Energy harvester powered wireless sensors

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NiPS Laboratory

Noise in Physical Systems

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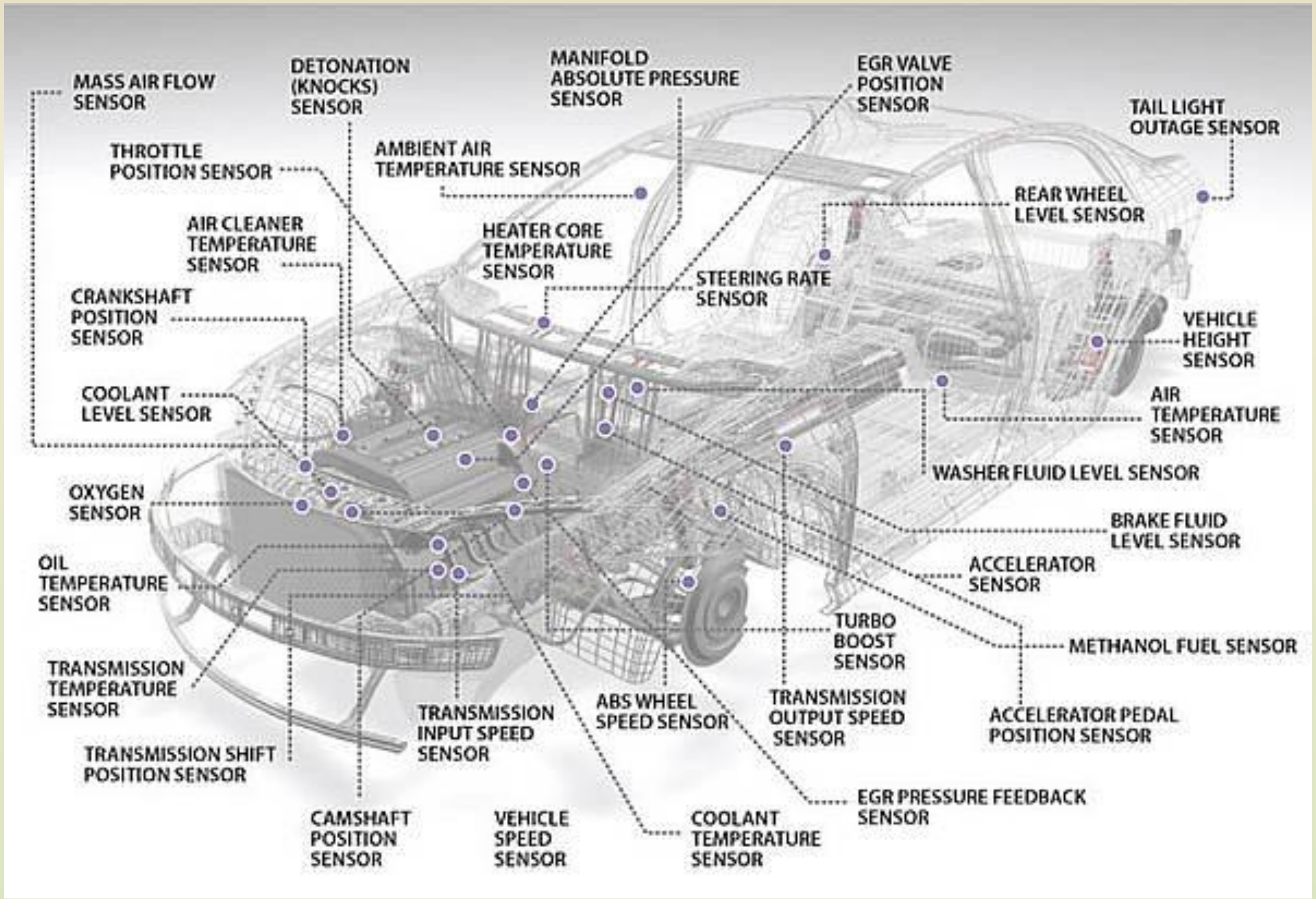
- Why autonomous wireless sensors?
- Power requirements
- Sources of energy
- Energy budget
- Hardware development
- Software development
- Some examples

Why autonomous wireless sensors?

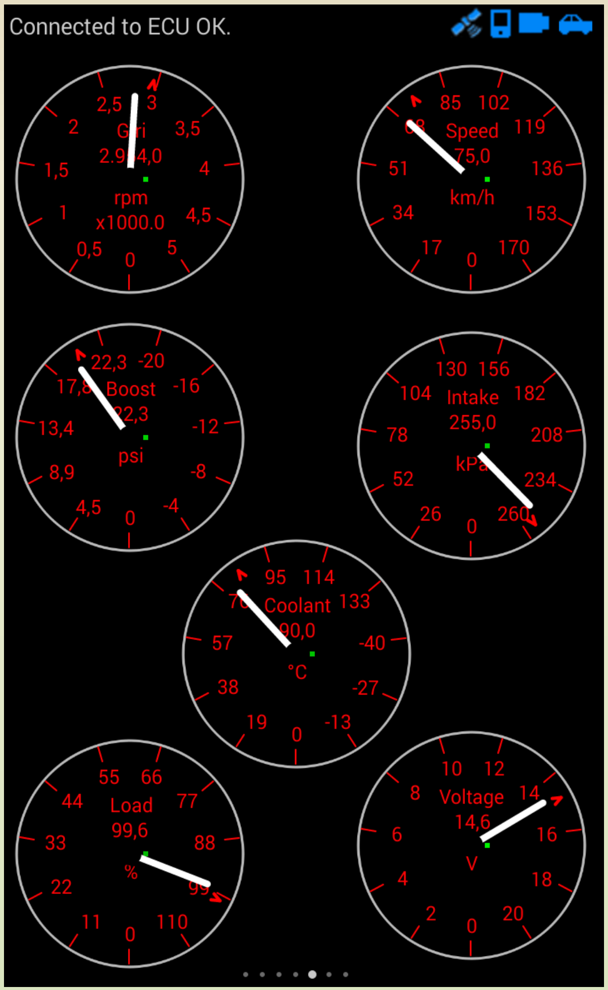
Ex. 1: there are a lot of sensors in a vehicle



Source http://www.can-cia.org/index.php?id=1691

Why autonomous wireless sensors?

Some of the sensors are acquired in realtime.



Why autonomous wireless sensors?

… and this is the result!

Why autonomous wireless sensors?

≈ 100 kg of wires

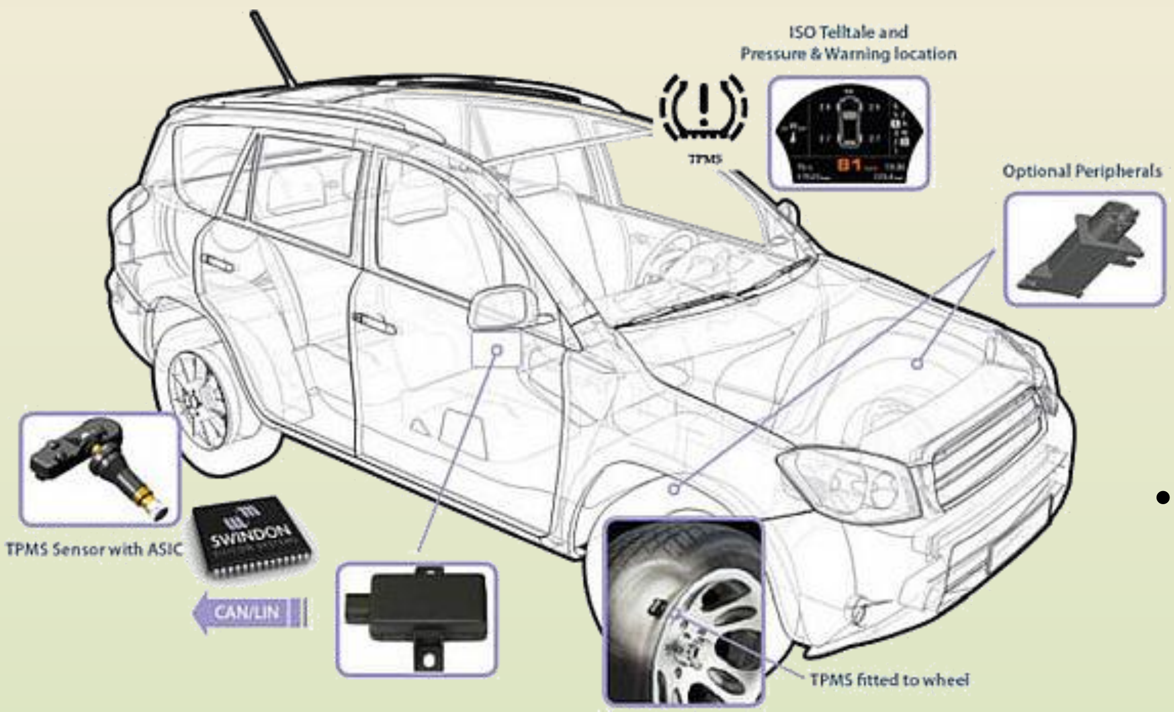
Cost?
Space?
Weight?
Reliability?
Time to assembly?

Fewer Wires, Lighter Cars IEEE 802.3 Ethernet standard will reduce the weight of wires used in vehicles
KATHY PRETZ Apr. 2013
http://theinstitute.ieee.org/benefits/standards/fewer-wires-lighter-cars

Why autonomous wireless sensors?

Can we move from WIRED to WIRELESS?

Which sensor can we move to wireless?
A TPS can be a good candidate!



Source http://www.can-cia.org/index.php?id=1691

We need to consider:

- safety concerns for people and for car itself
- in car and car-to-car networking/interferences problems

Why autonomous wireless sensors?

It makes sense to use wireless sensors in replaceable parts.

No wires can be used in some parts of the vehicle.

Losing the communication can impact the performances but not the safety!

Why autonomous wireless sensors?

We don't want wires (and batteries)!

http://www.chinabaike.com/z/keji/dz/772296.html

Pros:

- easy to use, light weight
- cheap and reliable
- quite high density of energy
- many size, voltages and capacity

They discharge, even when simply stored and not used.

They need to be replaced: maintenance expenses.

They need to be recycled!

Rechargeable batteries can be an option!

Why autonomous wireless sensors?

Ex. 2: extended structures monitoring

Golden Gate Bridge, San Francisco, California, USA
Total length: 8.981 ft (2,737.4 m)
Height: 746 ft (227.4 m)

Why autonomous wireless sensors?

Ex. 3: large open and wild area

Point Reyes National Seashore, California, USA

Area: 111 mi² (71,028 acres - 287.44 km²)[

Why autonomous wireless sensors?

Ex. 4: big cities

Los Angeles, California, USA

Area: 503 mi^2 (1302 km^2)

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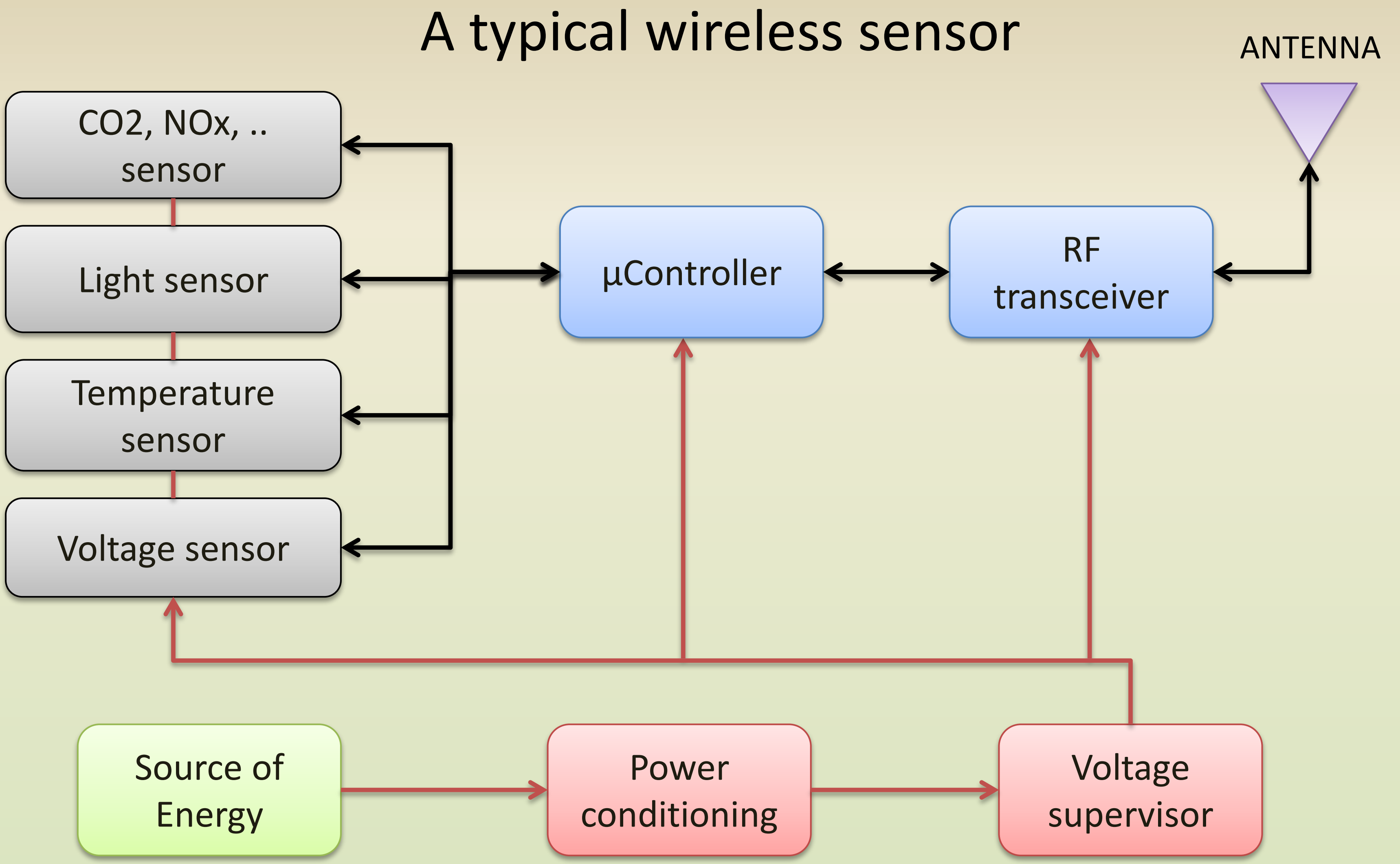
Power requirements

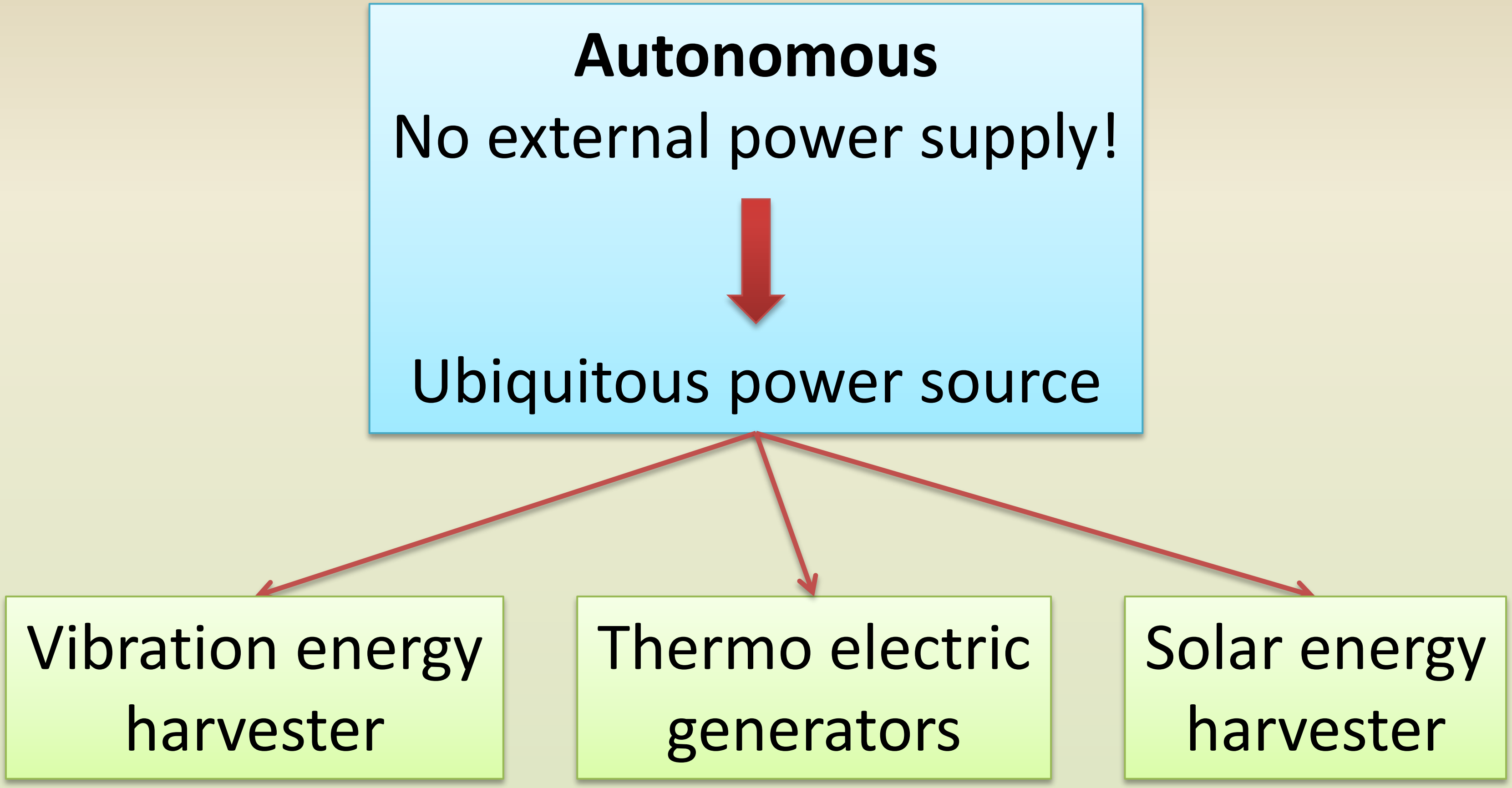
So… what are we talking about?

- **Autonomous** → No external power supply
- **Wireless** → No wires can be used
- **Sensor** → It has to be able to do measurements
- **No batteries** → The energy harvester has to replace batteries: small and low cost

Power requirements



Power requirements



Power requirements

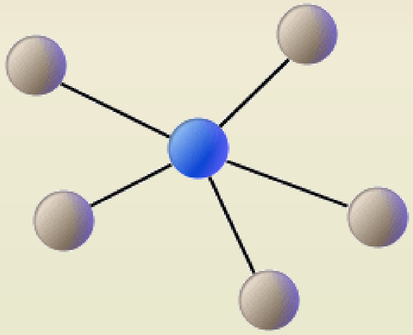
How much energy is available?

SOURCE		AVAILABLE ENERGY (typical)
CR2032 battery		240 mAh @ 3.0 V (to 2.0 V)
AAA NiMH battery		900 mAh @ 1.2 V
Vibration energy harvester		???
Solar energy harvester		???

