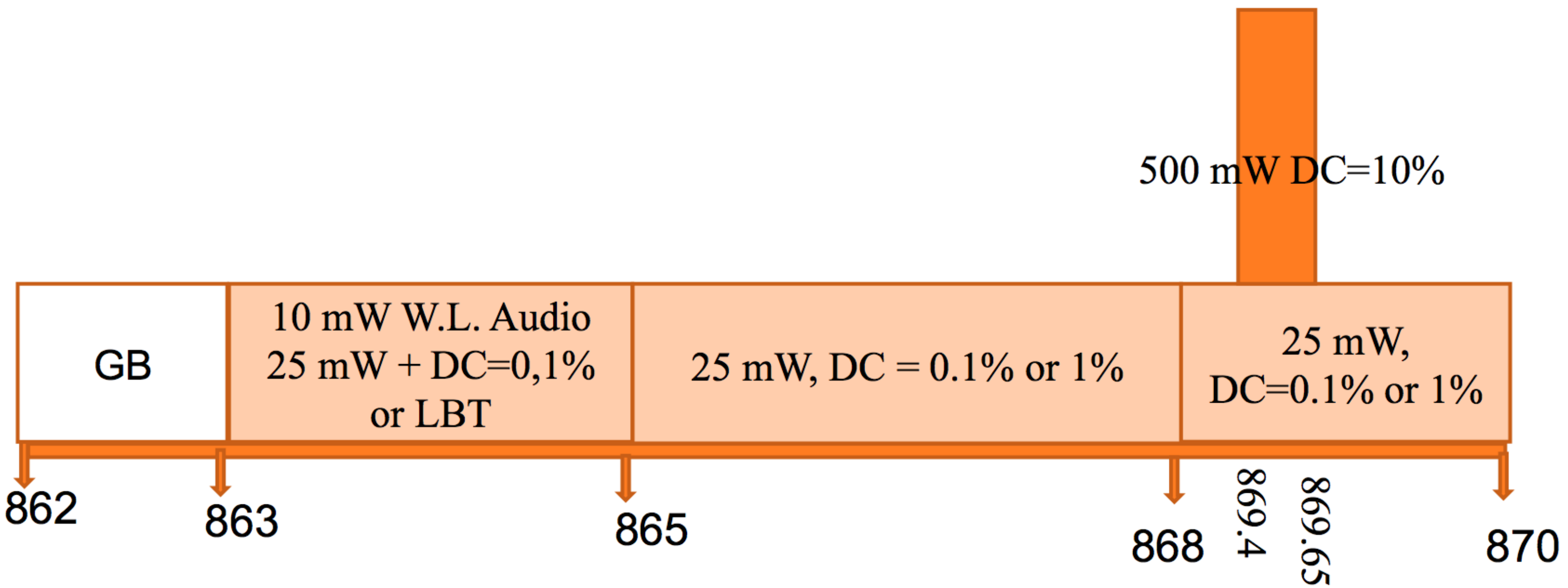
Spectrum, PHY layer and radio chips

Licensed-exempt spectrum

Licensed-exempt spectrum

License-exempt, but still regulated

- Maximum power, power density
- Duty cycle
- Usage
- E.g. DECT 1.9 GHz band, only to be used for DECT
- E.g., 862-870 MHz unlicensed band (CEPT ERC Rec 70-03)

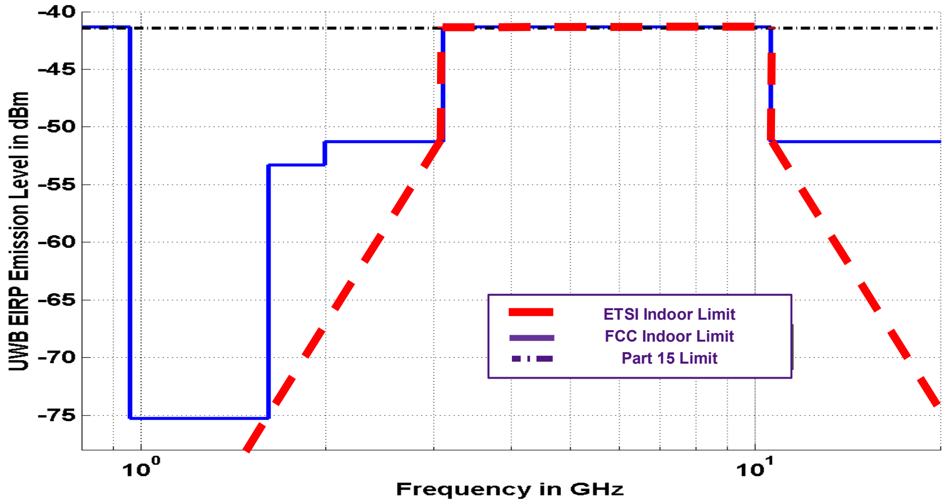


Unlicensed frequency bands (1/2)

- 2.4 GHz ISM band
  - 2.400-2.4835 GHz world-wide, 4W EIRP maximum
  - Microwave owens, 802.11 (WiFi), 802.15.4, Bluetooth, prop. radios
  - fairly polluted
  - line of sight propagation
  - short antennas
- UHF 900 MHz band
  - continent specific : 868 MHz Europe, 902-928 MHz USA, 915 Japan
  - W-MBus, Zwave, LoRa, SigFox, prop. radios
- UHF 400 MHz band
  - continent specific, 433 MHz in Europe
- VHF 169 MHz band
  - better indoor penetration, long antennas

Unlicensed frequency bands (2/2)

- 5 GHz UNII band
  - IEEE 802.11a
  - silicon-only transceiver less efficient
- 60 GHz
  - Very short transmission range
  - Silicon transceiver still to be designed
- Ultra-Wide Band
  - legal since 2003 in the USA
    - 3.1 – 10.6 GHz
    - -41,3 dBm/MHz max avg
    - 0 dBm/50 MHz max peak
  - good opportunity for positioning
  - opportunity for new radio design



Licensed spectrum

Telecom operator cellular IoT systems

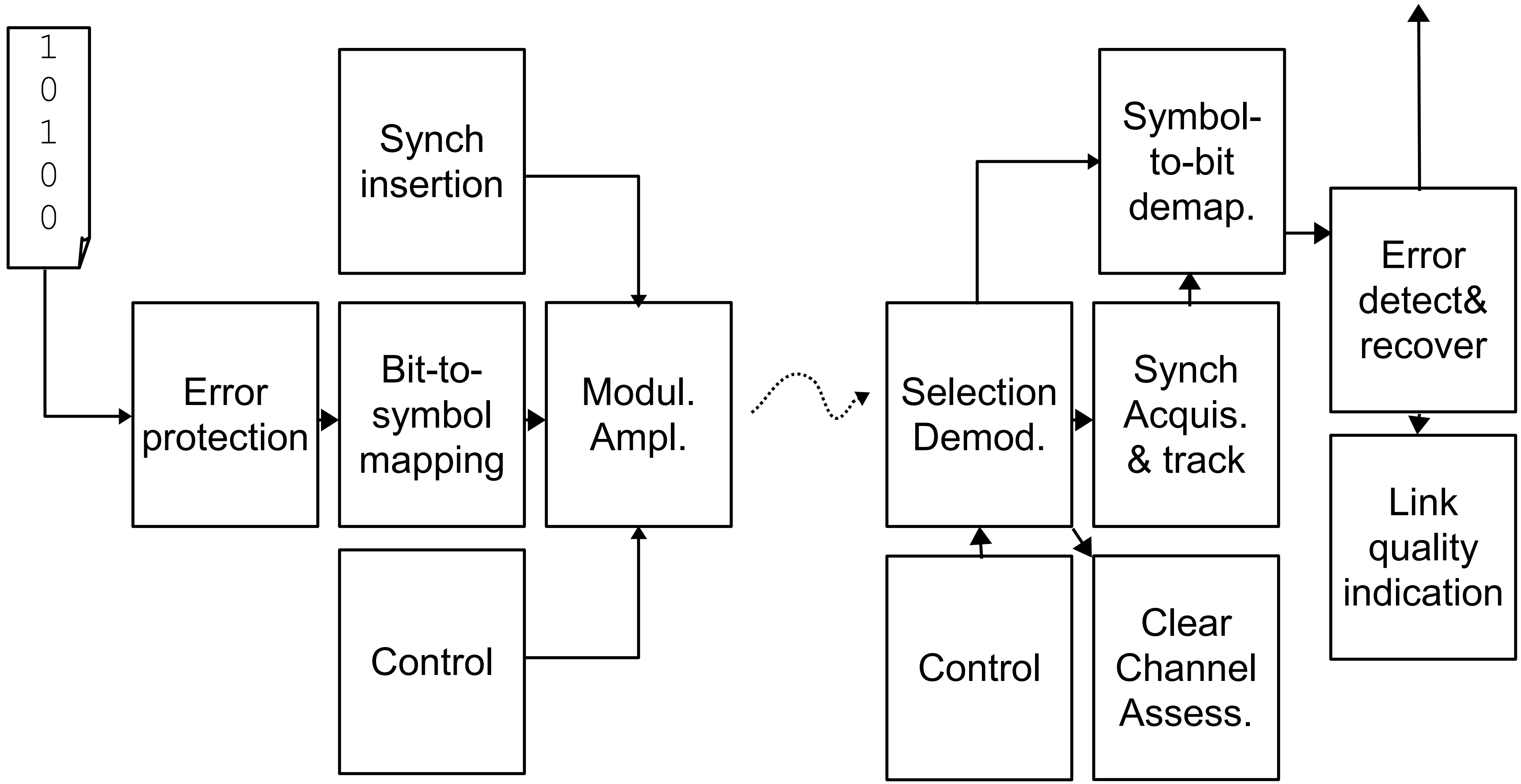
- 3GPP Release-13 (June 2016)
  - 10-20 dB coverage extension, reduced UE complexity/cost
  - 10 years on 5 W.h battery (Power Saving Modes, extended DRX)
- EC-GSM (2G improvement)
  - Extended-coverage through blind repetition
  - Base station and UE software upgrade
  - 350 bps – 240 kbps, 200 kHz bandwidth
- LTE-M (4G improvement)
  - 10 kbps – 1 Mbps, 1.08 MHz bandwidth
- NB-IoT (new radio for 4G)
  - Narrowband (180 kHz bandwidth), 20 kbps – 250 kbps
  - 3 modes of operation : LTE in-band, LTE guard band or standalone
- 5G
  - Will use LTE-M and NB-IoT, NR-Lite radio for Rel 17 (2022)

