ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IIEE
Department of Information Technology and Electrical Engineering

Toward Zero-Power Smart Sensing in the IoT Era

Michele Magno*°

° ETH Zurich, Switzerland,

*DEI, University of Bologna, Italy,

***ARM RESEARCH SUMMIT 2018.* September 17-19, 2018 at Robinson College in Cambridge, UK**

Credits: Luca Benini, Philipp Mayer, Raphael Strebel

Wearable and Sensing Devices

- Wearable devices are getting momentum
  - Sensors are common on a great number of wearables

Activity Trackers

Smartwatches

Smart eyewear

Smart footwear

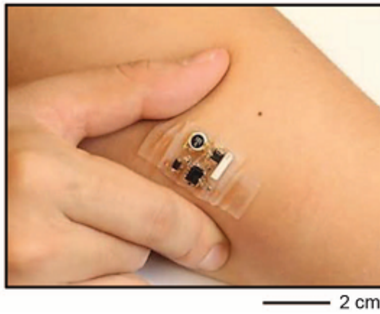
Smart clothing

Skin patch sensors

Motion capture clothing

Pressure sensor clothing

Healthcare

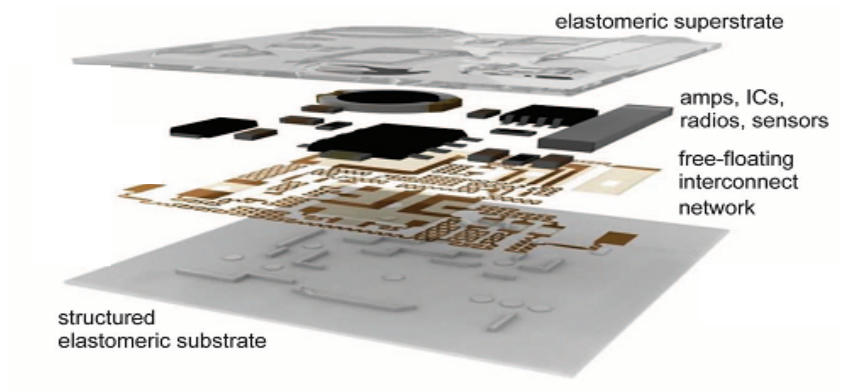


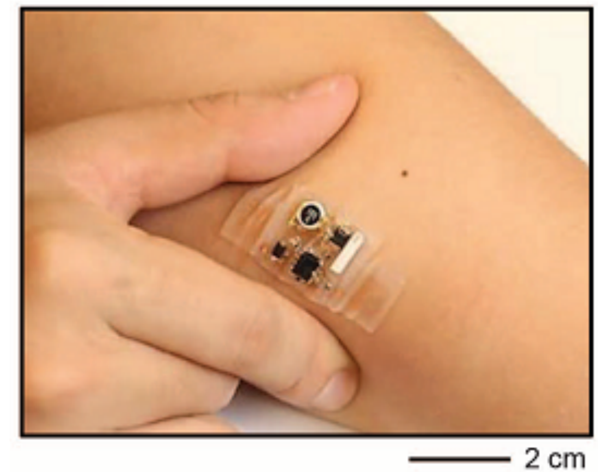
Smart Patches

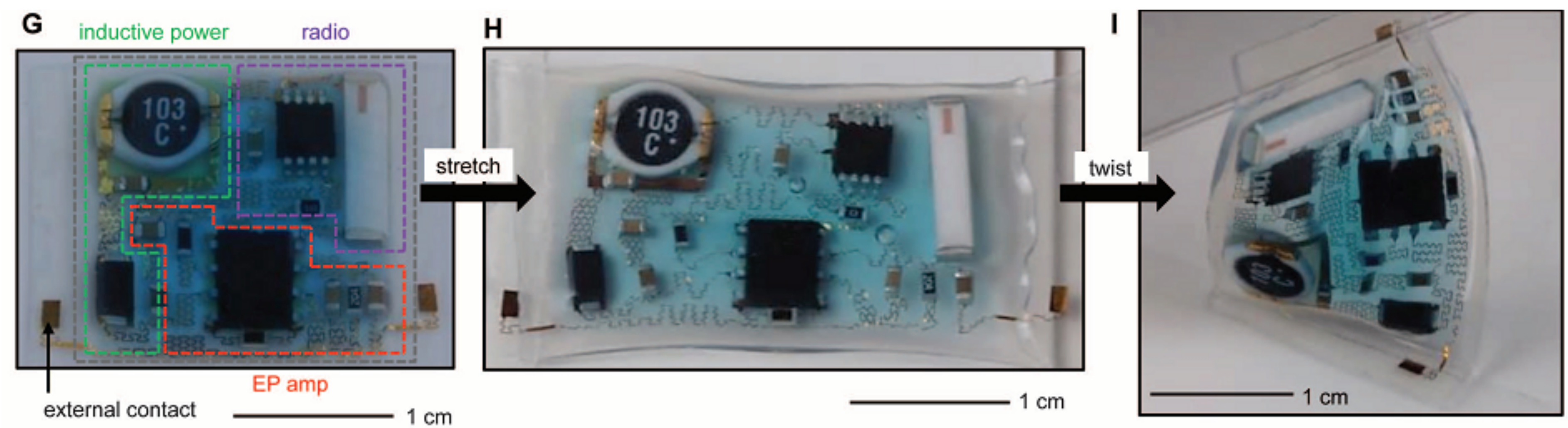
Trends → Flexible
Stretchable
LongTerm
Zero-power