Power requirements

Low power **wireless** sensor

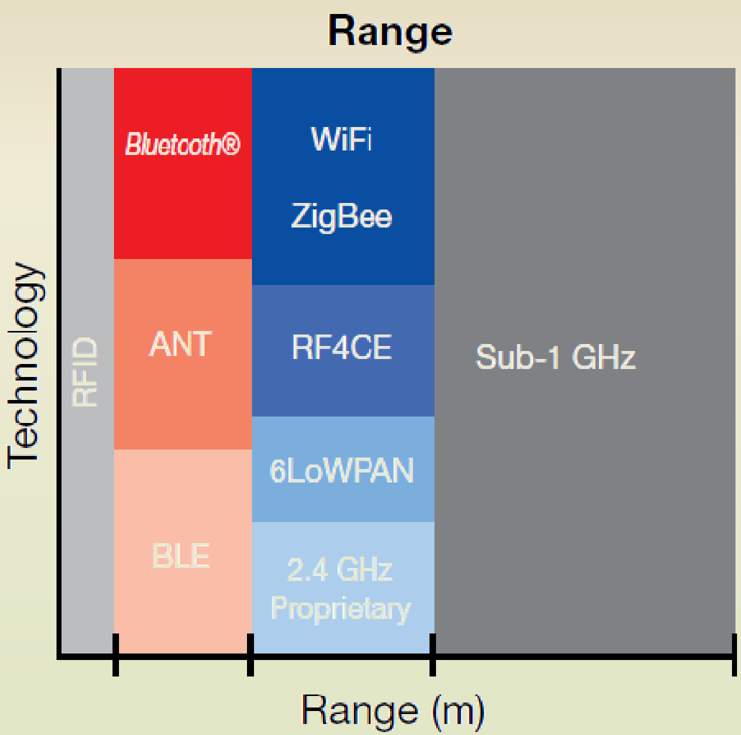
- Low power RF transceiver → $P_{RF} \leq 100\,mW$
- Star topology (typical)

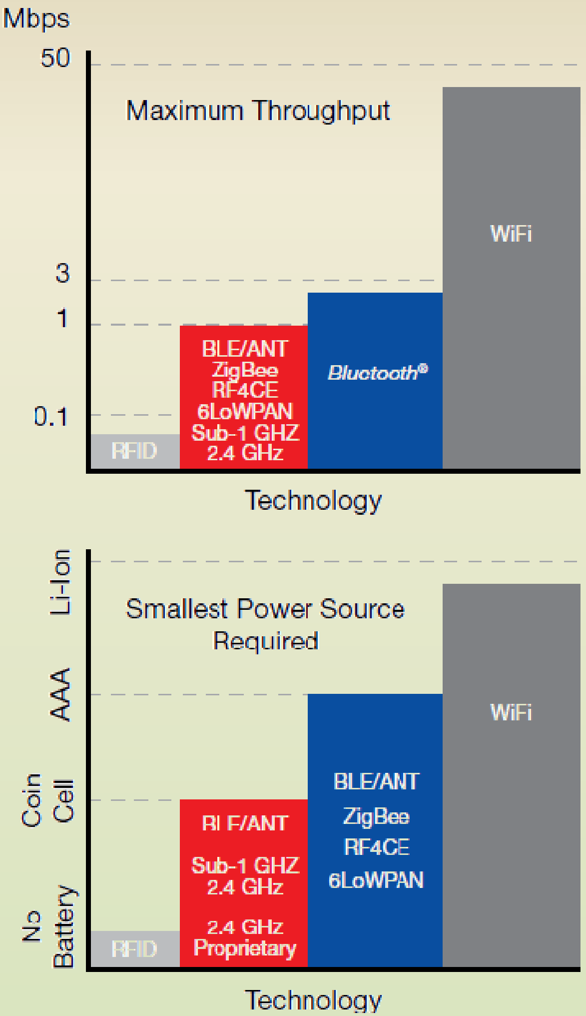


- Low duty cycle → $\delta \leq 1\% \quad typical$
- Short range → $\text{Distance} \leq 100\,m \quad typical$
- Long range → $\text{Distance} > 100\,m$

Power requirements

Many low power RF transceiver





<u>Many different options!</u>

Power requirements

Texas Instruments CC2500

RF Power: 0 dBm @ 3,0 Vdc 21,2 mA

Datarate: R = 250 kbaud FSK / OOK

P_{DC} = 63,6 mW

$$E_{SYM} = P_{DC} / R = 254{,}4 \cdot 10^{-9}\, J$$

$$\eta_{SYM} = \frac{P_{RF}}{P_{DC}} = \frac{4{,}0 \cdot 10^{-9}}{254{,}4 \cdot 10^{-9}} = 15{,}7 \cdot 10^{-3}$$

Microchip Technology MRF24J40

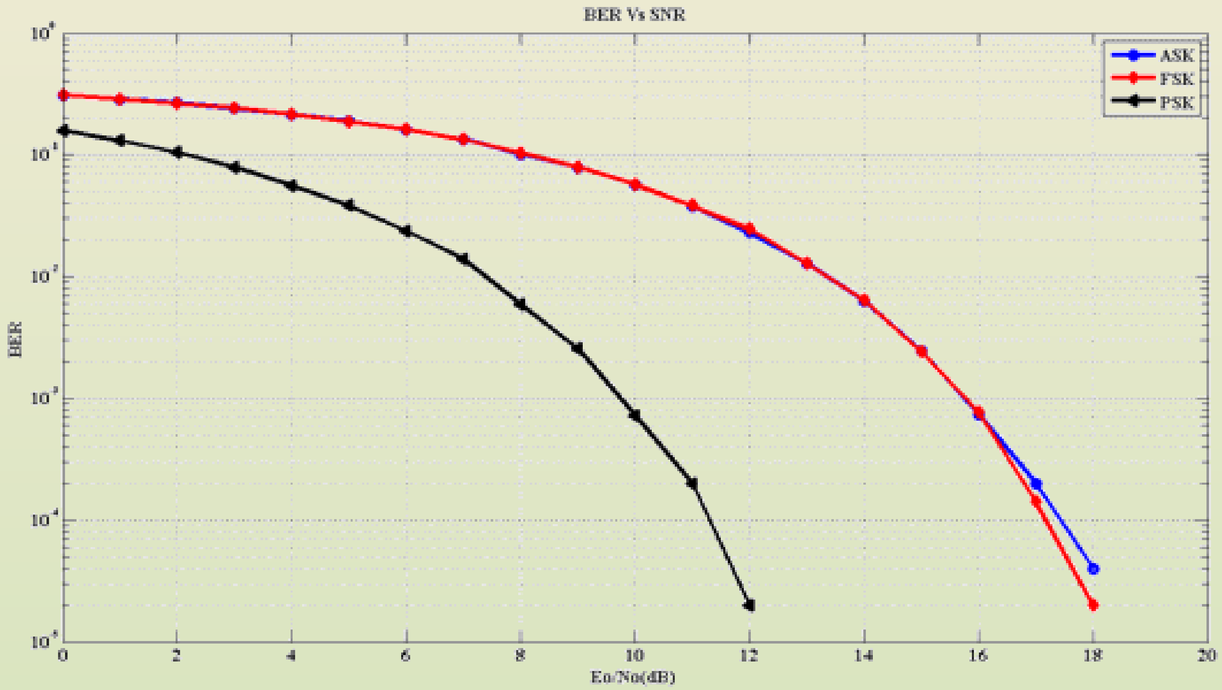
RF Power: 0 dBm @ 3,3 Vdc 23 mA

Datarate: R = 125 kbaud O-QPSK 802.15.4

P_{DC} = 75,9 mW

$$E_{SYM} = P_{DC} / R = 607{,}2 \cdot 10^{-9}\, J$$

$$\eta_{SYM} = \frac{P_{RF}}{P_{DC}} = \frac{8{,}0 \cdot 10^{-9}}{607{,}2 \cdot 10^{-9}} = 13{,}2 \cdot 10^{-3}$$



Power requirements

Sensor (sensing elements)

- Rain sensor ≈ 100 mJ
- Acceleration sensor ≈ 400µJ
- Pressure sensor ≈ 60 mJ
- Temperature sensor ≈ 20 µJ
- Light sensor < 0 µJ
- Sound sensor < 0 µJ
- …

Power requirements

16 bit µController (typ.)

- 16-Bit RISC Architecture
- Low Supply Voltage Range: 1.8 V to 3.6 V
- Ultra-Low Power Consumption
  - Active Mode: ≈ 2.5 mA @ 16MHz
  - Sleep mode + timer: ≈ 0.4 µA
  - Idele mode: ≈ 0.1 µA / MHz
  - Deep sleep mode: ≈ 30 nA
- 10-Bit 200-ksps ADC
- SPI, UART, Timer…

(Typ. LED 1.6 x 0.8 x 0.6 mm^3: 10 mA @ 1.8 V)

Power requirements

CASE STUDY: TIME DISTRIBUTION OF THE OPERATING MODES

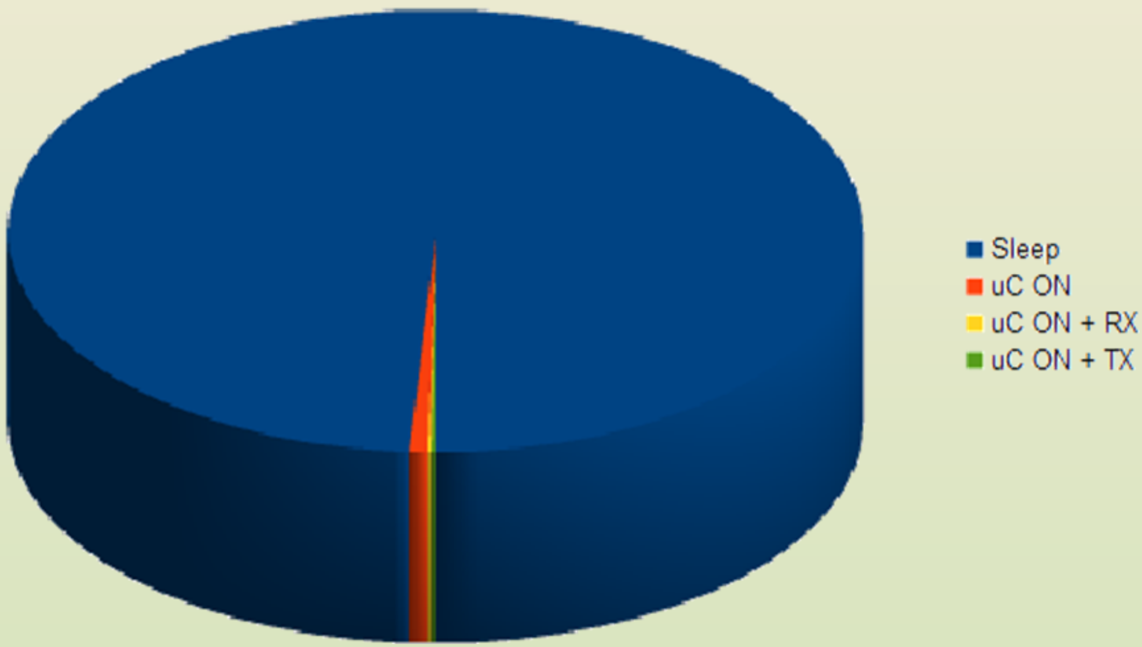
Period: 1 s

µController: sleep mode 0,990 s

µController: active mode 0,007 s

µController: active mode + RX 0,001 s

µController: active mode + TX 0,002 s



Power requirements

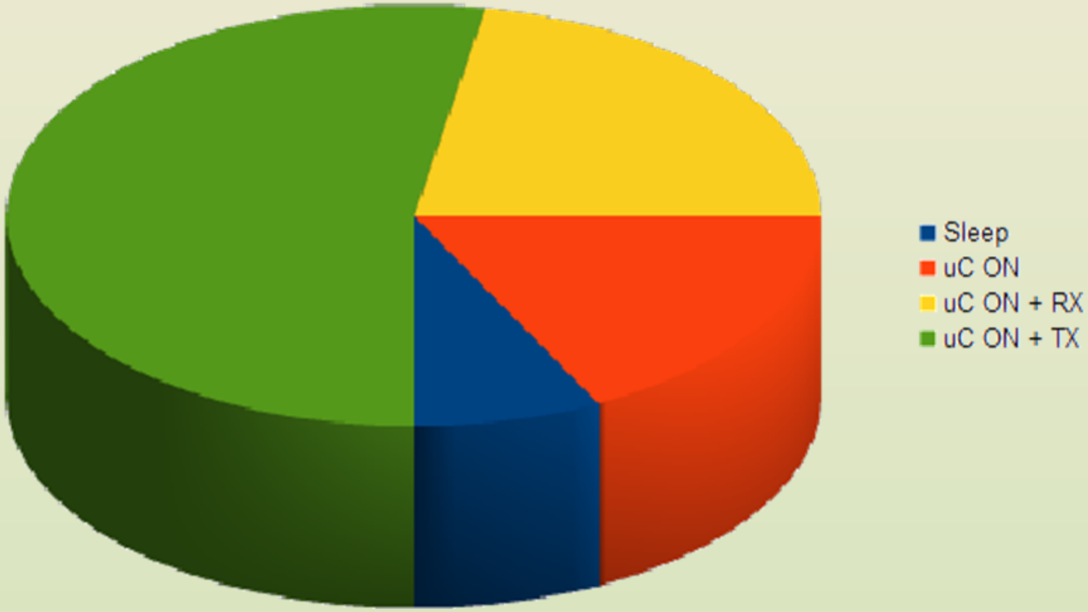
ENERGY CONSUMPTION vs OPERATING MODES

$$P_{TOT} = P_{\mu Controller} + P_{RX} + P_{TX} + P_{SUPERVISOR}$$

$$P_{\mu Controller} \propto I_{\mu Controller} = 2{,}4\, mA\, @\, 16\, MHz\, ,\, 270\, nA\, D-Sleep + WDT$$

$$P_{TX} \propto I_{TX} = 23\, mA\, @\, 0\, dBm \qquad P_{RX} \propto I_{RX} = 19\, mA$$

$$P_{SUPERVISOR} \propto I_{SUPERVISOR} = 7\, \mu A$$



Power requirements

ENERGY CONSUMPTION vs OPERATING MODES

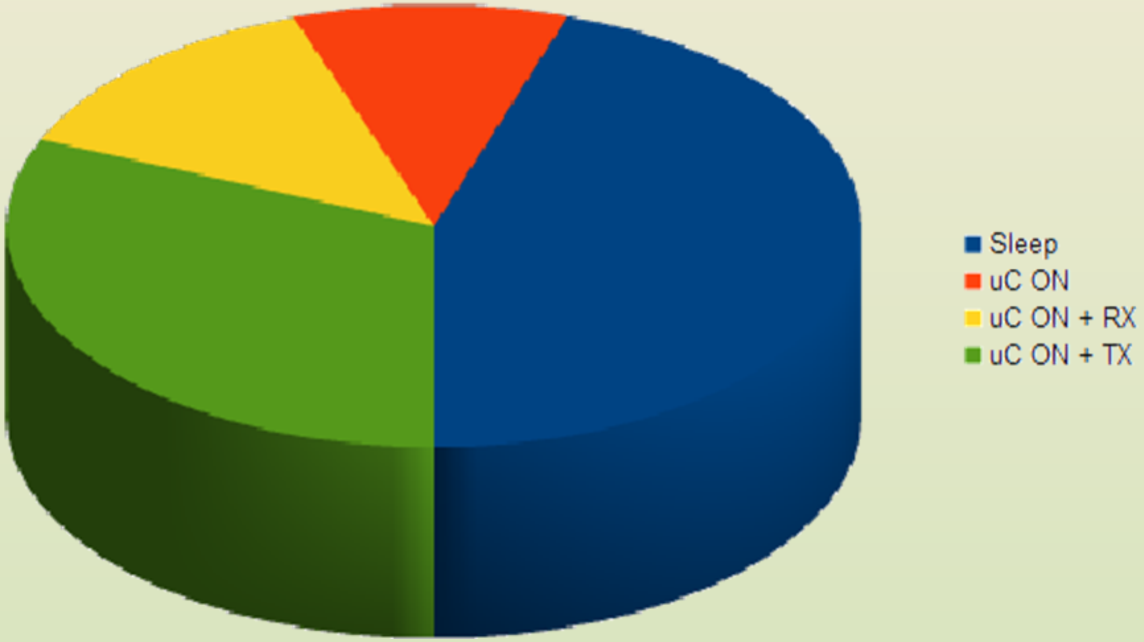
Period: 10 s

μController: sleep mode 9,990 s

μController: active mode 0,007 s

μController: active mode + RX 0,001 s

μController: active mode + TX 0,002 s



Power requirements

Required features

- Small → few centimeters
- Light → few grams
- Low cost → few euro
- Long life → no maintenance

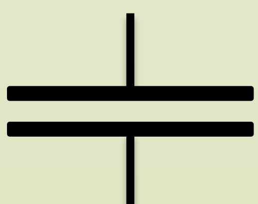
↓

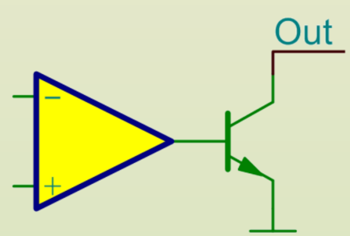
It must work with the energy harvested from the environment!

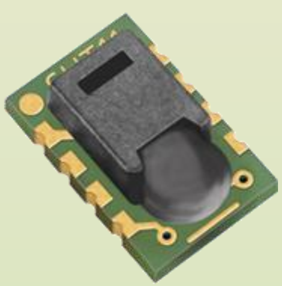
Power requirements

Energy is limited!

