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EnerHarv 2024 Workshop:

Empowering the Future of IoT: Always-On Smart Sensors, Energy Harvesting, and Tiny Machine Learning

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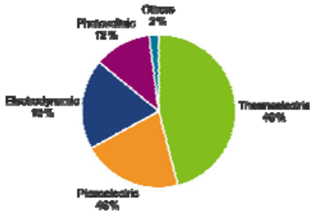
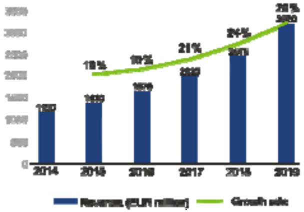
Smart Sensors and IoT are getting Momentum

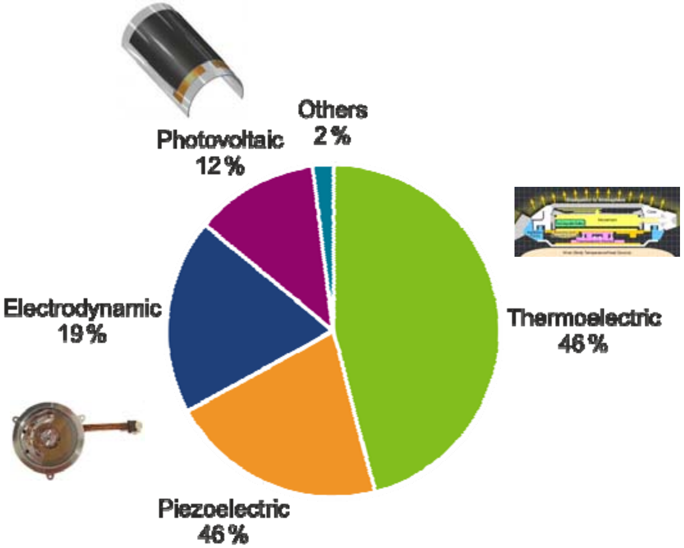
First Challenges:

- Energy storage/consumption/sources

Energy Harvesting as possible solution?





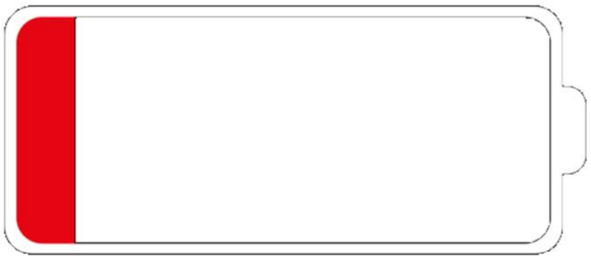


Energy harvesting is the process by which energy is captured and stored.

This term often refers to small autonomous devices – micro energy harvesting

Trends:

- Greater HW/SW complexity
- More functionality per area-



Energy density Li-ion battery:

2-2.5 $X/decade$ [2]

Efficiency improvements:

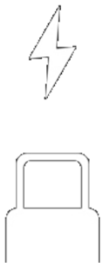
CPUs: **100** $X/decade$

DSPs: **110** $X/decade$

ADCs: **17** $X/decade$

Radios* **19-34** $X/decade$

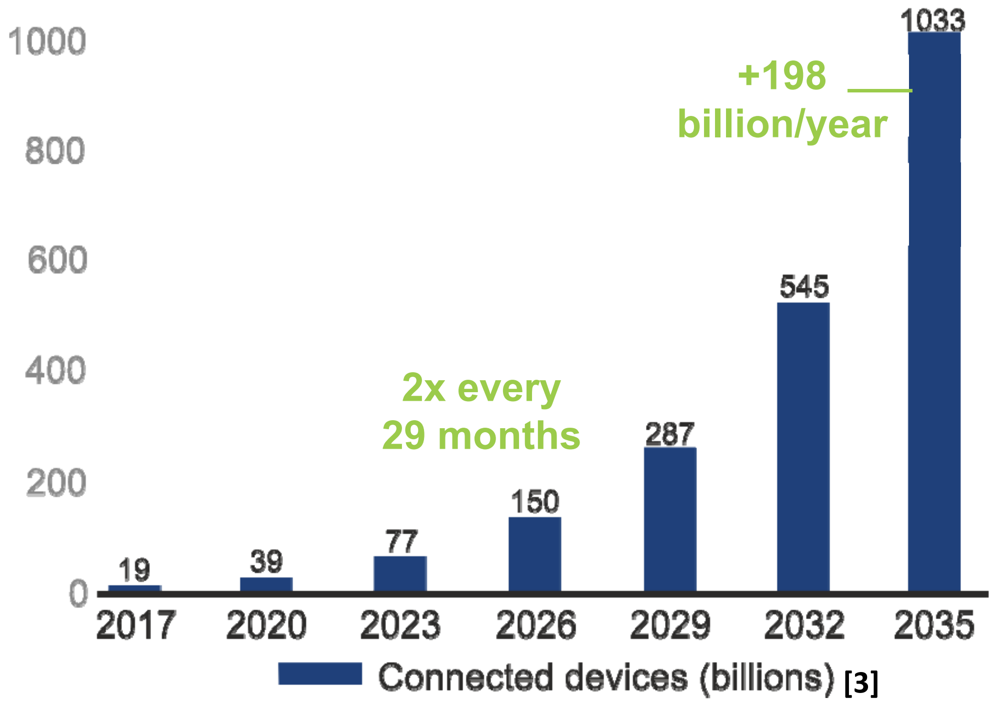
*short range [1]