Soft-Hard integration

Integration of thin high performance and commercial components with flexible technology to achieve long and continuous monitoring of physiological parameters



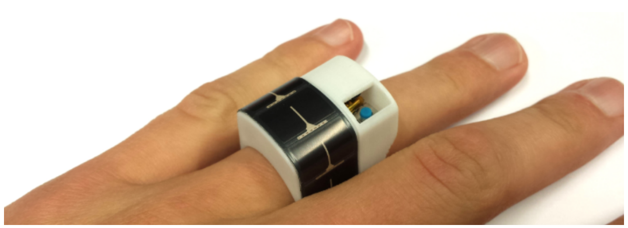


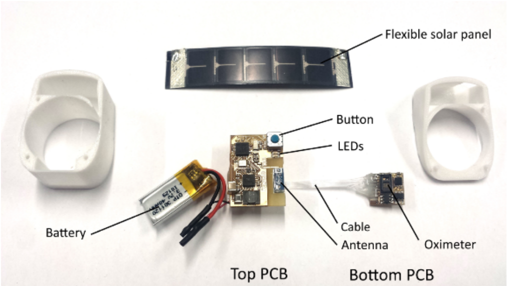


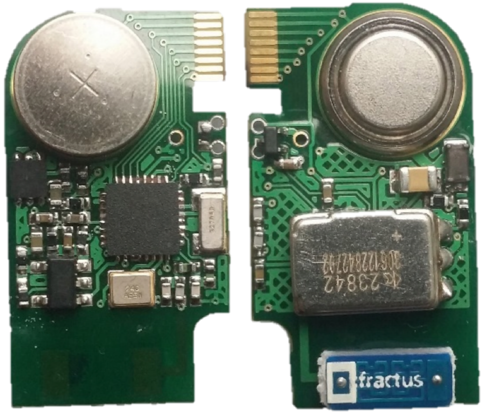
Xu, Sheng, Yihui Zhang, Lin Jia, Kyle E. Mathewson, Kyung-In Jang, Jeonghyun Kim, Haoran Fu et al. "Soft microfluidic assemblies of sensors, circuits, and radios for the skin." *Science* 344, no. 6179 (2014): 70-74.

IoT Devices/Sensors' Batteries

- Battery dominates devices size limiting **Lifetime** and **Intelligence** of IoT Devices
- Limited Energy Limits Computational resources
  - Very few examples of Long Lasting & smart devices
- Battery charging discourages the use of smart sensors in many IoT applications
  - Inaccessible places
  - Long-term monitoring
  - Wearables







Toward self sustainable IoT

1.) Low power system design

smart devices
for perpetual operation

3.) Intelligence

2.) Energy harvesting

4.) Energy Efficient Communication

Energy Harvesting

Energy Harvesting

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

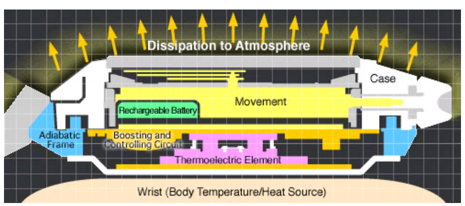
This term often refers to small autonomous devices – micro energy harvesting

All Energy is around

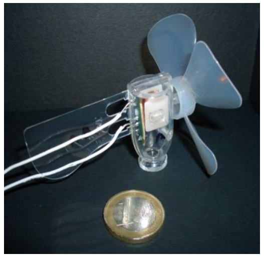
Heat

Motion and vibration

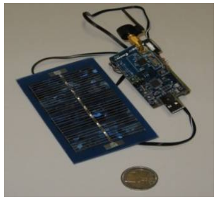
Light



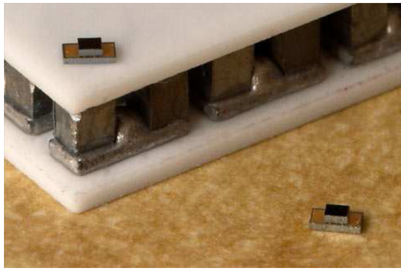
Thermal



Airflow



Photovoltaic



Electromagnetic

•*A Survey of Multi-Source Energy Harvesting Systems*, Alex Weddell, Michele Magno, Davide Brunelli, Geoff Merrett, Bashir Al-Hashimi and Luca Benini, in: DATE 2013, 2013

Which source from small IoT?