Telecom operator bands (3GPP)

- 2G (EC-GSM)
  - 900 MHz, 1800 MHz
- 4G (NB-IoT, LTE-M)
  - 850 MHz, 2.6 GHz
- 5G
  - 700 MHz, 3.6 GHz, 26 GHz

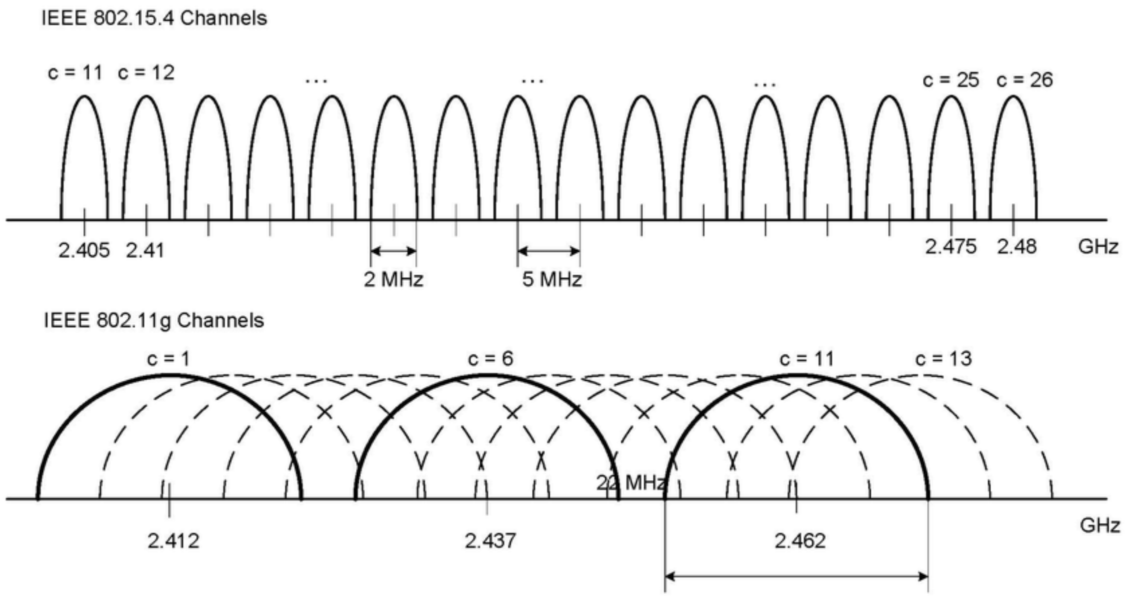
PHY layer

PHY layer block diagram



WPAN: IEEE 802.15.4 -2003 PHY

- 900 MHz and 2.4 GHz bands
  - 16 channels in 2.4 – 2.4835 GHz, 5 MHz spacing, 250 kbps
    - O-QPSK 2Mcps DSSS
- sensitivity
  - 2.4 GHz : better than -85 dBm at 1% PER
- at least -3 dBm output power
  - about 30 m range
- turn around-time
  - 12 symbol periods
- used in Zigbee, W-HART, ISA100



A survey of wireless technologies coexistence in WBAN: Analysis and open research issues - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Frequency-channels-of-IEEE-80211g-and-802154-in-the-24-GHz-band_fig4_271741147

Long Range Wide Area Low Power PHY

- **Sigfox**
  - 868 MHz band, 100 Hz channel, 100 bps, BPSK, 25 mW
  - All-proprietary system, originally unidirectional
  - https://build.sigfox.com/sigfox-device-radio-specifications
  - Single world-wide network
  - Simple IoT device, complexity in the network
  -
- LoRa
  - 868 MHz, 125 kHz channel, chirps, 300bps-5kbps, dynamic adaptation
  - LoRa Alliance www.lora-alliance.org
    - LoRaWAN 1.1 spec public, does not describe PHY layer
  - Semtech still sole chip vendor

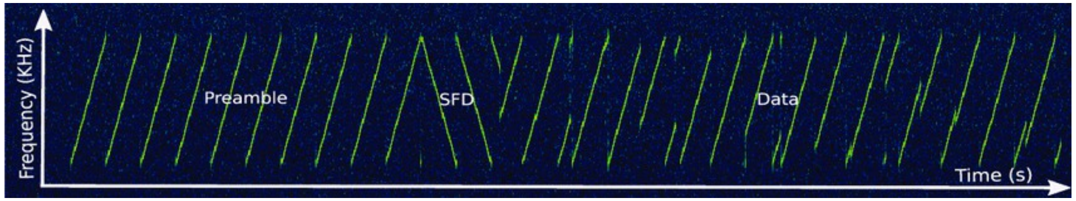


Figure on ResearchGate.
https://www.researchgate.net/figure/A-snapshot-of-LoRa-transmission-that-shows-up-down-and-data-chirps-as-seen-on_fig1_331294324