ENERGY HARVESTER → ENERGY STORAGE → VOLTAGE REGULATOR & SUPERVISOR → SENSOR





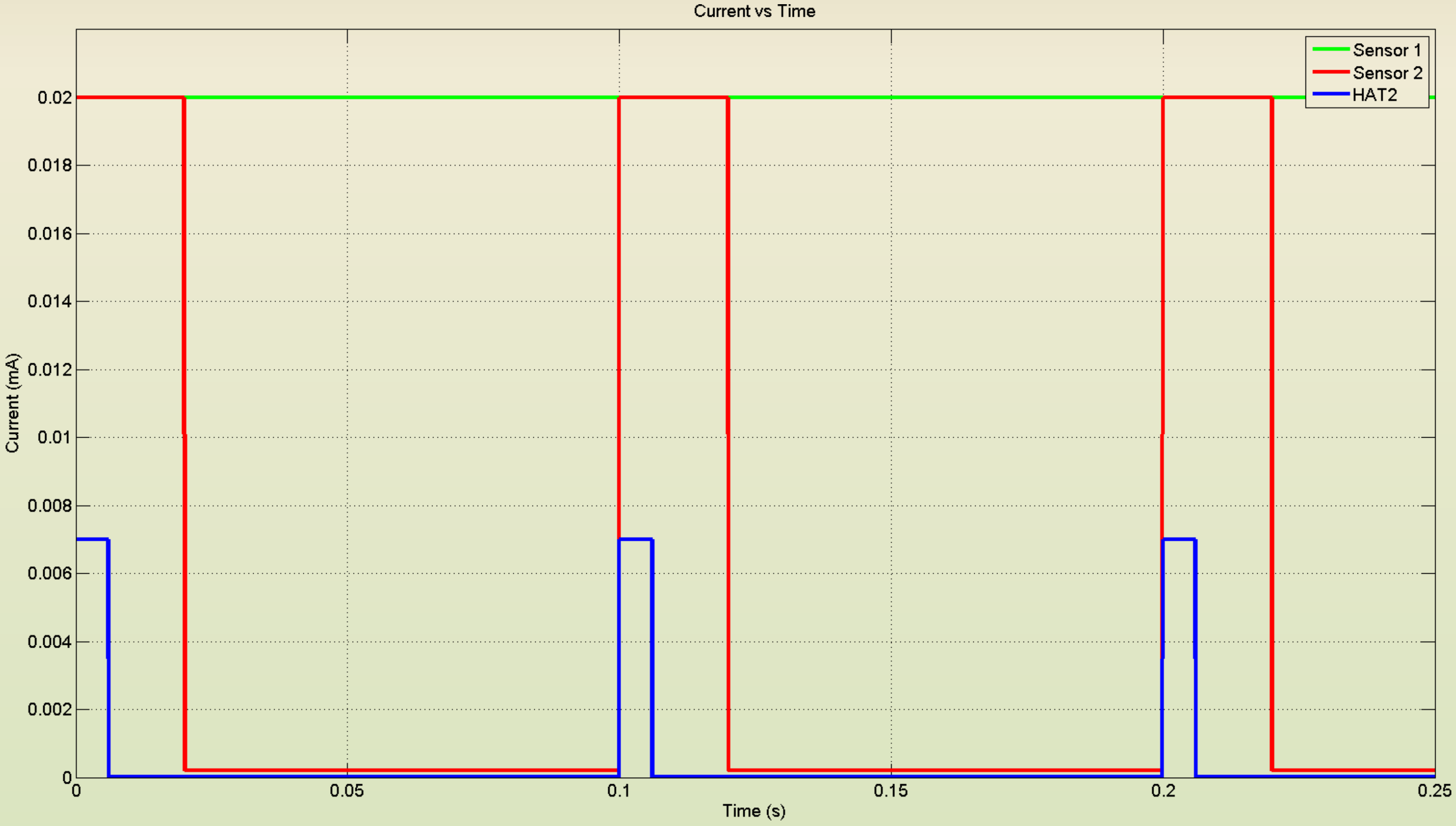


Power requirements

Sensor 1: 20 mA constant

Sensor 2: 20 mA rms, 20 ms active mode – 200 µA rms, 80 ms sleep mode

NiPS HAT2: 7 mA rms, 6 ms active mode – 0.6 µA rms, 94 ms sleep mode

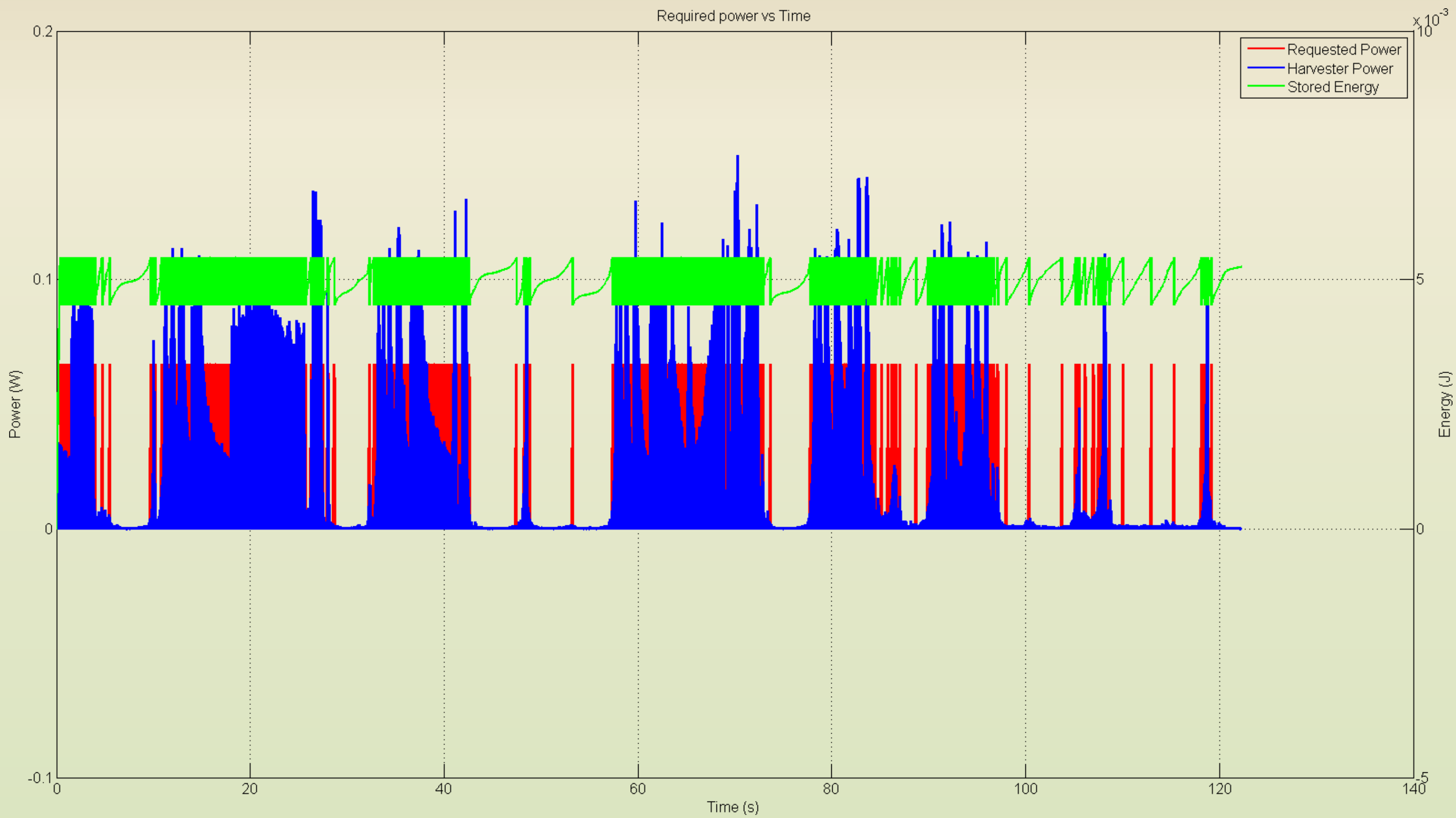


Power requirements

Time series: lap1, y axis
Von = 3.3 V

Capacitor = 0.001 F
Voff = 3.0 V

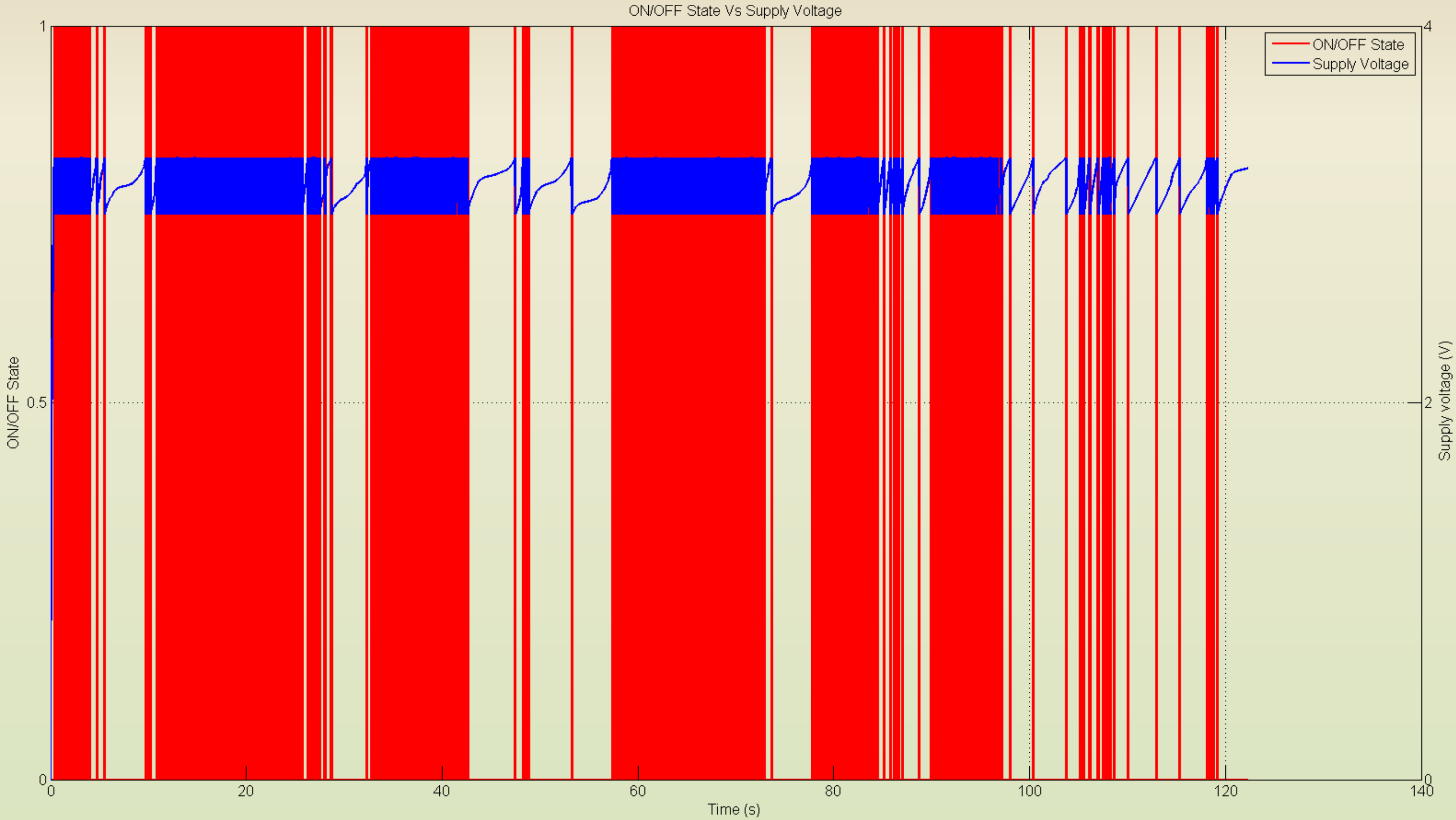
Sensor 1



Power requirements

ON Time = 24.636440 s
ON/(ON+OFF) Ratio = 20.149207 %
Good Acq. = 0
Max Theoretical Acq. = 246

Sensor 1

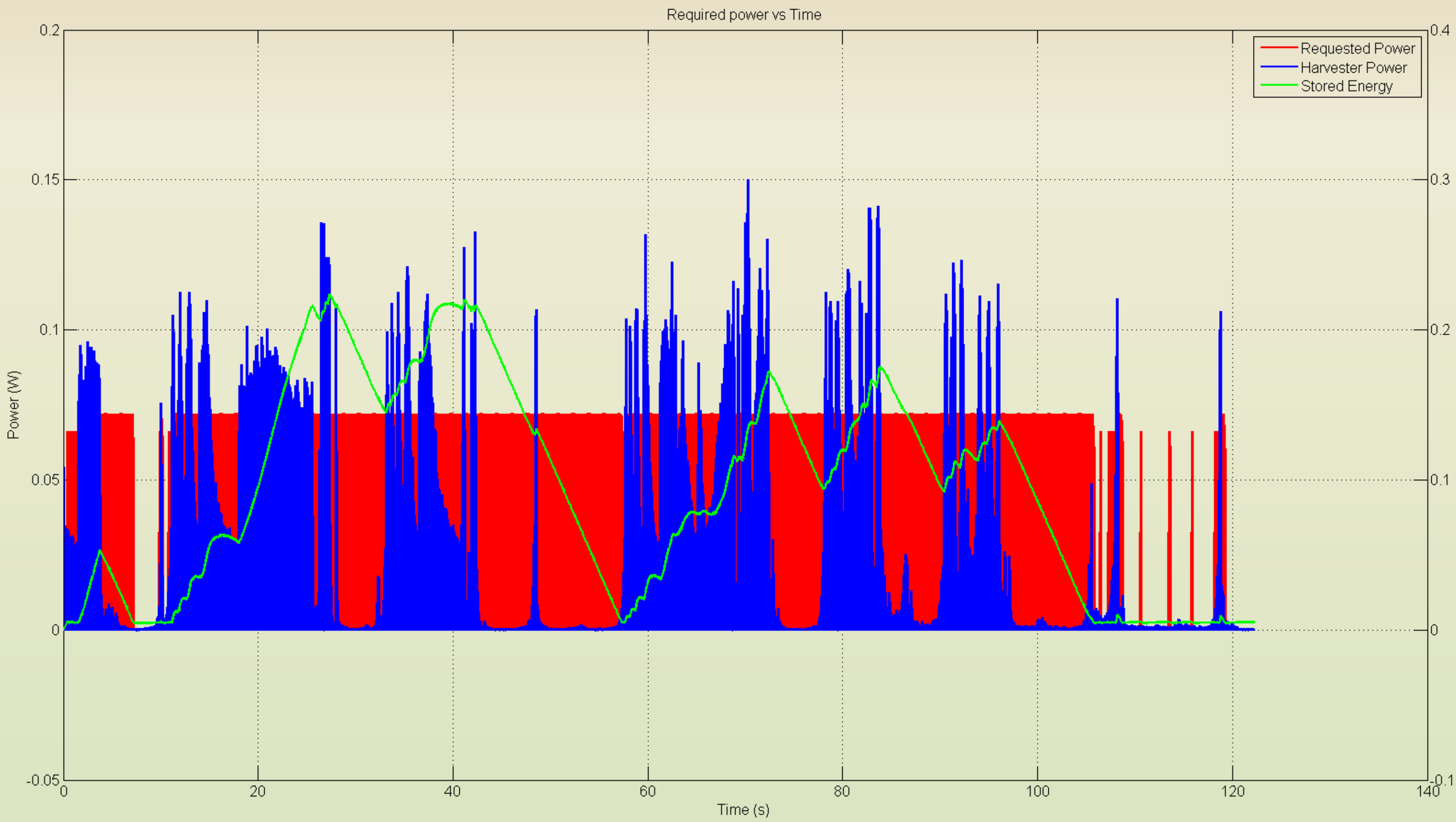


Power requirements

Time series: lap1, y axis
Von = 3.3 V

Capacitor = 0.001 F
Voff = 3.0 V

Sensor 2



Power requirements

Time series: lap1, y axis

Von = 3.3 V

Capacitor = 0.001 F

Voff = 3.0 V

Sensor 2

Power requirements

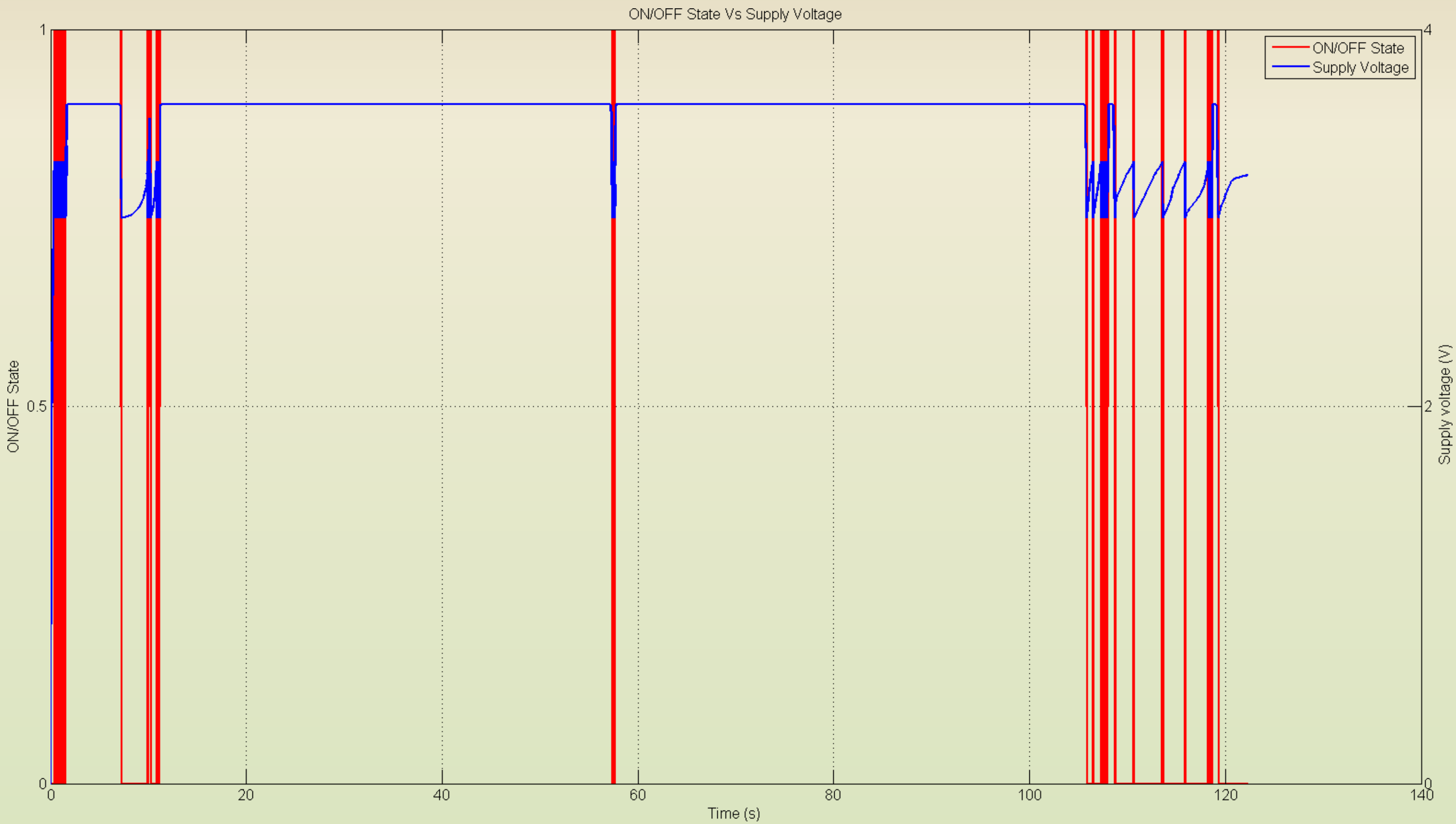
ON Time = 102.112380 s ON/(ON+OFF) Ratio = 83.513833 %

Good Acq. = 1016 Max Theoretical Acq. = 1021 **Sensor 2**

Power requirements

ON Time = 102.112380 s ON/(ON+OFF) Ratio = 83.513833 %

Good Acq. = 1016 Max Theoretical Acq. = 1021 **Sensor 2**



Power requirements

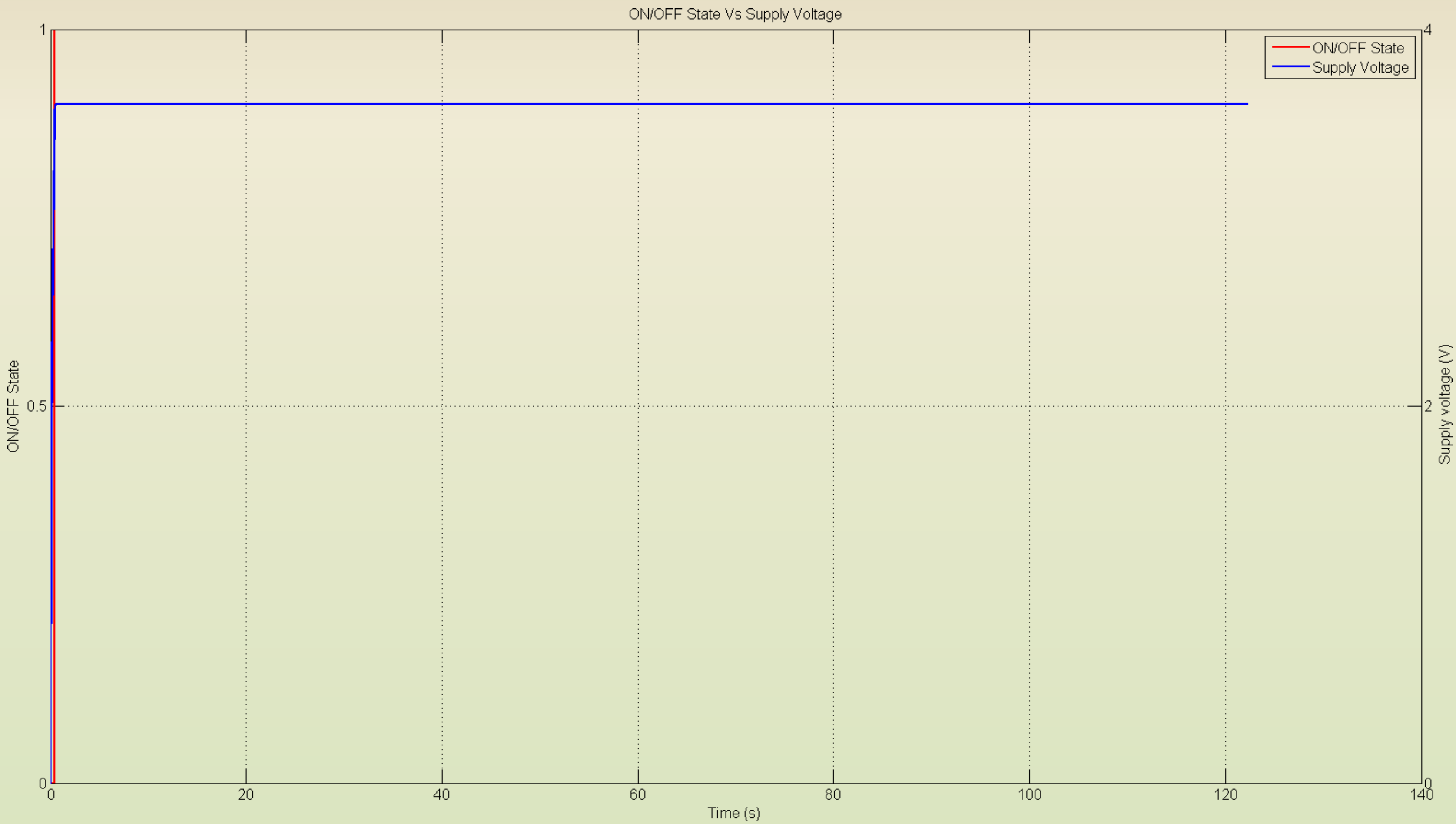
Time series: lap1, y axis
Capacitor = 0.001 F
Von = 3.3 V
Voff = 3.0 V