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

Self-Sustaining Smart Audio Detector

1.) Low power system design

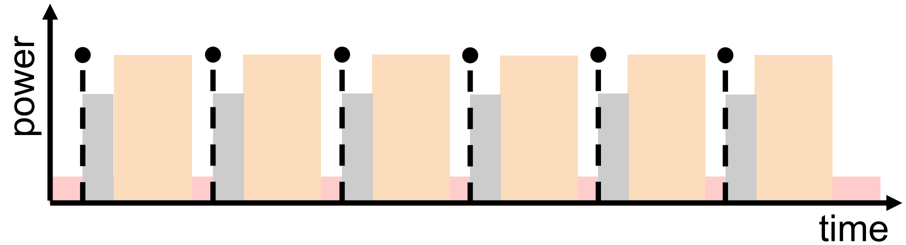
3.) Smart sensing

2.) Energy harvesting

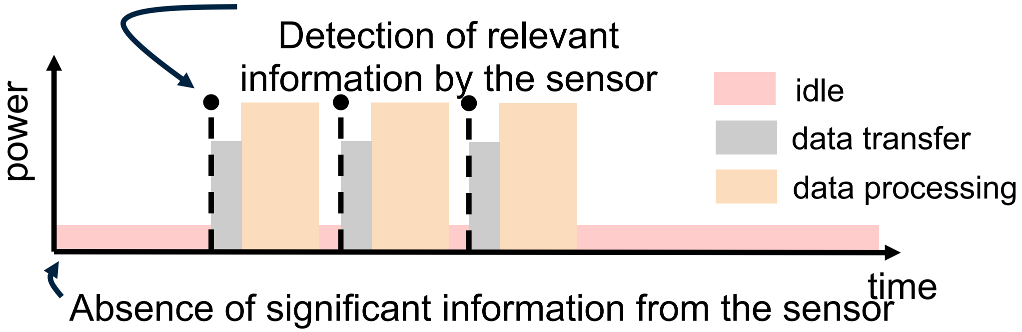
µW smart audio detector for perpetual operation

Event-Driven Sensing

Traditional Polling model

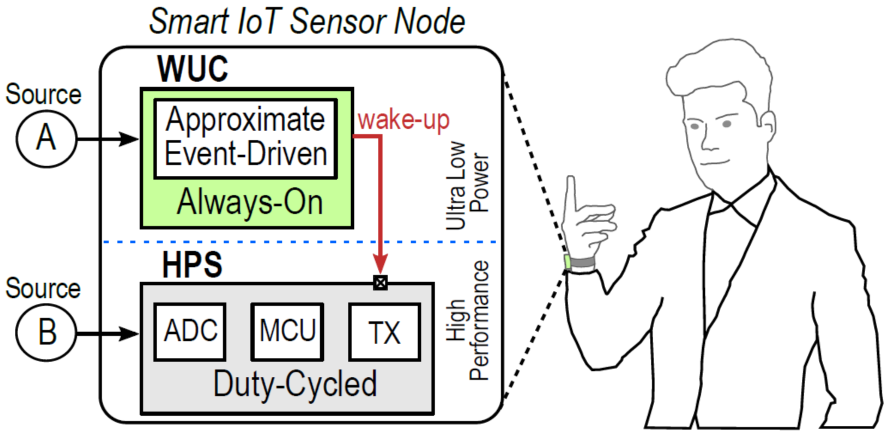


Event-Driven model



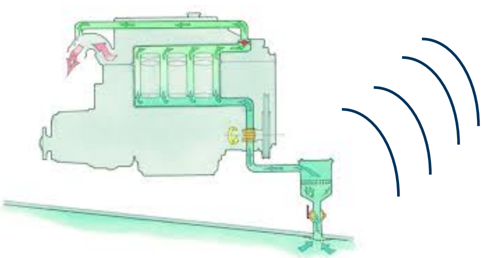
- Very low constant power
- Asynchronous events
- Lower Latency

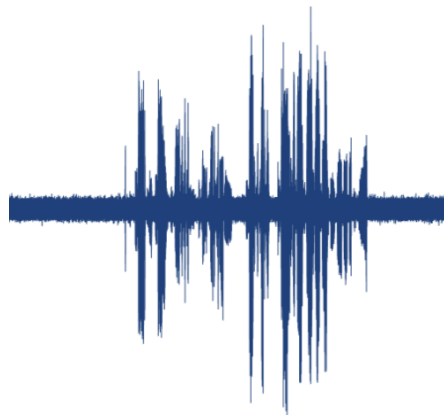
- Always-on electronics
- Suitable for long-term /rare events

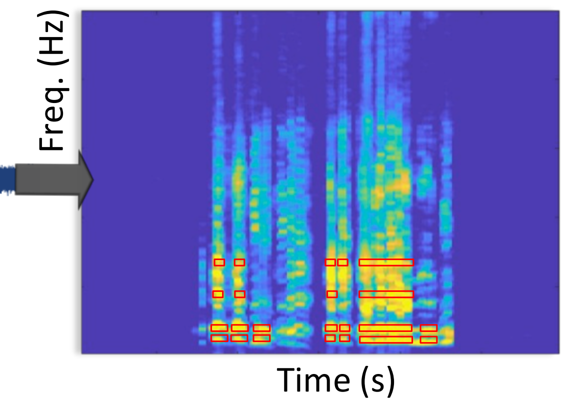


Always on Audio Features extraction

Diesel Marine engine noise



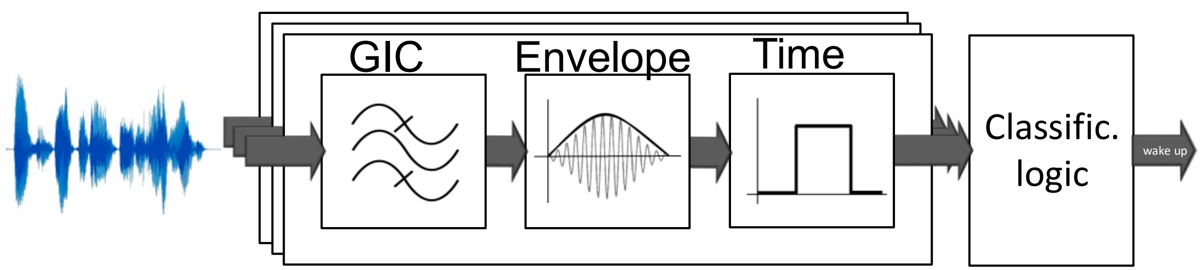




1.) Bandpass filter

2.) Envelope detector

3.) Comparator



Widely used approach with parallel filter banks.

