IEEE

IEEE Future NETWORKS

IEEE Future Networks Webinar - 18 Jan 2023 - 11:00 am ET

Micro/Nano Systems and Technologies as Enablers of 6G, Super-IoT, and Future

Register today: **bit.ly/FNIWebinarJan2023**

Jacopo Iannacci,
Fondazione Bruno Kessler (FBK)

IEEE Future Networks Initiative – FutureNetworks.ieee.org

Collaboration

20+ IEEE societies

Content

technical newsletter, podcasts, videos, articles

Events

+ more!

Research & Education

+ eLearning, webinar series, white papers, tutorials

Jacopo Iannacci

Speaker bio -- Jacopo Iannacci (SM of the IEEE) received the MSc degree and the PhD in electronics engineering from the University of Bologna, Italy, in 2003 and 2007. He received the Habilitation as Full Professor in Electronics from the Italian Ministry of University and Research, in 2021.

He worked in 2005 and 2006 at the DIMES Technology Center (currently Else Kooi Lab) of the Technical University of Delft, the Netherlands. In 2016, he visited the Fraunhofer Institute for Reliability and Microintegration IZM in Berlin, Germany. Since 2007, he is researcher at Fondazione Bruno Kessler, in Trento, Italy.

His research interests fall in the modelling, design, packaging and characterization of MEMS and RF-MEMS devices for sensors and actuators, energy harvesting and telecommunication systems.

Rationale

- Building **a vision of 6G**, Super-IoT and Future Networks (FNs) **from the bottom-up perspective of low-complexity miniaturized hardware components**, identifying potential limitations in the classical top-down current approaches, yet complementing them

Outlook

01 A simplified outlook on 6G

02 The HW-SW divide and beyond

03 The WEAF Mnecosystem

04 Micro/Nano devices supporting the WEAF Mnecosystem

05 Future devices inspired by the WEAF Mnecosystem

Micro/Nano Technologies as Enablers of 6G/FNs

01

A Simplified Outlook on 6G

Introducing the Paradigm Shifts (PSs)

Disruptive Challenges of 6G

- Visions of future 6G are shaping **two founding challenges** that will require innovative approaches

- 6G will mark a **100-1000x increase of performance** compared to 5G

- 6G will massively capitalize on **Artificial Intelligence** (AI)

The Concept of Paradigm Shift (PS)

- Services and technologies reconducted to a limited set of macro-areas in which 6G will mark **Paradigm Shifts (PSs)**
- Four PSs are defined in **[a,b]** with reference to
  - **Services and operation – Scattered Intelligence (SI)**
  - **Infrastructure – Seamless Coverage (SC)**
  - **Frequency – Spectrum Diversity (SD)**
  - **Security – Enhanced Security (ES)**

Reference

[a] X. You, et al., "Towards 6G Wireless Communication Networks: Vision, Enabling Technologies, and New Paradigm Shifts," Science China Information Sciences, 2021. doi: 10.1007/s11432-020-2955-6

[b] J. Iannacci, H. Vincent Poor, "Review and Perspectives of Micro/Nano Technologies as Key-Enablers of 6G," IEEE Access,, 2022, doi: 10.1109/ACCESS.2022.3176348

Micro/Nano Technologies as Enablers of 6G/FNs

02

The HW-SW Divide and the Way Beyond it

The Pivots of Separation and Symmetry

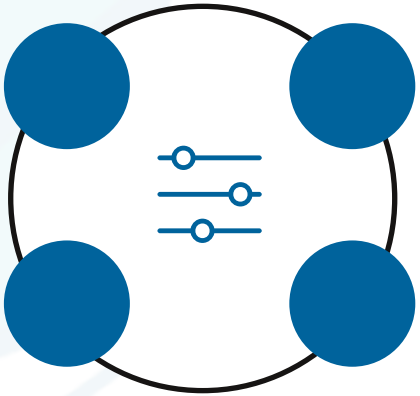
The Hardware-Software (HW-SW) Divide

neologism

The Hardware-Software (HW-SW) Divide is a neologism proposed in this work

founding characteristics

The HW-SW Divide identifies a few founding characteristics that differentiate the HW from the SW



physical materiality

Such features are linked to the materiality of the HW, opposed to immateriality of SW

unchanged attitude

The attitude towards the HW-SW Divide remained unchanged in the last 5-6 decades, from the market uptake of semiconductors, as from 1G to 5G

Beyond the HW-SW Divide

Transition from ***network softwarization*** (chased by 5G) to ***network intelligentization*** embraced by 6G through AI urges for a change of pace

