MICRO-461
Low-power Radio Design for the IoT

1. Introduction

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Outline

- Course description
- Introduction to the Internet of Things (IoT)

Course Description

- The basic function of an IoT node is to collect data and send it through a wireless channel to the cloud. The power consumption of IoT nodes is largely dominated by the wireless communication. It is therefore key to understand the trade-offs faced when designing a radio embedded into an IoT node.
- This course starts with a short introduction to the field of IoT with a particular emphasis on the wireless communication aspects, including a short description of the standards, including short-range connectivity (e.g. Bluetooth, BTLE,…) and Low Power Wide Area Network (LPAW) (e.g. Lora,…). It then gives a high-level description of a typical IoT node, before focusing on the radio. The different radio architectures that are appropriate to IoT nodes with respect to their complexity and power consumption are then presented. The main building blocks are then described and analyzed in details with a focus on their power consumption.

Course Pre-requisit

- Understanding the basic principles of analog and digital communication
- Understanding of main basic building blocks
- Understanding of baseband analog circuits

Course Overall Outline

1. Introduction to the IoT
2. Overview of wireless communication principles and standards
3. Basic concepts: linearity and time variance, distortion and intermodulation, intercept points, sensitivity and dynamic range, link budget
4. Modeling of active and passive devices at RF: MOS transistors, integrated R L C components
5. Noise at RF: noise figure definition, examples of noise calculations in RF circuits
6. Basic receiver architectures: super-heterodyne, low-IF, direct conversion, super-regenerative
7. Front-end circuits: low-noise amplifier (LNA) design, mixers
8. Oscillators: basic tuned oscillators (Colpitts, Pierce, Clapp, cross-coupled), phase-noise
9. Phase-locked loops (PPLs)
10. RF Power Amplifiers: class A, AB, B, and C power amplifiers; class D, E and F amplifiers

Course Program 2021

Low-power Radio Design for the IoT		
Lecture #	**Date**	**Topic**
1	25.02.2021	Introduction to IoT, Passive RF circuits and impedance matching
2	04.03.2021	Wireless communication principles and standards
3	11.03.2021	Basic concepts in RF design
4	18.03.2021	Modeling of active and passive devices at RF
5	25.03.2021	Modeling of active and passive devices at RF
6	01.04.2021	Noise at RF
	08.04.2021	Easter break
7	15.04.2021	Basic transceiver architectures
8	22.04.2021	Basic transceiver architectures
9	29.04.2021	Low-noise amplifiers (LNAs)
10	06.05.2021	Mixers
11	13.05.2021	Oscillators
	20.05.2021	Ascencion
12	27.05.2021	Oscillators
13	03.06.2021	Power amplifiers (PAs)

Course Lecture Notes

- Lectures notes are available in pdf format on Moodle

  moodle.epfl.ch

- Enrolment key: radiot

Wireless is Easy!

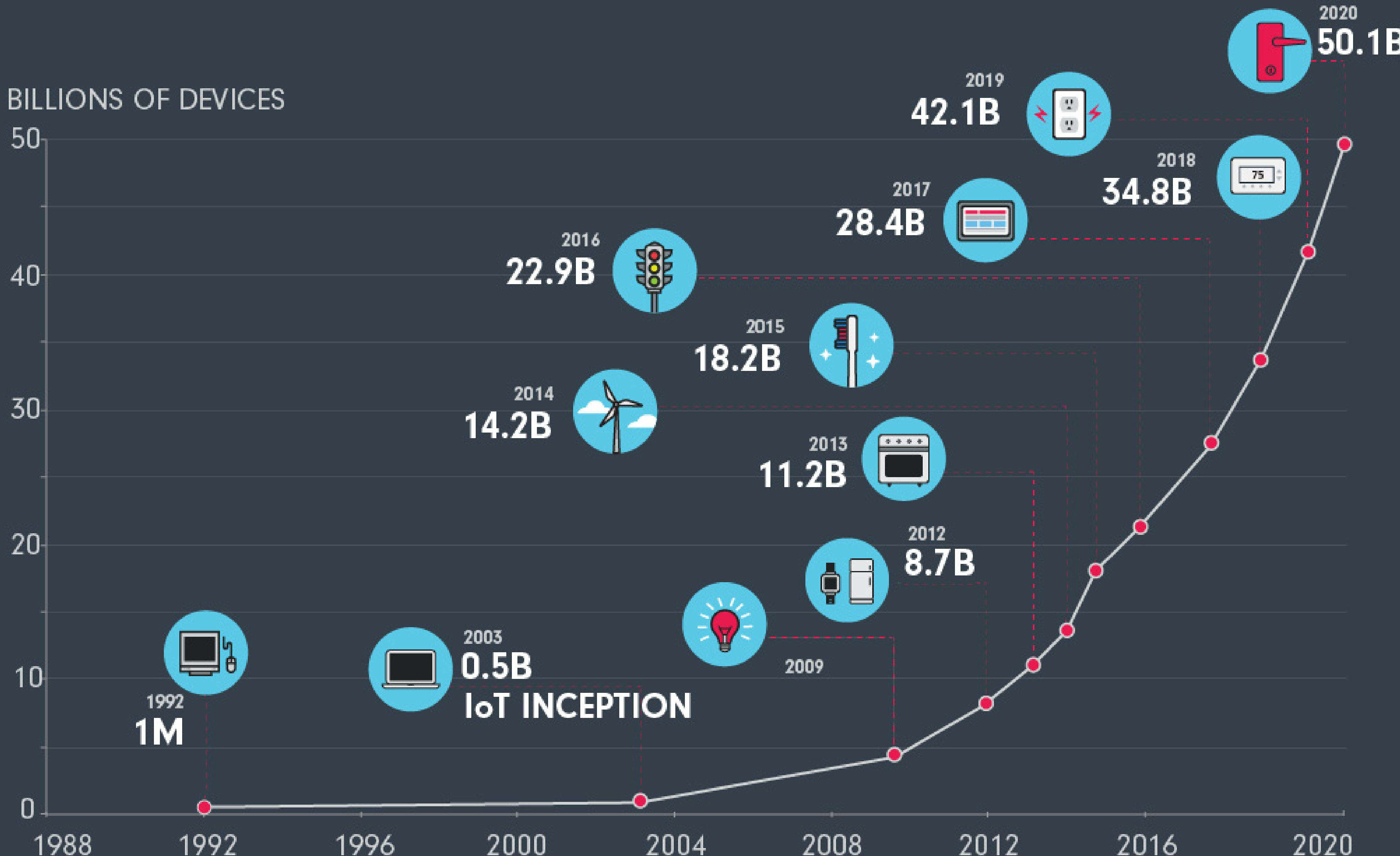
The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York, and it meows in Los Angeles. The wireless is the same, only without the cat.

Albert Einstein, 1938

📖 As quoted in the September 2002 issue of *Scientific American* ("Antigravity" by Steve Mirsky)