Practical implementation

Typical radio transceiver architecture

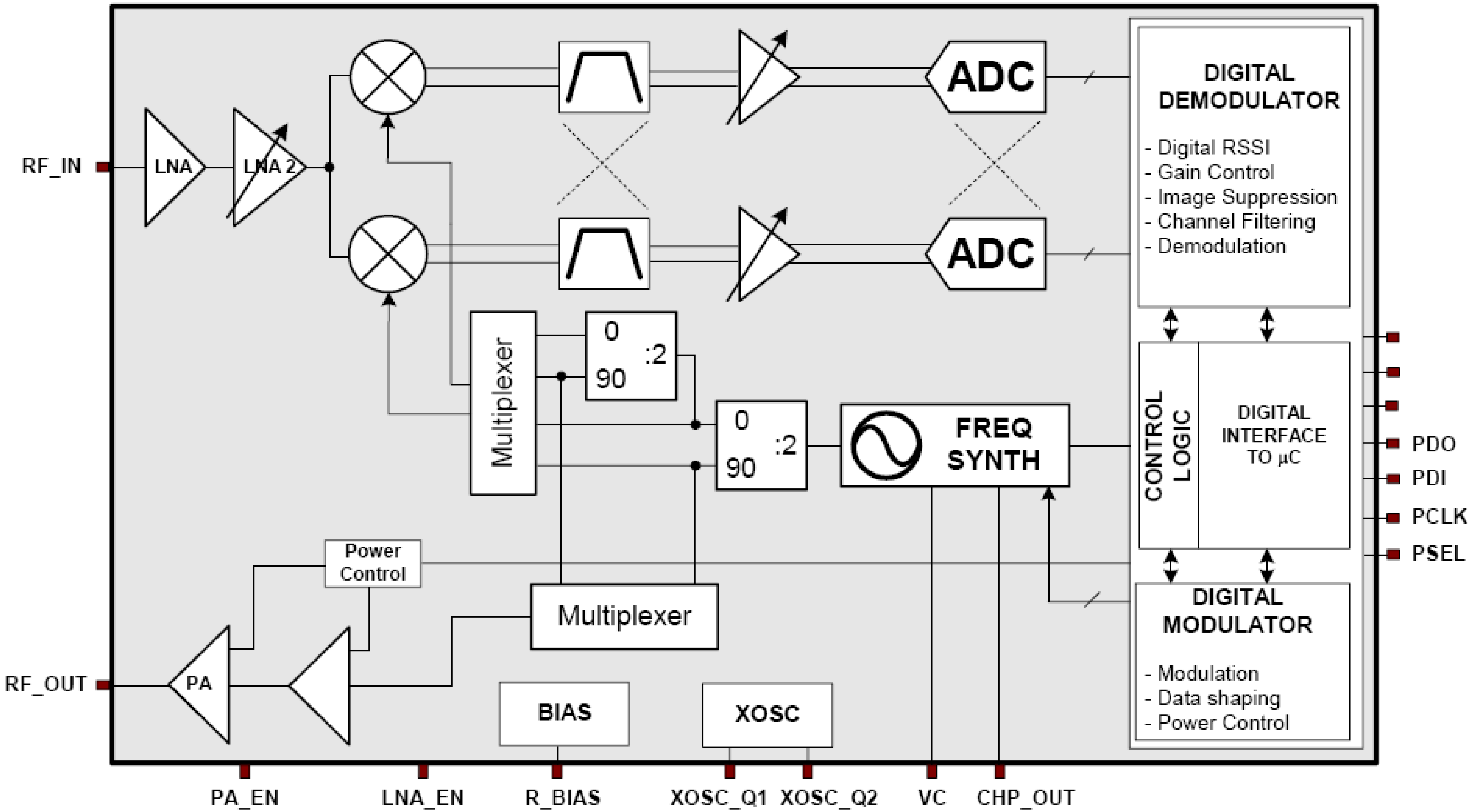
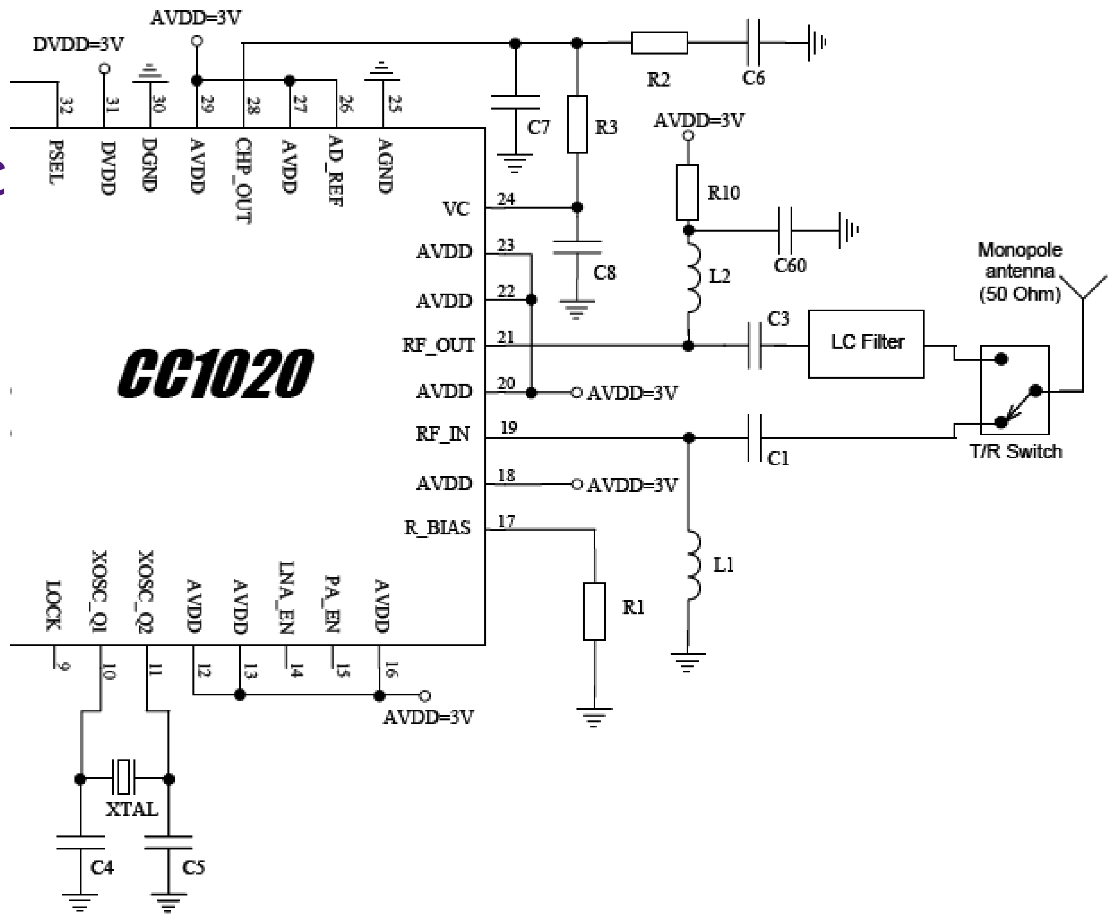


Figure 2. ***CC1020*** simplified block diagram

Radio transceiver in analogue world

- 5€ radio chip
- Minimal external electronic components
- Antenna implementation
  - PCB tracks : free, fair perf
  - Discrete : 0.5€, good perf
- Resonnator
  - Quartz crystal : 0.5€
  - Temperature compensation

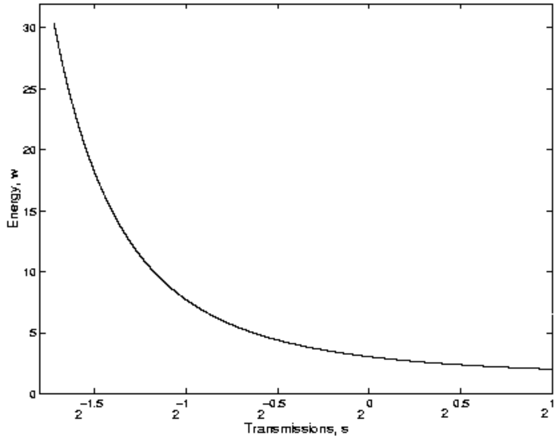


Energy optimizations at PHY layer

- Semiconducteur technology
  - well-known Moore's law does not really apply to analogue or RF electronics
    - bias current pretty much constant
    - voltage can't go below a few Vt
- Frequency band
  - Higher operating frequencies require more bias current in linear circuits
- Receive sensitivity
  - lower gain can do with lower bias current in linear circuits
  - bypass some filtering stages
  - low-performance wake-up receiver (totally passive?)
- Short wake-up, carrier sensing, sync and turn-around time
  - spend less time in un-productive states

Other ideas for PHY layer

- Transmit power control
  - transmit at minimal power required for correct decoding
    - reduces interference to other nodes
    - power saving is marginal below 0dBm
- Transmit speed
  - Shannon's law $C = B \log2 (1+S/N)$ suggests that less energy is required for slow transmission
    - just in time transmission[1]
  - but (real) receivers will have to stay on longer



- Brand new architectures
  - Non-standard electronics (weak inversion CMOS)
  - MEMS/NEMS passive receivers
  - Impulse-based UWB radios (cf. infra)

[1]. B. Prabhakar, E. Uysal, A. El Gamal, "Energy-efficient transmission over a wireless link via lazy packet scheduling," *Proc. of the IEEE INFOCOM*, Anchorage, 2001

Radio chips

Transceivers gallery

- IEEE 802.11 (WiFi)

- Sub-GHz narrowband
  - TI/ChipCon CC1020
  - TI CC1200

- IEEE 802.15.4-2003
  - Freescale MC13192
  - TI CC2538 (SoC)

- Research directions

IEEE 802.11 (WiFi) radios

- 802.11b
  - 2.4 GHz, DSSS, 1-11 Mbps
- 802.11a,g
  - 5 GHz, 2.4 GHz, OFDM, 54 Mbps
- typical power consumption [1]

Chipset	Sleep (mW)	Idle (mW)	Receive (mW)	Transmit (mW)
ORiNOCO PC Gold	60	805	950	1400
Cisco AIR-PCM350	45	1080	1300	1875

@ 11 Mbps

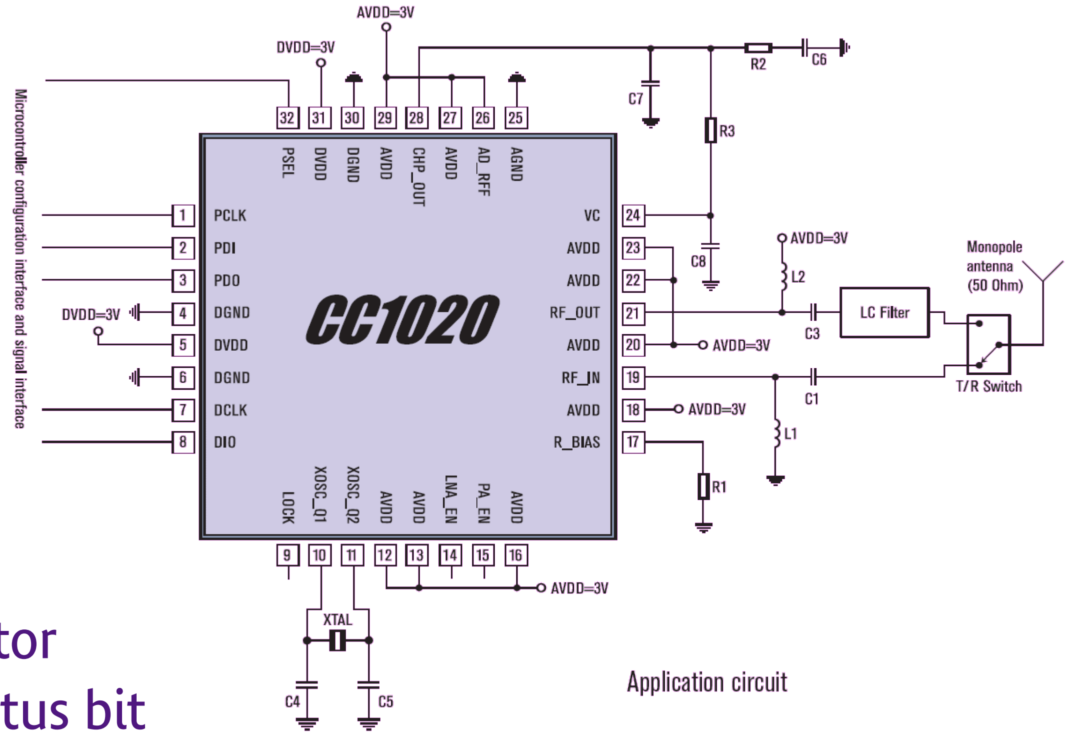
  - i.e. 150 nJ/bit transmitted, 90 nJ/bit received