Biggest Challenges:

- Energy storage
- Energy consumption
- Energy source

Scaling the IoT



Capacity:	235 mAh
Weight:	3 g
Lithium:	109 mg
Volume	1 cm^3

1 trillion

Manufacturing: **109 000 t**
~ 1 year global Li extraction **[4]**

Replacement: **2 T$/year**
~ GDP of Italy

Disposal: **200 000 m^3/year**
~ 2x colosseum/year

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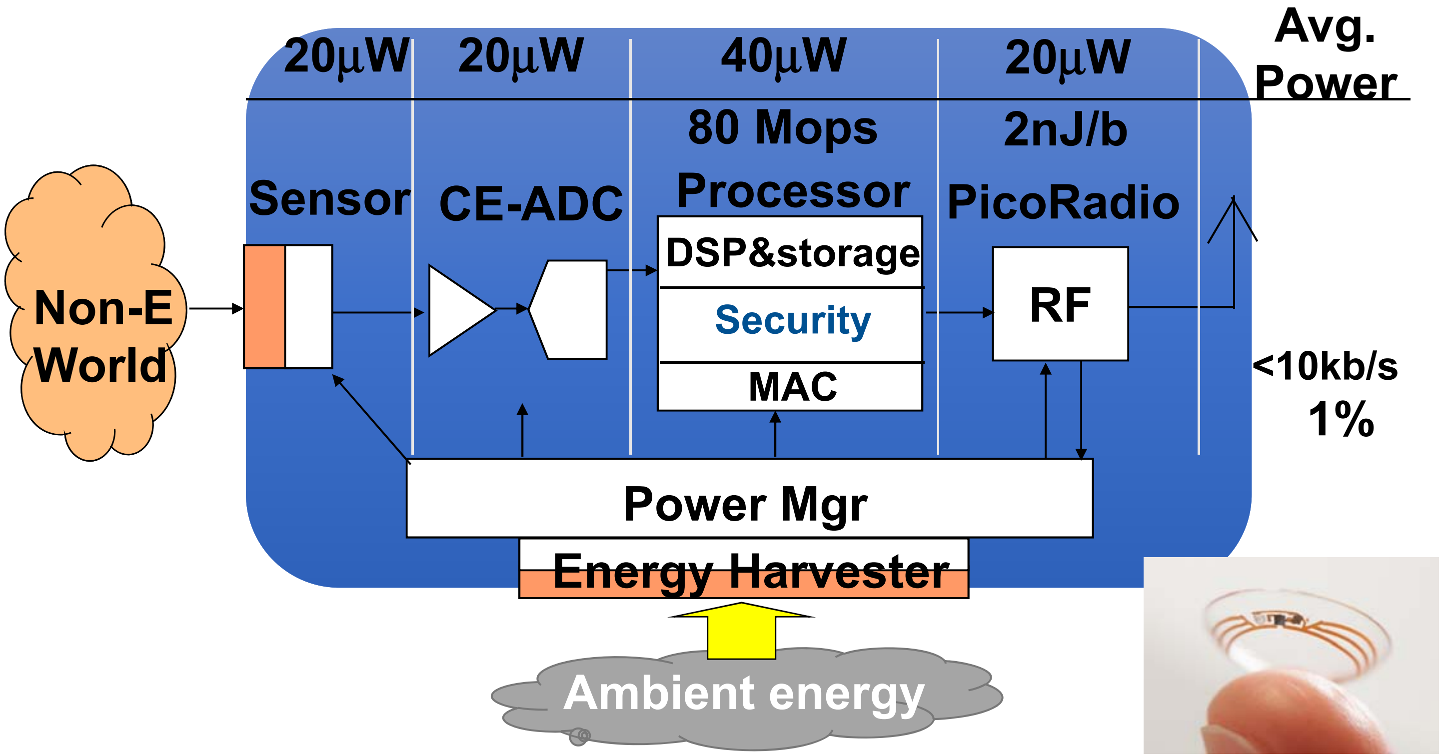
ETH Zürich

Which source from IoT and Smart Sensor?

Energy Source	Source Polarity	Efficiency	Harvested Power	Characteristics
Light	DC	10~24%	100 mW/cm^2 (Outdoor) 100 µW/cm^2 (illuminated office)	Operating conditions vary widely with environment light level. MPPT algorithms needed to achieve maximum power transfer
Thermal	DC	~0.1% ~3%	60 µW/cm^2 (Human) ~1-10 mW/cm^2 (Industrial)	Low output voltage. Step-up circuit needed. Impedance matching to achieve maximum power transfer
Vibration	AC	25~50%	~4 µW/cm^3 (Human motion - Hz) ~800 µW/cm^3 (Machines - KHz)	High AC output voltage with positive and negative fluctuations (spikes). Rectifier & Step-down circuits are needed.
Ambient Air flow	AC	~39% (Dynamic) ~41% (Generator)	35 µW/cm^2 (@ <1 m/s) 3.5 mW/cm^2 (@ 8.4 m/s)	Dual or 3-phase output. Rectifier is needed. MPP varies slightly with wind speed. Impedance matching is sufficient to achieve maximum power transfer in many applications
RF	AC	~50%	0.1 µW/cm^2 (GSM 900 MHz) 0.001 mW/cm^2 (WiFi)	Impedance matching to achieve maximum power transfer