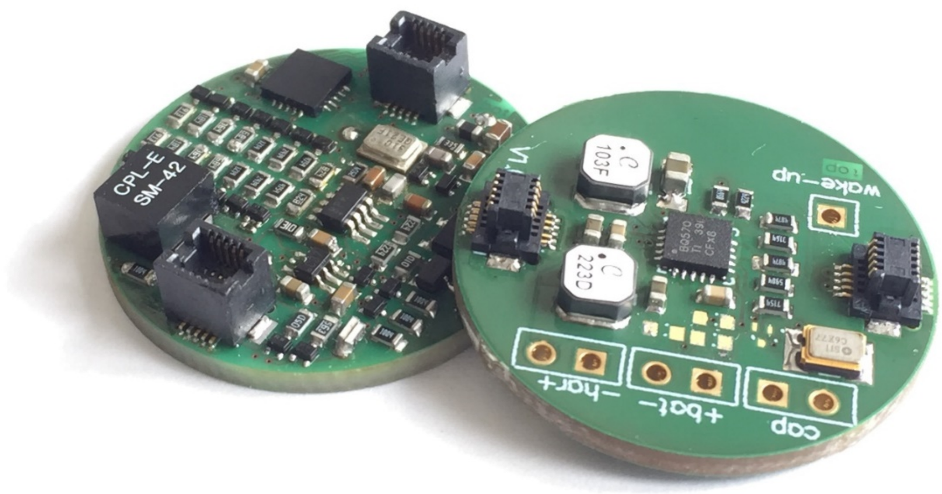
Experimental results.

- **Sensitivity:**
  59 dB SPL @ 1kHz (i.e. Conversation at 2m)
- **128 programmable frequencies:**
  200 Hz – 3.35 kHz in 25 Hz steps

5

- **Adaptive gain:**
  3.3, 5, 10
- **Interfaces:**
  I2C, UART, GPIO
- **Dimension:**
  26 x 26 mm

ALWAYS ON WITH 62µW



Submarine

	sub. present	no sub.
detected	100 (TP)	0 (FP)
not detected	0 (FN)	100 (TN)

mean time until wake-up: 2.23 s

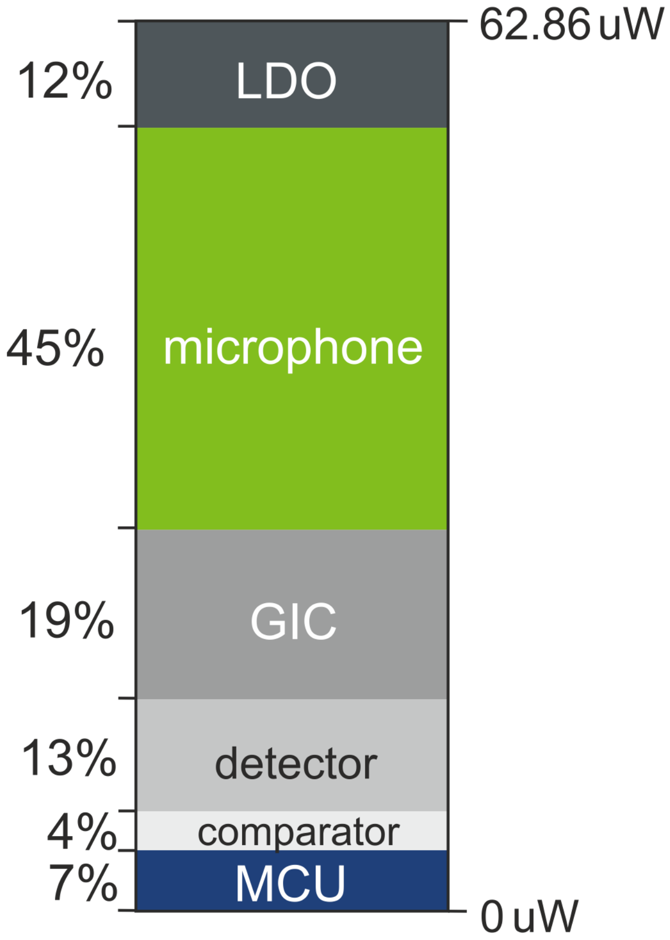
Crying baby

	baby crying	no crying
detected	100 (TP)	0 (FP)
not detected	0 (FN)	100 (TN)

mean time until wake-up: 14.67 s

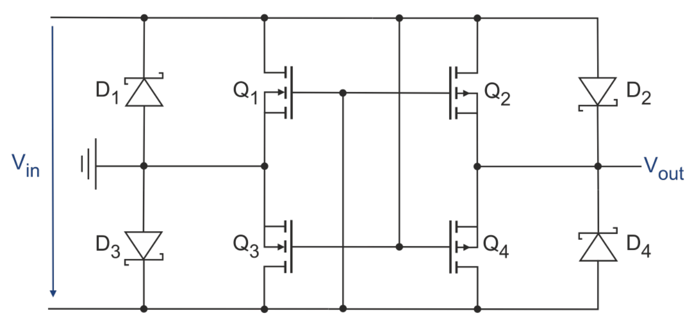
Power consumption

0.9 V supply	LT3009	7.60 µW
Microphone	ICS-40310	28.37 µW
GIC filter	OPA2379	11.97 µW
Detector	OPA379	7.88 µW
Comparator	LPV7215	2.74 µW
Microcontroller active	PIC12LF1509	4.30 µW
Microcontroller idle	PIC12LF1509	0.04 µW
Detection multiple freq.		**62.86 µW**
Detection single freq. (idle)		**58.59 µW**