- Microchip RN1723 802.11b,g (2016)
  - 40 mA Rx, 120 mA Tx @ 0dBm (190mA @+12dBm), 3.3V
  - 2-10 nJ/bit received

[1] Shih et al, "Reducing Energy Consumption of Wireless, Mobile Devices Using a Secondary Low-Power Channel". MIT RR March 03

CC 1020

- Monolithic narrowband UHF transceiver
  - dual-band 400 and 900 MHz
  - FSK/GSK and ASK/OOK
  - -20 +10 dBm output power
  - 0.45 -153 kbps
  - 12.5 – 500 kHz channels



Application circuit

- Digital RSSI
  - Received Signal Strengh Indicator
  - Carrier Sense threshold and status bit

CC1020

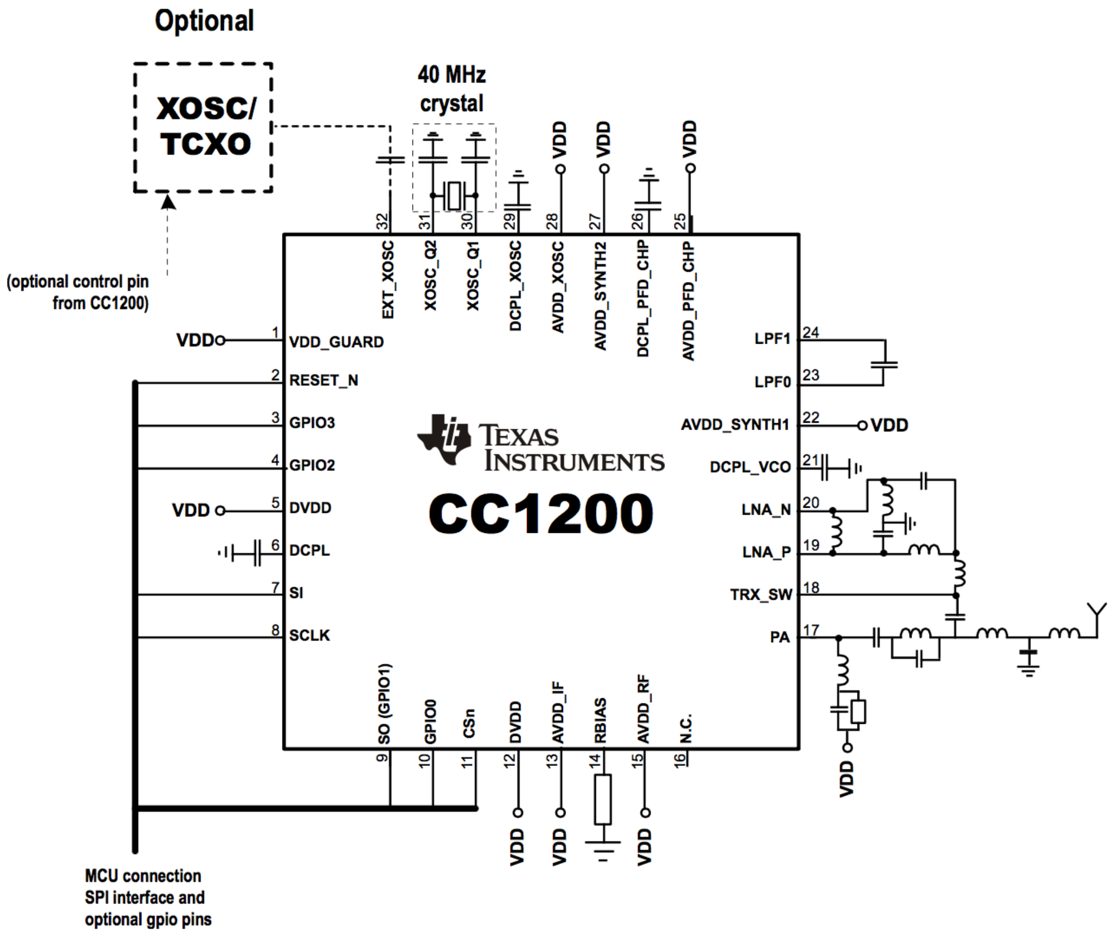
Current Consumption					
Power Down mode		0.2	1.8	µA	Oscillator core off
Current Consumption, receive mode 434/868 MHz		17.3/17.9		mA	
Current Consumption, transmit mode 434/868 MHz:					
P = −20 dBm		10.3/13.7		mA	The output power is delivered to a 50 Ω single-ended load, see also page52.
P = −5 dBm		12.1/18.1		mA	
P = 0 dBm		13.7/21.9		mA	
P = 5 dBm		16.8/33		mA	
P = 10 dBm (434 MHz only)		23.7		mA	
Current Consumption, crystal oscillator		77		µA	14.7456 MHz, 16 pF load crystal
Current Consumption, crystal oscillator and bias		500		µA	14.7456 MHz, 16 pF load crystal
Current Consumption, crystal oscillator, bias and synthesizer		11.5		mA	14.7456 MHz, 16 pF load crystal

350nJ/bit rec.

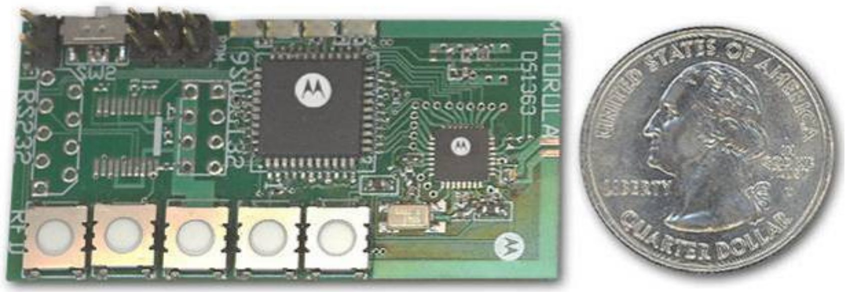
CC 1200 (2013)

- Monolithic narrowband VHF/UHF transceiver
  - 169, 400 and 868/900 MHz
  - FSK/GSK/MSK/OOK
  - +16 dBm output power
  - Tx 46mA @+14dBm
  - Rx 19-23 mA
  - 2.0 – 3.6 V supply

- 40 kHz RC int. oscillator
- WakeOnRadio
- AES128 accelerator
- Auto-ACK



Freescale MC13192



- IEEE 802.15.4 2003 compliant
  - -30 dBm (min) to 0 dBm (typ) output power, (+3.6 dBm) max
  - transmit 34 mA @ 0dBm (under 2.7 V)
  - receive 37 mA (under 2.7V)
  - several power-down modes 1-500 µA
- 7 external components
- On-chip voltage regulator
- Some MAC support on-chip
  - timers
  - automatic ACKnowledge hardware generator

400nJ/bit rec.

4 bytes	1 byte	1 byte	125 bytes Max	2 bytes
Preamble	Start of Frame Delimiter	Frame Length	Payload	FCS