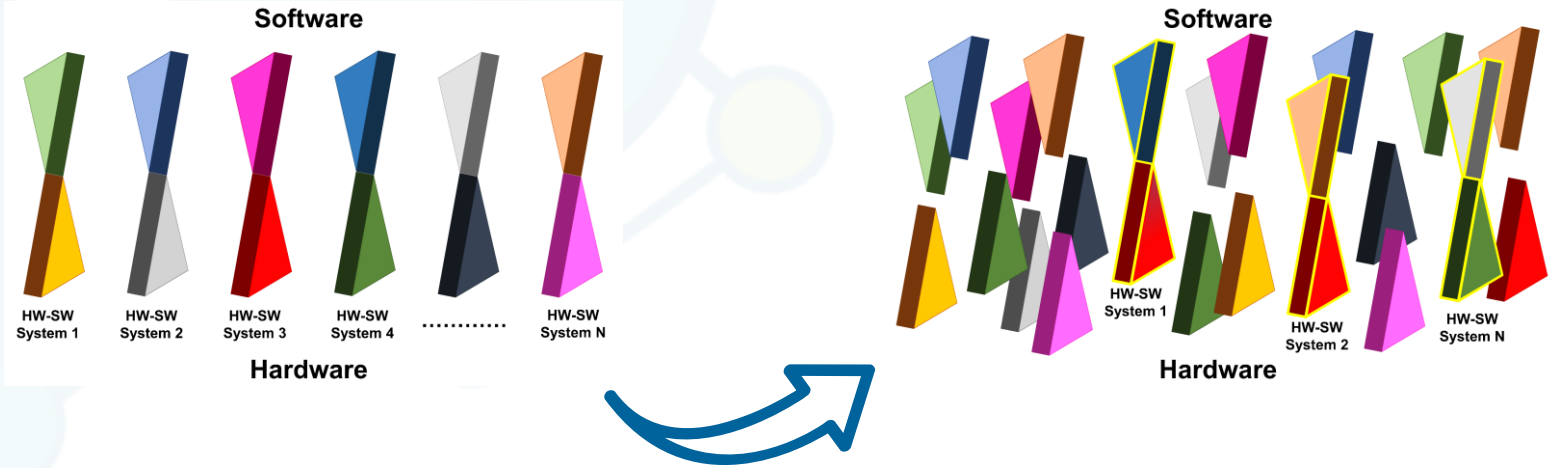
It is proposed that the concept of HW needs to be reformulated, along with the HW-SW relationship

Increasing trends should be triggered concerning

- **Separation** between HW and SW
- **Symmetry** between HW and SW

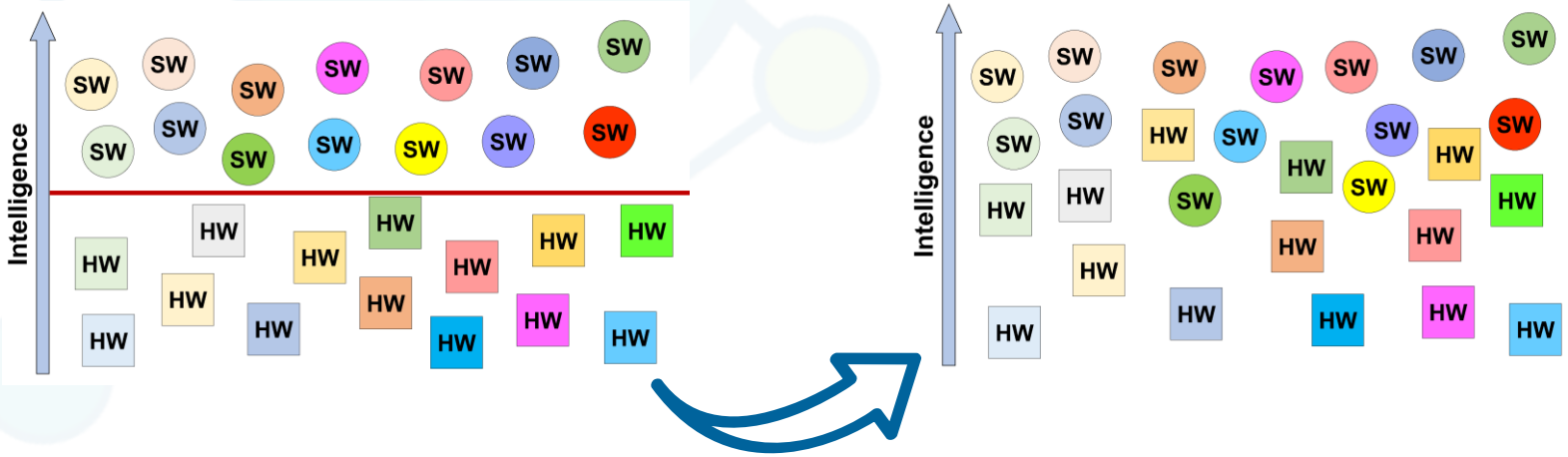
Increased Separation

- Increased separation contrasts with co-design approach and mutual optimization
- HW and SW modules could **interchange and dynamically combine**, realizing temporary functions, not necessarily defined ab-initio, i.e., evolution