A dream? Achieving Autonomous and intelligent "IoT"



Objective: 100 µW Avg → Energy neutrality becomes "easy"

Main Challenges of Energy-autonomous IoT Devices

1) Miniaturization and Energy Limitations

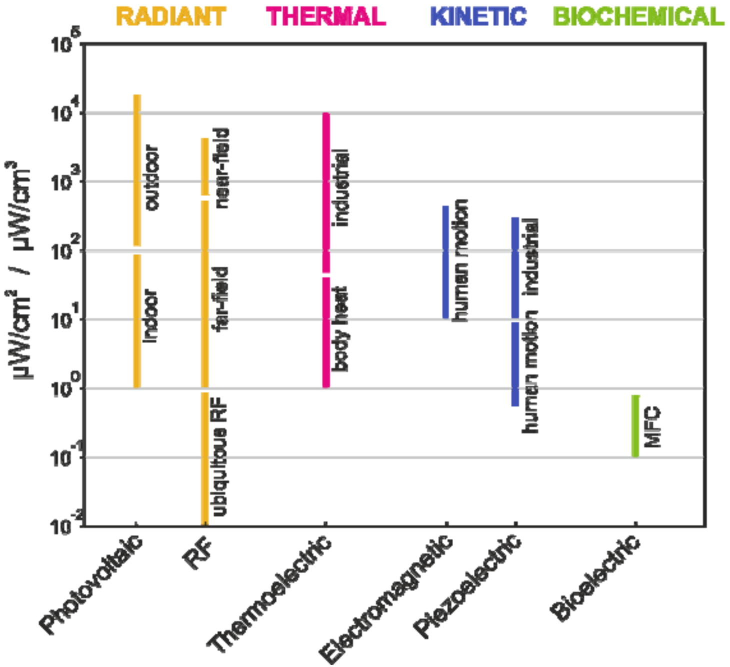
- Minimal energy consumption for maximum battery lifetime
- Limited instantaneous power

2) Energy Uncertainty and Resilience

- Robust and fault-tolerant power paths
- Decades of mission lifetime

3) Individuality

- Limited reusability of designs



Pursue multiple and distend design goals

Next generation of IoT devices for surveillance:
Always-on Smart Sensors.