MC13192 states and power consumption

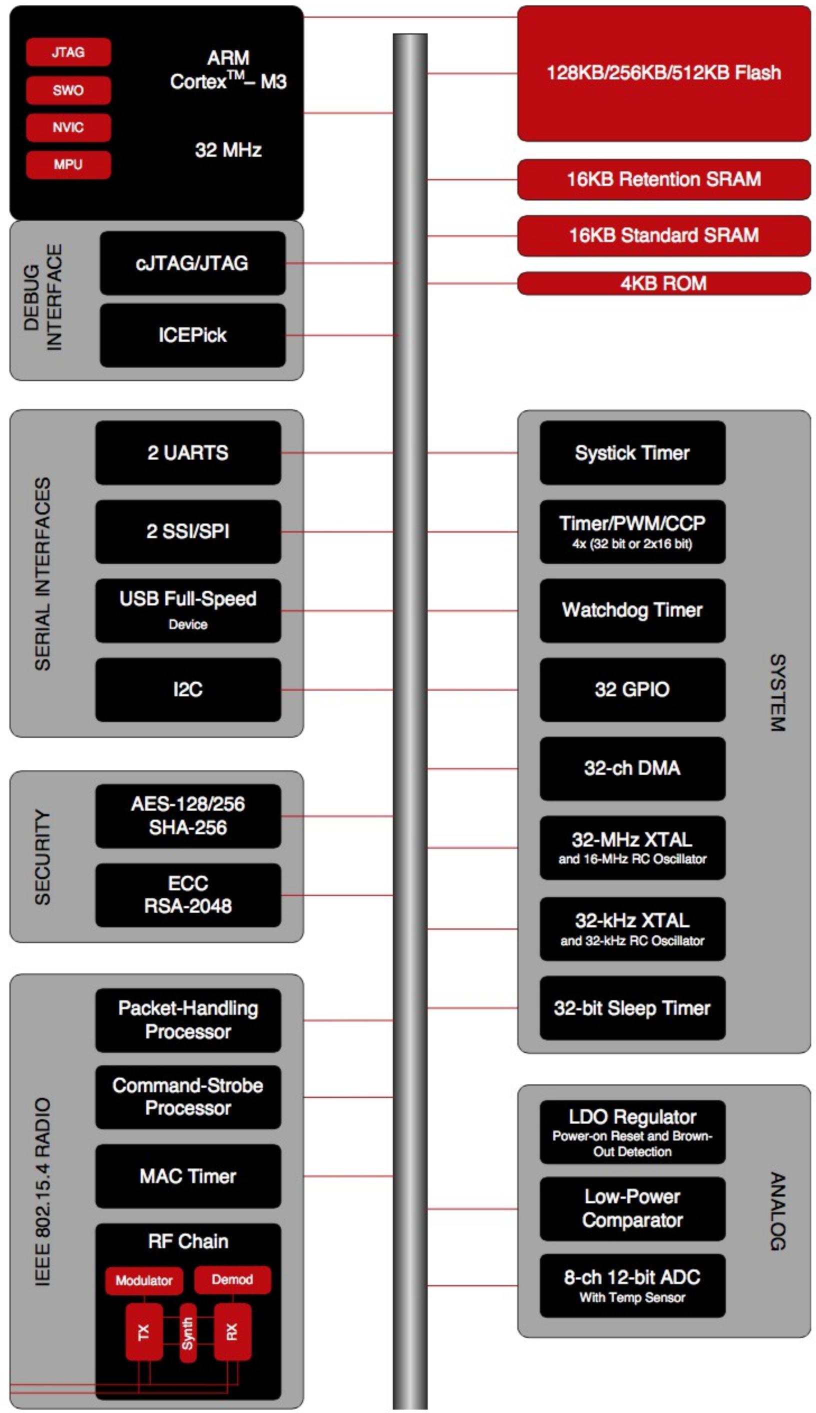
(V_{CC} = 2.7 V, T_A = 25°C, unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
Power Supply Current (V_{BATT} + V_{DDINT})					
Off	$I_{leakage}$	-	<1.0	-	µA
Hibernate	I_{CCH}	-	3.0	-	µA
Doze (No CLKO)	I_{CCD}	-	40	-	µA
Idle	I_{CCI}	-	500	-	µA
Transmit Mode	I_{CCT}	-	34	-	mA
Receive Mode	I_{CCR}	-	37	-	mA

Mode	Definition	Transition Time To or From Idle
Off	All IC functions Off, Leakage only. $\overline{\text{RST}}$ asserted.	23.332 ms to Idle
Hibernate	Crystal Reference Oscillator Off. (SPI not functional.) IC Responds to $\overline{\text{ATTN}}$.	18.332 ms to Idle
Doze	Crystal Reference Oscillator On but CLKO output available only if Register 7, Bit 9 = 1 for frequencies of 1 MHz or less. (SPI not functional.) Responds to $\overline{\text{ATTN}}$ and can be programmed to enter Idle State through an internal timer comparator.	332 µs to Idle
Idle	Crystal Reference Oscillator On with CLKO output available. SPI active.	
Receive	Crystal Reference Oscillator On. Receiver On. SPI should not be accessed.	144 µs from Idle
Transmit	Crystal Reference Oscillator On. Transmitter On. SPI should not be accessed.	144 µs from Idle

CC2538 System-on-Chip

- 2012
- IEEE 802.15.4 2003 radio
  - +7 dBm output power
  - transmit 24 mA @ 0dBm (2.0 – 3.6 V)
  - receive 20 mA
  - several power-down modes 1-500 μA
- ARM Cortex-M3 32 MHz processor
  - 128 - 512 KB Flash
  - 16+16 KB RAM
- 32 MHz xtal / 16 MHz RC / 32 kHz xtal / 32 kHz RC
- $5 in 1k quantities



Summary table

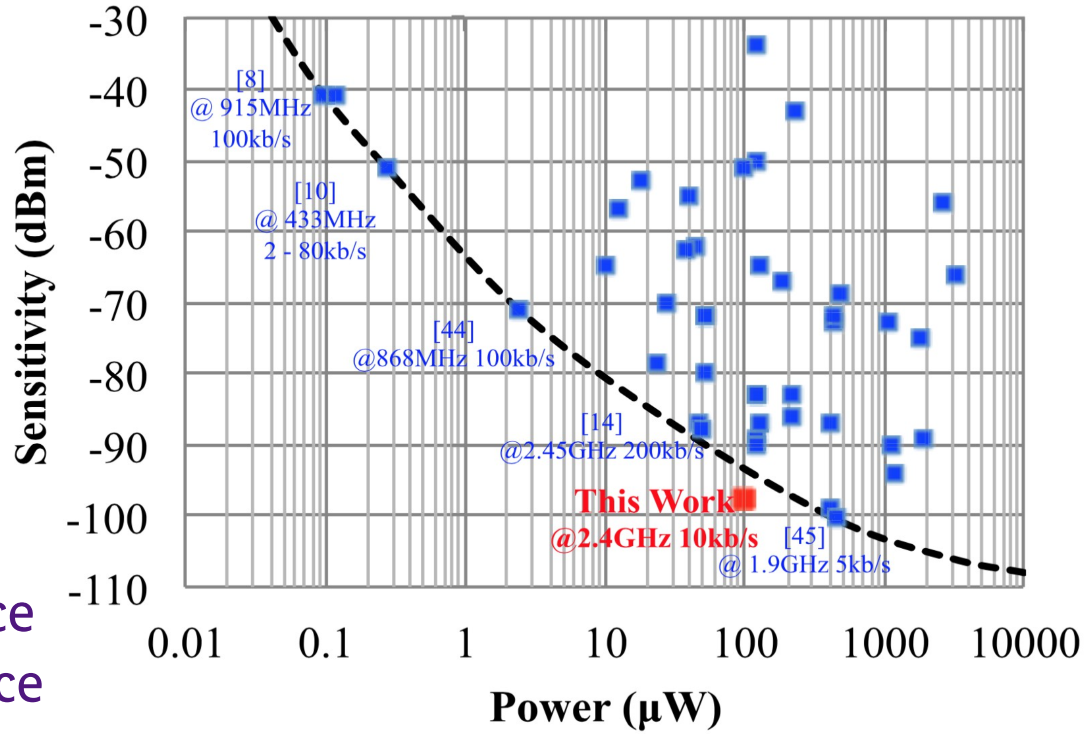
	Band	Std	Rx current	Sensitivity	Tx current @ 0dBm
CC1021 (2003)	868 MHz	FSK, GSK. OOK	18 mA	~ -110 dBm	22 mA
CC1201 (2013)	868 MHz	FSK, GSK, MSK, OOK	19 – 23 mA	~ -115 dBm	28 mA
MC13192 (2003)	2.4 GHz	IEEE 802.15.4	37 mA	-92 dBm	34 mA
CC2538 (2012)	2.4 GHz	IEEE 802.15.4	20 mA	- 96 dBm	24 mA
LTC5800 (2013)	2.4 GHz	IEEE 802.15.4	4.5 mA	- 93 dBm	5.5 mA
SX1276	868 MHz	LoRa, FSK	11 mA	-136/-118 dBm @ 125kHz BW	20 mA @ +7dBm

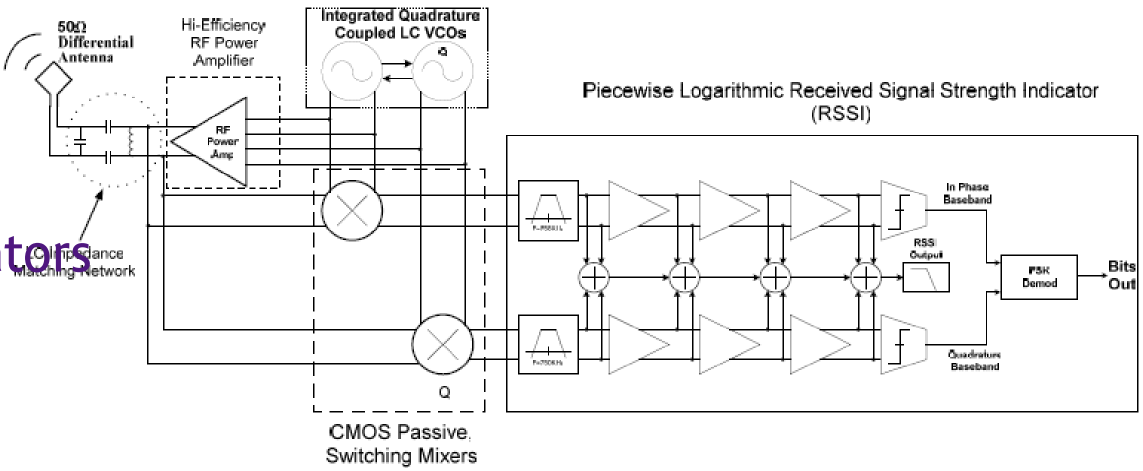
- Active power 10 – 100 mW
  - Duty cycling needed to meet long lifetime
- Long range = slow = high energy per bit (up to 1 mJ/bit)