Increased Symmetry

- Increased separation implies increased symmetry between HW and SW
- 6G will demand for **augmented abstraction (*intelligence*) of the HW**, weakening its currently tight constraints to the physical dimension
- Intelligence is intended as a set of HW resident features, i.e., not requiring for a (sub-)system



Supporting Literature

- The sketched scenario is a vision of what 6G could possibly be; yet it is not unliked from what discussed in literature
- Concerning RF transceivers, **[a]** reports that HW capabilities, like number of antennas, RF chains, the resolution and sampling rates of ADCs, etc., remained quasi-static in the jointly designed HW-SW systems, from 1G to current 5G
- Also relevantly, **[a]** states that: "*6G will not be operating under the conventional joint design, which fails in allowing agile adaptation to a diversified and upgradable hardware*."

Reference **[a]** K. B. Letaief, W. Chen, Y. Shi, J. Zhang, Y. A. Zhang, "The Roadmap to 6G: AI Empowered Wireless Networks," IEEE Commun. Mag., vol. 57, no. 8, pp. 84–90, Aug. 2019, 10.1109/MCOM.2019.1900271

Micro/Nano Technologies as Enablers of 6G/FNs

03

The WEAF Mnecosystem

Definition and Examples

Reformulation of the Concept of Hardware

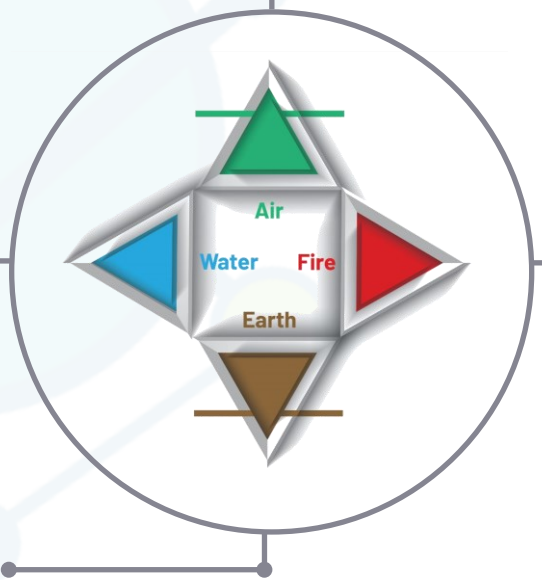
DEFINE

reformulation of the concept of HW is proposed through the WEAF Mnecosystem, i.e., the Water, Earth, Air and Fire Micro/Nanotechnologies Ecosystem

BUILD

building an analogy with the four classical elements in nature, and focusing on low-complexity miniaturized (MEMS/NEMS) HW devices, like sensors, actuators and transducers

The WEAF Mnecosystem (At a Glance)



Air (A)

Classical concept of SW

Water (W)

Novel concept of HW for
Micro/Nano sensors and devices

Fire (F)

Novel concept of HW for
Micro/Nano energy devices

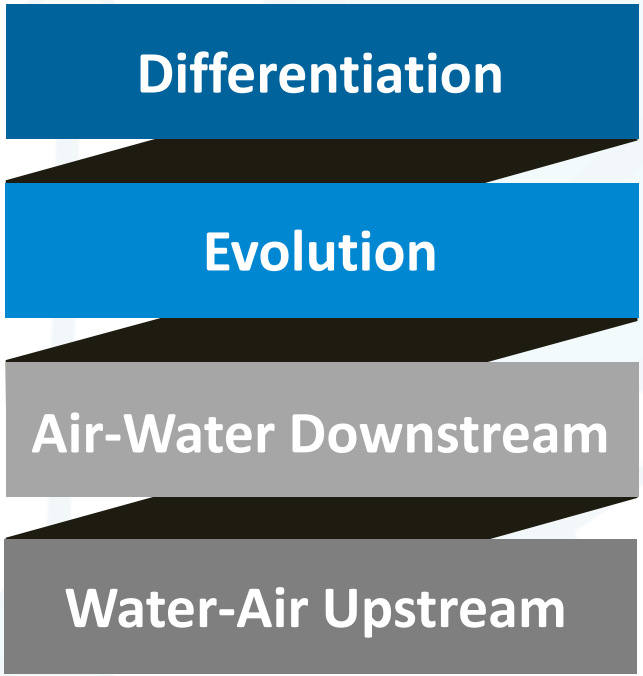
Earth (E)