NiPS HAT2

Power requirements

ON Time = 121.882280 s ON/(ON+OFF) Ratio = 99.682882 %

Good Acq. = 1219 Max Theoretical Acq. = 1219 **NiPS HAT2**



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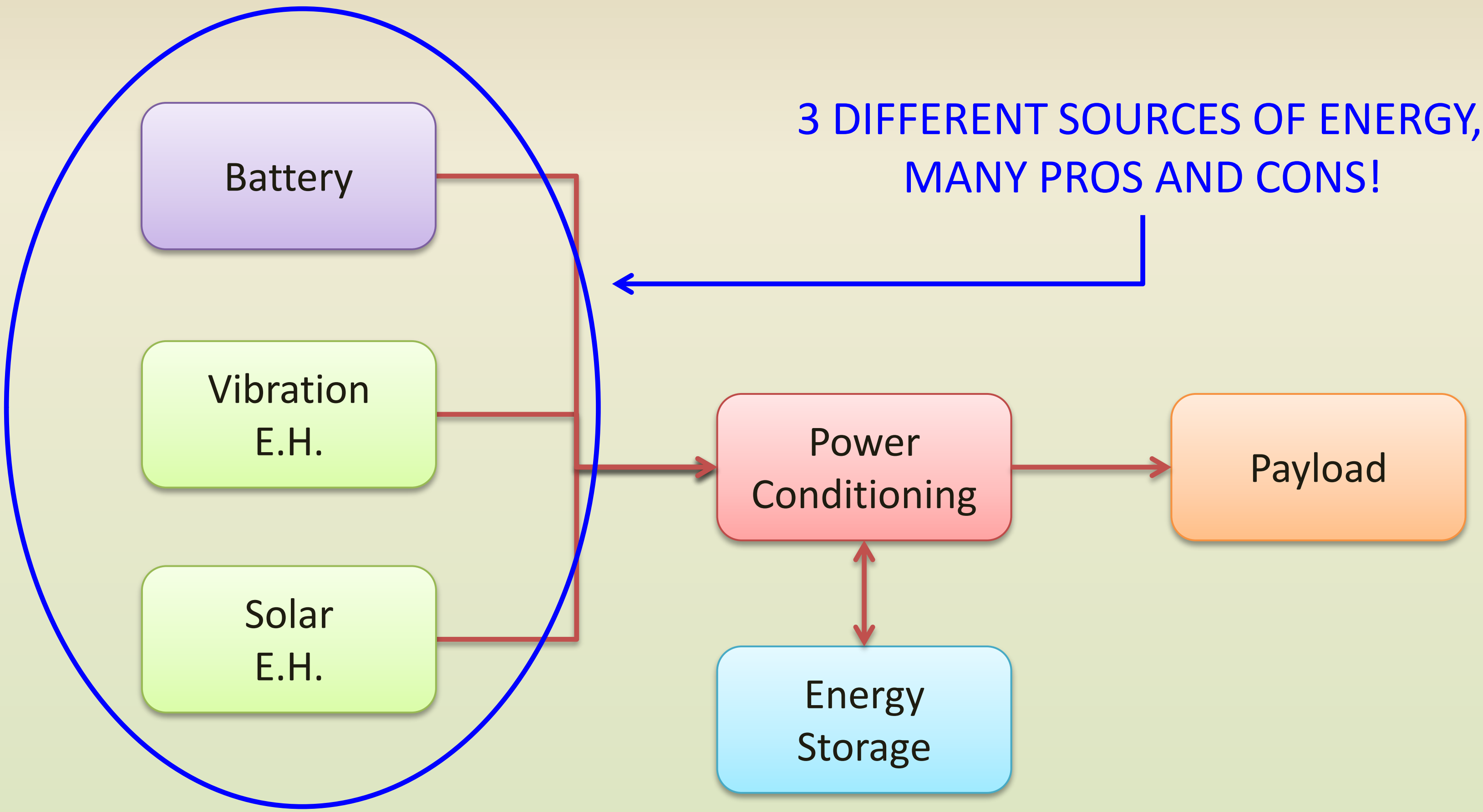
Sources of energy

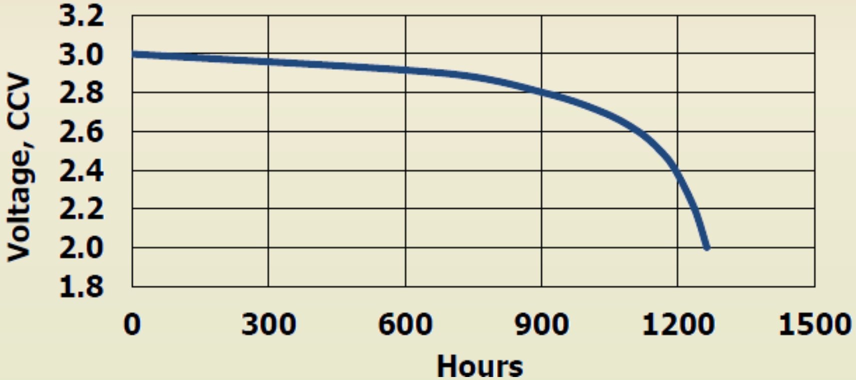
Typical supply chain of an autonomous sensor



Sources of energy

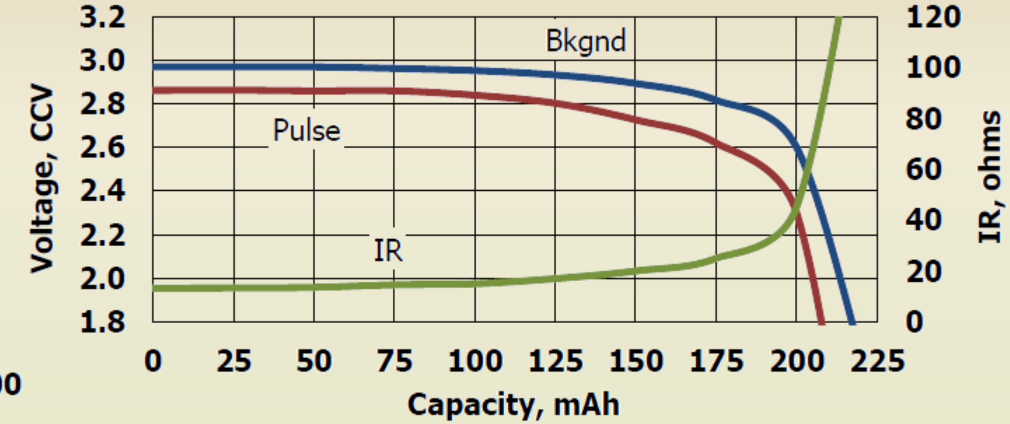
Discharge characteristic of a CR2032 battery.
(from ENERGIZER CR2032 datasheet)

Load: 15K ohms - continuous 21°C (70°F)
Typical Drain @ 2.9V: 0.19 mA

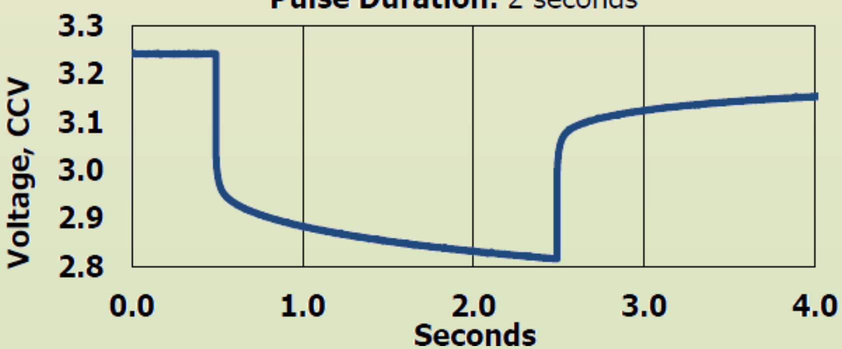


Bkgnd Drain: Continuous
21°C (70°F) 15K ohms
0.19 mA @2.9V

Pulse Drain: 2 seconds X 12 times/day
400 ohms
~6.8 mA @2.7V

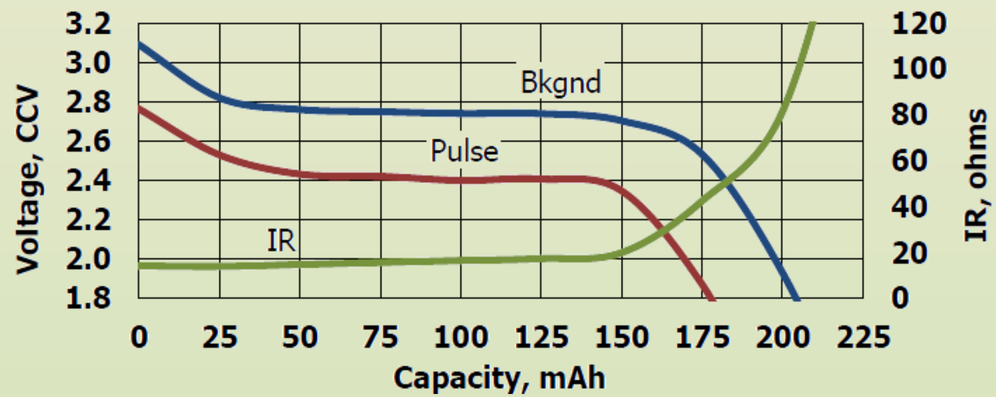


Load: 100 ohms - 21°C (70°F)
Pulse Duration: 2 seconds



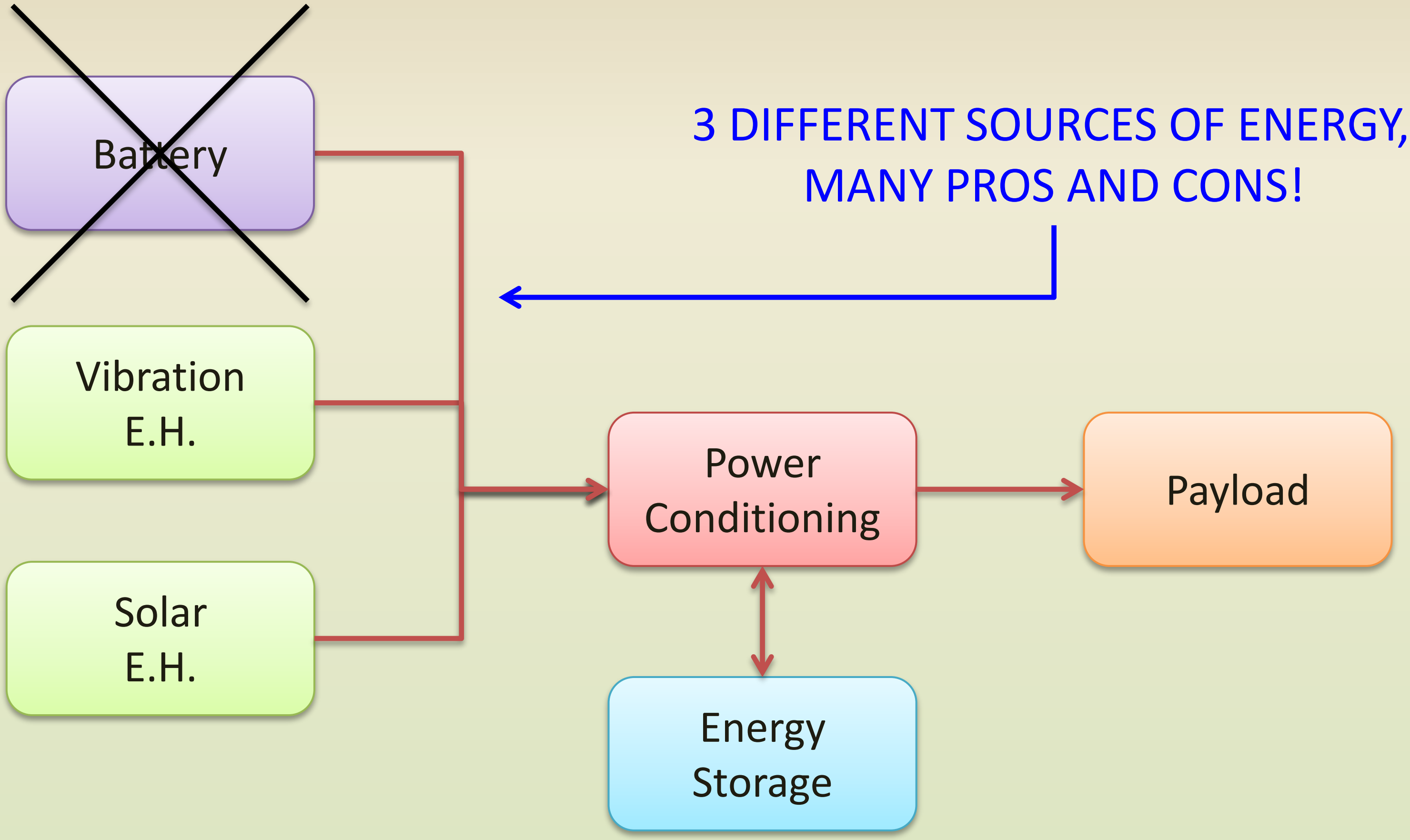
Bkgnd Drain: None
21°C (70°F)