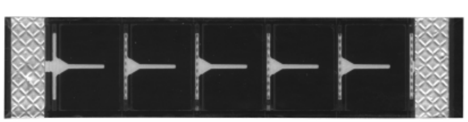
Energy Harvesting

- Thermoelectric (heat)
- Piezoelectric (vibration)
- Photovoltaics (light)
- Microbial Fuel Cell

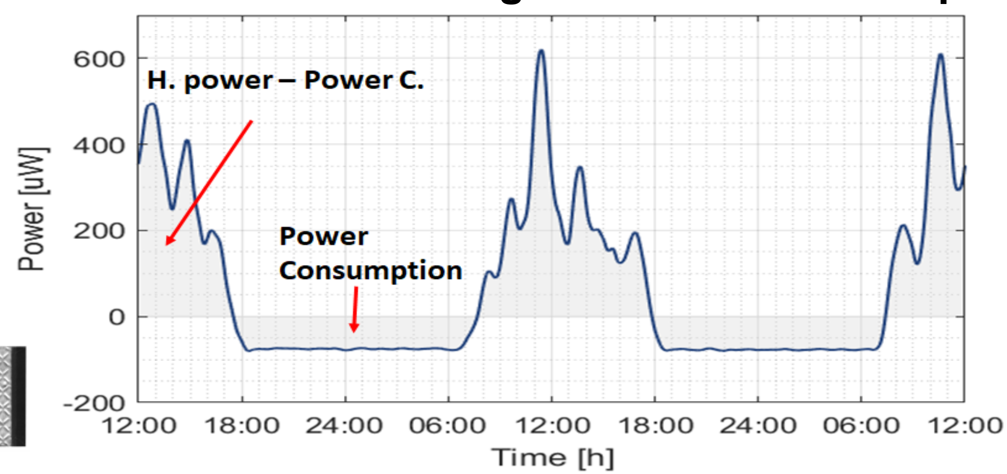


NVC rectifier For AC sources

Flexible: Thin-Film



Tested with indoor light and flexible solar panel



Zero-Power Touch Receiver for Communication and sensing

Short-Range Communication

Using Body as Medium

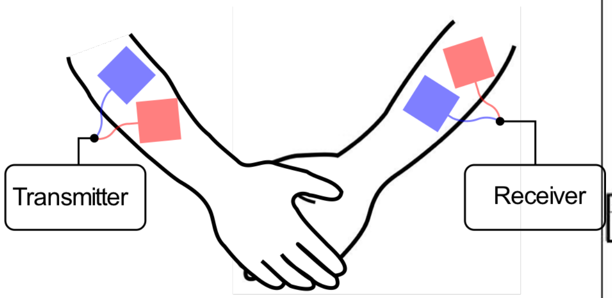
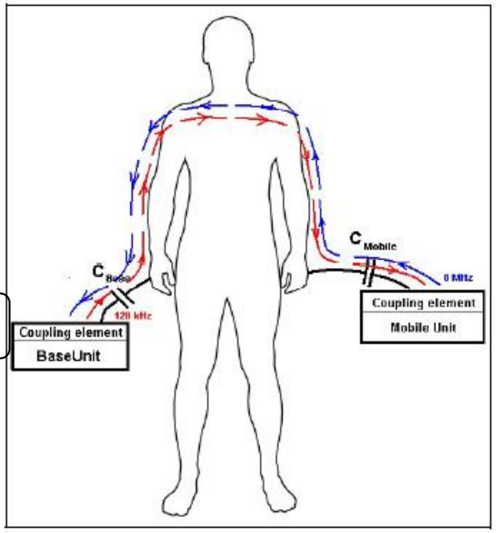
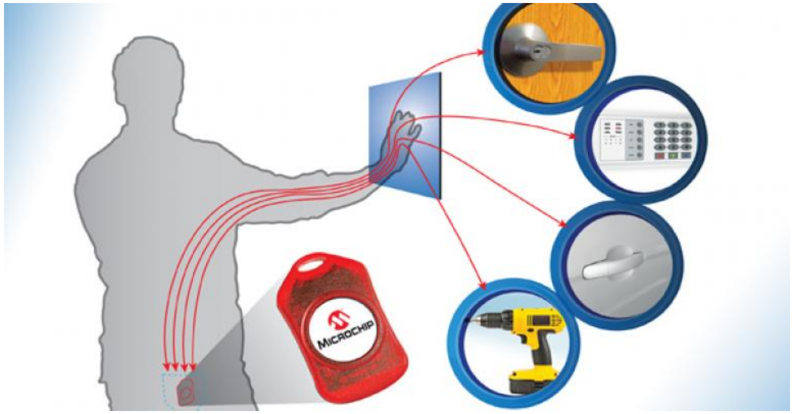


FIGURE 1: BODYCOM SYSTEM WORKING PRINCIPLE



- ZigBee-Bluetooth , 10-100m, 10-100mW, 10Kbps-5Mb
- Wi-Fi. Medium Range, 100mW-few W , 20-100Mbps
- **Near field achieves passive receivers (NFC /RFID)**