Classical concept of HW
(in the Micro/Nanotechnologies domain)

Earth and Air – Outlook

- In the WEAF Mnecosystem, **Earth and Air are the standard concepts of HW and SW**, respectively
- Earth groups current Micro/Nano standard technologies, which are key-enablers nurturing novel Water/Fire compliant devices and solutions
- Air is a pivotal reference as novel Water/Fire HW solutions aim at implementing and incorporating features typical of the SW

Water – Pivotal Concepts



A unique piece of HW modifies the implemented function, as well as water (being liquid) change shapes

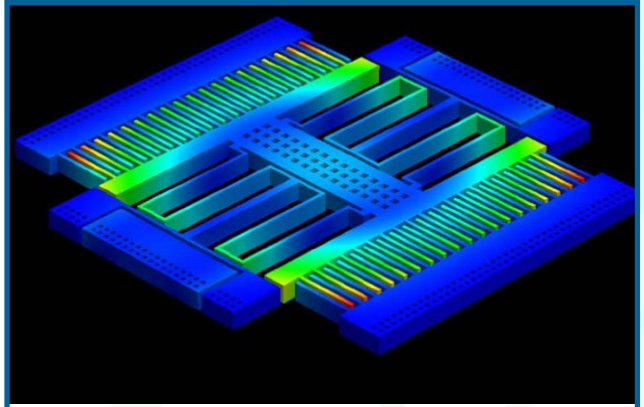
Capacity of pieces of HW of evolving in physical terms, realizing unprecedented functionalities

Full HW implementation of low-complexity SW algorithms and routines, as well as air condenses into water

Extension of the capabilities of a unique piece of HW embodying simple functionalities typically ensured by a dedicated SW algorithm, as well as water evaporates in air

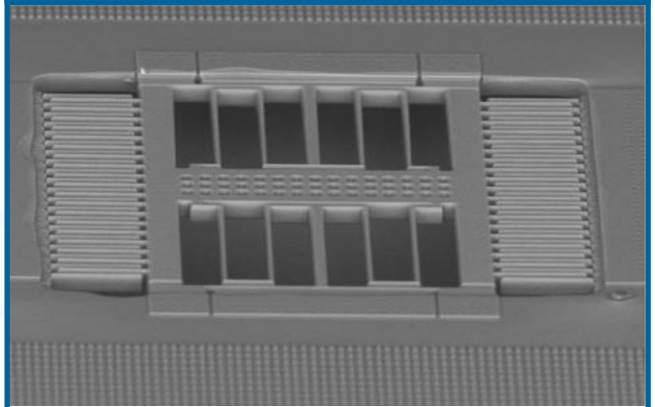
Water – Differentiation

Concept Recap



Unique HW device realizing orthogonal sensing/transducing functionalities

Practical Example

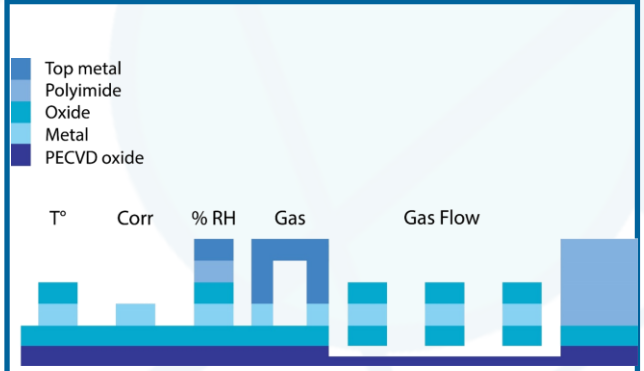


Unique MEMS resonator used as temperature and pressure sensors, as well as inertial sensor (accelerometer)

Reference F. Y. Kuo et al., "Monolithic Multi-Sensor Design With Resonator-Based MEMS Structures," IEEE Jour. of the Electron Dev., 2017, doi: 10.1109/JEDS.2017.2666821