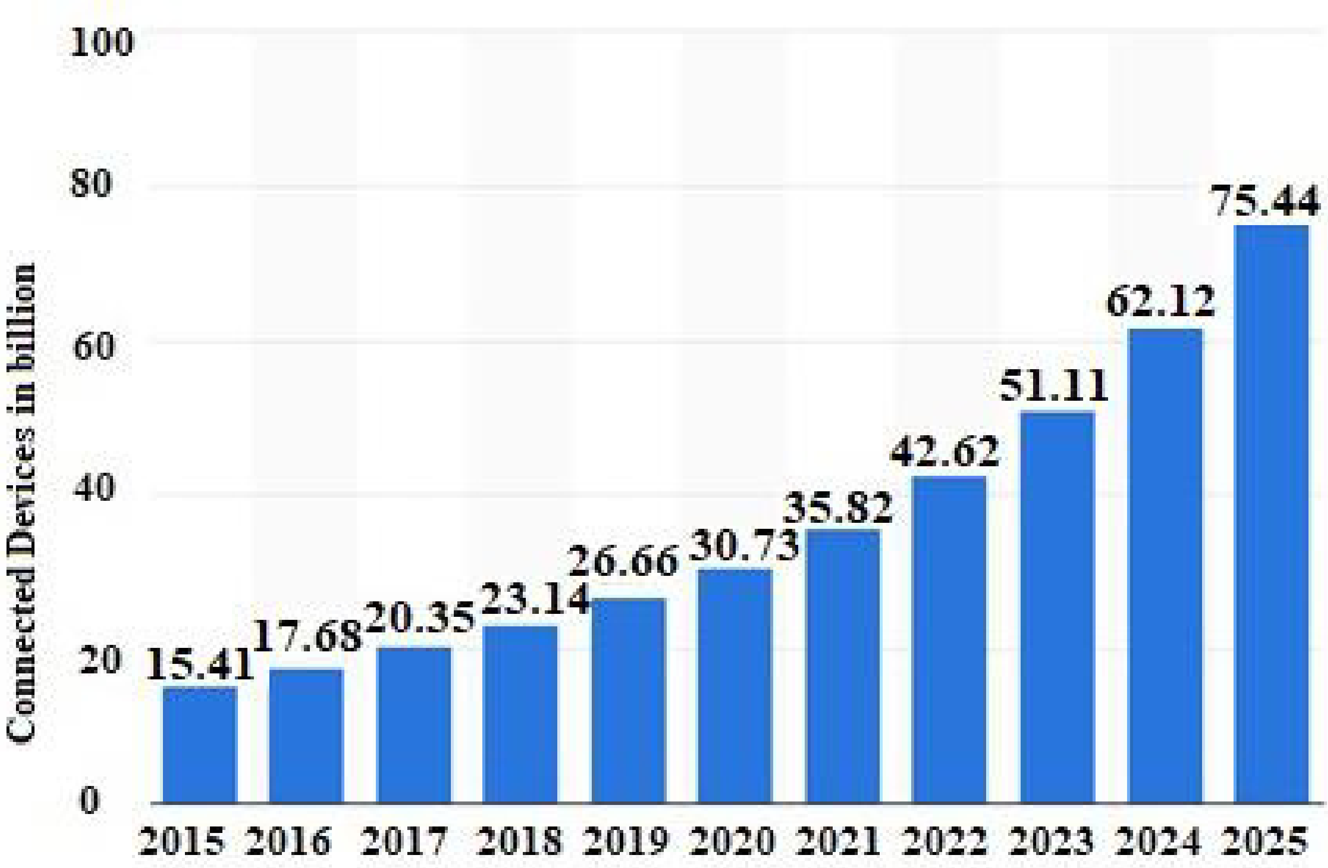
GROWTH IN THE INTERNET OF THINGS

THE NUMBER OF CONNECTED DEVICES WILL EXCEED **50 BILLION** BY 2020



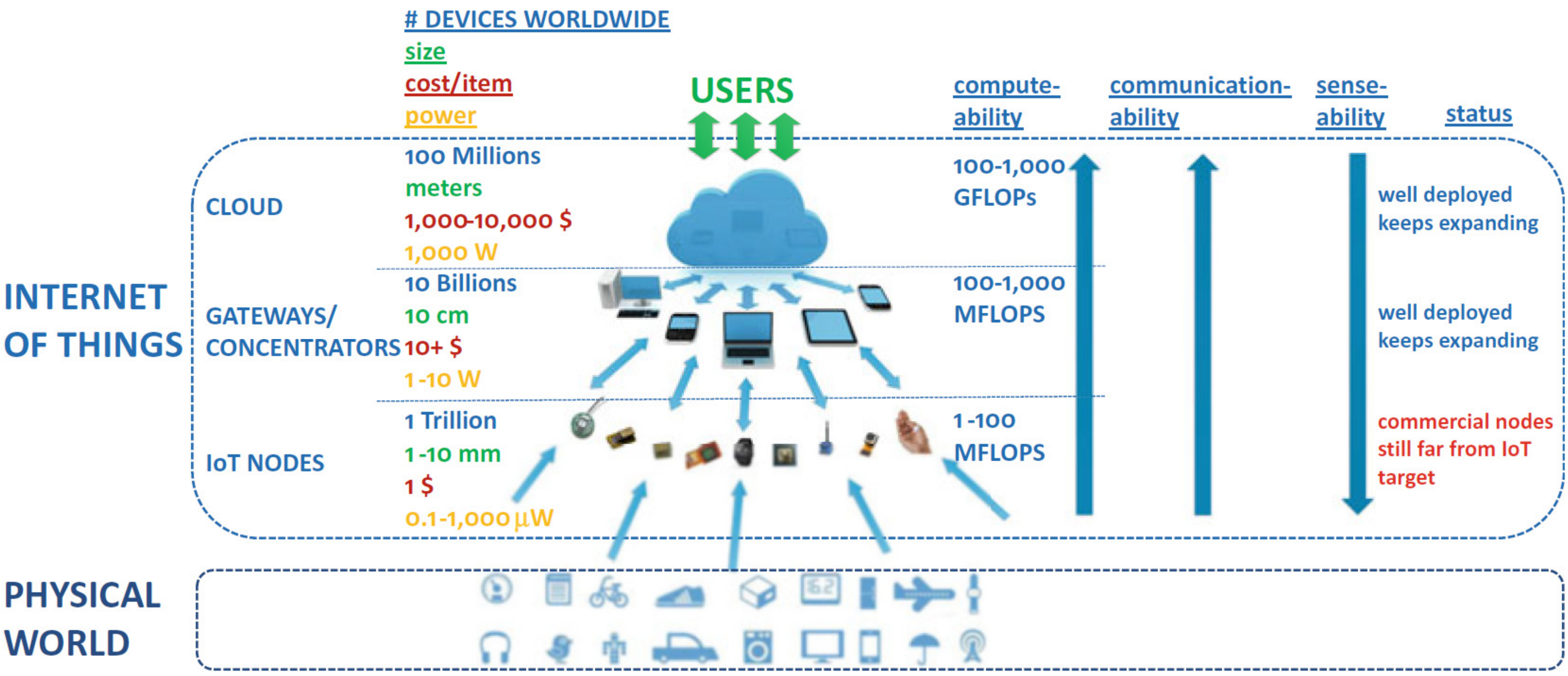
Source: Cisco

Growth of IoT Connected Devices



https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/

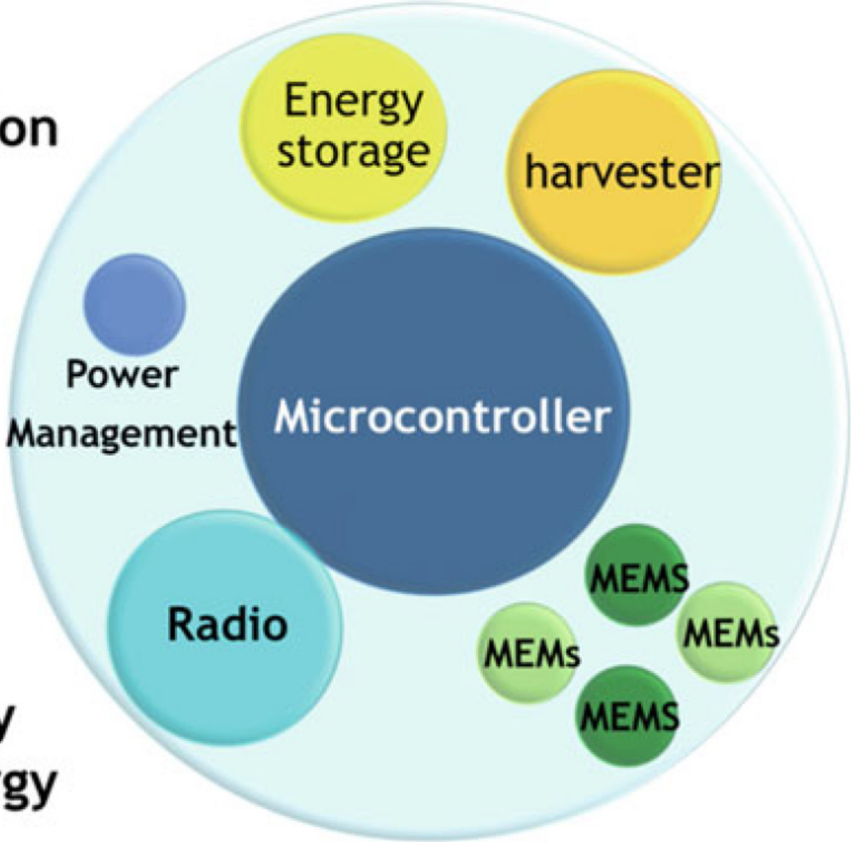
A Simplified Architecture of the IoT



📖 Enabling the Internet of Things – From Integrated Circuits to Integrated Systems, Ed. M. Alioto, Springer, 2017

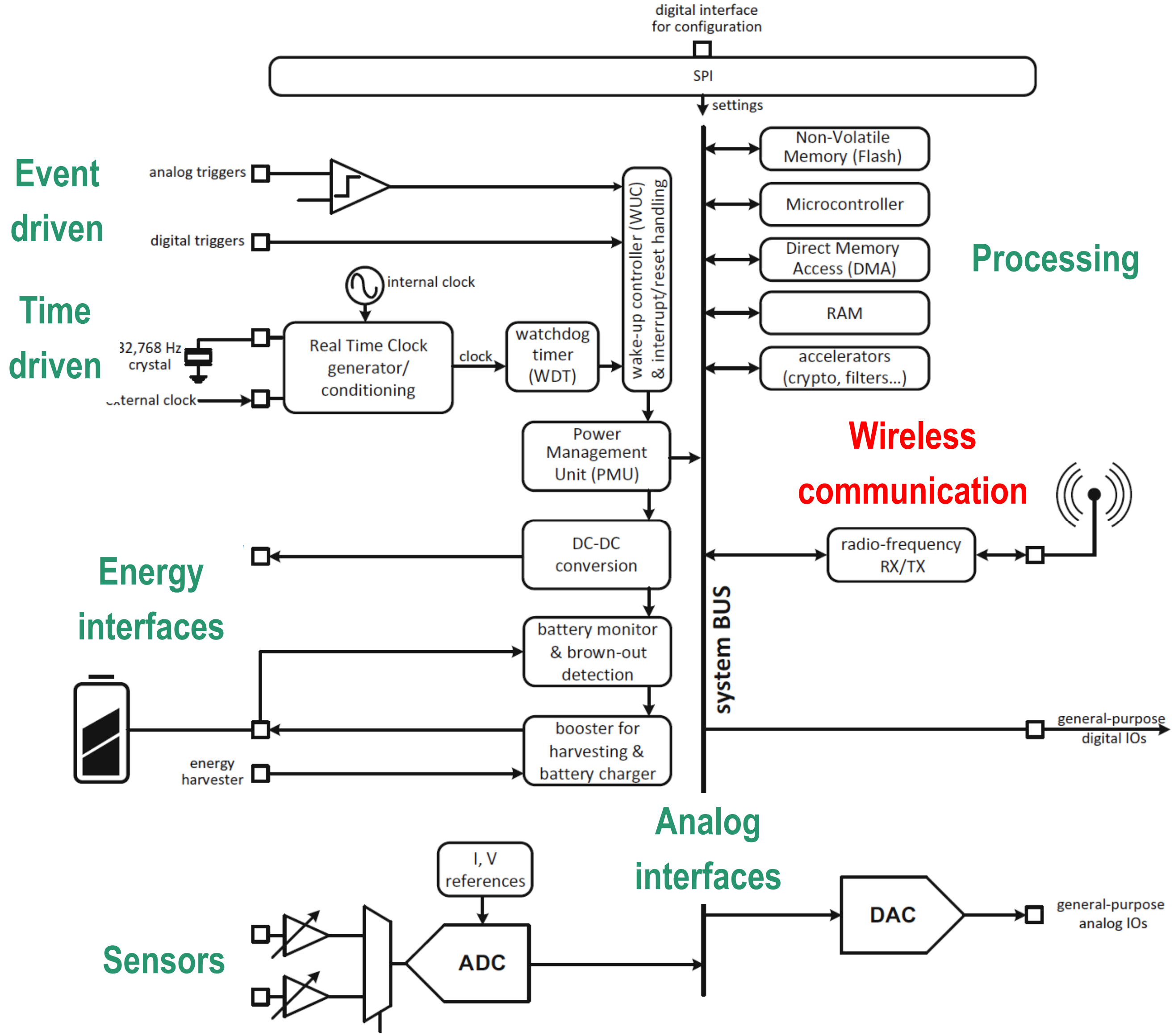
Possible IoT Node Architecture

Collecting data
Treating information
Communicating...