1.) Edge Signal Processing and AI

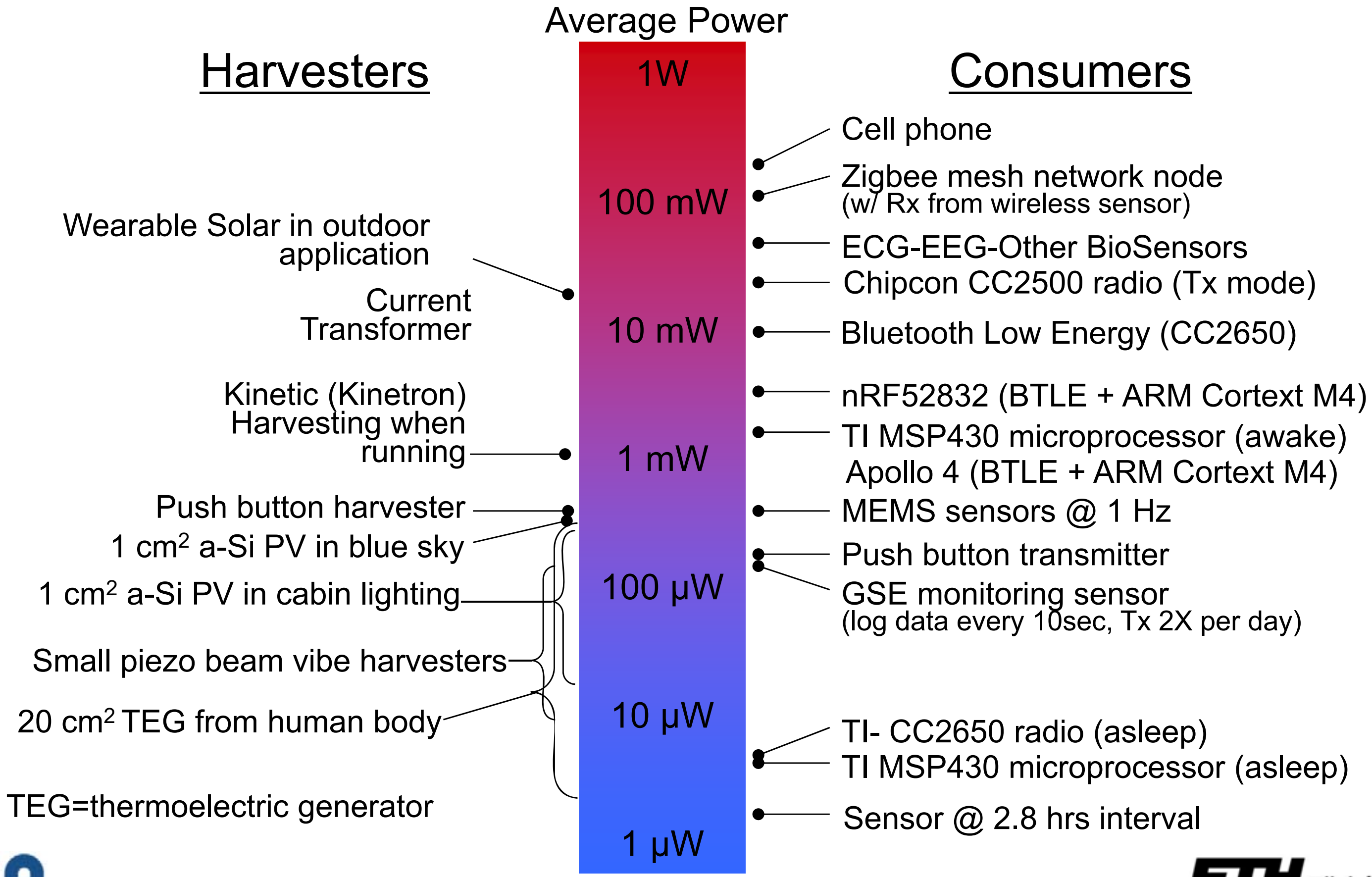
Smart IoT devices

3.) Low power system design

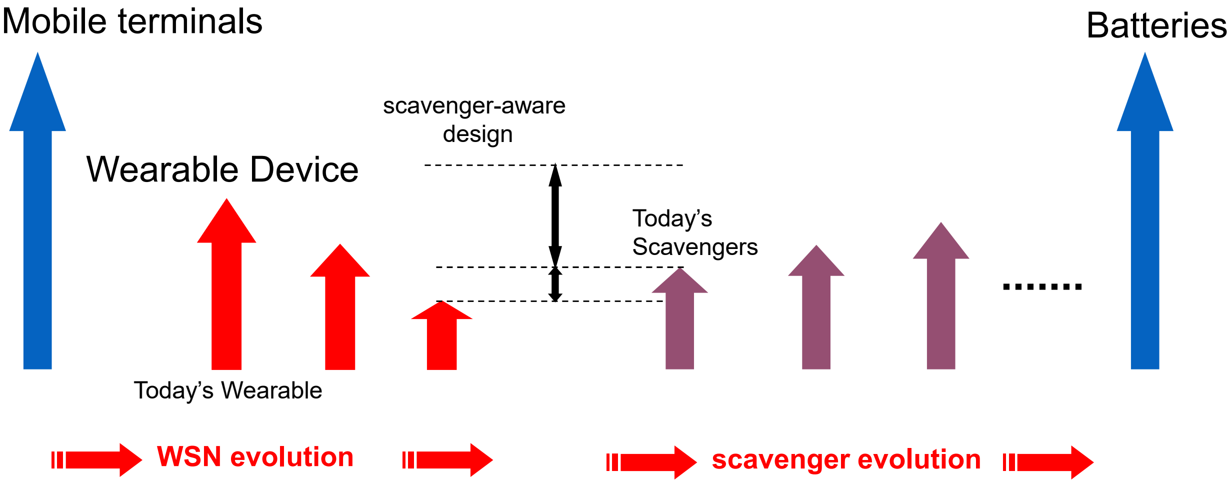
2.) Energy harvesting

4. Energy Efficient and long-range communication

System Design Consideration



The Good News

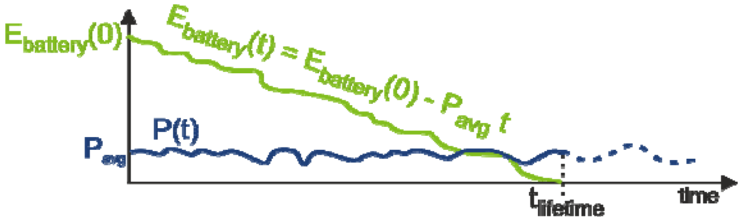


- **The gap between scavengers energy and requirements of digital systems is shrinking**
- **Exploit energy management strategies and improvements in scavenger technology**
  - Overcome traditional energy management strategies (battery-driven)
- **An new unified design methodology is required**
  - Smart adaptation
  - Design for unreliability
  - Exploit unpredictable power sources

Supply Concepts

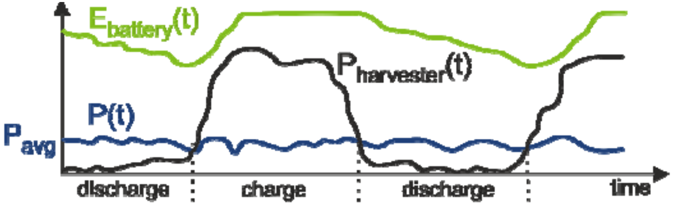
1) Battery-powered:

- defined and limited lifetime



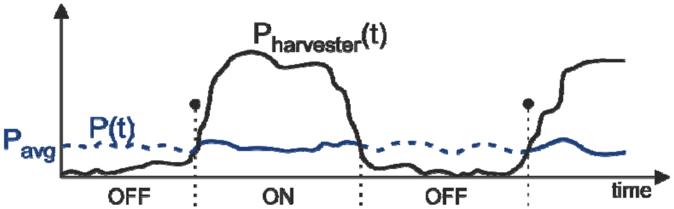
2) Hybrid-powered

- limited battery scaling



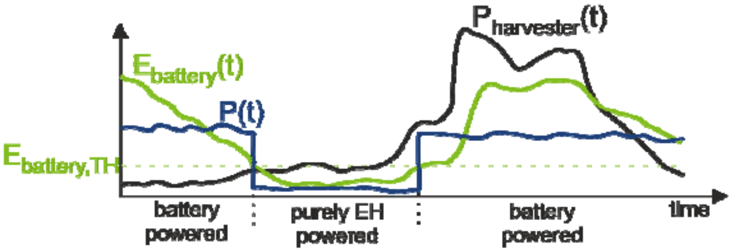
3) Transient System

- temporal coupling source and load



4) Battery-indifferent System

- adaptive QoS



Next generation of smart sensors:
Always-on Smart Sensors.