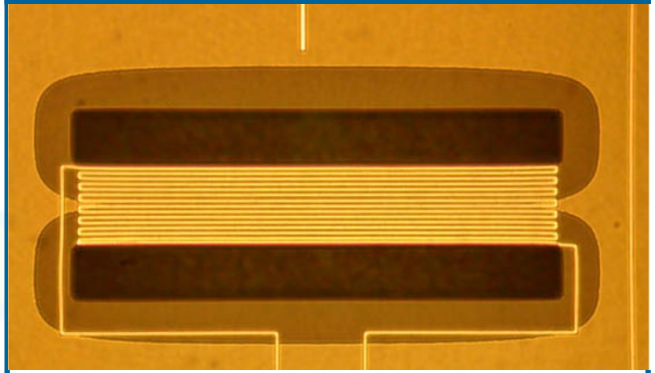
Water – Evolution

Concept Recap



Redundant inexpensive HW devices realizing sensing/transducing functionalities not known ab-initio

Practical Example

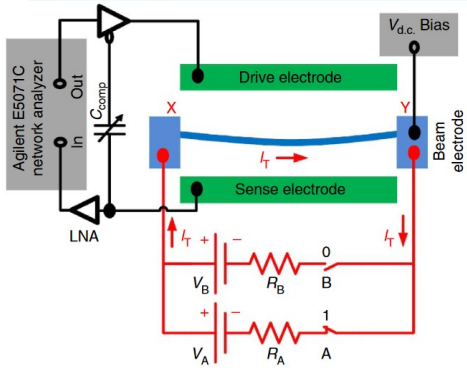


Humidity, temperature, corrosion, gas and gas flow velocity sensors, monolithically integrated in a 3 x 3 mm^2 chip

Reference | M. Hautefeuille et al., "Miniaturised multi-MEMS sensor development," Microelectron. Reliab., 2009, doi: 10.1016/j.microrel.2009.02.017

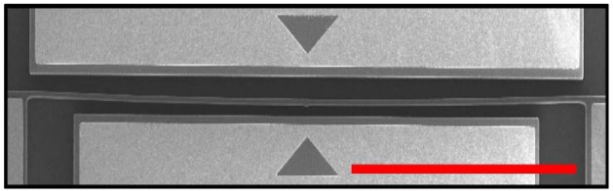
Air-Water Downstream – HW-SW Condensation

Concept Recap



HW implementation of typical low-complexity SW algorithms and routines

Practical Example

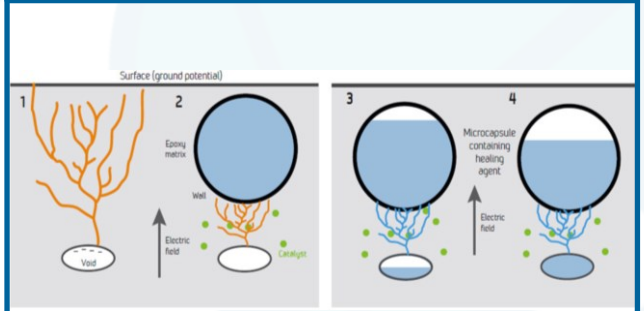


Basic logic gate (AND) with a MEMS resonating bar subjected to thermal expansion due to variable electric current driven through it

Reference | M. A. A. Hafiz et al., "Microelectromechanical reprogrammable logic device," Nat. Commun., 2016, doi: 10.1038/ncomms11137

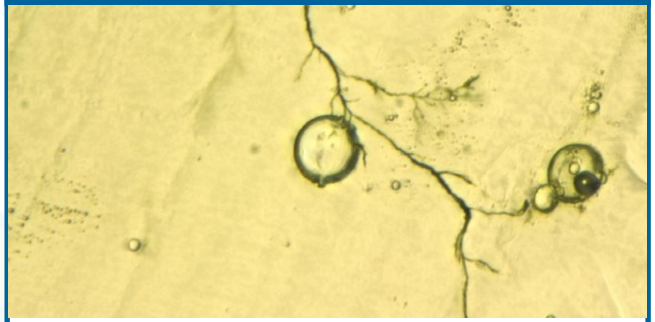
Water-Air Upstream – HW-SW Evaporation

Concept Recap



HW device embodying in its physical behavior features typically implemented by SW control routines