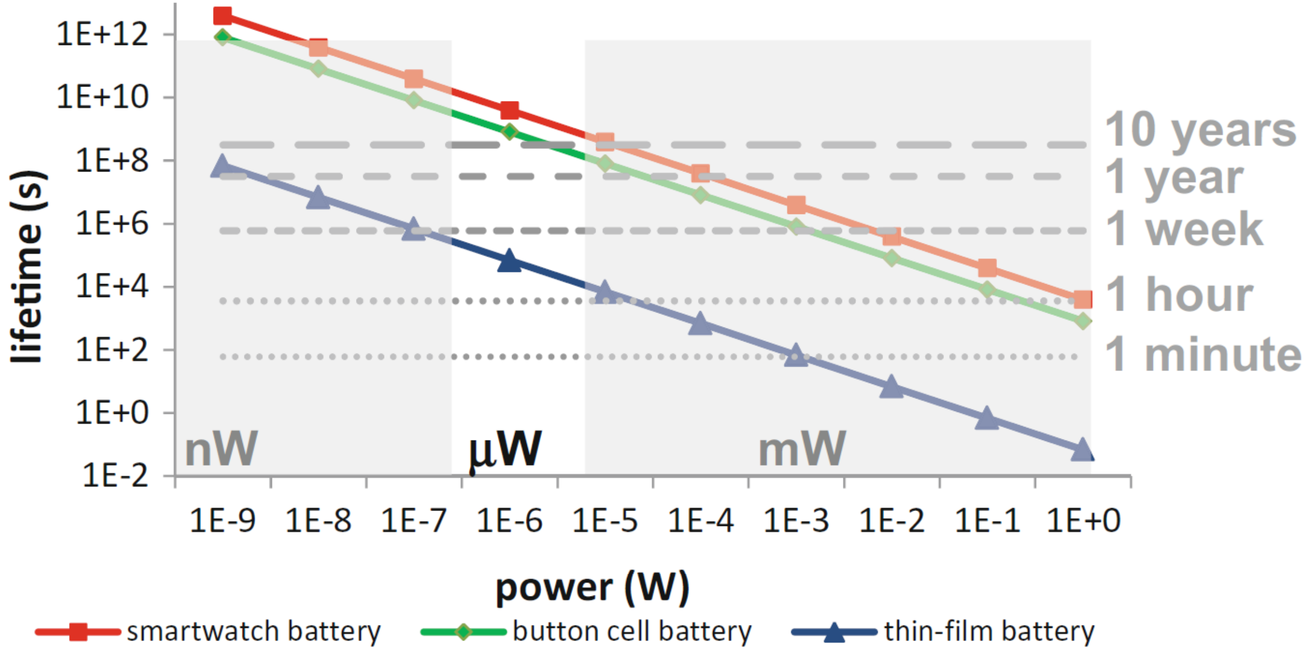


...and possibly
harvesting energy

Possible IoT Node Architecture



The Energy Challenge



type	cost	capacity	volume	energy density
GH43-03992A	30$	300 mAh	2,400 mm^3	0.12 mAh/mm^3
LR44	<1$	150 mAh (non-rechargeable)	500 mm^3	0.28 mAh/mm^3
Cymbet CBC005	0.2$	5 µAh	0.7 mm^3	6.5 $µAh/mm^3$

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Energy harvesting

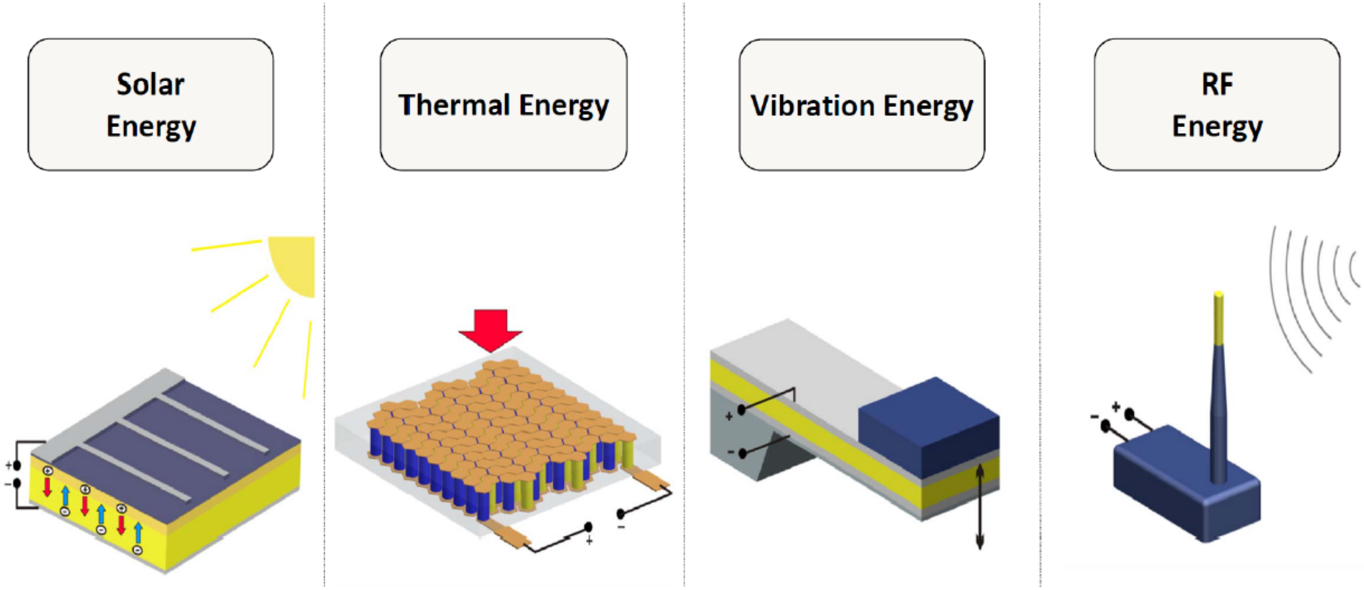
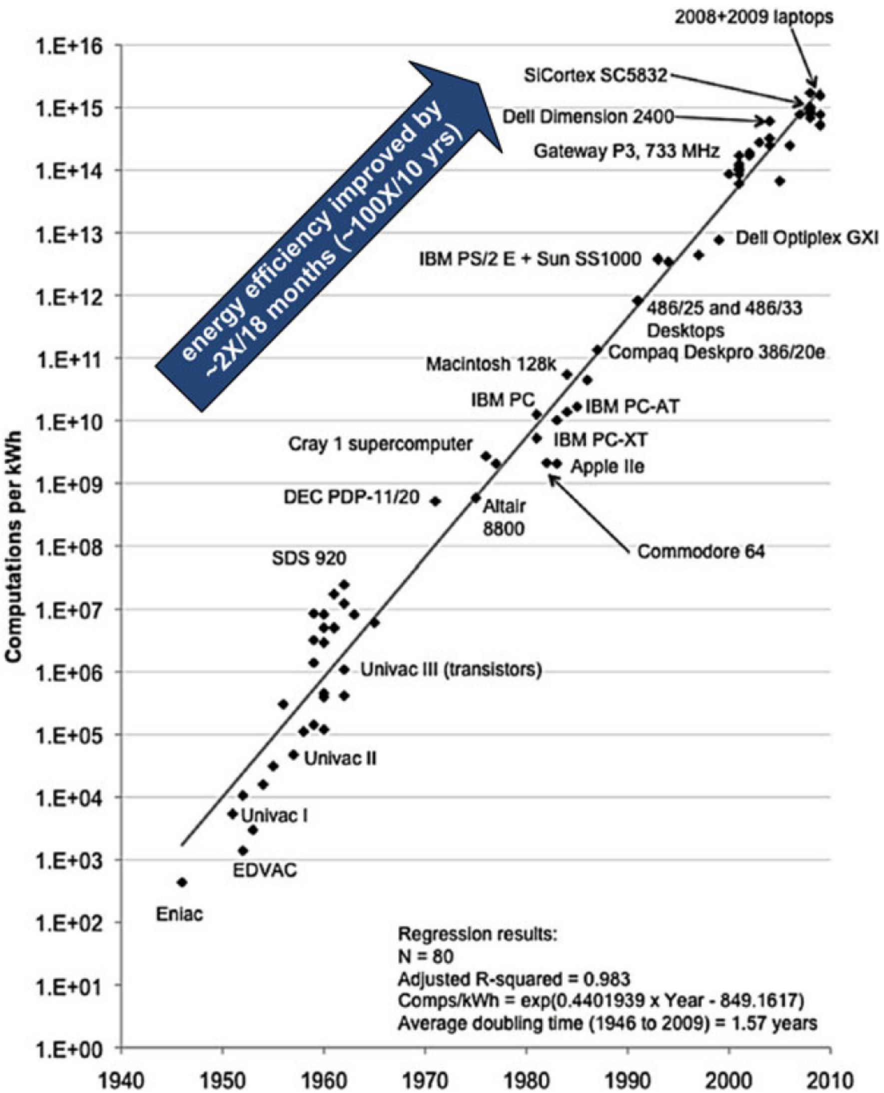
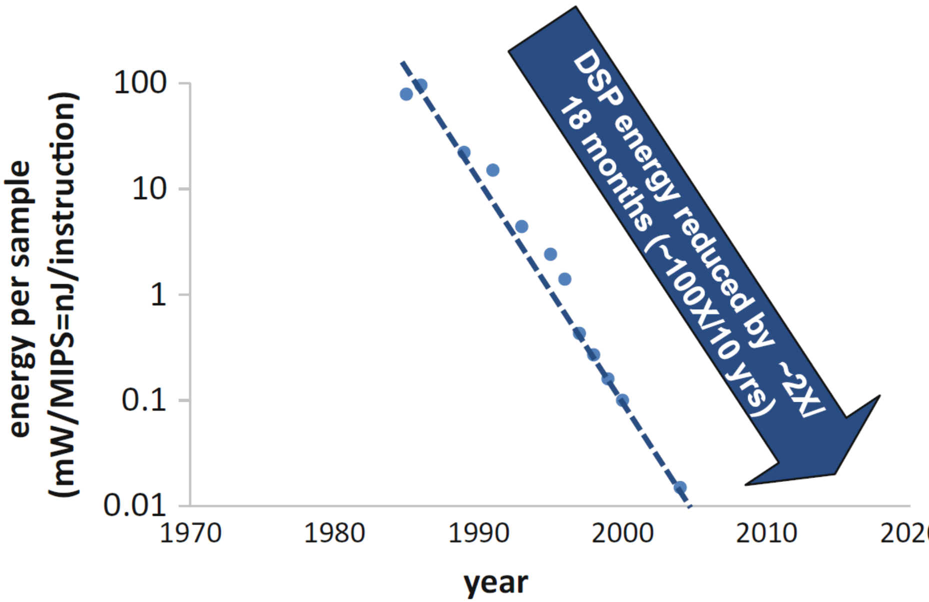