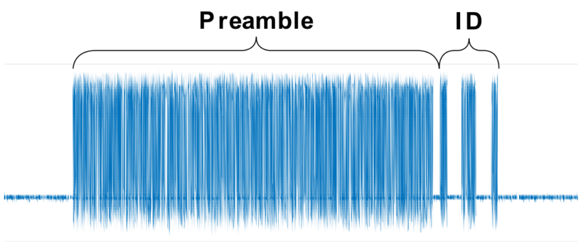
MICROCHIP

Source: Microchip

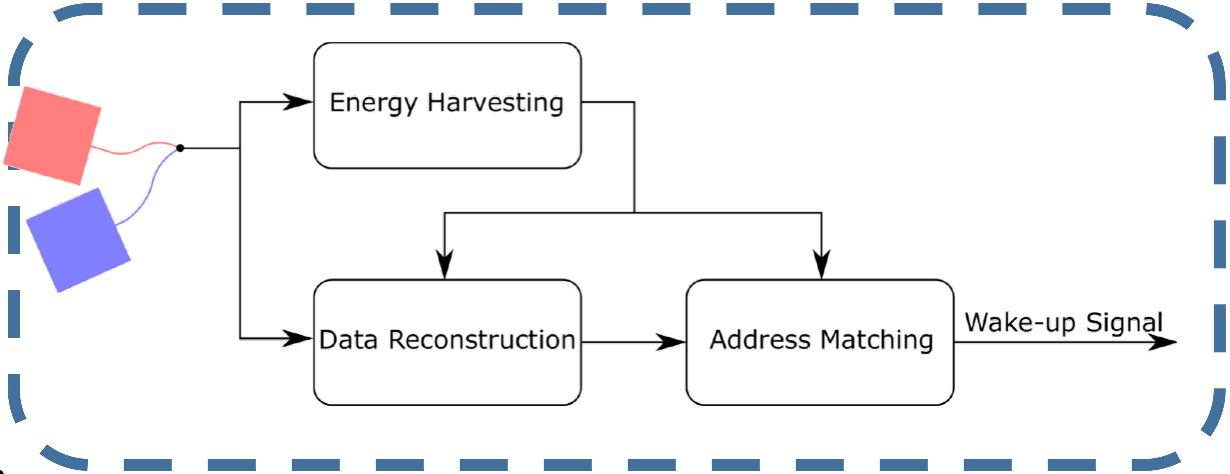
Zero-Power Receiver for Touch communication and sensing

Features:
- **Battery-Free Receiver**
- Always-on Touch Switch
- Data Parsing
- Addressing
- MCU battery less
  - **Security**
- Wake up External Logic
- Intra-Body Extra-Body

ETH Patent Pending

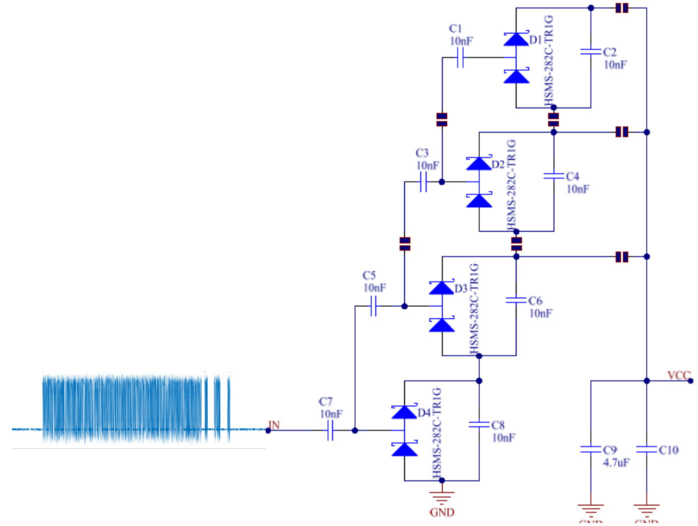


8 MHz carrier
FSK; On-off keying
Example of OOK consisting of:
    Preamble
    8-16 bits Data/ID @ 1 kbit/s

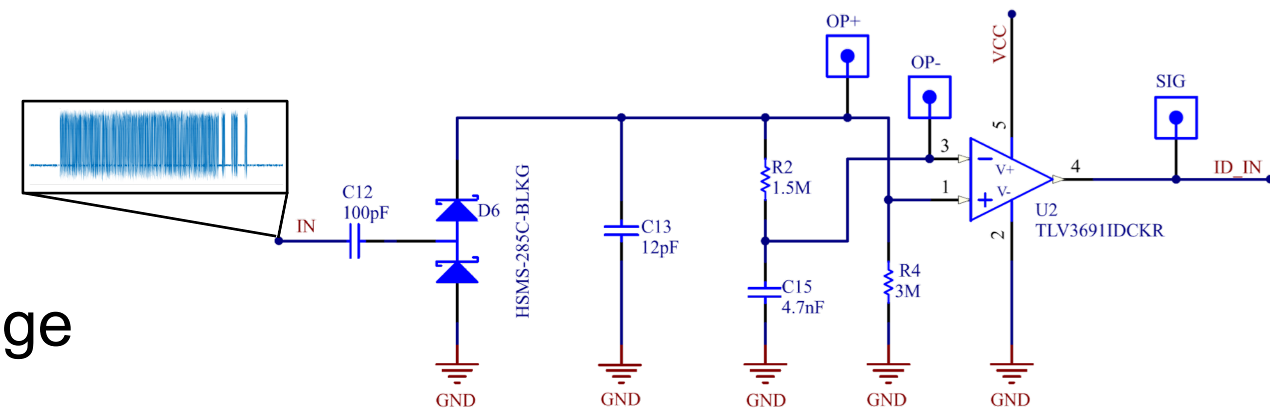


Hardware – EH & Data Reconstruction

- Small capacitor
- Can cold start.
- Villard voltage doubler
  - Low leakage diodes
  - Selectable number of stages