1.) Edge Signal Processing and AI

Smart devices
for perpetual operation

3.) Low power system design

2.) Energy harvesting

4.) Low Power and energy efficient communication

How can we do?
Self-sustainable Asset Tracking

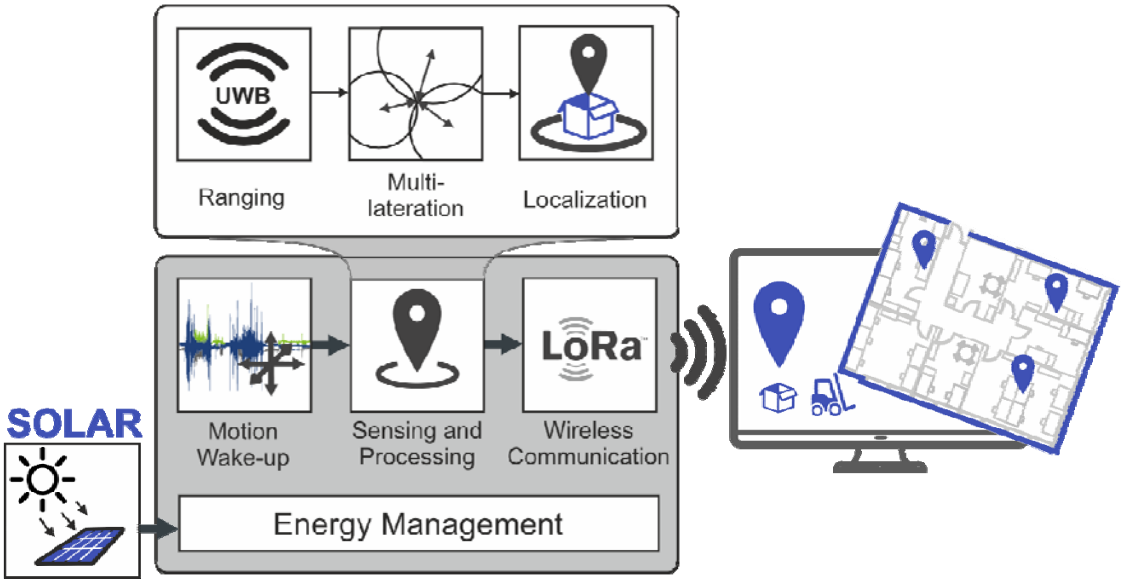
Self-sustainable Asset Tracking with Novel UWB radio

Objective:

“Place and forget” indoor asset tracking system with a localization accuracy below 0.5m.

Challenges:

- Limited environmental energy
- Robust and accurate multiroom localization (NLOS)
- Wireless communication is power-hungry and we use as sensors.
  - High dynamic load I_{bat} = >50mA



P. Mayer, M. Magno and L. Benini, "Self-sustaining Ultra-wideband Positioning System for Event-driven Indoor Localization," submitted to IEEE Internet of Things Journal

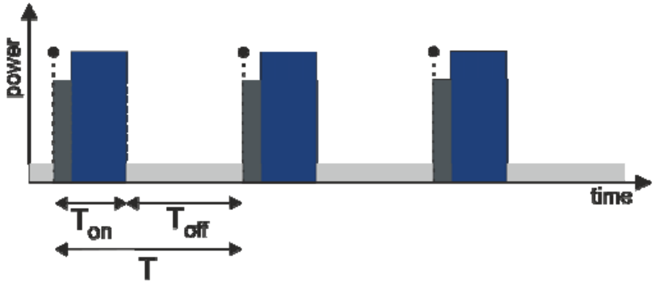
Sensing Paradigms

1) Duty-cycled operation

Short time periodical activation of sensing stage.

Challenge: latency

$$P_{avg} = P_{off} + E_{active}/T_{on}$$

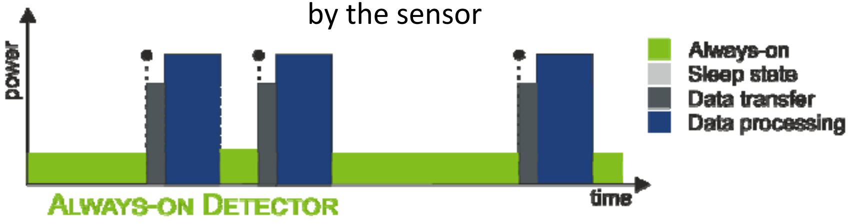


2) Event-driven operation

Always-on data analytics to spot events of interest.