Radio research

Research directions

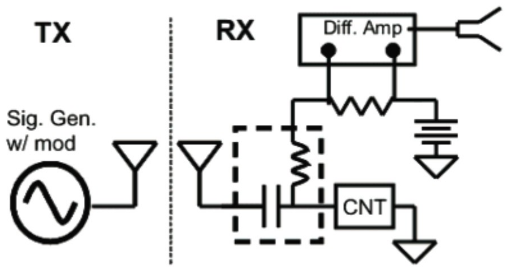
- Wake-up radios
  - Lower sensitivity: non-detection
  - Interference: false positives
  - Separate frequency: different propagation
  - Same frequency: collision avoidance
  - IEEE 802.11ba, 5G wake-up sequence
- Ultra-low voltage design
  - Weak inversion mode
  - Use of switches for mixers
- Passive electronics
  - Micro-electromechanical resonators
- Passive transmitter
- UWB impulses, short times

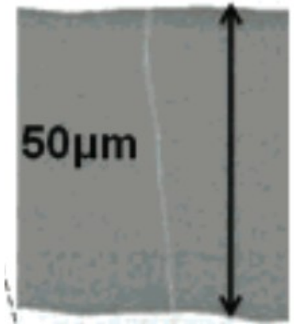




Passive radios (1/2)

- Passive *receivers*
  - Galena (lead-sulfite) receivers (1894, J.C. Bose)
  - Single Carbon Nanotube receivers
  - NEMS/MEMS-based receivers
  - Passive mixers





Rutherglen C., Burke P., 2007, “Carbon Nanotube Radio”. Nano Lett., 7 11 (November 2007), 32963299 , 0028-0836

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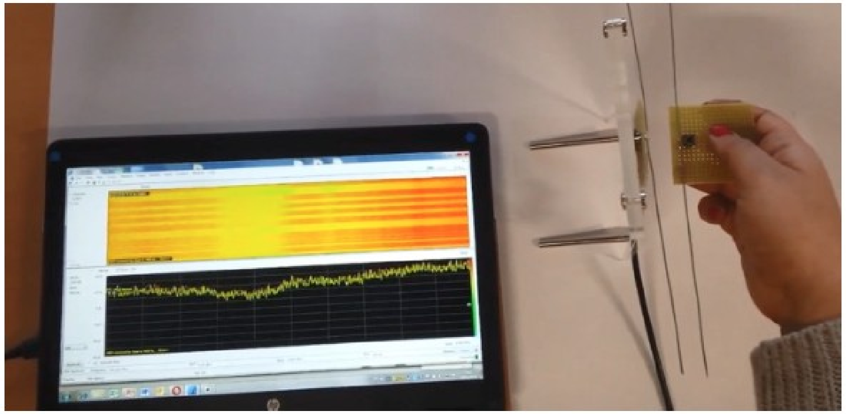
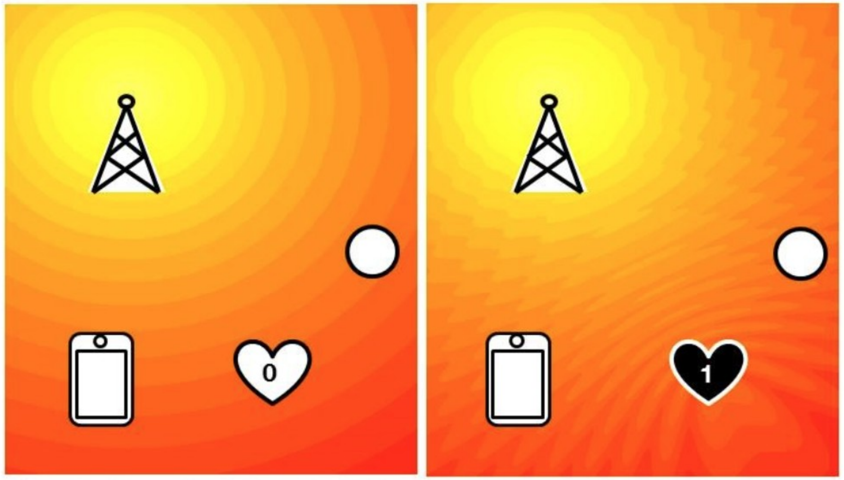
https://commons.wikimedia.org/w/index.php?curid=5228955

Passive radios (2/2)

- Passive *transmitters*
  - Passive RFIDs
  - Illumination source can also be unknowing third party.
- LoRaWAN passive transmitter
  - 2.8 km range reported

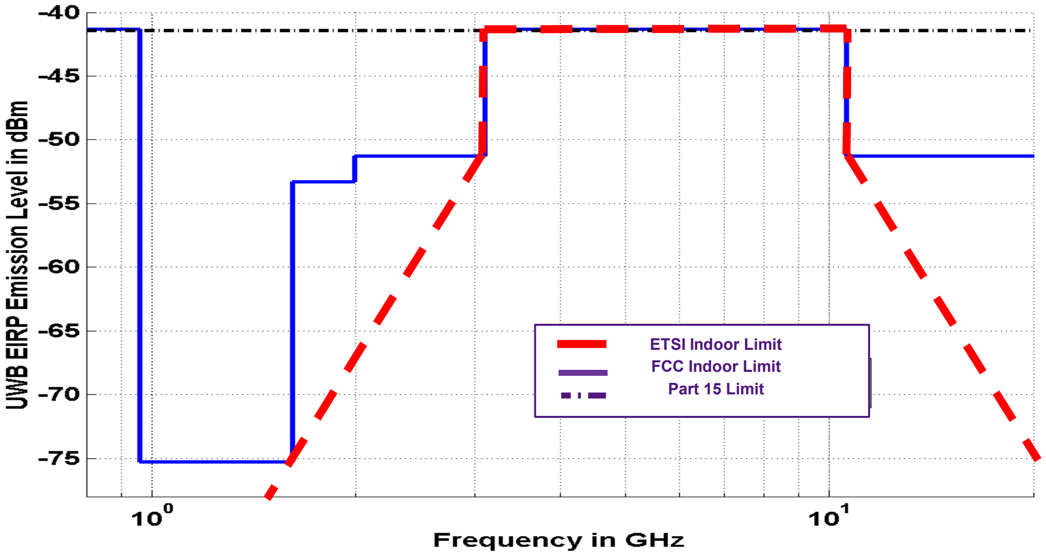
V. Talla, M. Hessar, B. Kellogg, A. Naja, J. R. Smith, S. Gollakota.
LoRa Backscatter: Enabling The Vision of Ubiquitous Connectivity. IMWUT, 2017





Ultra Wide Band

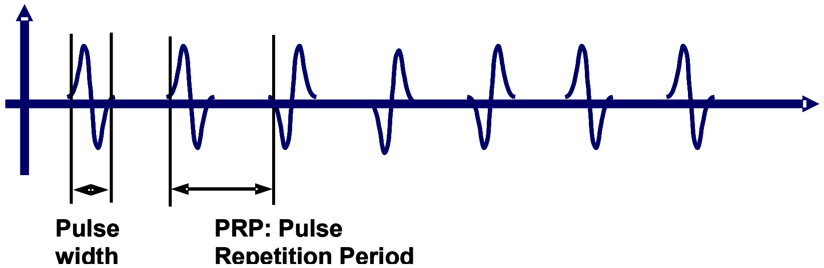
- Benefits
  - Robust to narrow-band interference
  - Robust to multipath
  - Licence-free

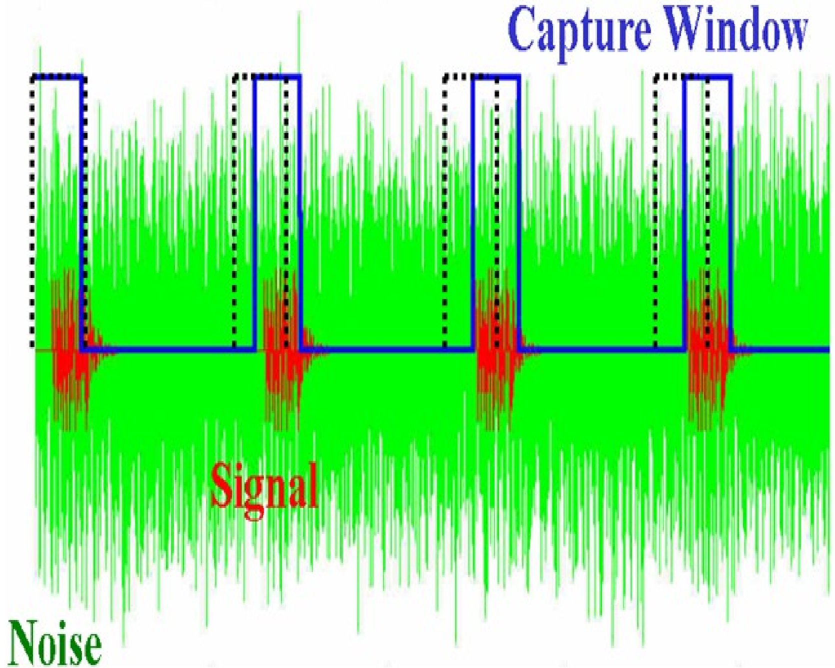


- IEEE 802.15.4a Task Group, went into Revision 2007
  - 100 kbps – 6.8 Mbps, 100 m
  - Focus on low power radio, ranging
- A few chips available
  - BeSpoon.com (CEA-Leti spin-off), Decawave