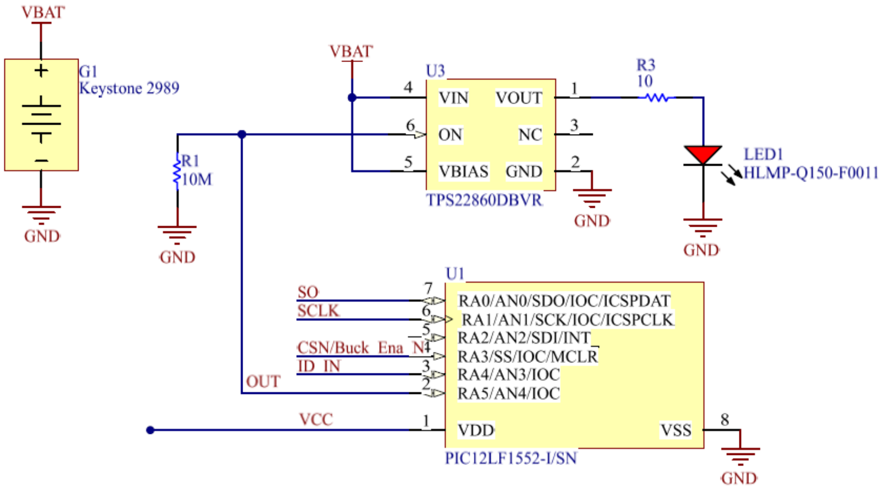


- Low $V_{forward}$ diodes
- Ultra low power comparator (75 nA)
- Low pass filter voltage as reference

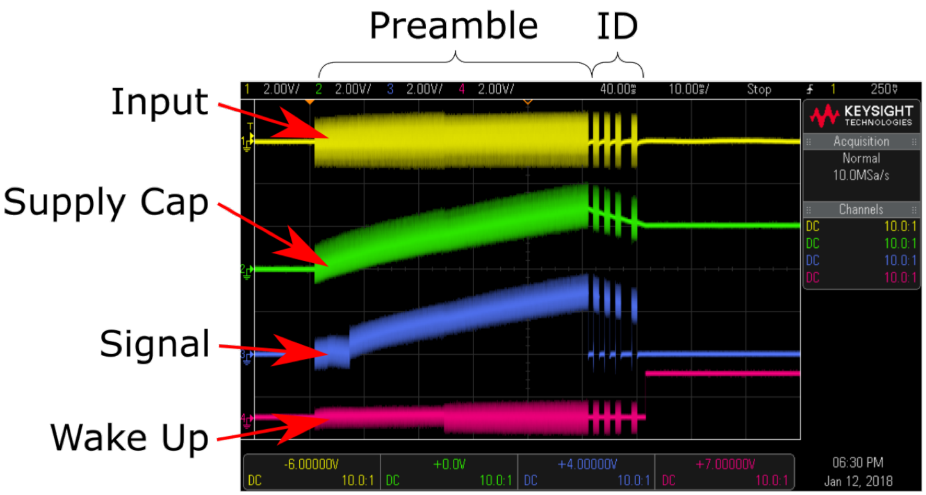


Hardware – Address Matching / Security Algorithms

- Low power microcontroller
  - PIC12LF1552
  - 20 nA sleep
  - 270 μA @ 2 MHz
- Low power switch
  - 2 nA leakage
  - switches LED for demonstration



Experimental Results - Table



Zero Power Touch Receiver

Data Rate: 1 kbit/s

Wake Up time : 20 ms

Data Packet: tested up 128bytes with 200ms preamble (50% bits ‘0’ and bit ‘1’).

Distance: 170cm

Very Low Transmission Energy: 1.1356uJ per bit, Energy neutral with small size solar cell or kinetic EH

Whole System Power consumption: Zero Power in sleep mode.

Security algorithms can be implemented the on-board microcontroller

Round Electrodes 16 cm^2

Transmission Voltage	Distance	Max. Voltage	Total Energy	Average Energy Transmission	ID Received
3.0 V	0 cm	4.49 V	48.9 μJ	246 nJ/ms	Yes
	5 cm	2.57 V	18.1 μJ	69.1 nJ/ms	Yes
	10 cm	1.66 V	8.0 μJ	38.9 nJ/ms	No
	15 cm	1.61 V	7.0 μJ	28.0 nJ/ms	No
	20 cm	1.61 V	6.9 μJ	25.5 nJ/ms	No
	25 cm	1.41 V	6.1 μJ	22.9 nJ/ms	No
5.5 V	0 cm	8.16 V	164 μJ	1617 nJ/ms	Yes
	5 cm	8.01 V	152 μJ	868 nJ/ms	Yes
	10 cm	7.54 V	138 μJ	720 nJ/ms	Yes
	15 cm	6.88 V	118 μJ	603 nJ/ms	Yes
	20 cm	7.06 V	120 μJ	591 nJ/ms	Yes
	25 cm	6.21 V	102 μJ	466 nJ/ms	Yes
	170 cm	2.53 V	15.1 μJ	62.3 nJ/ms	Yes

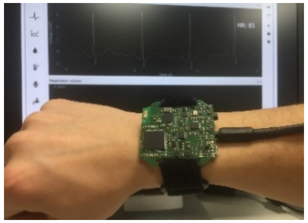
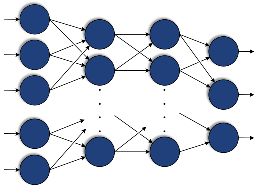
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IEE
Department of Information Technology
and Electrical Engineering