Pulse Drain: 1mSec ON / 14mSec OFF
120 ohms
~23 mA @2.7V



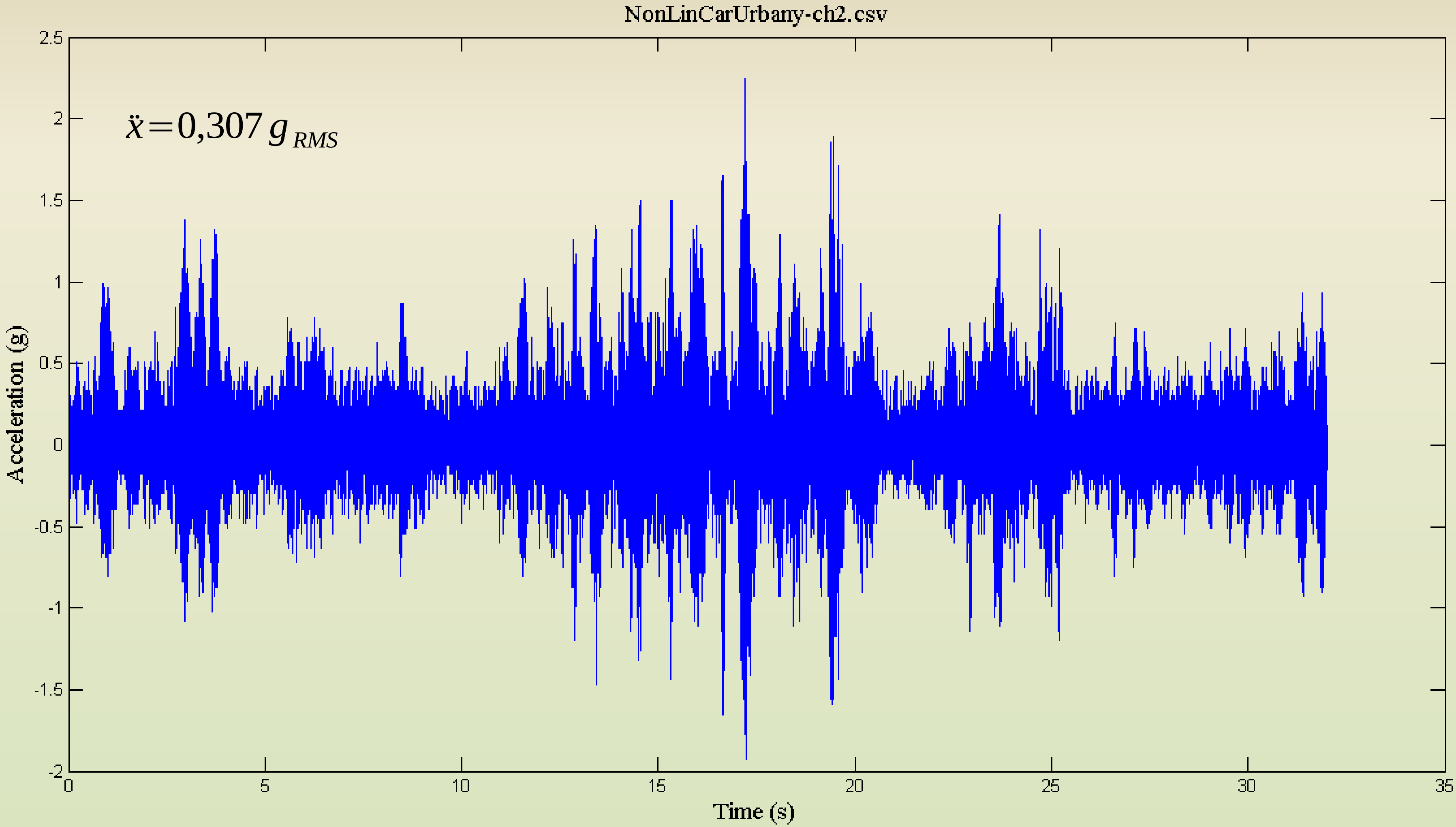
Sources of energy

Typical supply chain of an autonomous sensor



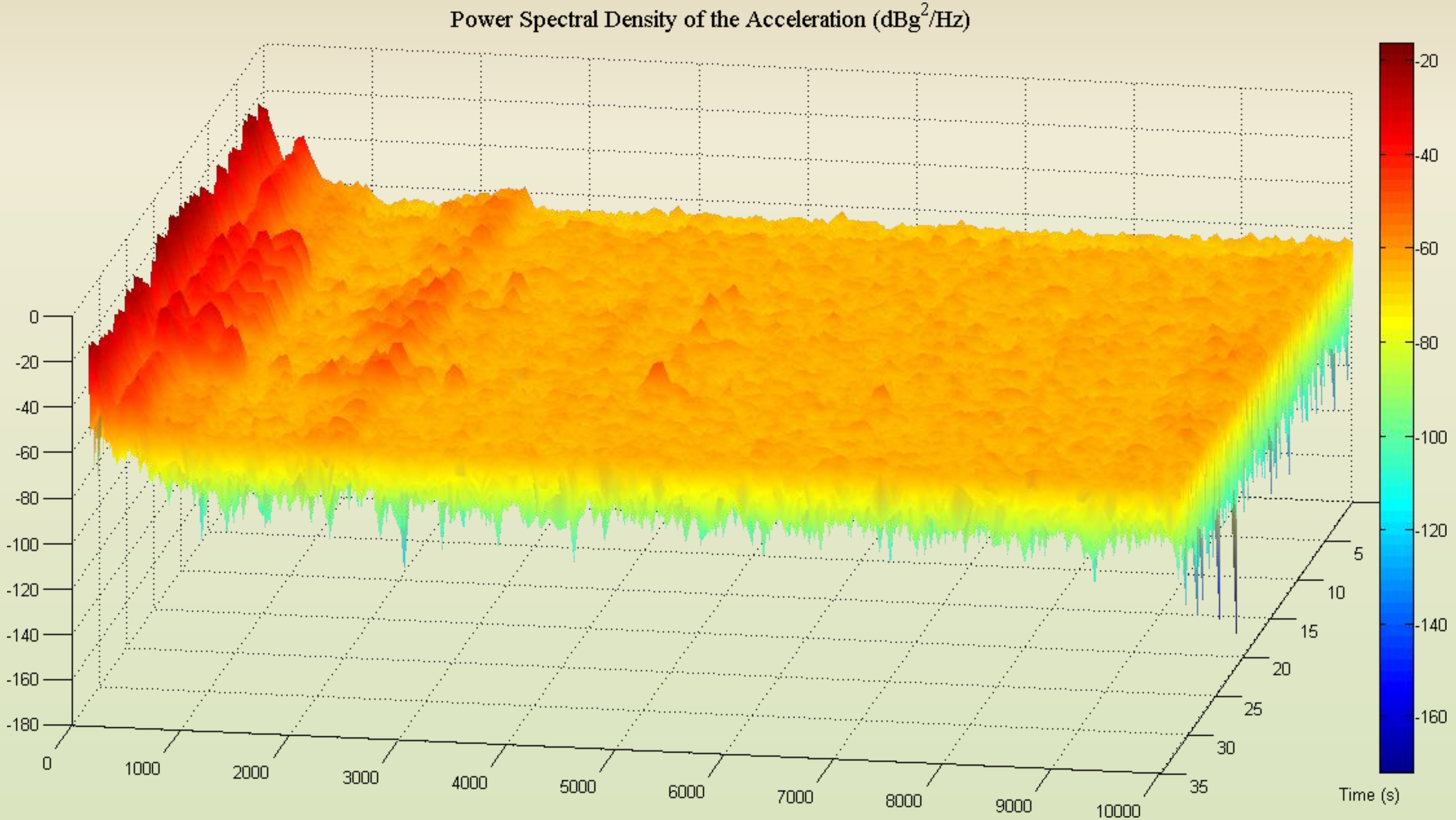
Sources of energy

Vibration energy harvesting



Sources of energy

Vibration energy harvesting

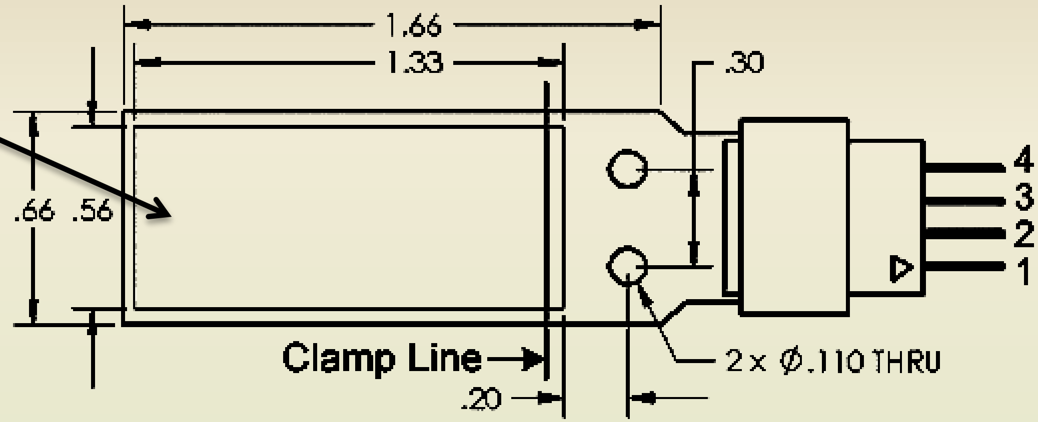


Sources of energy

Piezoelectric vibration energy harvesting

≈50 gr. Tip Mass

Resonant frequency down to 37,5 Hz



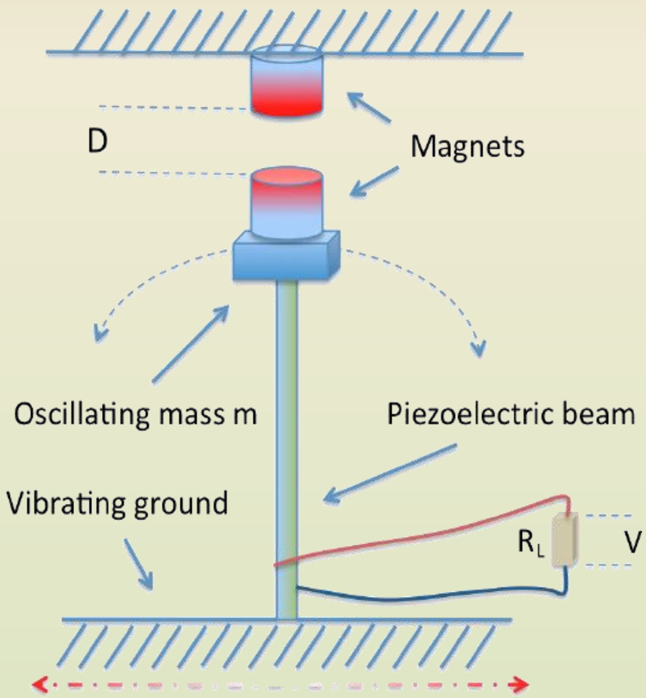
Harvesting Bandwidth (Hz):	3
Frequency Range (Hz):	80 - 205
Device size (in):	2.74 x 0.67 x 0.032
Device weight (oz):	0.115
Active elements:	1 stack of 2 piezos (PZT)
Piezo wafer size (in):	1.40 x 0.57 x 0.008
Device capacitance:	3 - 4 nF

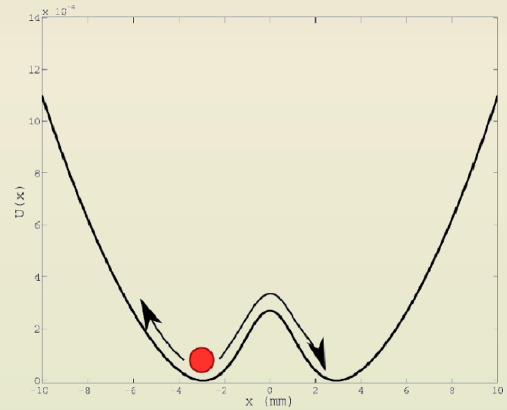
NOT SUITABLE FOR OUR APPLICATION!

Wide Band Noise!

Sources of energy

Piezoelectric vibration energy harvesting





$$\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - K_v V - \sigma\xi(t)$$

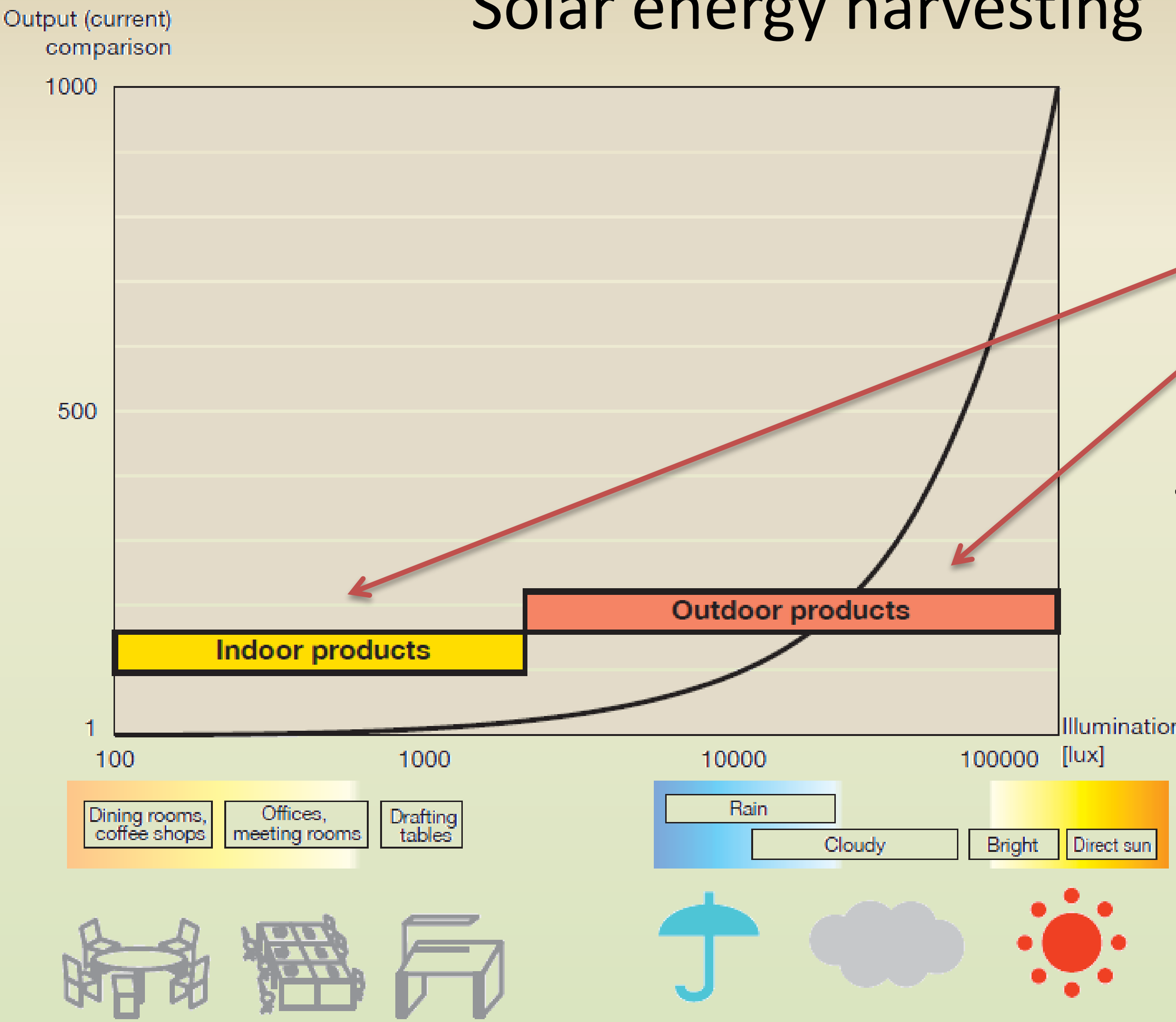
$$\dot{V} = -K_c\dot{x} - \frac{1}{\tau_p}V$$

	Linear E.H.	**Nonlinear E.H.**
Accel. g_{RMS}	0,307	0,302
$V_{OUT\ RMS}$ R_L = 18kΩ	1,966 V	2,160 V
$P_{OUT\ RMS}$ RL = 18kΩ	0,215 mW	0,259 mW

F. Cottone, H. Vocca, L. Gammaitoni, "**Nonlinear Energy Harvesting**"
Phys. Rev. Lett. 102, 080601 (2009)

Sources of energy

Solar energy harvesting



2 typical scenarios

Several illumination conditions

http://us.sanyo.com/Dynamic/customPages/docs/solarPower_Amorphous_PV_Product_Brochure%20_EP120B.pdf

Sources of energy

Solar energy harvesting (some definitions)

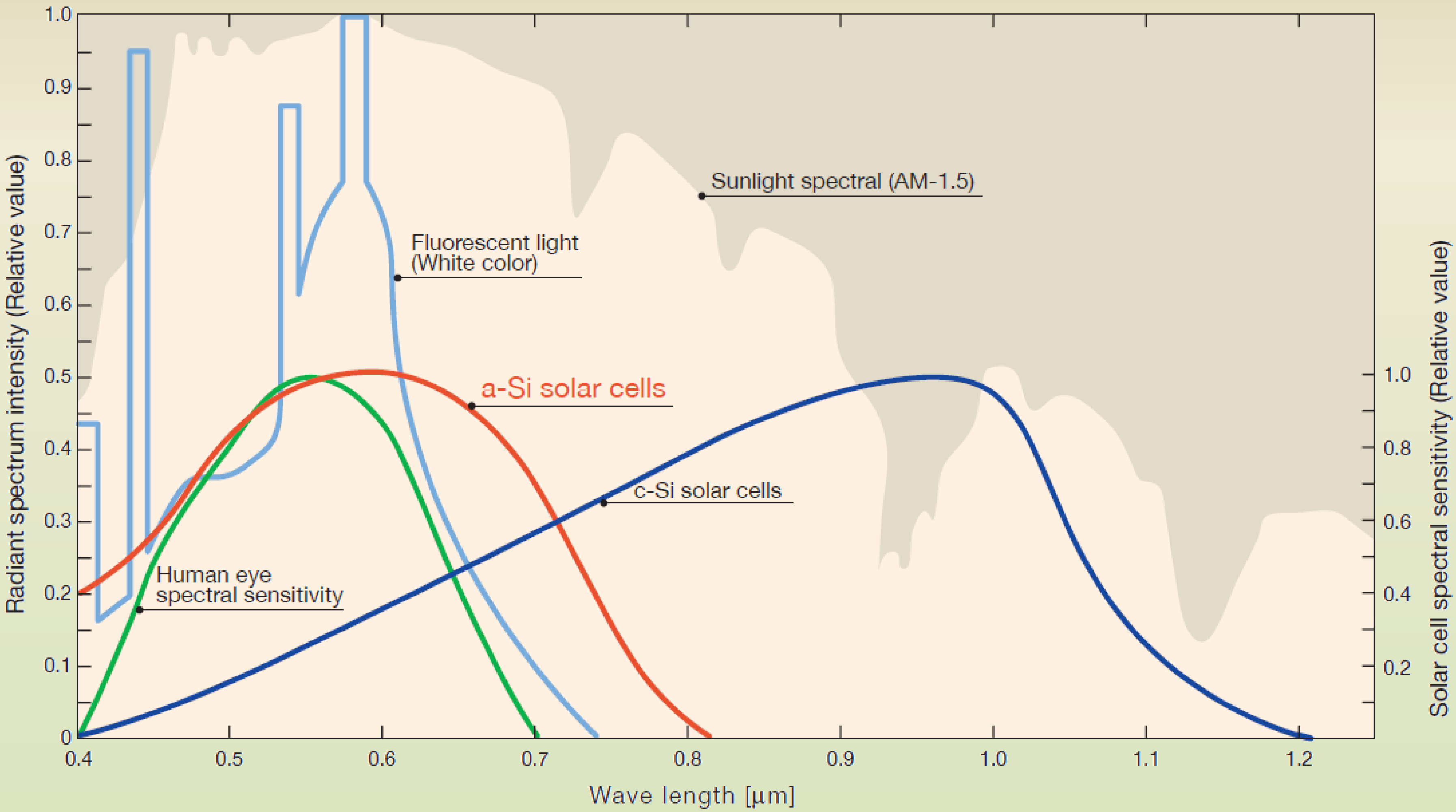
Light source			
	Sunlight		Artificial light
AM-0	Outer space (solar light at global average revolution orbit)	Incandescent light	General-use incandescent light, halogen lamp
AM-1	When the sun is directly overhead (0m above sea level at the equator, vertical sunlight at meridian passage)	Fluorescent light	Daylight, white, and warm white colors
AM-1.5	When zenithal angle (Sunlight angle 0° when sun is directly overhead) is 48.2°.	Electric discharge lamp	Mercury-vapor lamp, sodium-vapor lamp, xenon lamp
Other	AM-2 (when zenithal angle is 60°), etc.		

[Light Source] Sunlight		Fluorescent light	
Condition	Illuminance (lux)	Condition	Illuminance (lux)
Direct sun	100,000 to 120,000	Design stand (partially illuminated)	Around 1,000
Bright	50,000 to 100,000	Office/conference room	300 to 600
Cloudy	10,000 to 50,000	Restaurants/coffee shops	Below 200
Rain	5,000 to 20,000		

$$P_{(W)} = \frac{Ev_{(lux)} \cdot S_{(m^2)}}{\eta_{(\frac{lm}{W})}}$$

Sources of energy

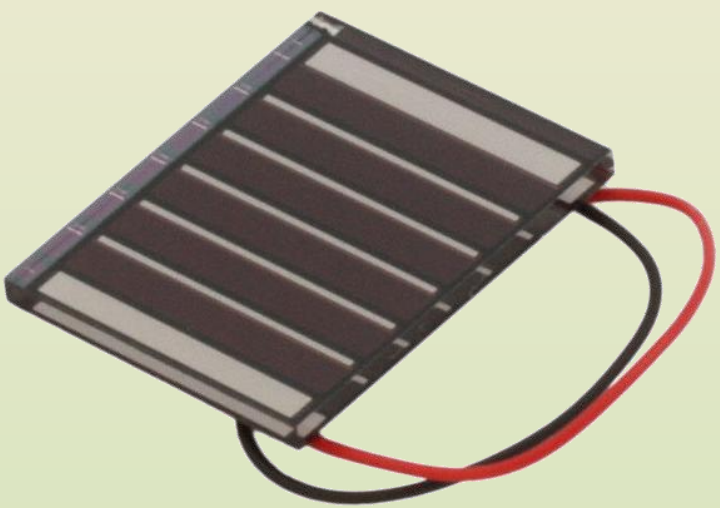
Radiant spectrum of light source and spectral sensitivity of solar cells



Sources of energy

Solar energy harvesting

Model	100mW/cm²		SS-50k lux (Initial)		External dimensions (mm)	Weight (g)
	Typical operating characteristics (Initial)	Pmax (Vop-Iop)	Typical operating characteristics (Initial)	Pmax (Vop-Iop)		
AM-5308	(1.7V- 68.8mA)	117mW (1.9V- 61.5mA)	(1.7V- 31.1mA)	58mW (1.9V- 29.2mA)	50.1× 47.2★	6.4
AM-5302	(1.7V- 105.0mA)	181mW (1.9V- 95.5mA)	(1.7V- 47.0mA)	86mW (1.9V- 45.1mA)	31.2× 117.8	16.3
AM-5413	(2.2V- 16.7mA)	39mW (2.6V- 15.0mA)	(2.2V- 7.5mA)	18mW (2.6V- 7.1mA)	33.0× 23.9★	2.1
AM-5412	(2.2V- 39.8mA)	93mW (2.6V- 35.8mA)	(2.2V- 17.9mA)	44mW (2.6V- 16.9mA)	50.1× 33.1	7.3
AM-5610	(3.3V- 5.1mA)	18mW (3.9V- 4.6mA)	(3.3V- 2.3mA)	8mW (3.9V- 2.2mA)	25.0× 20.0	2.2
AM-5613	(3.3V- 31.6mA)	110mW (3.9V- 28.2mA)	(3.3V- 14.5mA)	52mW (3.9V- 13.3mA)	60.1× 36.7	9.8
AM-5608	(3.3V- 36.0mA)	125mW (3.9V- 32.0mA)	(3.3V- 16.5mA)	59mW (3.9V- 15.1mA)	60.1× 41.3	11.0
AM-5605	(3.3V- 115.4mA)	401mW (3.9V- 102.7mA)	(3.3V- 52.9mA)	189mW (3.9V- 48.6mA)	62.3× 117.8	32.5



Amorphous Silicon Solar Cell from Sanyo Semiconductor Co., Ltd.