Challenge: idle consumption

Detection of relevant information by the sensor



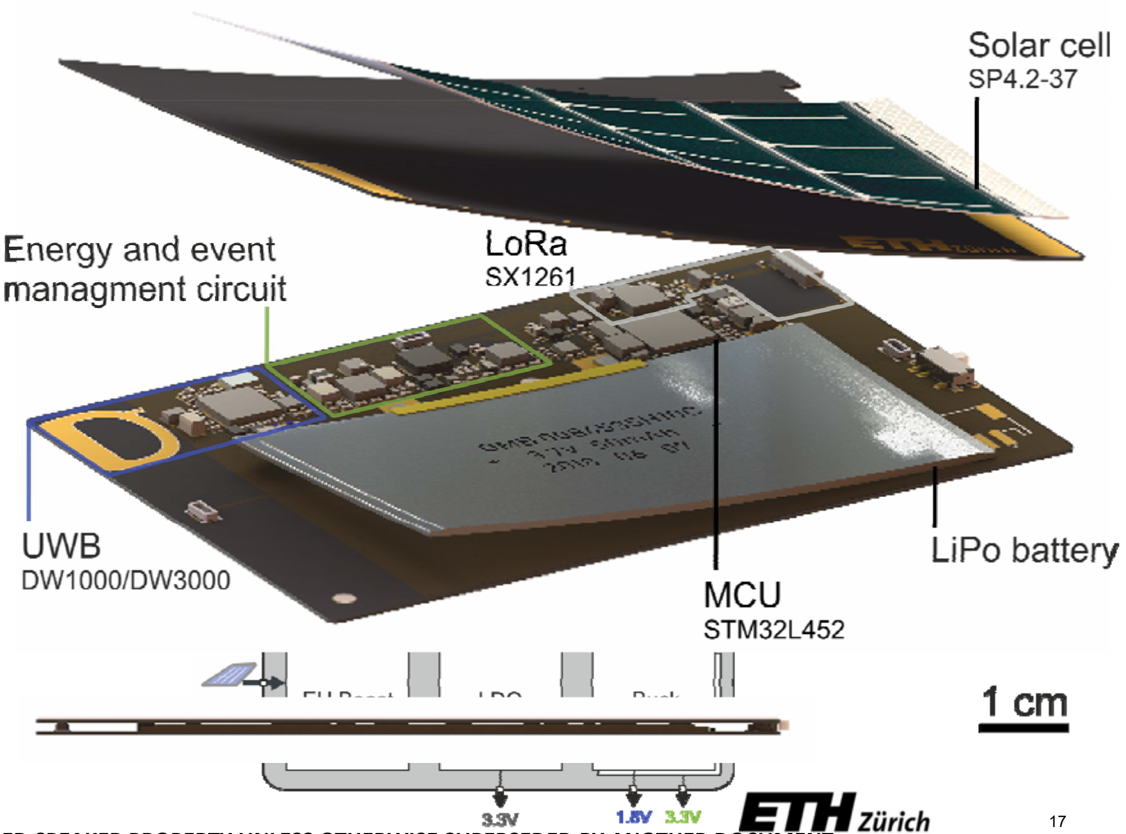
Background – The current market of UWB and BLE

	BLE	*UWB*		
	NRF5x *[1]*	**Qorvo DW3000 *[4]***	**NXP SR040 *[5]***	**Microchip ATA8352 *[6]***
Frequency band [MHz]	2.4	6-8.5	6.2-8.2	6.2-8.3
IEEE 802.15.4z PHY	-	HRP	HRP	LRP
OTA data rate [Mbps]	2	6.8	6.8	1
Ranging accuracy [cm]	+/-60 *[2]*	+/-5	+/-10	+/-5
AoA accuracy [°]	+/-10 *[3]*	+/-5	+/-3	-
Standby power [µW]	1.62	0.46	0.9	0.09
TX Power draw [mW]	**11.2**	**63**	**236**	**30**
RX Power draw [mW]	**9.5**	**158**	**207**	**130**

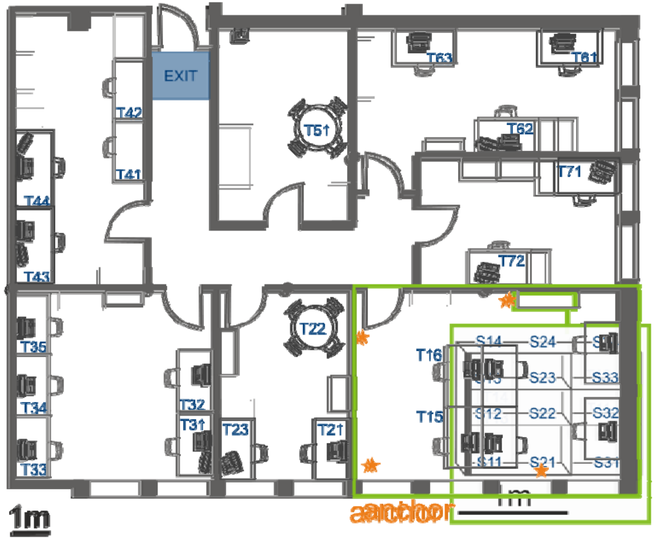
Self-sustainable Asset Tracking - Architecture