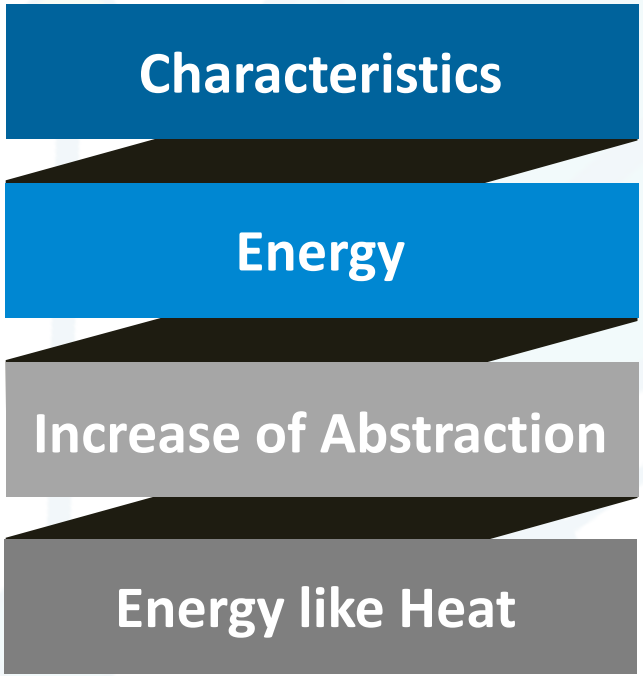
Practical Example



Self-healing materials able to recover from cracking and treeing due to high electrostatic stress

Reference | C. Lesaint et al., "Self-healing high voltage electrical insulation materials," Proc. IEEE Electr. Insul. Conf., 2014, doi: 10.1109/EIC.2014.6869384

Fire – Pivotal Concepts



Fire HW borrows the main ideas of liquidity, ubiquity and functional evolution typical of Water

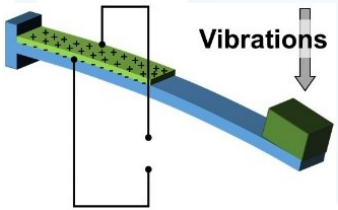
Differently from Water, Fire focuses exclusively on the concept of energy

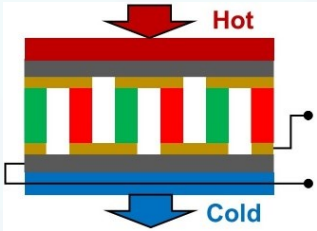
Fire HW aims at increasing the abstraction of energy available for powering functionalities at the network edge

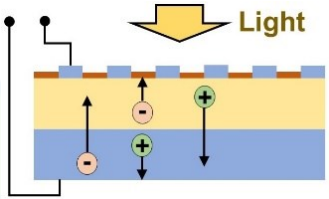
Energy must unlink from the concept of HW (batteries or harvesters delivering it), becoming like heat that flows through bodies

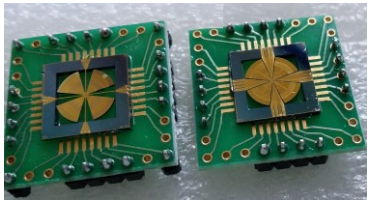
Fire – Making Energy Flow as Heat

Practical Example









Miniaturized (MEMS-based) Energy Harvesting (EH) devices to convert environmental energy (from vibrations, heat, light) into electricity

Reference J. Iannacci, "Microsystem based Energy Harvesting (EH-MEMS): Powering pervasivity of the Internet of Things (IoT) – A review with focus on mechanical vibrations," Jour. of King Saud Uni. - Science, 2019, doi: 10.1016/j.jksus.2017.05.019

Micro/Nano Technologies as Enablers of 6G/FNs

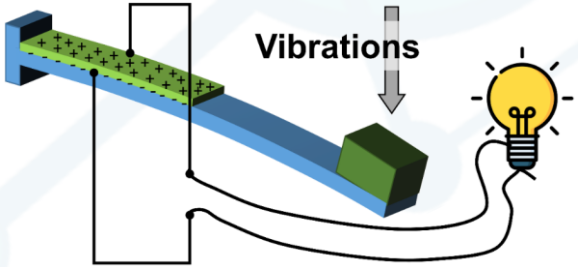
04

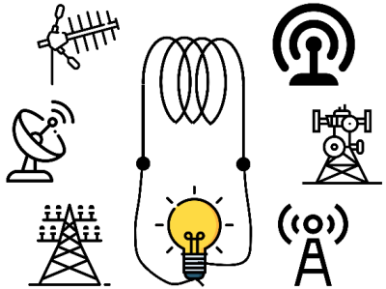
Micro/Nano Technology Devices

Supporting the WEAF Mnecosystem

Water-Air and Fire – A few Examples

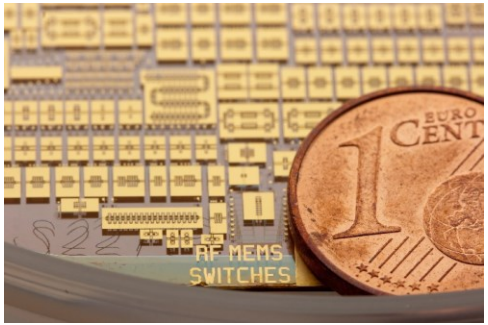
- Materials and devices with self-healing properties **[Water-Air upstream]**
- Monolithic orthogonally multi-functional devices **[Water]**
- Logic circuits and memories based on MEMS/NEMS **[Air-Water downstream]**
- Multi-source Energy Harvesting (EH) converters and platforms **[Fire]**