Table 1: Available power from various energy sources

Source	Source power	Harvested power
Ambience Light		
Indoor	0.1 mW/cm^2	10 $\mu W/cm^2$
Outdoor	100 mW/cm^2	100 $\mu W/cm^2$
Vibration/motion		
Human	0.5 m 1 Hz, 1 m/s^2 50 Hz	4 $\mu W/cm^2$
Industrial	1 m 5 Hz, 10 m/s^2 1 kHz	100 $\mu W/cm^2$
Thermal energy		
Human	20 mW/cm^2	30 $\mu W/cm^2$
Industrial	100 mW/cm^2	1-10 mW/cm^2
RF		
Cell phone	0.3 $\mu W/cm^2$	0.1 $\mu W/cm^2$

Energy Efficiency Trend for Computers and DSPs





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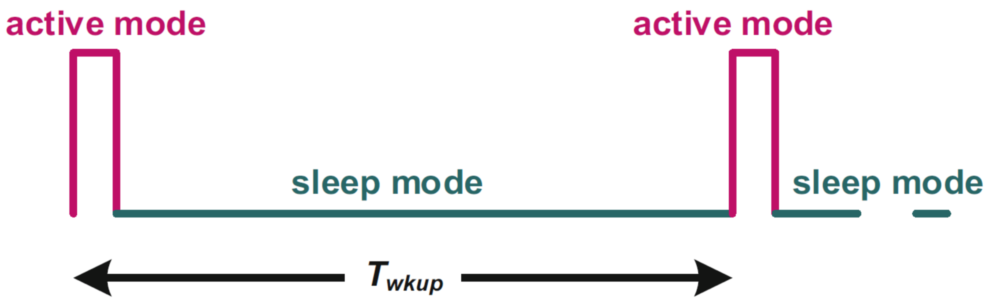
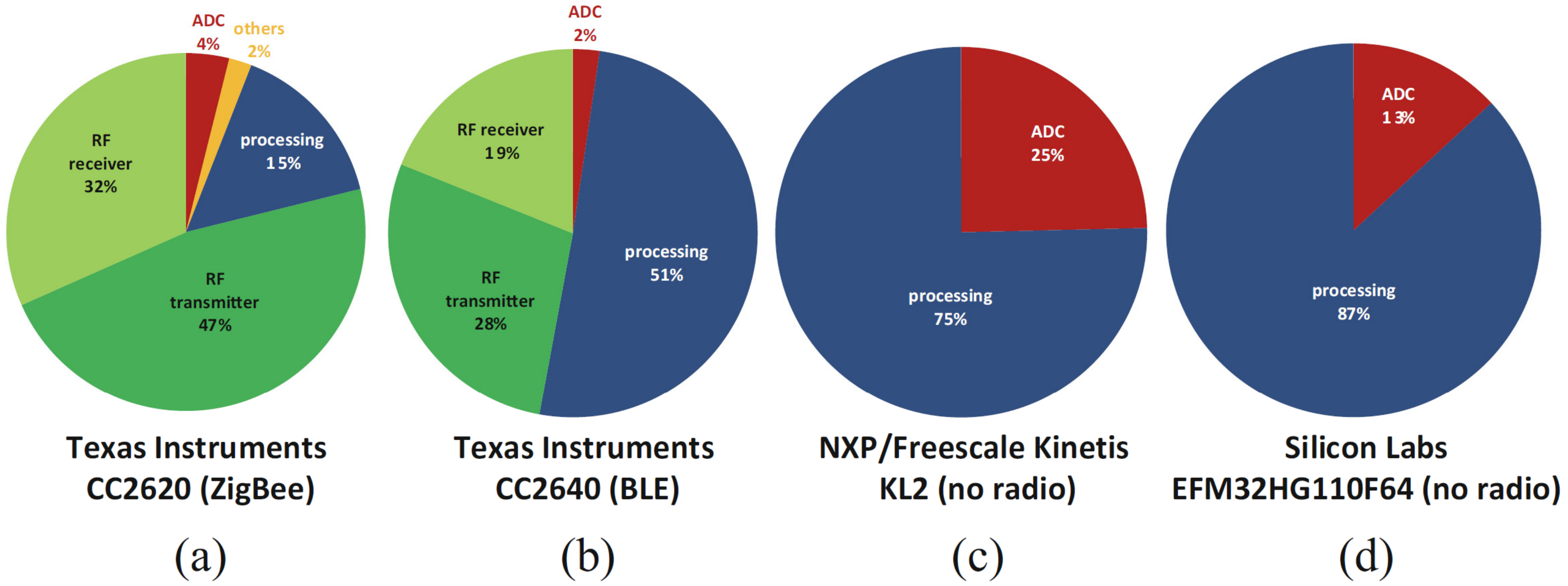
The Necessity for Duty Cycling



$$P_{avg} = P_{ALWON} + \frac{E_{DCYC}}{T_{wkup}}$$

- Meeting power budgets of few µWs or below is feasible only if the IoT node actively performs tasks (e.g., sensing, processing) only infrequently.
- In other words, power needs to be aggressively reduced by duty cycling the IoT node operation, alternating active tasks and long sleep periods.
- From an architectural standpoint, this means that IoT nodes are organized into an always-on (ALWON) sub-system that manages the periodicity of the wake-up cycle and stores information across active tasks, consuming a power P_{ALWON}, and a duty-cycled (DCYC) sub-system that periodically performs the active task with an energy per cycle E_{DCYC}

Wireless Communication Power Dominates



- The power consumption of current IoT nodes is dominated by the wireless communication power, considering short-range communication standards with low average and peak current, as required by IoT nodes (e.g., ZigBee and Bluetooth Low Energy-BLE)

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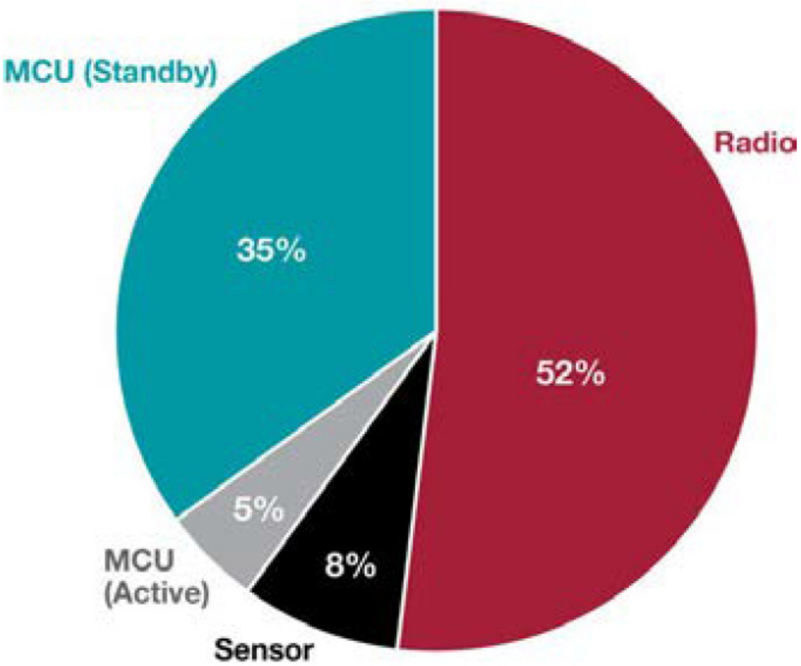
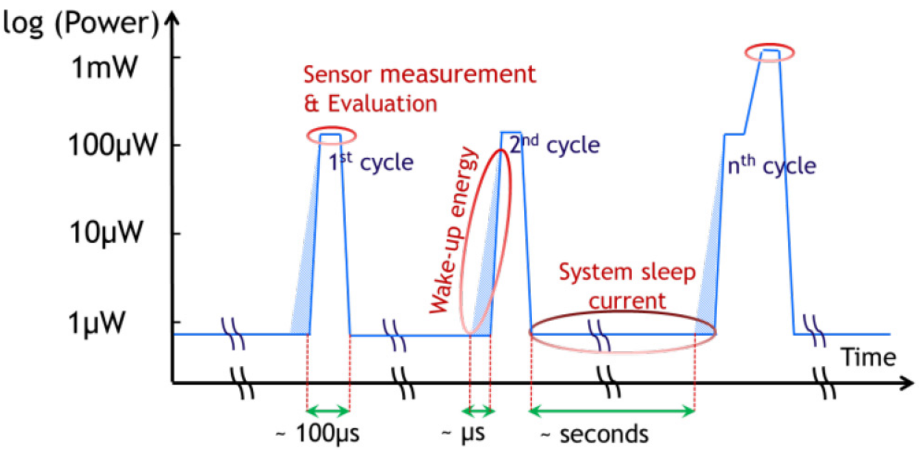
Radio Power Consumption is Dominant





- The radio for enabling wireless communication is consuming more than 50% of the node power

- BT radios are typically in the 4mA range and can therefore not be on continuously
- The system has to be duty cycled
- The energy that is wasted when the system sleeps, wakes-up of turns off is overhead energy that has to be minimized