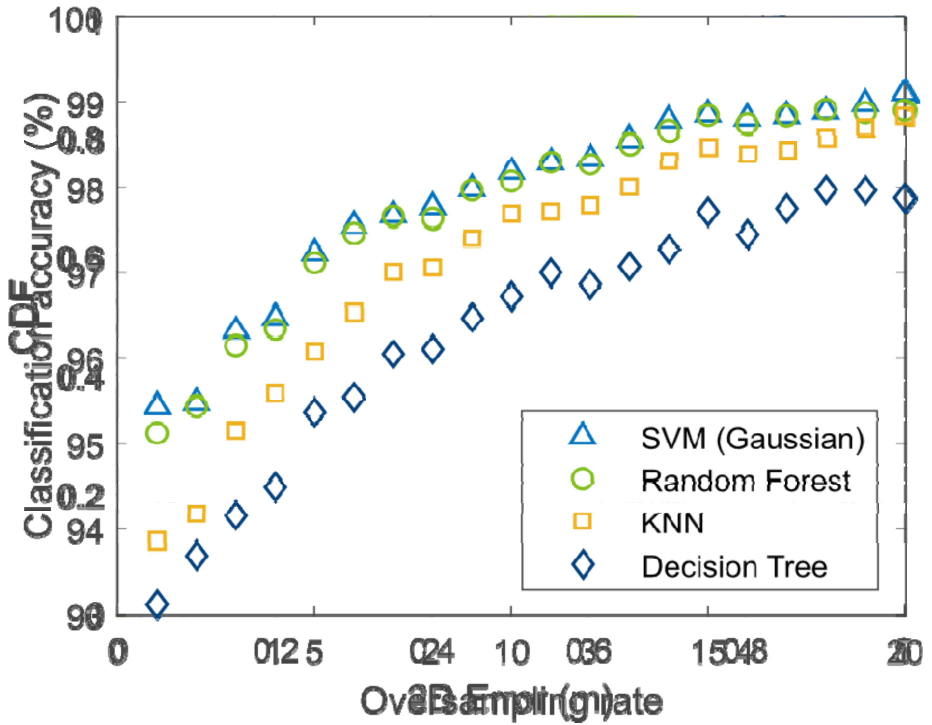
Solution:

- Tag-centralized operation
- Fully embedded processing
- Event-driven sensing
- Heterogeneous system design
- Energy efficient ML at the Edge



Self-sustainable Asset Tracking - Localization Performance



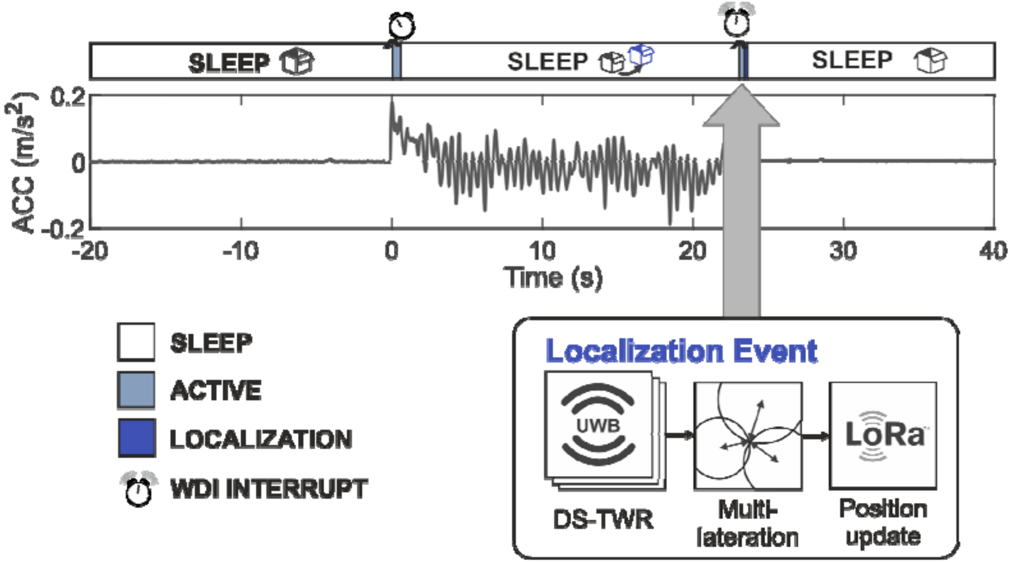


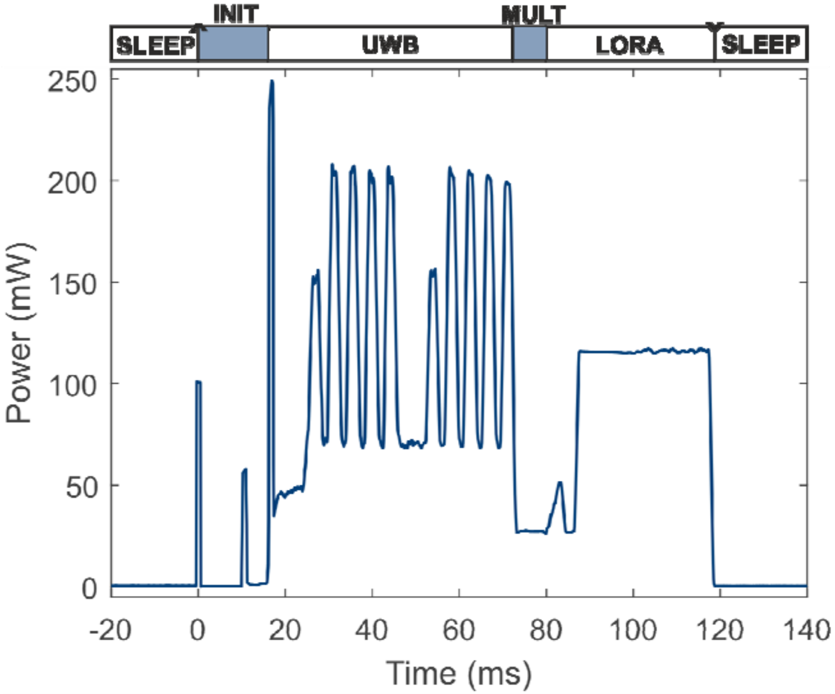
Coverage:

Dataset:

Class. Accuracy: **>95.3 %**

Self-sustainable Asset Tracking - Implementation





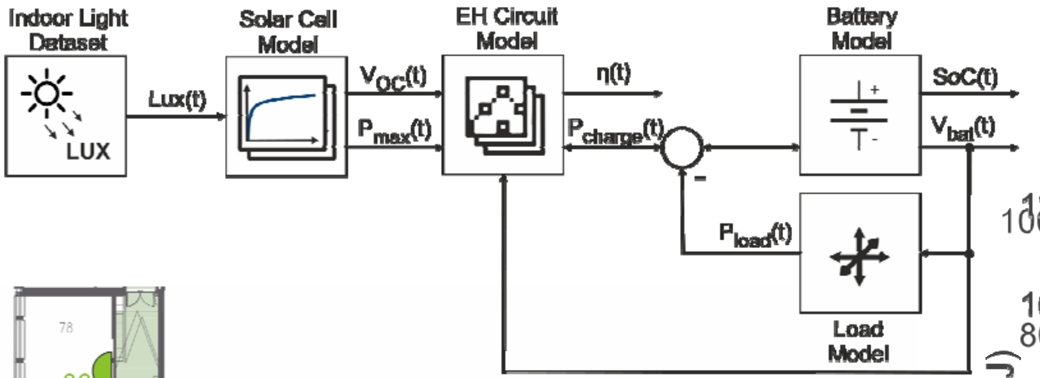
1.26 µA*

*(includes motion wake-up and EH)

10.84 mJ**

**(DS-TWR, Channel 5, Data rate: 850kbit/s, EIRP: -41.3dBm/MHz)

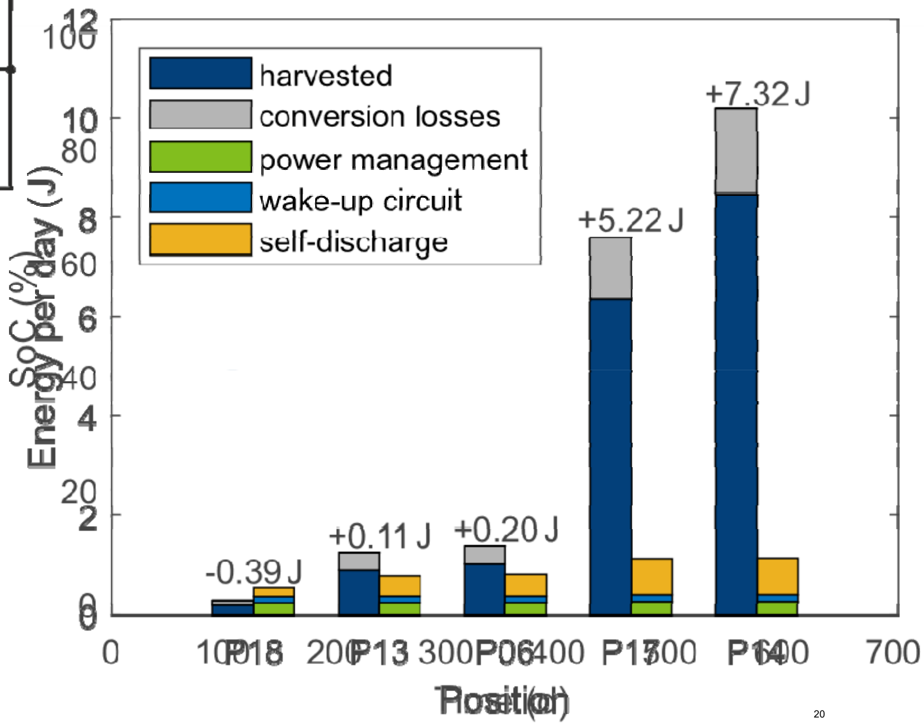
Self-sustainable Asset Tracking - Long-time Energy Neutrality



RMSE: **6.3 µW**

R^2: **0.988**

E_{err}: **1.18 %**



[5]

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Self-sustainable Asset Tracking - results

- With event-driven sensing and a heterogeneous Intelligent and energy **efficient** architecture, we could address very distant design goals of high accuracy, long-range, and energy autonomy.
- We demonstrated the effectiveness of the model-based design approach to gain non-trivial insights into longtime behavior.

Localization per Day:	Quiescent Current:	Multiroom Localization Accuracy:	Classification Accuracy:
up to 700	**1.26µA**	**0.4m (2D)**	**85.3% (38C)**

Conclusions

- **EH is becoming attractive for Intelligent IoT**
- **TinyML can boost the success of always-on IoT**
- **A system overview is necessary**
- **Event-based sensing and low power design can increase the energy efficiency.**
- **Use-case UWB self-sustaining patch**

Q & A

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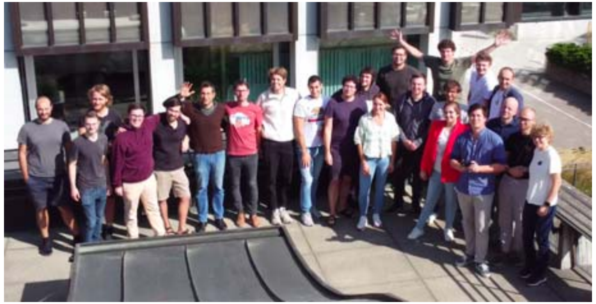

Thanks very much for your time and attention!

Questions/comments???

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