Ultra Wide Band impulse radio

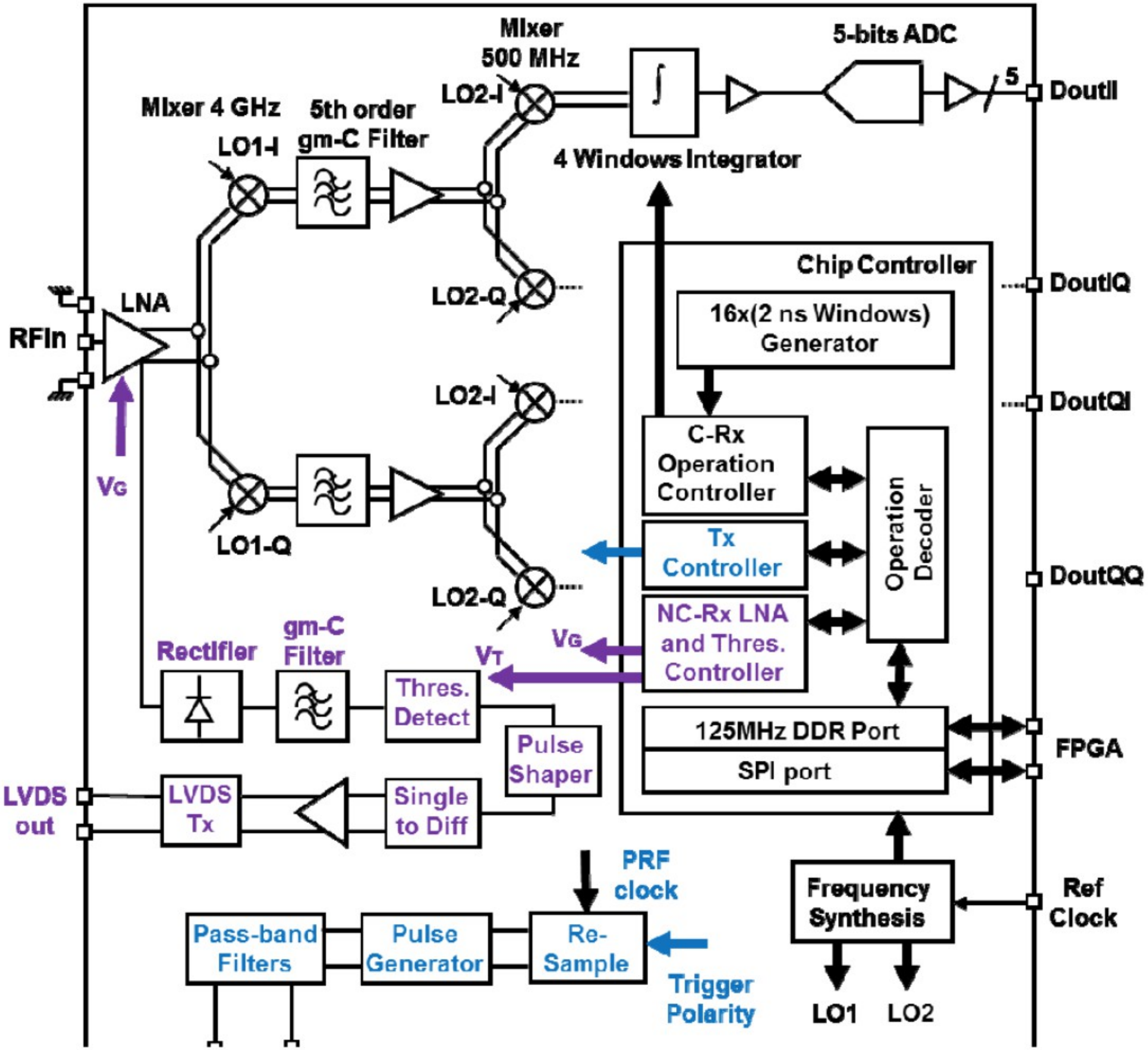
- Transmission
  - 1 ns pulses, wideband
  - Pulse shaping, filtering
  - Time-dithering
  - On-Off, Polarity or Position modulation
- Reception
  - Expected pulse time windows
  - Coherent or non-coherent detection
  - Several pulses per bit of information
- Ranging
  - RF time of flight





Ultra Wide Band impulse radio

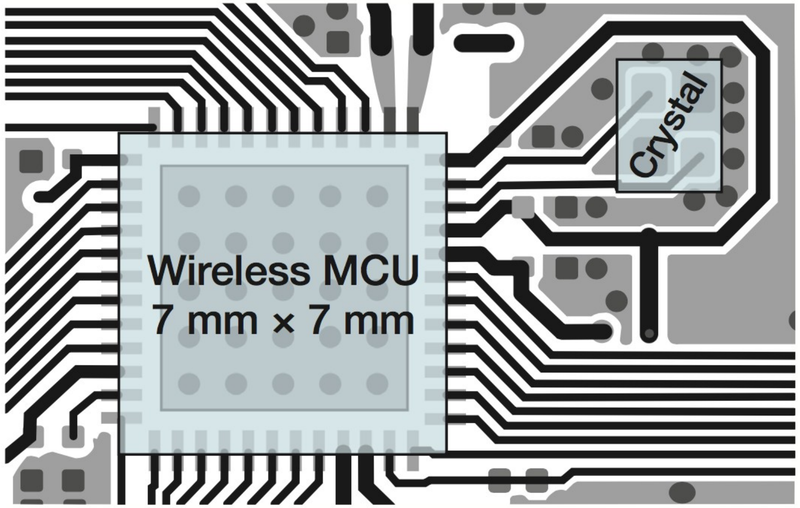
- Amenable to ultra low power consumption
  - very few linear circuits
  - idle most of the time
- Wideband electronics settles quickly
- Receiver circuits can be turned off between expected pulses
  - Including between multipath replicas

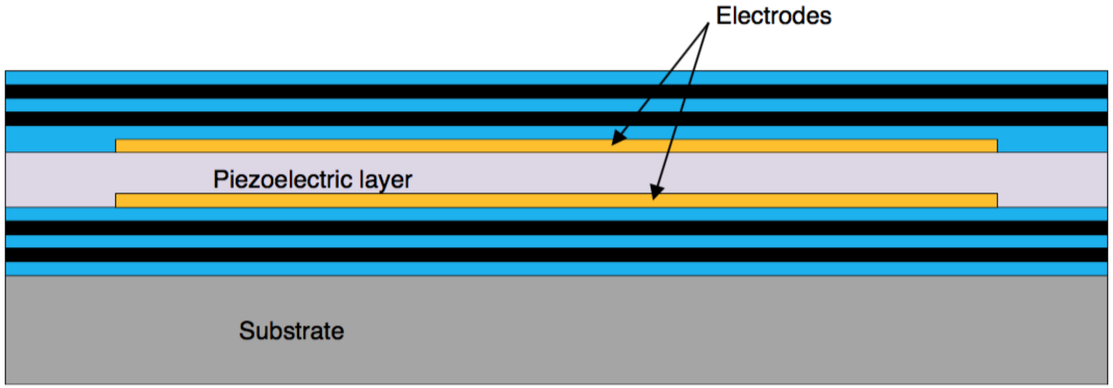


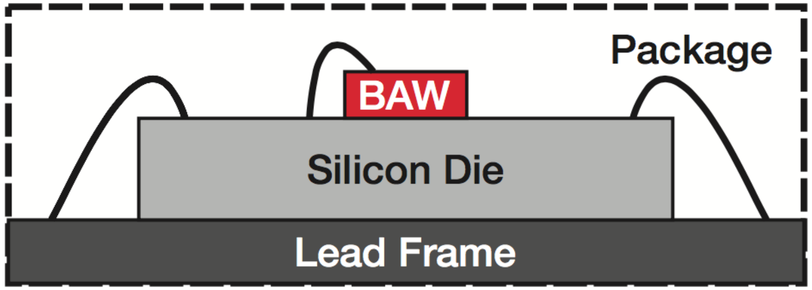
Ouvry, L.; Masson, G.; Pezzin, M.; Piaget, B.; Caillat, B.; Bourdel, S.; Dehaese, N.; Fourquin, O.; Gaubert, J.; Meillere, S.; Vauche, R., "A 4GHz CMOS 130 nm IR-UWB dual front-end transceiver for IEEE802.15 standards," Proceedings of the 21st IEEE International Conference on Electronics, Circuits and Systems (ICECS), pp.798,801, Marseille, France, Dec. 2014.