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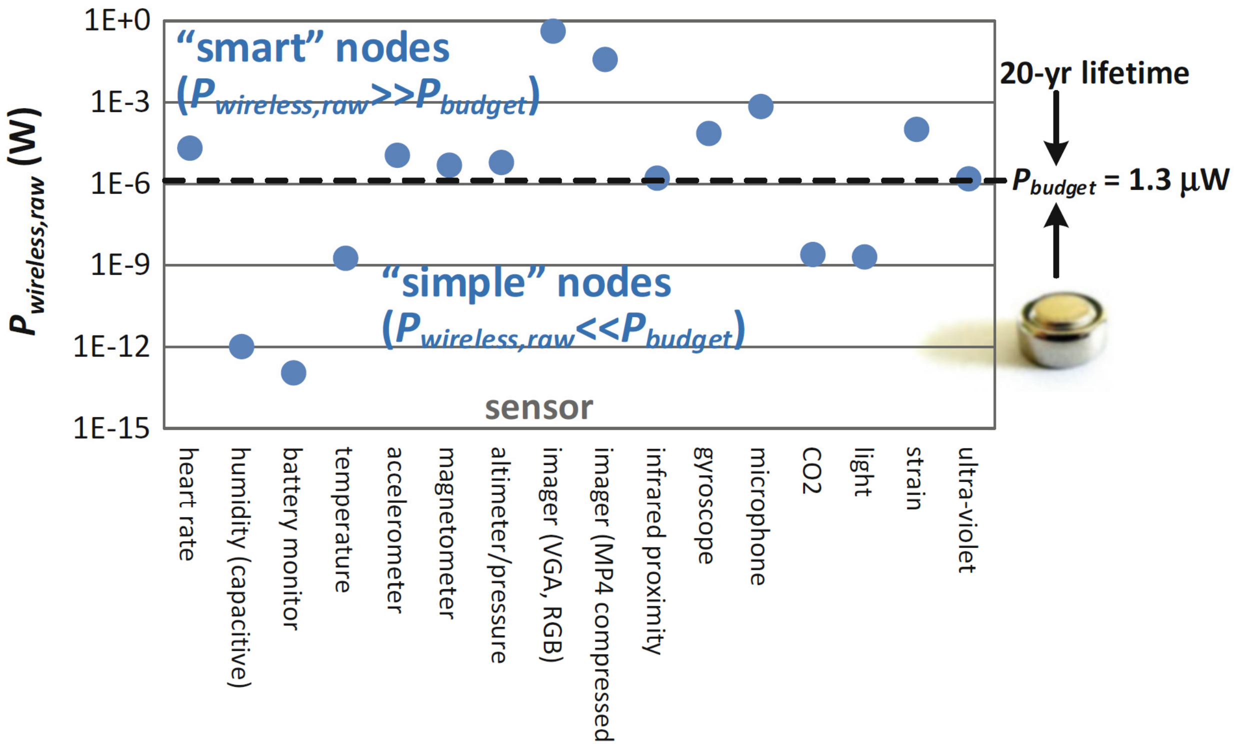
The Communication-Computation Tradeoff

$$P_{wireless,raw} = E_{bit} \cdot N_{bit,measure} \cdot f_{measurements}$$



E_{bit} is the average energy necessary to transmit 1 bit usual measured in nJ/bit, $N_{bit,measure}$ is the number of bits transmitted per measurement and $f_{measurements}$ is the number of measurements per unit of time.

Raw wireless power required for a 20 years lifetime, with a LR44 button battery of 150 mAh and a 5 nJ/bit transmit energy for a power budget of 1µW.

- Environmental sensors (e.g., humidity, temperature) and battery monitors are "simple" nodes thanks to aggressive duty cycling enabled by the slow dynamics of the physical quantities monitored
- All other types of IoT need to be "smart", in the sense that some on-board processing is needed to reduce the amount of transferred data

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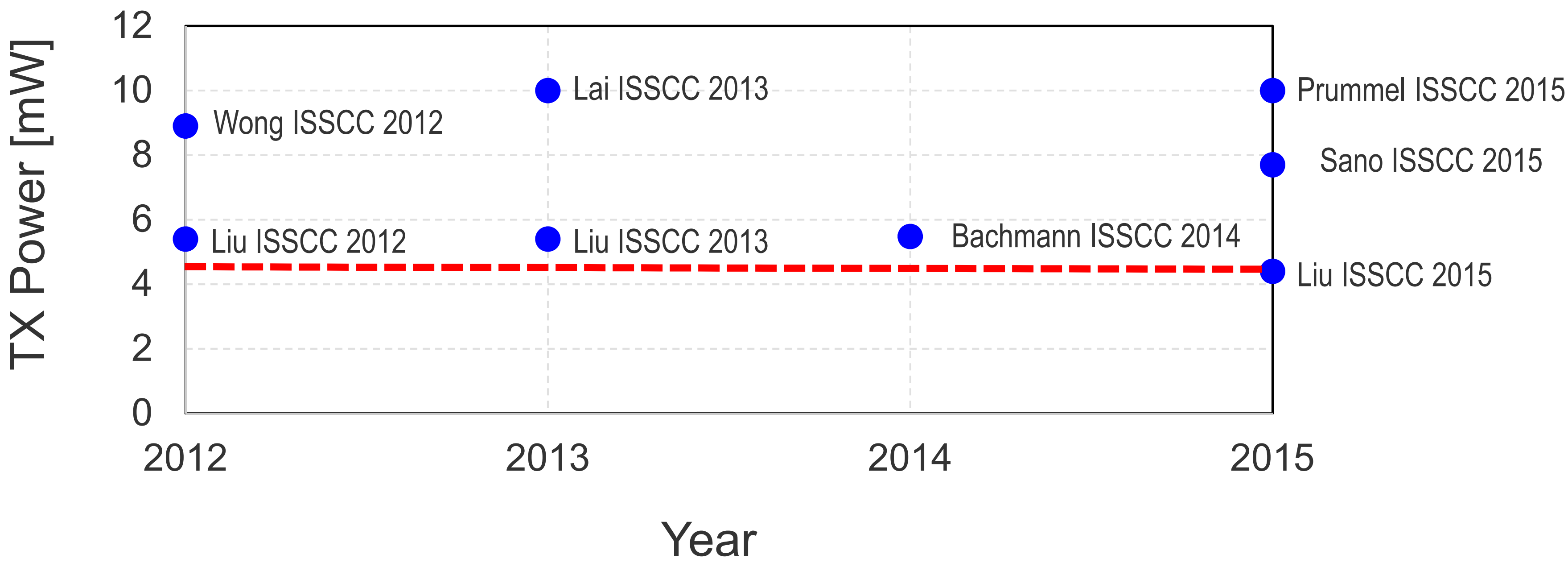
Duty Cycling Radios to Further Lower Power

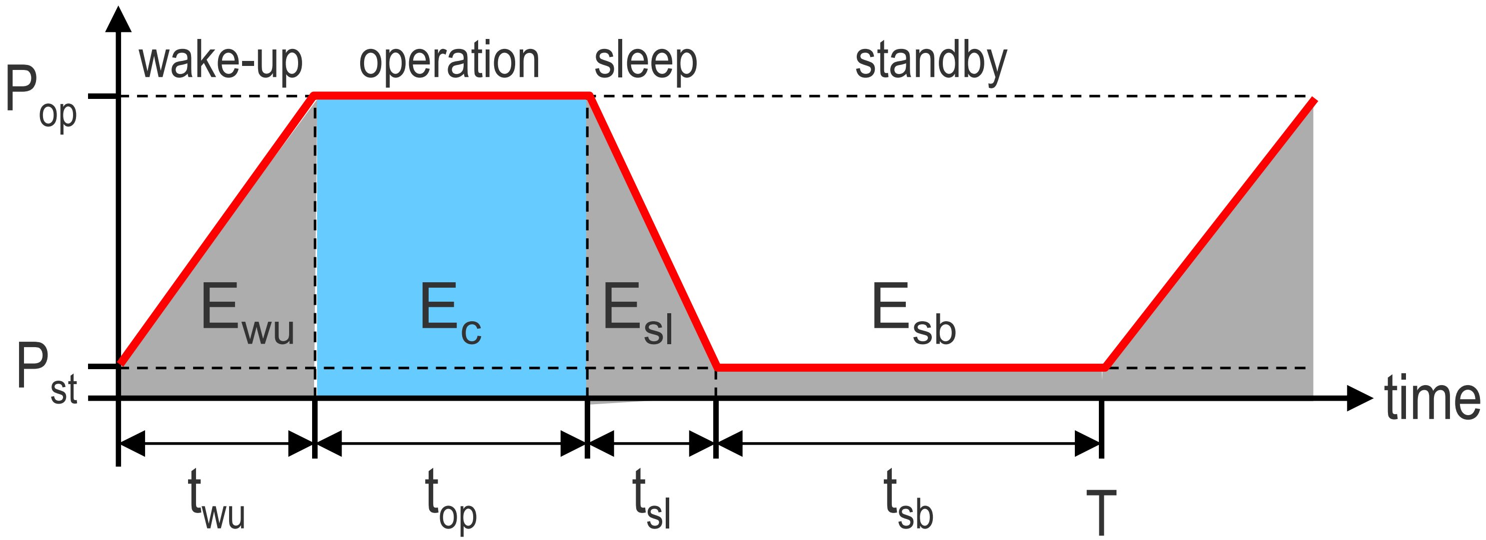


- Power of conventional radios seems to level off (>4 mW)
- Data rates up to 2 to 3 Mb/s
- **Average power** can be further reduced by **duty cycling**

Duty Cycling

- The average energy $P_{av} \cdot T$ includes the **communication** (receive or transmit) energy E_c, the **wake-up** energy E_{wu}, the **sleep** energy E_{sl} and the **standby** energy E_{sb}