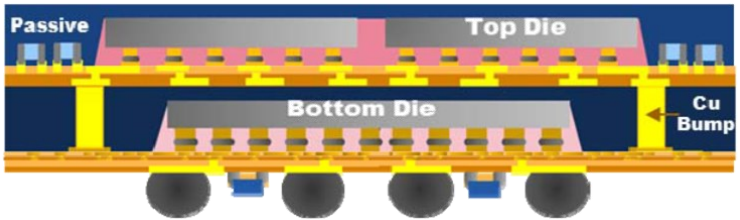




Earth Technologies – A few Examples

- MEMS-based Radio Frequency passives (RF-MEMS)
- Metasurfaces and metamaterials
- Flexible electronics
- Heterostructure-based semiconductors
- Device fusion through packaging and integration
- Additive Manufacturing (AM)
- Photonic devices
- Quantum Technologies (QTs)





Micro/Nano Technologies as Enablers of 6G/FNs

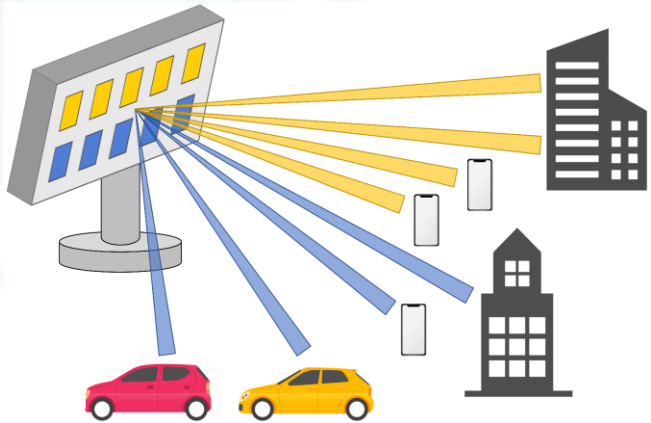
05

Future Micro/Nano Solutions

Inspired by the WEAF Mnecosystem

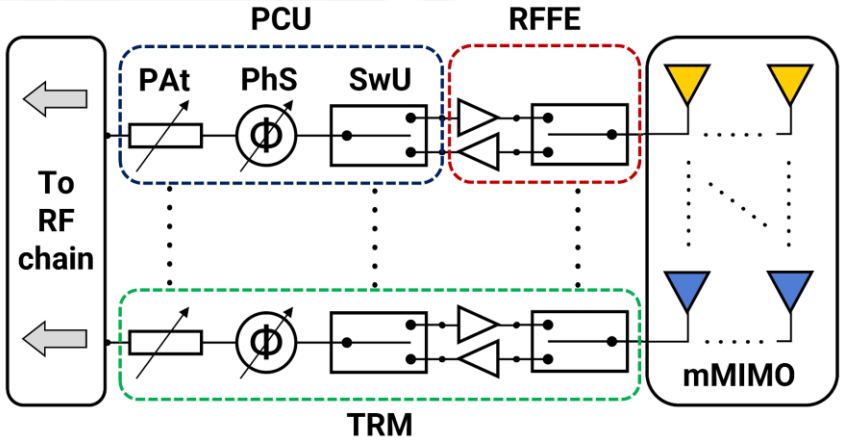
mMIMO – Context

- 6G will further leverage **mMIMO for advanced beamforming** of small-/pico-cells
- Realization of high-order compact antenna arrays is evolving
- mMIMOs need **complex and redundant HW**, both in Tx/Rx mode