L x W x T: 25,0 x 20,0 x 2,3 mm

Efficiency: 3,6% @ 100 mW/cm²

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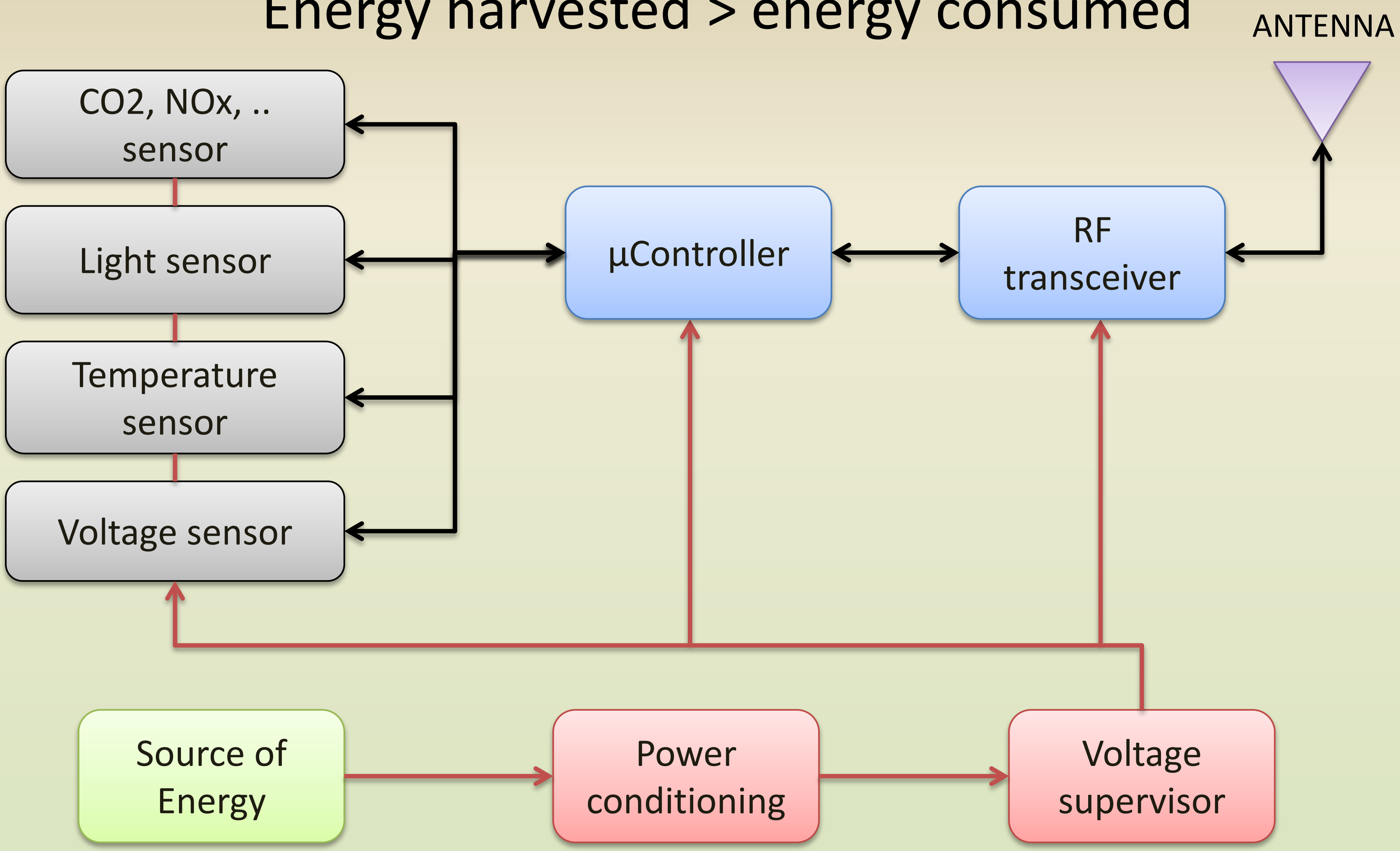
Energy budget

Energy harvested > energy consumed



Energy budget

Energy consumed @ 3.3 V in 10 s ≈ 450 μJ (1 transmission)

- 16-Bit μController: 95.7 μJ
  - Active Mode: ≈ 2.5 mA @ 16MHz x 10 ms
  - Sleep mode + timer: ≈ 0.4 μA x 9.99 s
- RF transceiver: 151.8 μJ
  - TX mode: 23 mA x 2 ms
- Sensing elements: 33 μJ
  - Active mode: 5 mA x 2 ms
- Voltage regulator and supervisor: 165 μJ
  - Always active: 5 μA x 10 s

Energy budget

Energy consumed @ 3.3 V in 10 s ≈ 2.9 mJ (10 transmissions)

- 16-Bit µController: 825 µJ
  - Active Mode: ≈ 2.5 mA @ 16MHz x 10 x 10 ms
  - Sleep mode + timer: ≈ 0.4 µA x 9.9 s
- RF transceiver: 1518 µJ
  - TX mode: 23 mA x 10 x 2 ms
- Sensing elements: 330 µJ
  - Active mode: 5 mA x 10 x 2 ms
- Voltage regulator and supervisor: 165 µJ
  - Always active: 5 µA x 10 s

Energy budget

Energy consumed @ 3.3 V in 10 s ≈ 450 μJ (1 transmission)

Energy consumed @ 3.3 V in 10 s ≈ 2.9 mJ (10 transmissions)

Energy harvested by a piezoelectric non-linear
bi-stable energy harvester (*) in 10 s
10 x 0.259 mW = 2.59 mJ

↓

Less than 1 transmission per second!

(no "real-time" monitoring)

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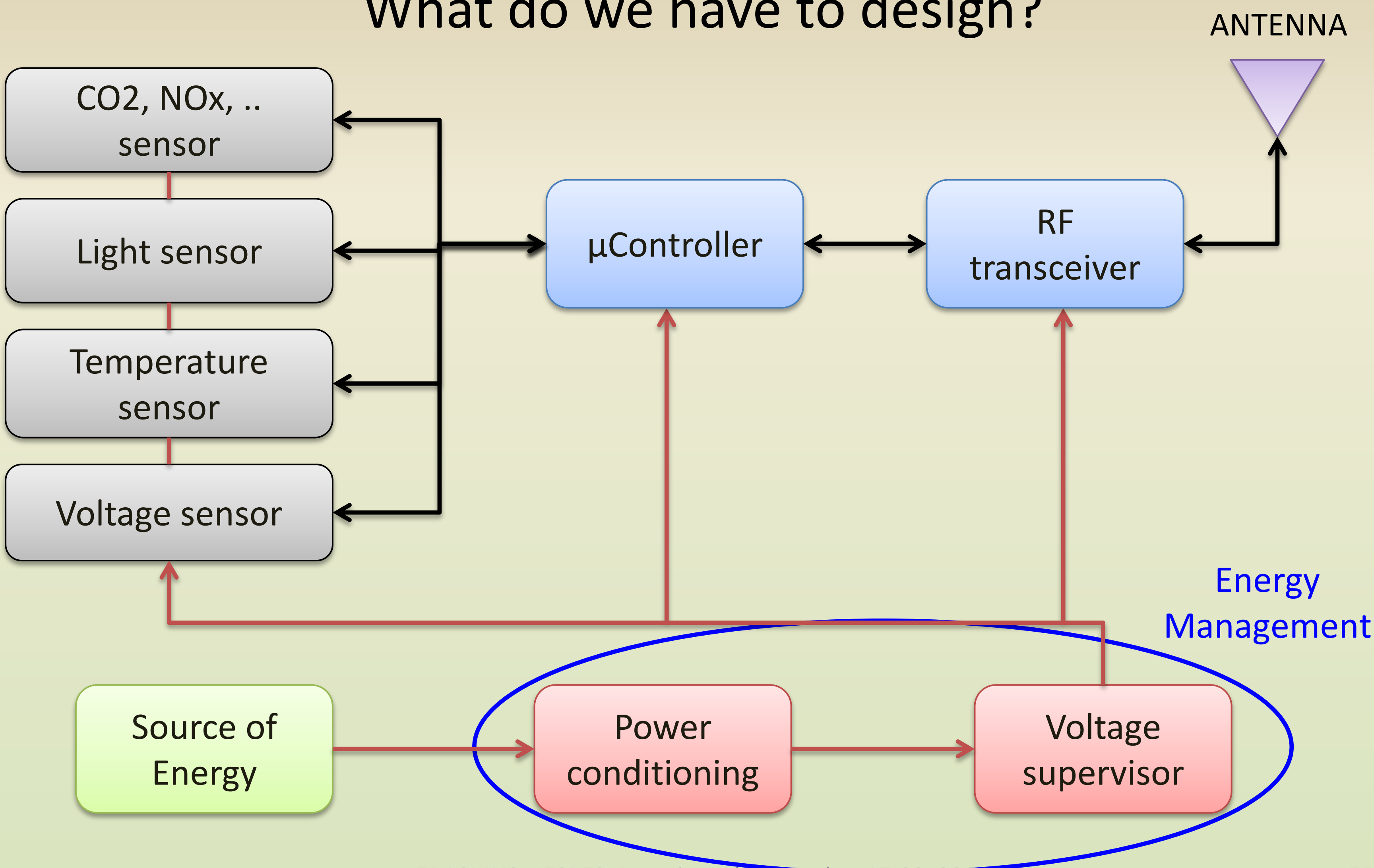
Hardware development

What do we have to design?

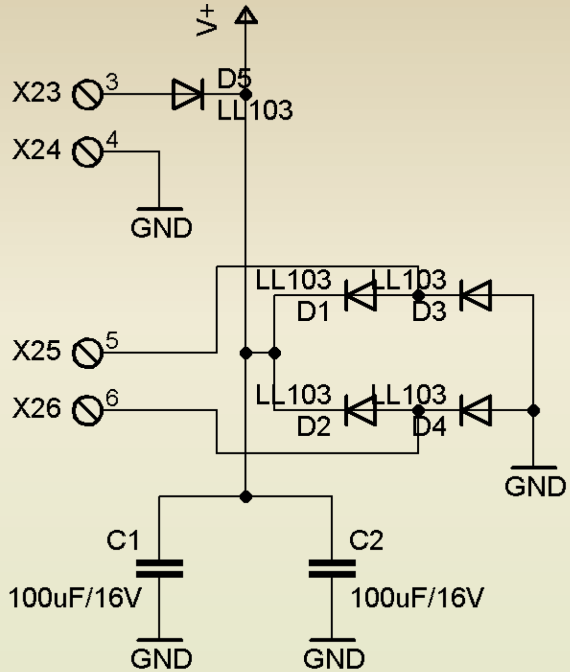


Hardware development

Energy management

Rectifier + Voltage Regulator + Supervisor

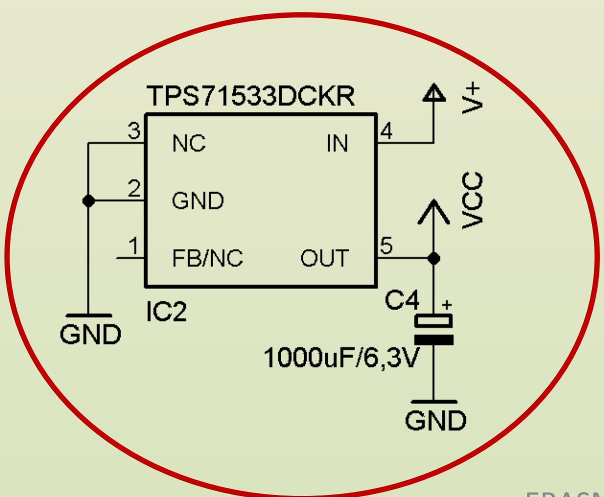
Total Current loss < 7 µA

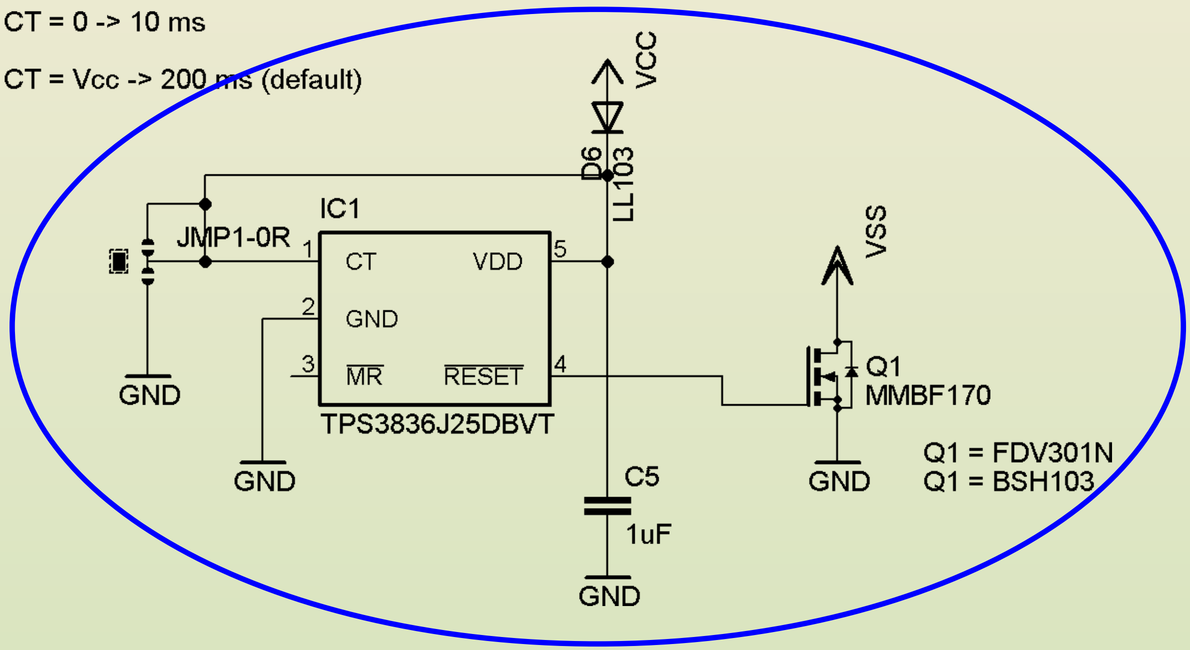


Delay time of IDLE state of reset

CT = 0 -> 10 ms

CT = Vcc -> 200 ms (default)