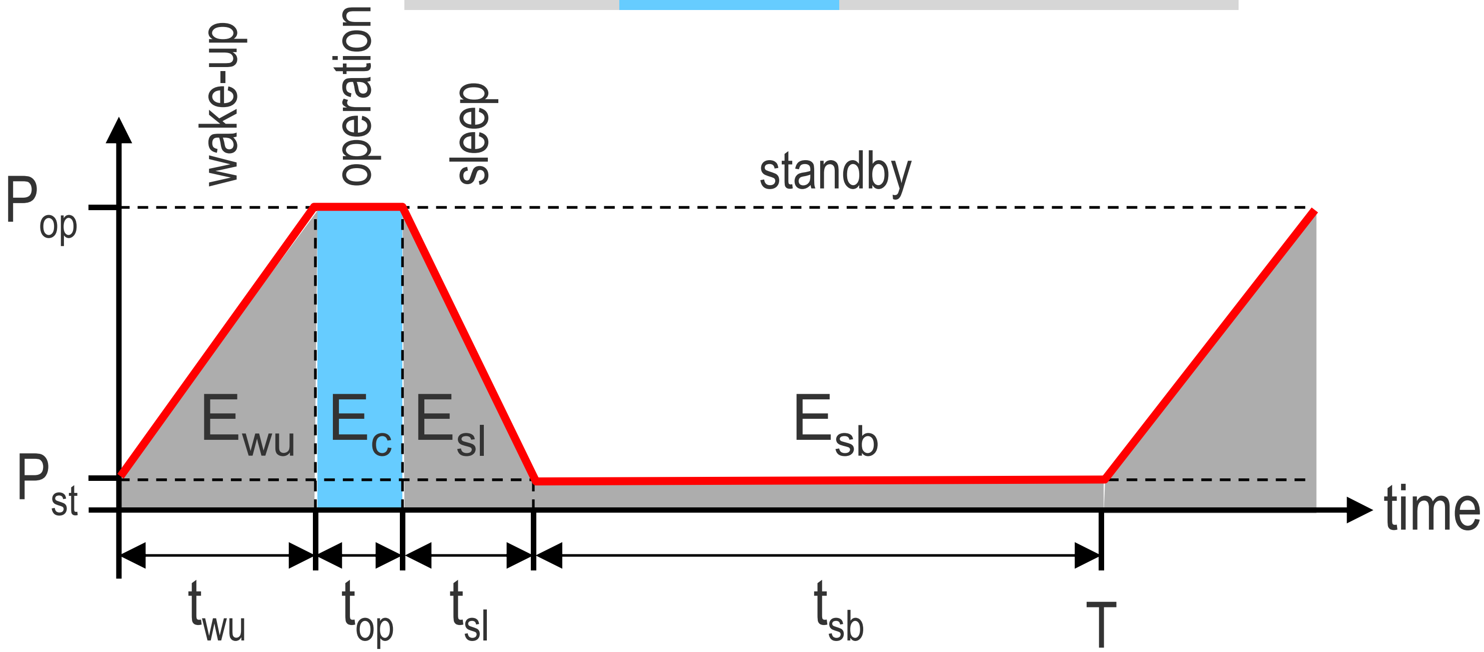
$$P_{av} = P_{wu} \cdot \frac{t_{wu}}{T} + P_{op} \cdot \frac{t_{op}}{T} + P_{sl} \cdot \frac{t_{sl}}{T} + P_{sb} \cdot \frac{t_{sb}}{T}$$



Duty Cycling

- Reduce P_{av} by increasing peak data rate PDR and hence decreasing t_{op} and duty cycling DC maintaining constant mean data rate MDR

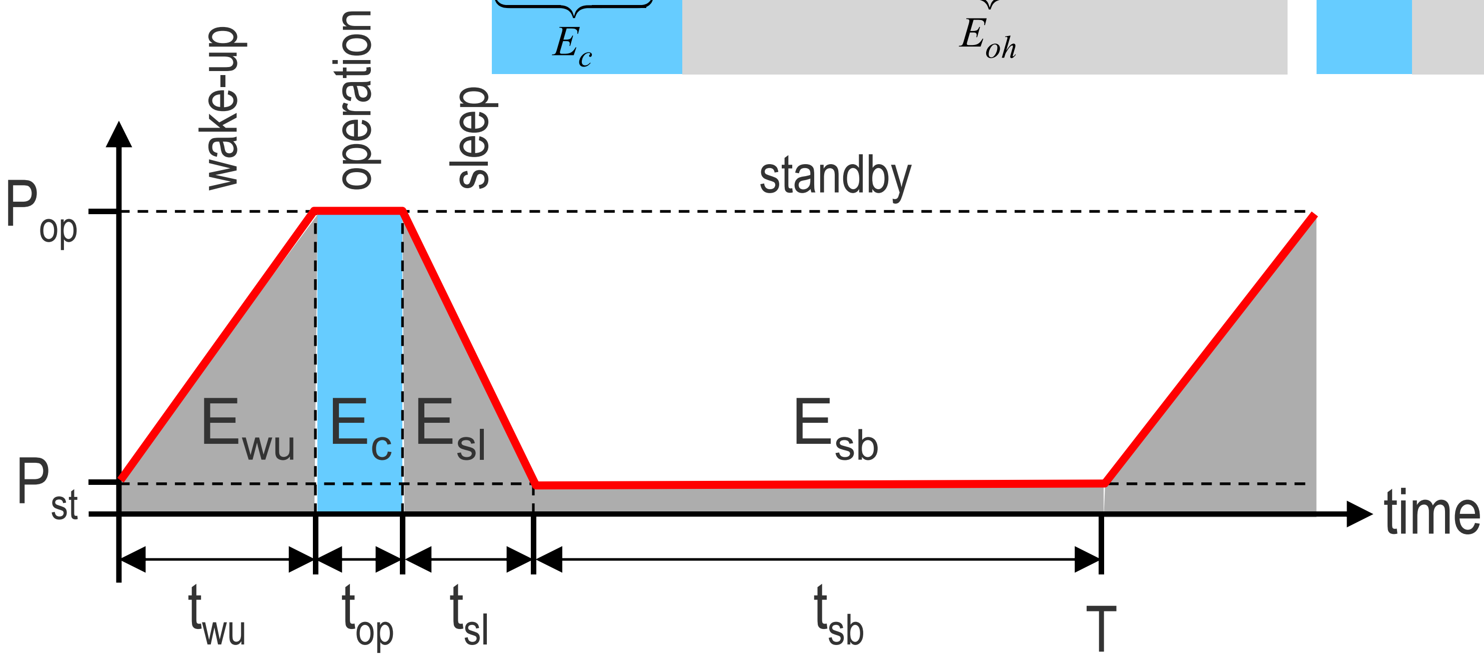
$$P_{av} = P_{wu} \cdot \frac{t_{wu}}{T} + P_{op} \cdot \frac{t_{op}}{T} + P_{sl} \cdot \frac{t_{sl}}{T} + P_{sb} \cdot \frac{t_{sb}}{T}$$



Duty Cycling

- Overhead energy E_{oh} starts to dominate
- Traditional J/bit FoM is no more relevant because it only includes E_c, however E_{oh} also has to be accounted for

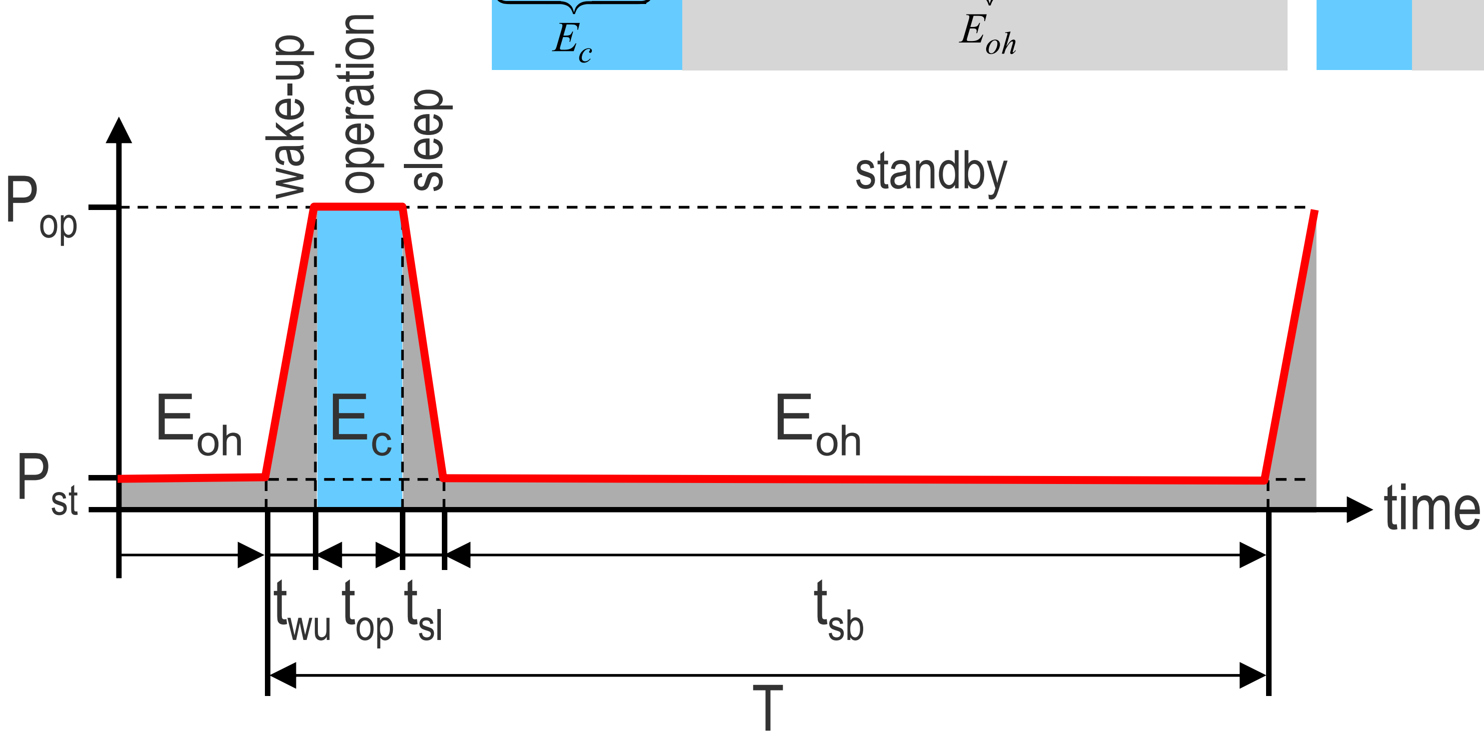
$$E_{av} = \underbrace{P_{op} \cdot t_{op}}_{E_c} + \underbrace{P_{wu} \cdot t_{wu} + P_{sl} \cdot t_{sl} + P_{sb} \cdot t_{sb}}_{E_{oh}} = E_c + E_{oh}$$