Cheaper radios (1/2)

- In-package Bulk Acoustic Wave (BAW) resonator
- TI CC2652RB (Feb 2019)
  - BT, 15.4 radio, Zigbee stack
  - 48 MHz BAW, 40 ppm accuracy







Cheaper radios (2/2)

- Crystal-less radio
  - Network-based synchonization
- On-chip antenna
  - Deemed viable above > 10 GHz

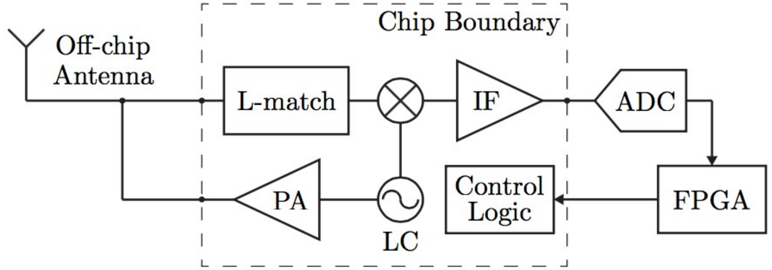


Fig. 1. System level block diagram of the transceiver.

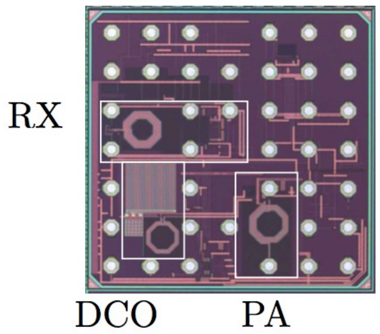
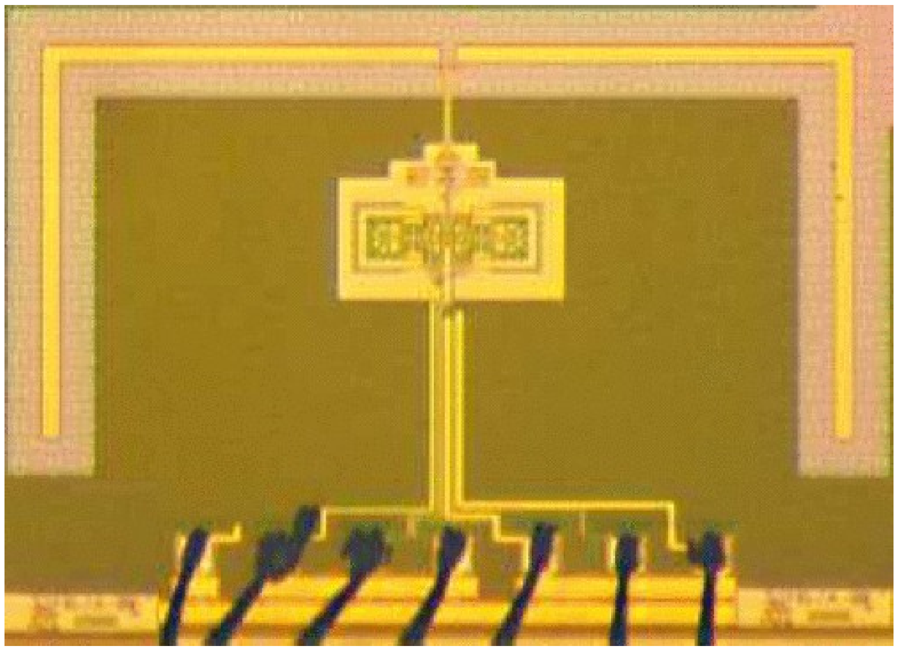


Fig. 2. Die photo of the 1.83 mm * 1.83 mm flip-chip IC, of which the radio occupies 1.2 mm^2.

B. Wheeler et al., "Crystal-free narrow-band radios for low-cost IoT," 2017 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Honolulu, HI, 2017, pp. 228-231.doi: 10.1109/RFIC.2017.7969059



M. Pons et al., "Study of on-chip integrated antennas using standard silicon technology for short distance communications," 2005 European Microwave Conference, Paris, 2005, pp. 4 pp.-1714.

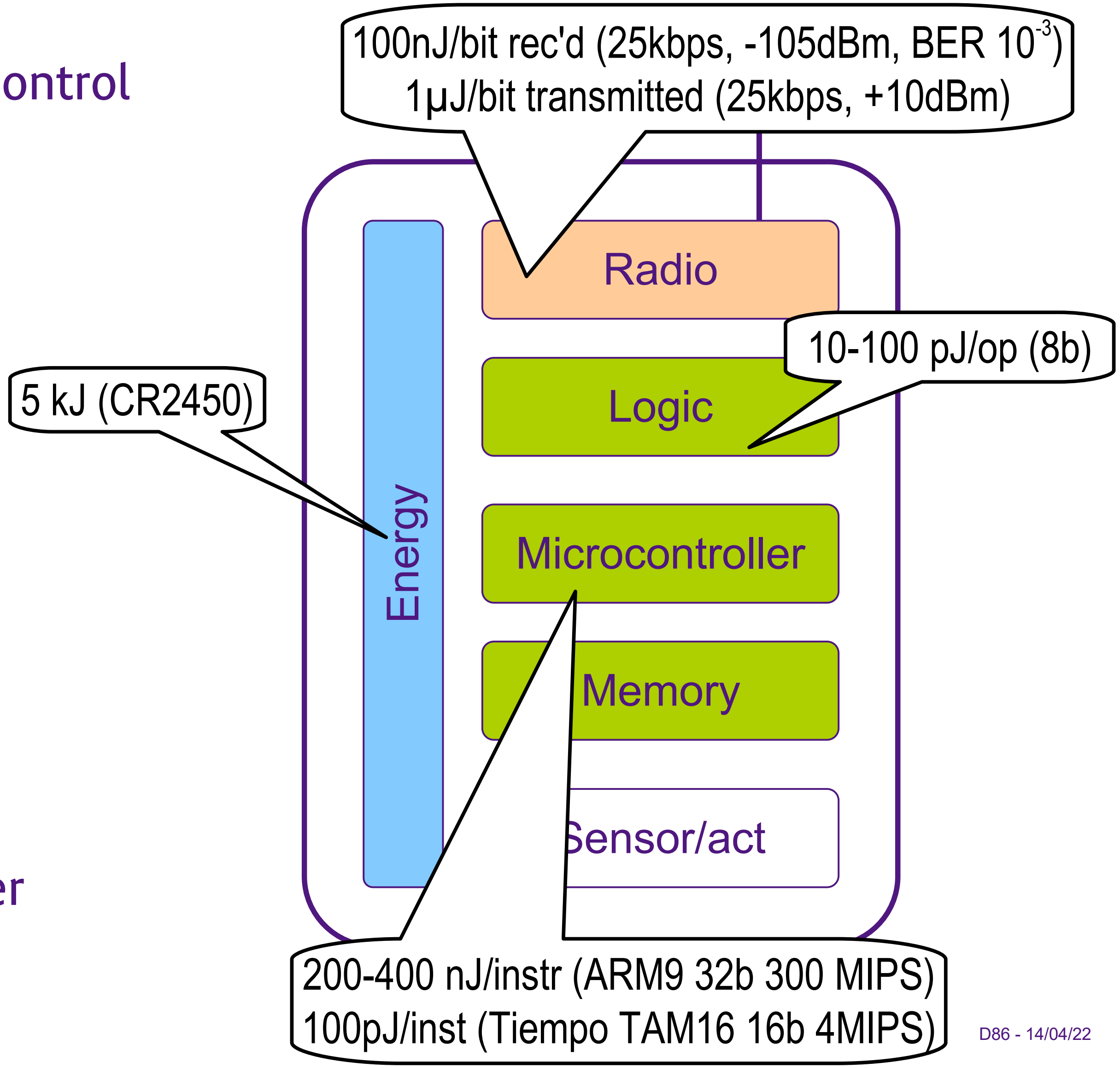
Agenda

- Introduction
- Some experimentation boards and platforms
- Energy source, energy consumption
- Microcontrollers, memory
- Spectrum, PHY layer and radio chips
- Conclusions

Conclusions

Sensor Node energy balance

- Energy
  - monitoring/conversion/control
  - battery
  - from environment
    - solar cell
    - vibrations
    - heat
- Radio
  - low power
  - highly efficient
  - unlicensed
- Computation
  - hard-wired
  - microprocessor/controller
- Sensing/Actuation



Transmission vs. Computation

- Wireless transmission = 0.1 µJ - 1mJ per bit
- Microcontroller computation = 0.1 - 10 nJ per instruction

- Saving 1 bit on the air is worth 100 computation instructions

- Trend to reducing communication cost
  - by using more computation
  - smart protocols, compression

- The opposite in wired (fiber) networks !

End of Session