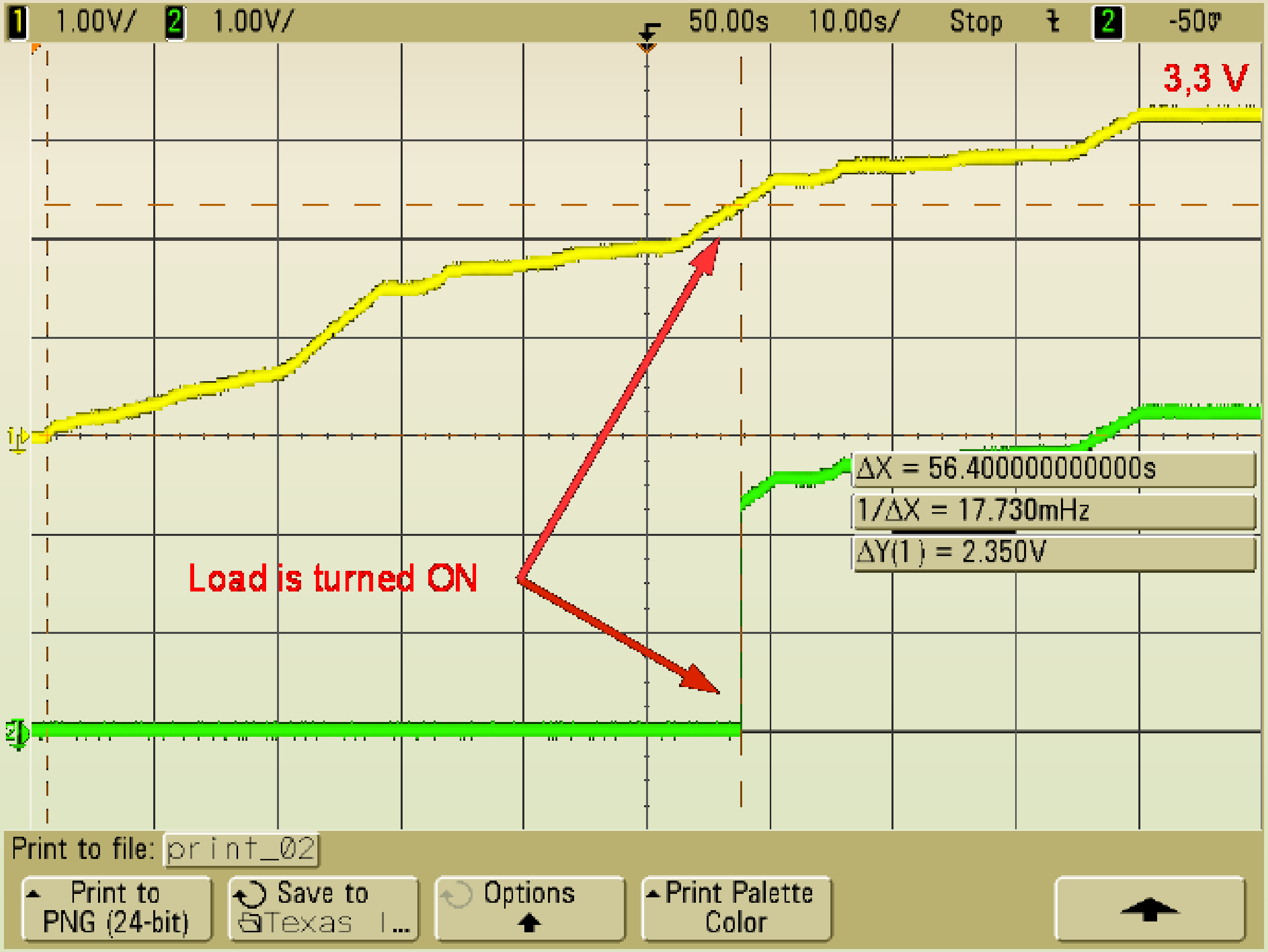


Hardware development

Energy management

Voltage across the storage capacitor

Supply voltage to the load

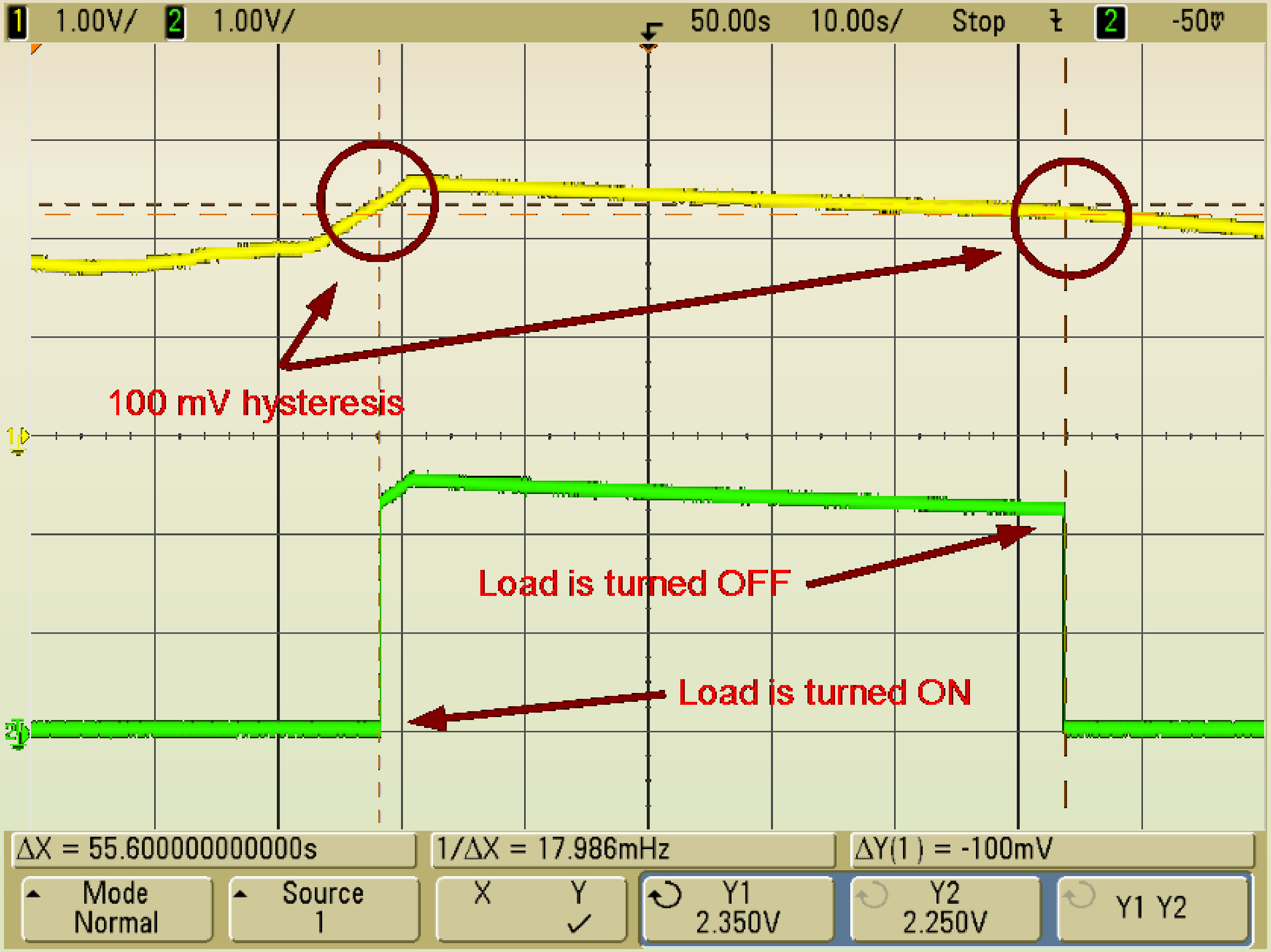


Hardware development

Energy management

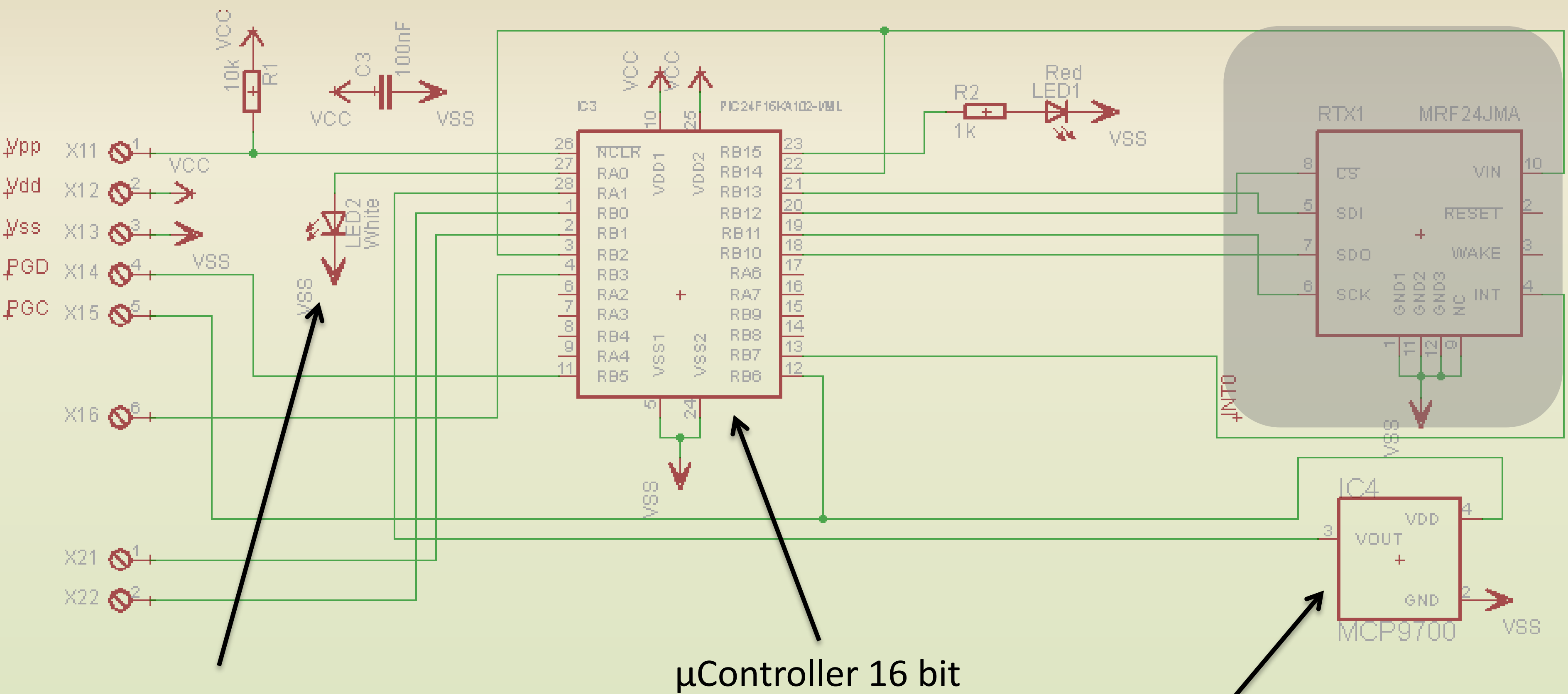
Voltage across the storage capacitor

Supply voltage to the load



Hardware development

µController



Light Sensor

µController 16 bit

16KB Flash

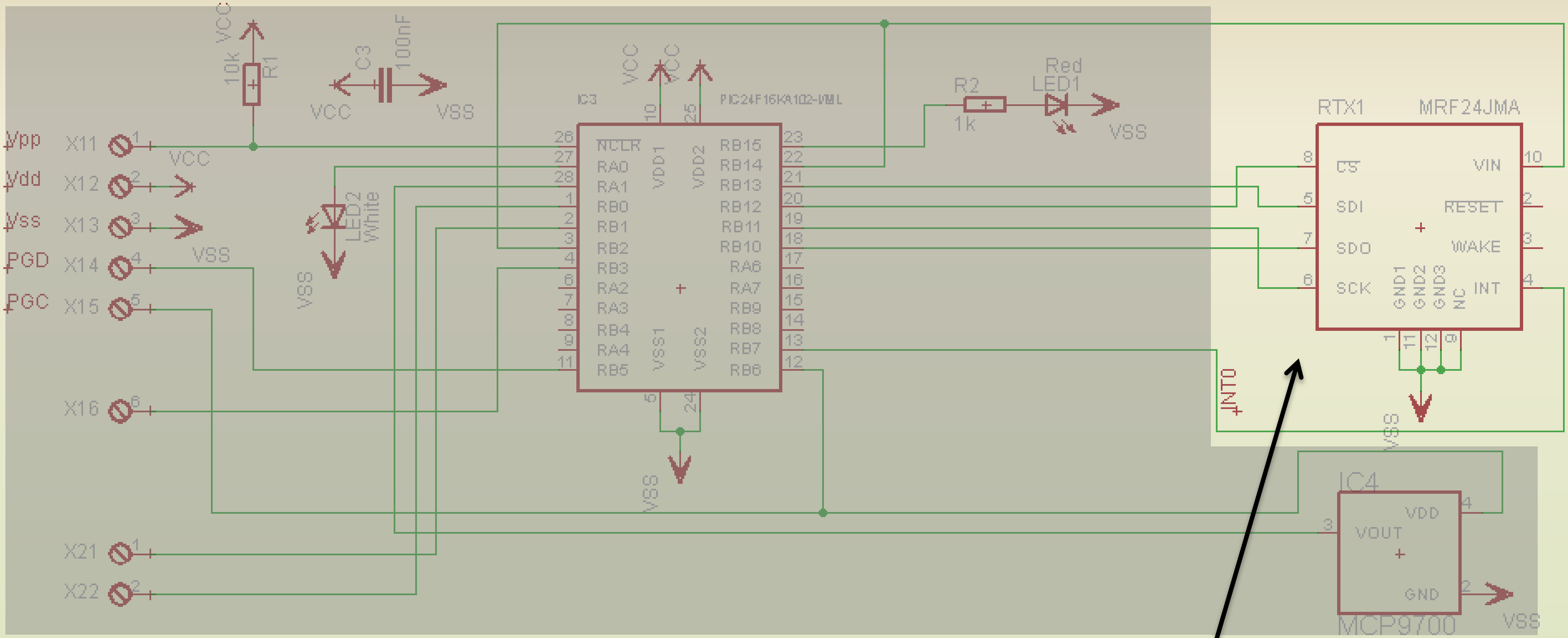
1.5KB SRAM

Temperature Sensor

6 µA @ 3.3 V

Hardware development

RF Transceiver



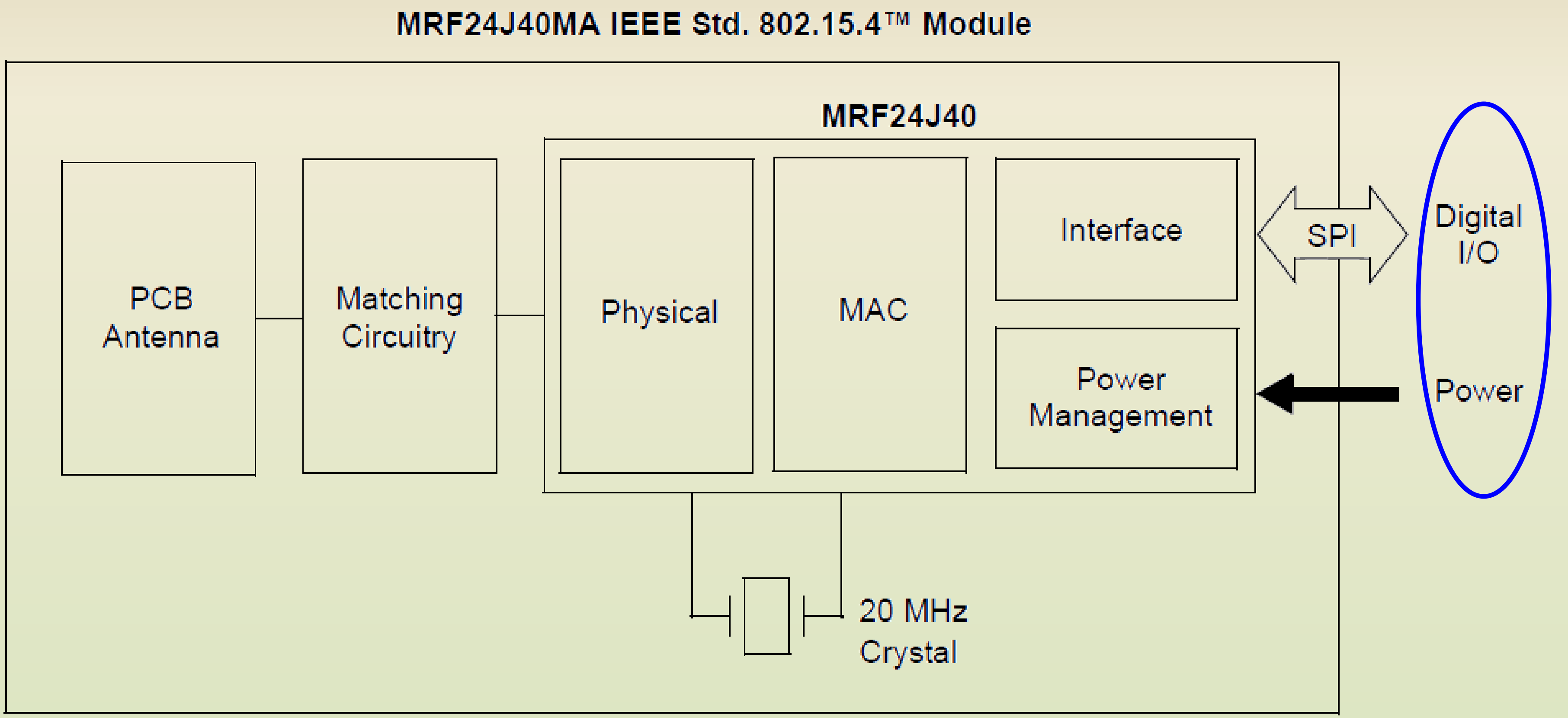
IEEE 802.15.4 compliant RF Transceiver Module

2.4 GHz band, 0 dBm RF power, -95 dBm RX sensitivity

Range: up to 400 ft

Hardware development

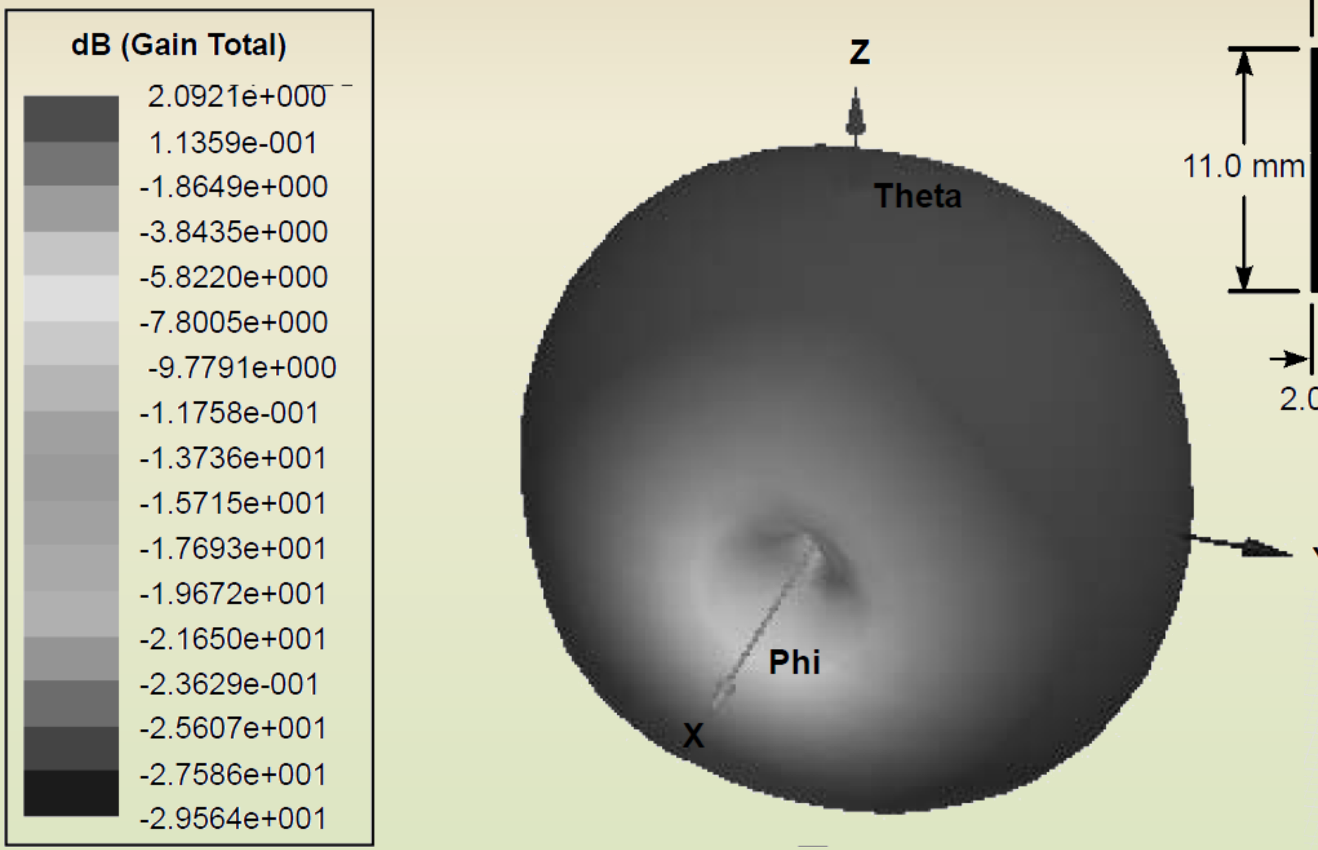
RF Transceiver

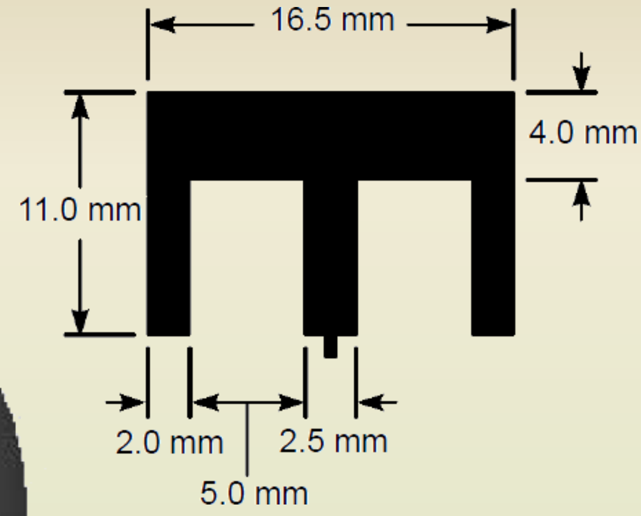


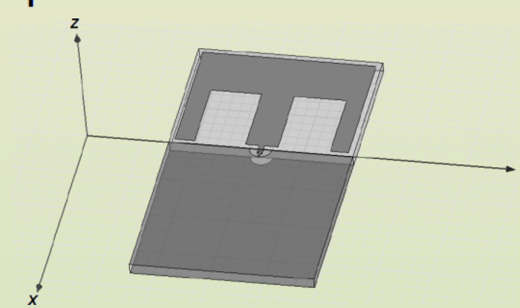
MRF24J40MA Datasheet - http://www.microchip.com/wwwproducts/Devices.aspx?dDocName=en027752

Hardware development

RF Transceiver – PCB Antenna







MRF24J40MA Datasheet - http://www.microchip.com/wwwproducts/Devices.aspx?dDocName=en027752

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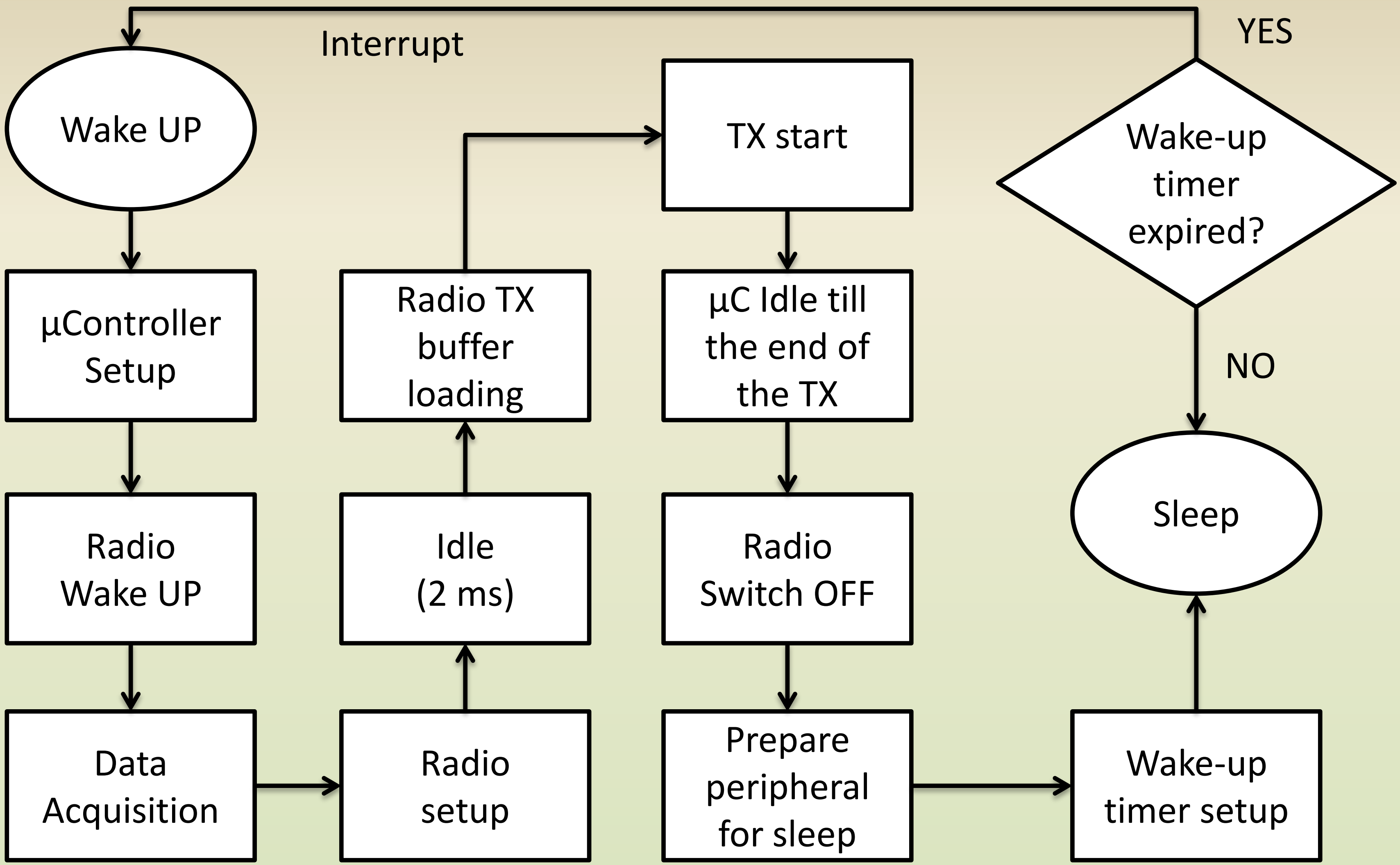
- Power requirements
- Sources of energy
- Energy budget
- Hardware development
- Software development
- Some examples