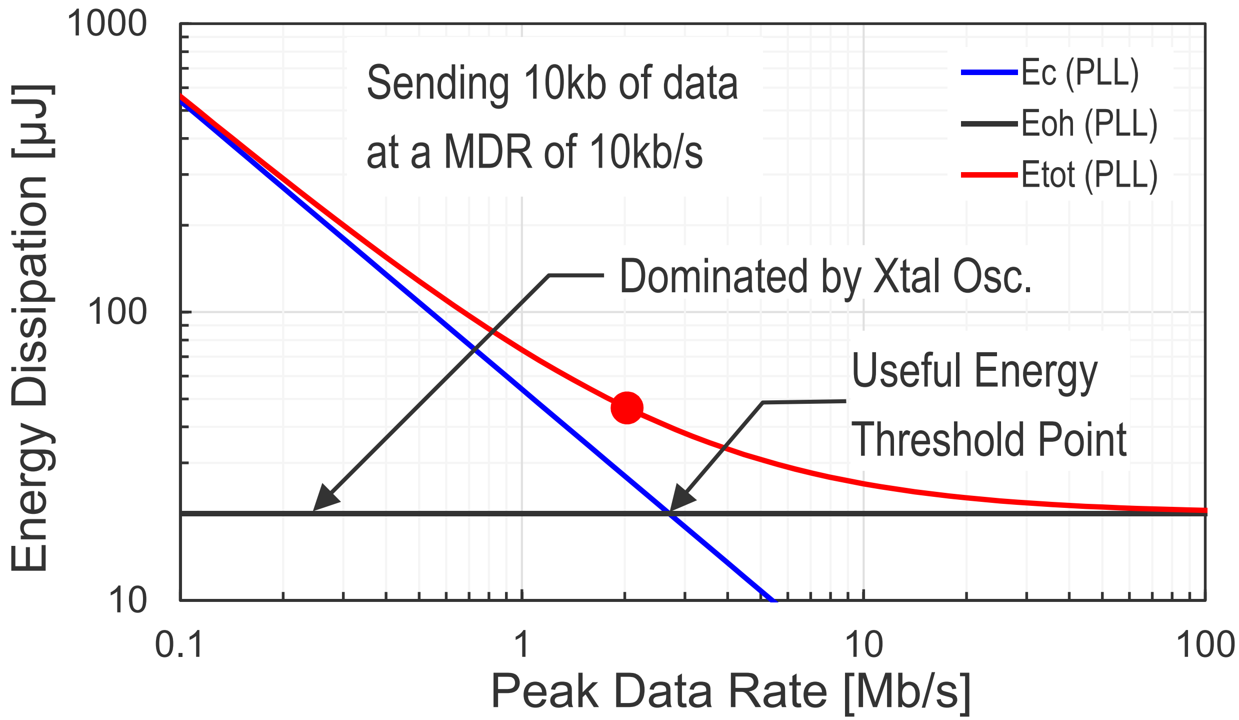
Duty Cycling

- Overhead energy E_{oh} has to be reduced at the same time than communication energy E_c to take full advantage of increased PDR

$$E_{av} = \underbrace{P_{op} \cdot t_{op}}_{E_c} + \underbrace{P_{wu} \cdot t_{wu} + P_{sl} \cdot t_{sl} + P_{sb} \cdot t_{sb}}_{E_{oh}} = E_c + E_{oh}$$



Reduction of Energy Overhead



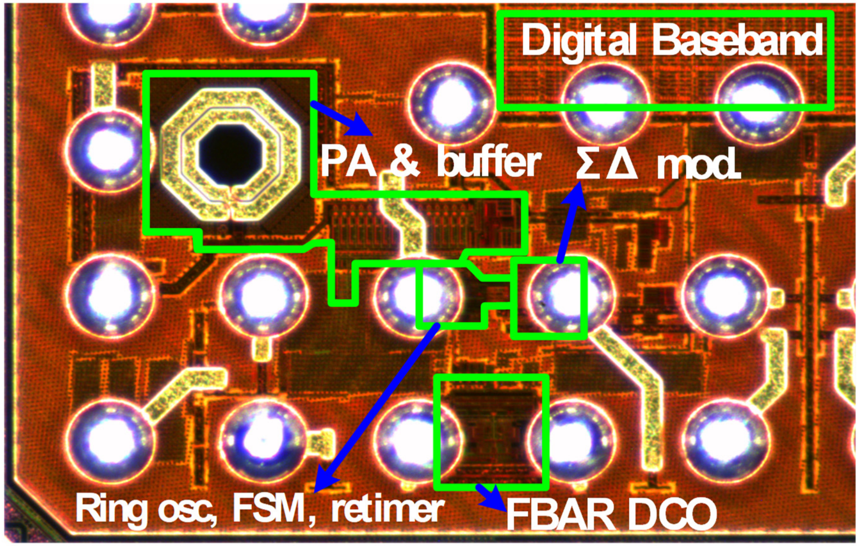
	Unit	PLL
Total data to be sent K	**kbits**	**10**
Mean data rate MDR	**kb/s**	**10**
Total transmission duration Td	s	1
Packet length L	bytes	32
Number of packets		40
Peak data rate PDR	Mb/s	2
Duty cycle DC	%	0.50%
Power during transmission Pop	mW	5.4
Packet rate Rp	packet/s	40
Packet duration Dp	µs	128
Packet energy	nJ	691
Transmission energy Ec	**µJ**	**27.6**
Start-up power	mW	0.5
Start-up time	ms	1.0
Overhead energy per packet	nJ	500
Overhead energy Eoh	**µJ**	**20**
Total energy Etot	**µJ**	**47.6**
Total energy per bit	**nJ/b**	**4.8**
Energy efficiency	**%**	**58.0%**

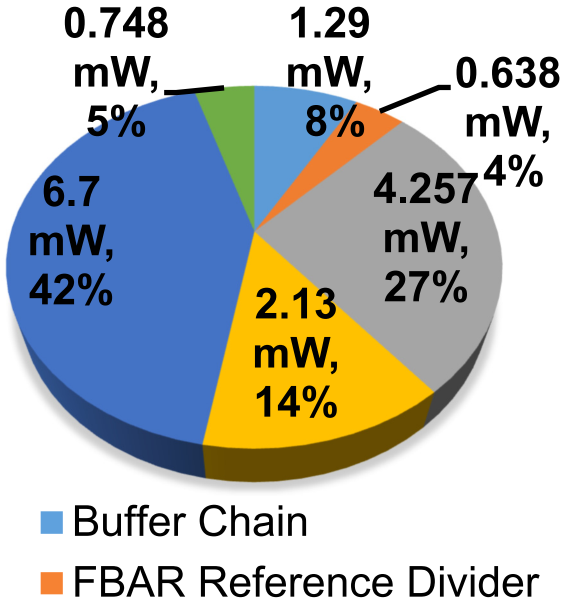
- **Energy overhead** has to be reduced at the same time as communication energy

R. Thirunarayanan, *et.al*. TMTT, March 2015.

Chip Photograph and Power Breakdown

- Integrated in 65 nm CMOS process



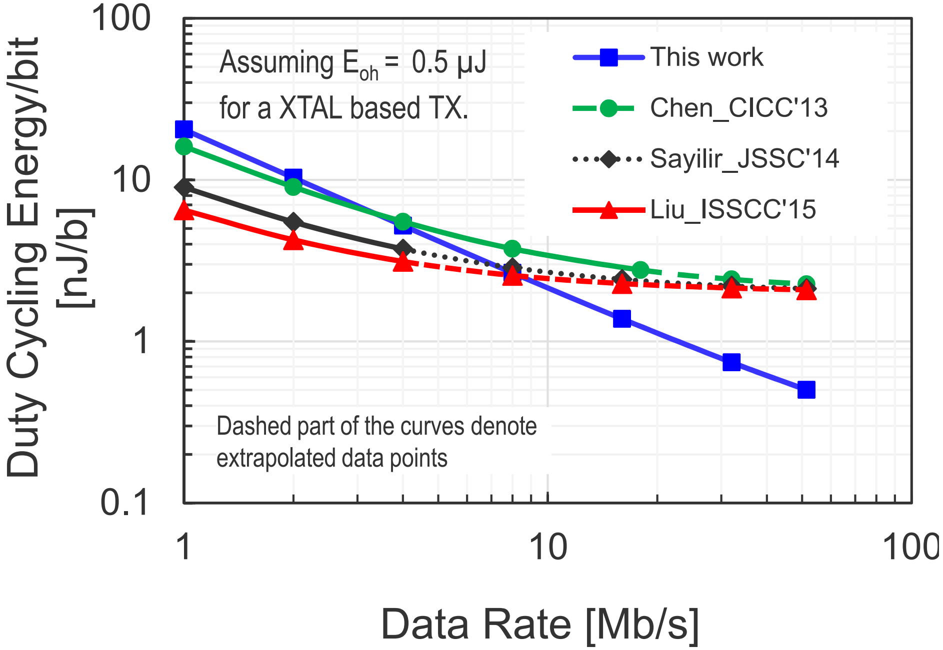


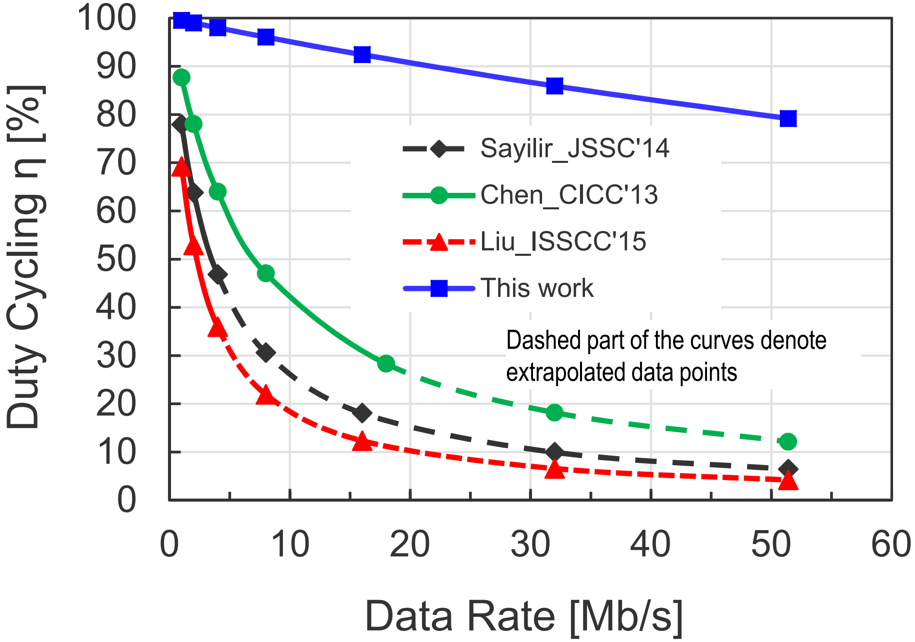
R. Thirunarayanan, *et.al*. ESSCIRC 2016.