Conclusions

- Importance of low power in battery operated devices
- Achieving self-sustainable devices is possible also in challenging applications
  - Low power design
  - Energy harvesting
  - Intelligence on board
  - Low power communication
- Two different devices ready for flexible electronics
  - Zero Power Touch
  - Smart Audio
- **Open-Source Fast Artificial Neural Network Library for ARM-Cortex-M Family! --→ Visit the Poster Session**

Open-Source Provided by ETH Zurich
https://github.com/lukasc-ch/FANN-on-ARM

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Department of Information Technology
and Electrical Engineering

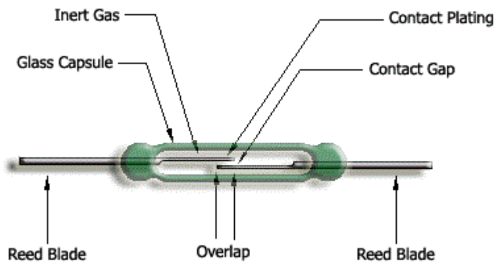
Thank you!

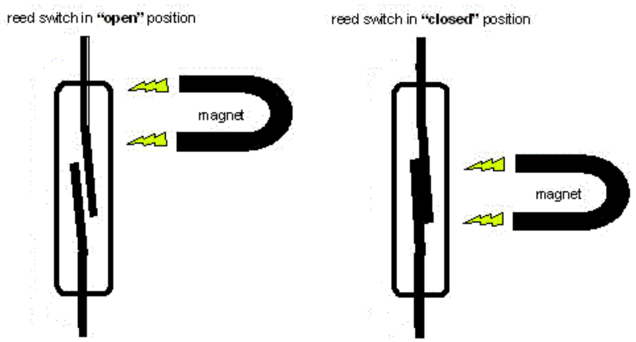
Michele.magno@iis.ee.ethz.ch

- Jokic, Petar, and Michele Magno. "Powering smart wearable systems with flexible solar energy harvesting." In *Circuits and Systems (ISCAS), 2017 IEEE International Symposium on*, pp. 1-4. IEEE, 2017.
- Strebel, R. and Magno, M., 2018, April. Zero-power receiver for touch communication and touch sensing. In *Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks* (pp. 150-151). IEEE Press.
- Mayer, P., Magno, M., & Benini, L. (2018, March). Combining microbial fuel cell and ultra-low power event-driven audio detector for zero-power sensing in underwater monitoring. In *Sensors Applications Symposium (SAS), 2018 IEEE* (pp. 1-6). IEEE.

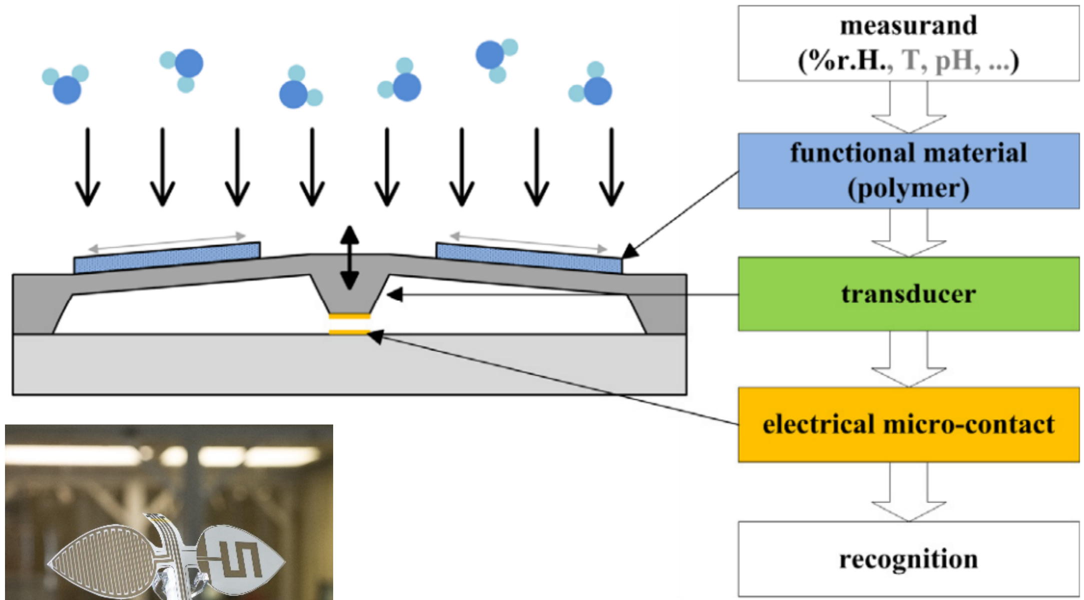
Zero-Power Sensing

Simple example sense and achieving zero power switches



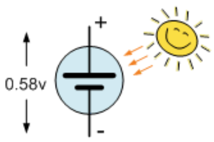


binary zero-power sensor - similar idea used in the magnetic switches

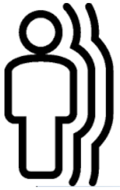


An inkjet-printed agricultural "origami leaf" wireless sensor fabricated with the unique inkjet printing capabilities of Georgia Tech

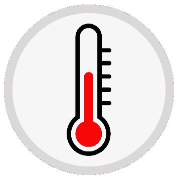
Source: http://phys.org/news/2013-10-unique-origami-shaped-antennas.html#jCp



Light sensor



Tilt/vibration Sensor



Temp. Sensor

RF - Sensor