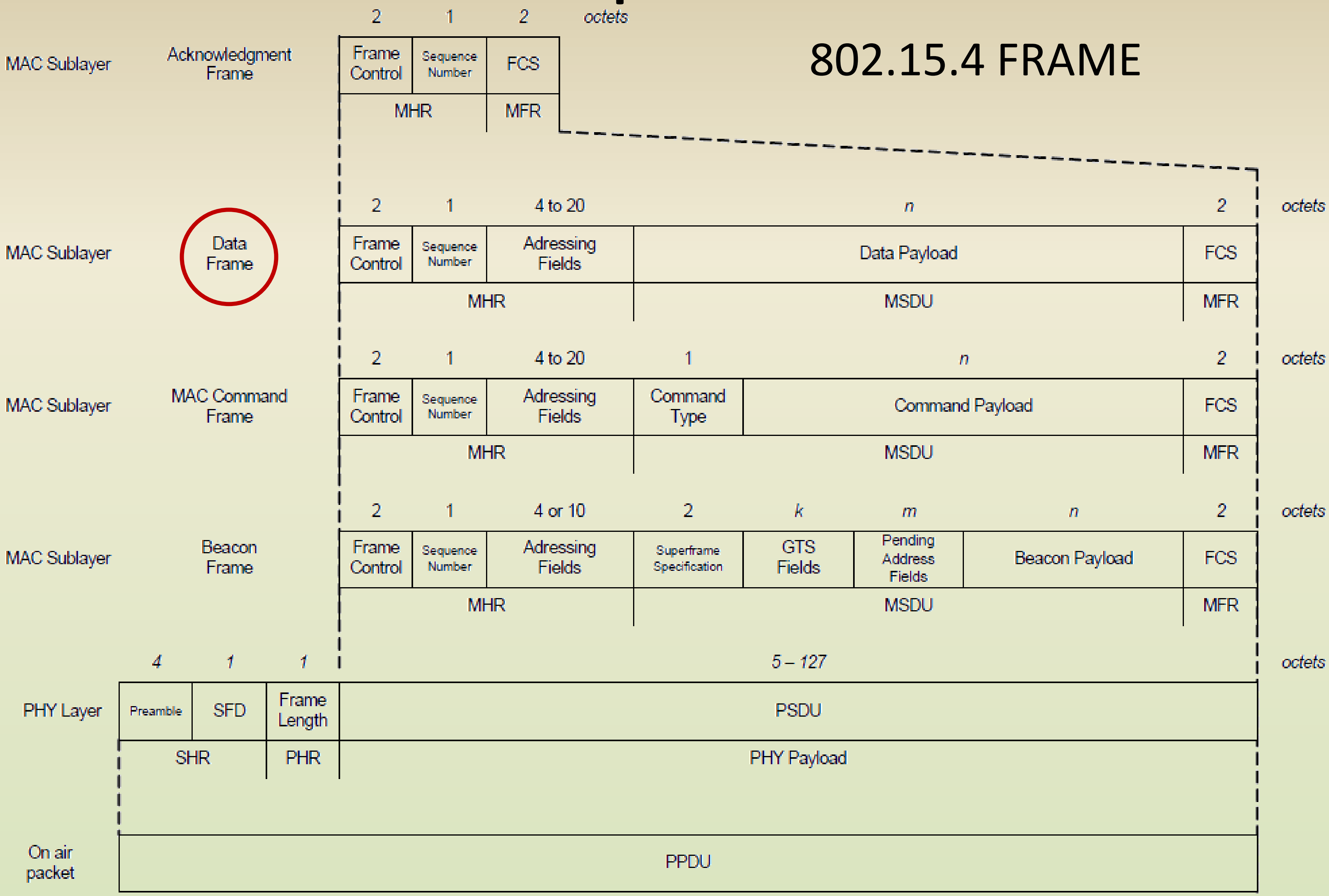
Software development



Software development

- Mixed C and Assembly code is possible
- No Operating System
- Each block of operations (function) must be optimized to reduce the execution time (e.g. cost of the multiplication “2 x 3” is not equal to cost of the multiplication “3 x 2”)
- Peripherals can be switched OFF when unused
- Reduced system and peripheral clock, when possible
- Intense use of timers, interrupts and Idle/Sleep mode
- Smaller code = faster execution? Not always!
- Chose the best transmission protocol

Software development



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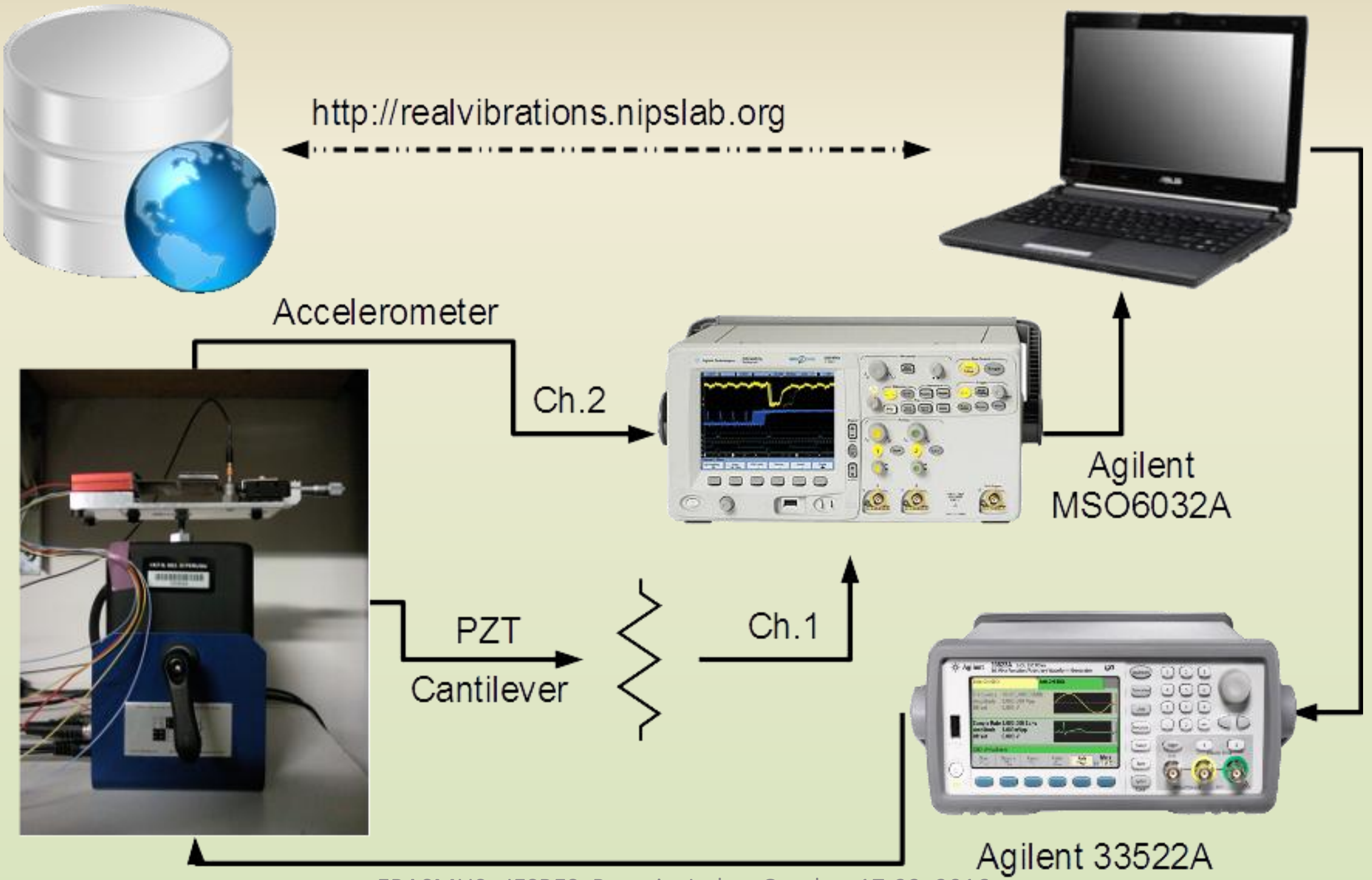
Test

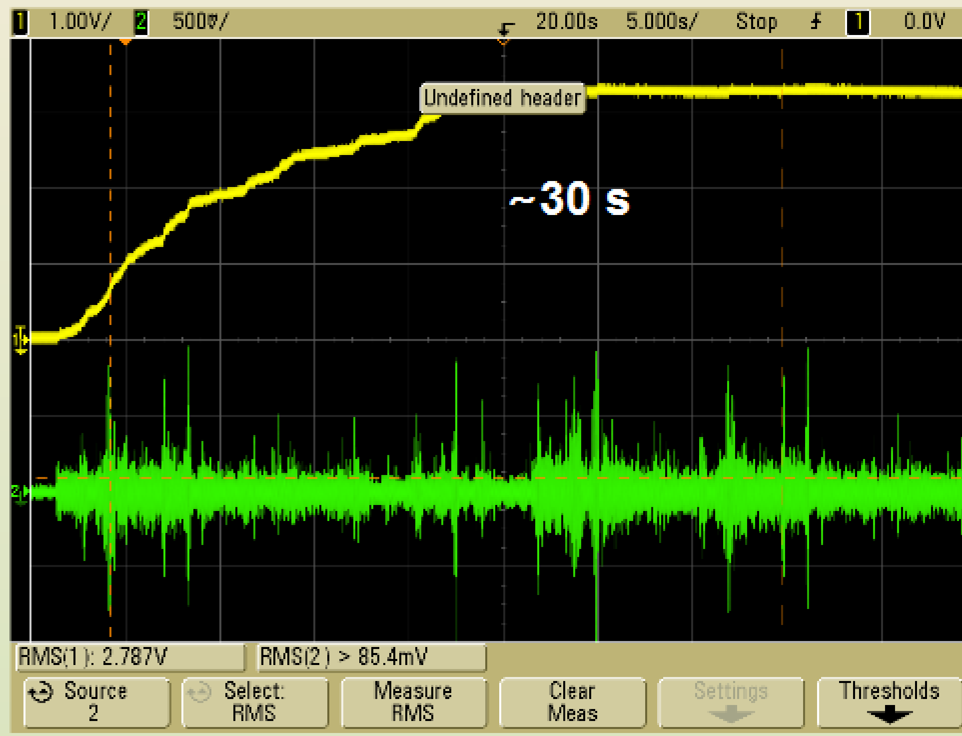
Typical vibration E.H. test setup



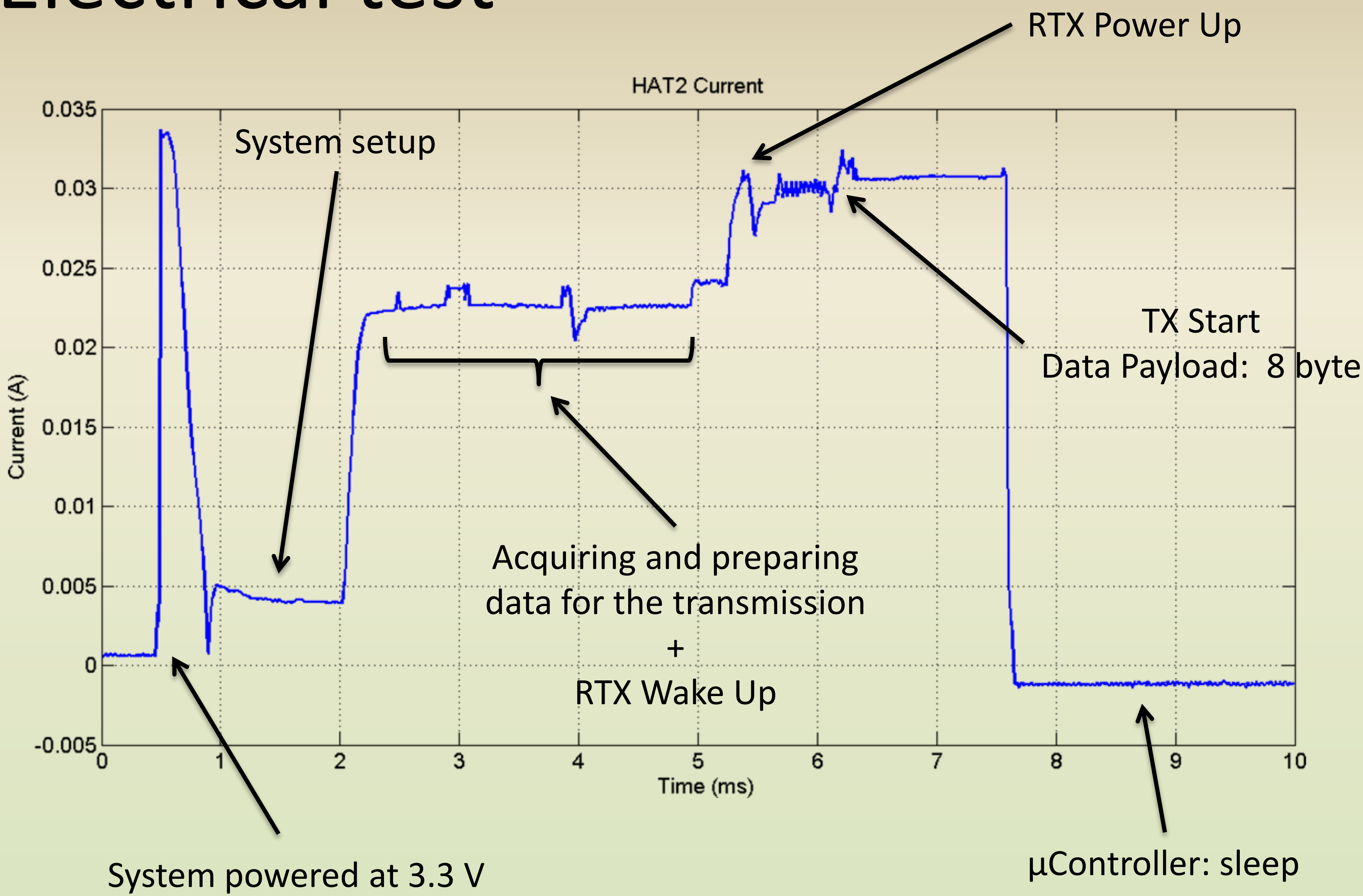
Test

Test on the shaker: no solar cells

Real vibrations can be used to evaluate the time required to charge the storage capacitor (e.g. 1000µF).

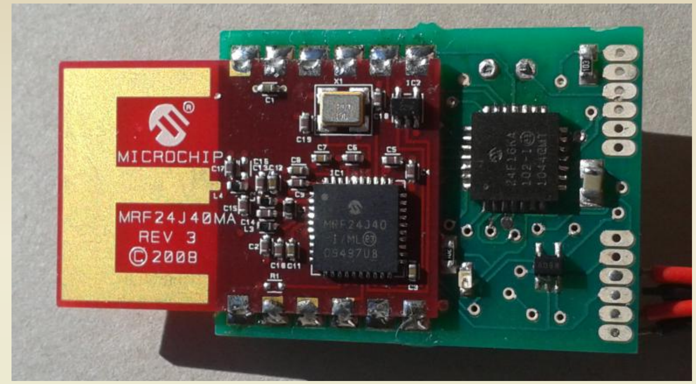


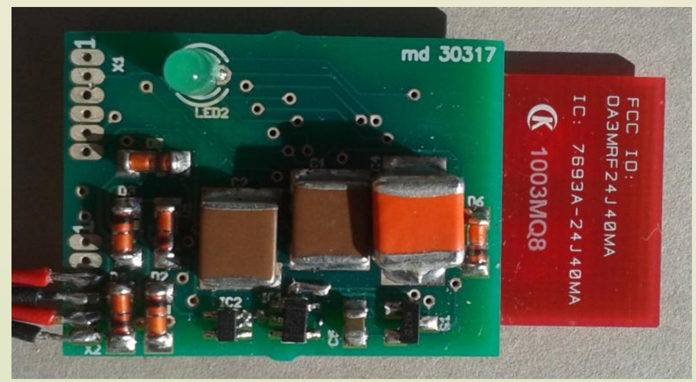
Electrical test



Autonomous sensor

Small (Hybrid) vibration and FV powered Autonomous wireless Temperature and light sensor (HAT) operating on 2.4 GHz ISM Band



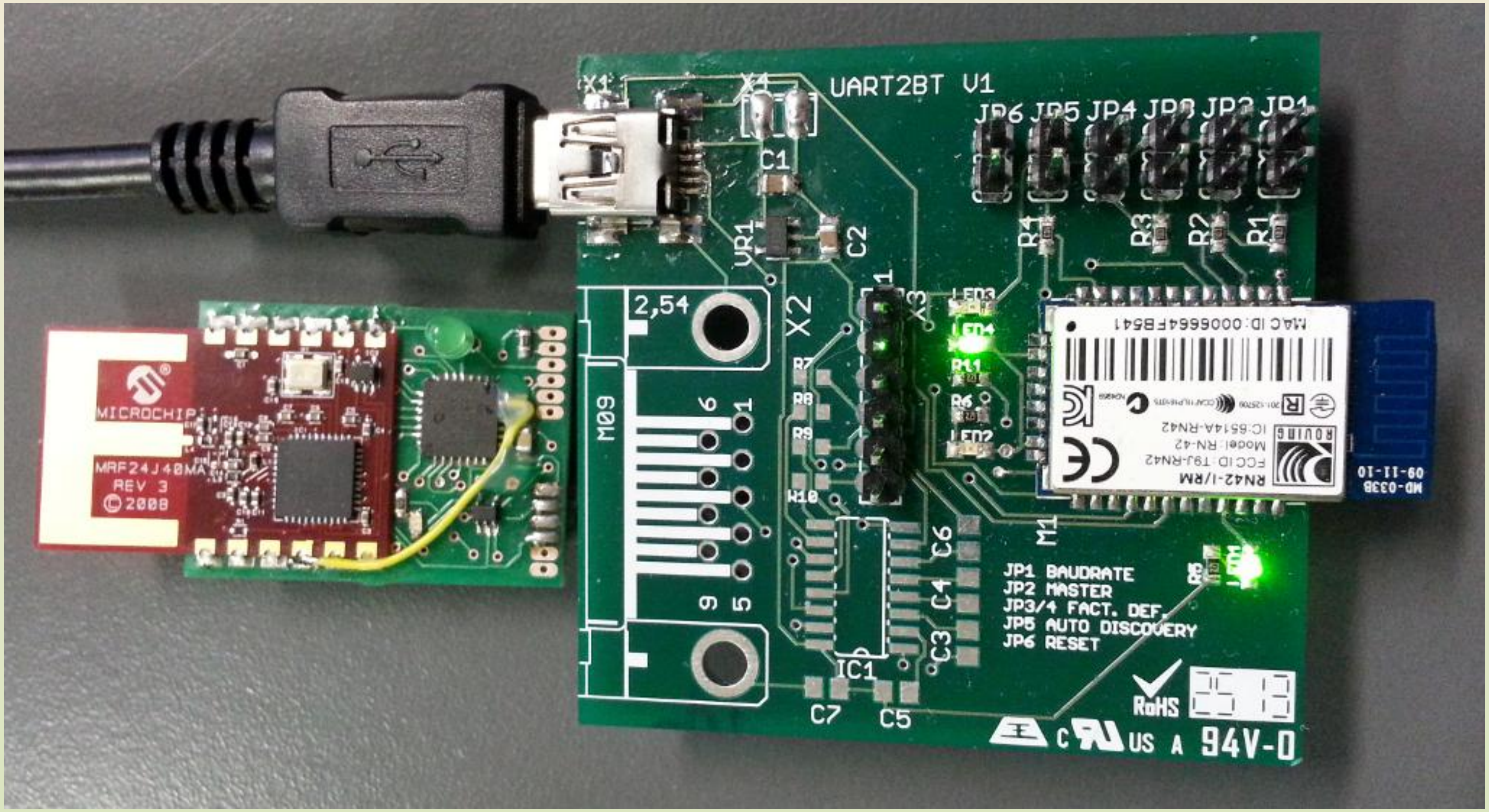


Small enclosure: 60 x 35 x 25 mm
2 solar cells: 20 x 25 mm, Pmax = 8 mW @ 3,9 V
1 piezoelectric non-linear bi-stable vibrations harvester

Low power receiver

802.15.4 to Bluetooth and USB gateway

Data can be directly received on a computer



Low power LoRa transceiver

Long range (15+ km) 433 MHz and 868 MHz node

RN2483 LoRa (10 mW) transceiver from Microchip

+

STM32L053R8 (ARM Cortex M0+) 32 bit microcontroller from ST Microelectronics


Thank you!