Duty Cycling Energy Efficiency

$$E_{bit} = \frac{P_c}{PDR} + \frac{E_{oh}}{L}$$

$$\eta_{EDC} = \frac{E_c}{E_c + E_{oh}}$$



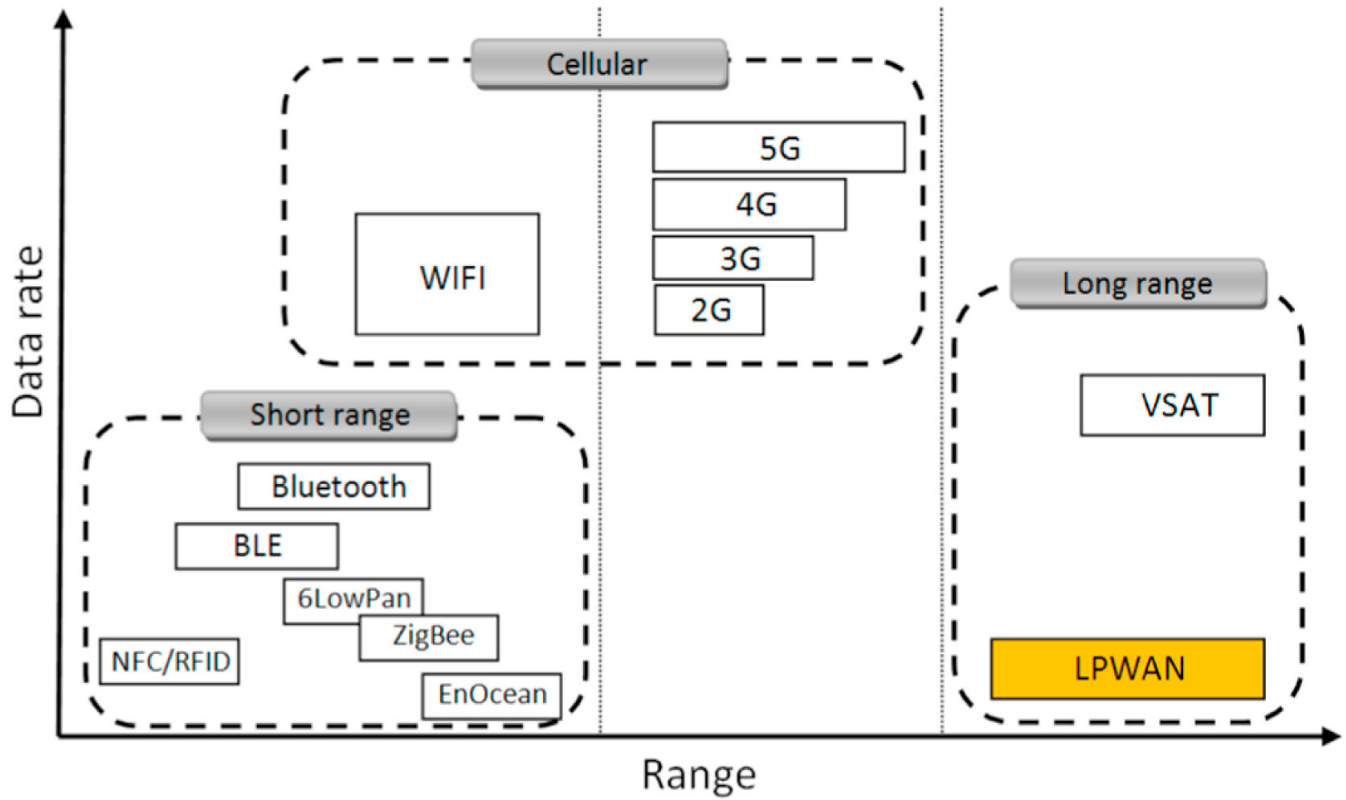


R. Thirunarayanan, *et.al.* ESSCIRC 2016.

How to Reduce the Energy Overhead?

- **Standby energy** E_{st} dominated by **Xtal oscillator**
- **Start-up energy** E_{wu} dominated by **wake-up time of PLL**
- **Reduce both** E_{st} and E_{wu} by replacing Xtal oscillator by a **FBAR oscillator** running at GHz
- **Avoid PLL** by using open-loop frequency synthesizer
- High-Q of FBAR oscillator also provides **low phase noise**
- Very limited frequency tuning of FBAR oscillator compensated by **new transceiver architectures**

Wireless Communication Standards



K. Mekki, et al., ICT Express, Jan. 2018 (https://doi.org/10.1016/j.icte.2017.12.005.) .

IoT Communication Standards

Technology	Frequency	Data Rate	Range	Power Usage	Cost
2G/3G	Cellular Bands	10 Mbps	Several Miles	High	High
Bluetooth/BLE	2.4Ghz	1, 2, 3 Mbps	~300 feet	Low	Low
802.15.4	subGhz, 2.4GHz	40, 250 kbps	> 100 square miles	Low	Low
LoRa	subGhz	< 50 kbps	1-3 miles	Low	Medium
LTE Cat 0/1	Cellular Bands	1-10 Mbps	Several Miles	Medium	High
NB-IoT	Cellular Bands	0.1-1 Mbps	Several Miles	Medium	High
SigFox	subGhz	< 1 kbps	Several Miles	Low	Medium
Weightless	subGhz	0.1-24 Mbps	Several Miles	Low	Low
Wi-Fi	subGhz, 2.4Ghz, 5Ghz	0.1-54 Mbps	< 300 feet	Medium	Low
WirelessHART	2.4Ghz	250 kbps	~300 feet	Medium	Medium
ZigBee	2.4Ghz	250 kbps	~300 feet	Low	Medium
Z-Wave	subGhz	40 kbps	~100 feet	Low	Medium

https://iot.eetimes.com/top-wireless-standards-for-iot-devices/

Low Power Wide Area Network (LPWAN) Standards

Table 1
Overview of LPWAN technologies: Sigfox, LoRa, and NB-IoT.

	Sigfox	LoRaWAN	NB-IoT
Modulation	BPSK	CSS	QPSK
Frequency	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Licensed LTE frequency bands
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	100 bps	50 kbps	200 kbps
Bidirectional	Limited / Half-duplex	Yes / Half-duplex	Yes / Half-duplex
Maximum messages/day	140 (UL), 4 (DL)	Unlimited	Unlimited
Maximum payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	1600 bytes
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)
Interference immunity	Very high	Very high	Low
Authentication & encryption	Not supported	Yes (AES 128b)	Yes (LTE encryption)
Adaptive data rate	No	Yes	No
Handover	End-devices do not join a single base station	End-devices do not join a single base station	End-devices join a single base station
Localization	Yes (RSSI)	Yes (TDOA)	No (under specification)
Allow private network	No	Yes	No
Standardization	Sigfox company is collaborating with ETSI on the standardization of Sigfox-based network	LoRa-Alliance	3GPP

Table 2
Different costs of Sigfox, LoRa, and NB-IoT.

	Spectrum cost	Deployment cost	End-device cost
Sigfox	Free	>4000€/base station	<2€
LoRa	Free	>100€/gateway >1000€/base station	3–5€
NB-IoT	>500 M€ /MHz	>15 000€/base station	>20€

K. Mekki, et al., ICT Express, Jan. 2018 (https://doi.org/10.1016/j.icte.2017.12.005.) .

Comparison of LPWAN Standards

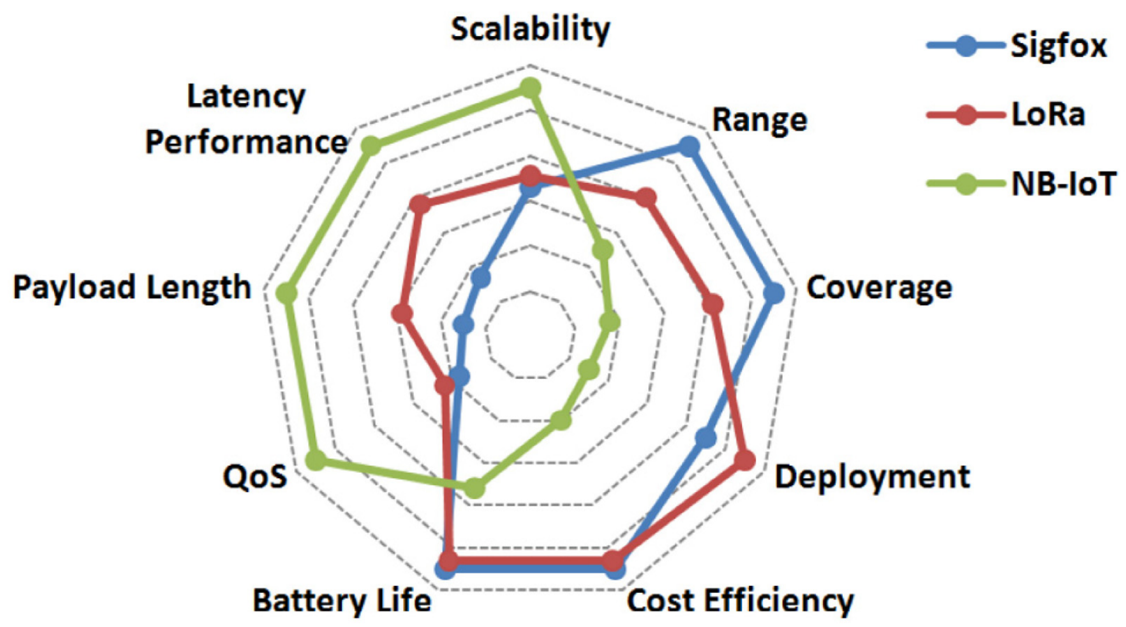


Fig. 4. Respective advantages of Sigfox, LoRa, and NB-IoT in terms of IoT

K. Mekki, et al., ICT Express, Jan. 2018 (https://doi.org/10.1016/j.icte.2017.12.005.) .