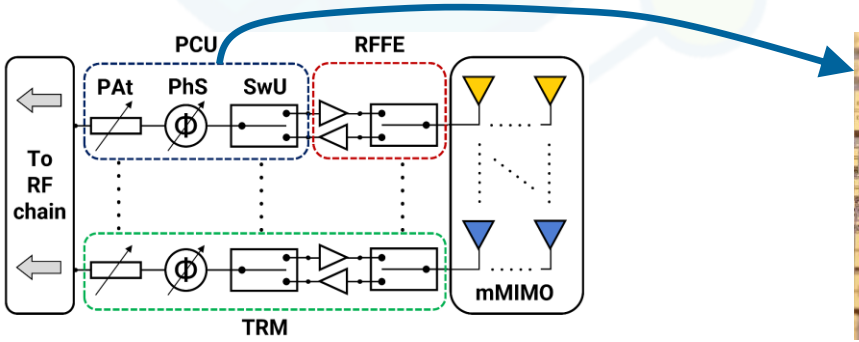
mMIMO – Technical Challenges

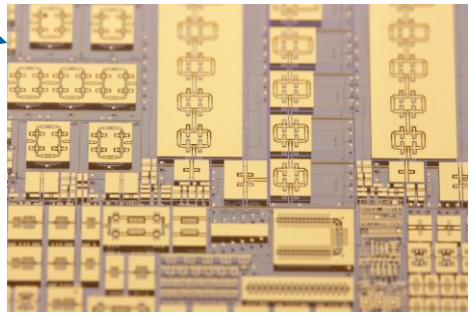
- TRM (Tx/Rx Module) is **physically duplicated** per each of the antenna elements (64 x 64 and more)
- Frequency operation as high as **sub-THz (100-300 GHz)**, will make the realization and integration of TRM building blocks challenging



mMIMO – Possible Solutions

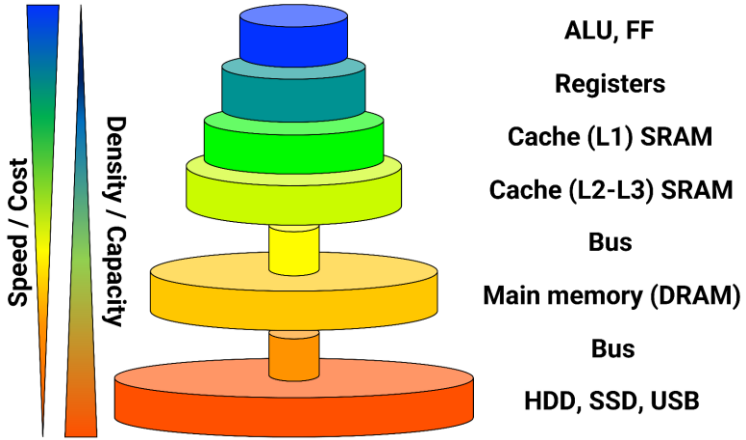
- The Passive Control Unit (PCU) comprises a variable Power Attenuator (**PAt**) and Phase Shifter (**PhS**), and a Switching Unit (**SwU**)
- RF-MEMS technology (Earth) already demonstrated for PAts, PhSs and SwUs
- **Monolithic PCUs** are possible, elevating RF-MEMS to Water HW solutions





Computing In-Memory (CIM) – Context/Challenges

- **Huge demands** ahead in terms of computation and memory **at the edge**
- Current **centralization** of network intelligence is **not the best strategy**
- Constraints in terms of speed are **not intrinsic to** the levels of **memory**
- They are inherent to the fact that data must be transferred, via Bus, among **physically separated devices**

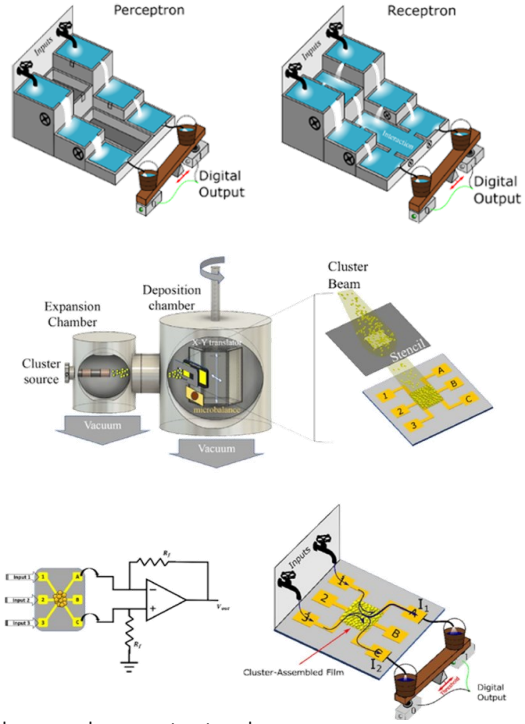


CIM – Possible Solutions

- **Data storage and elaboration** capacities **within unique pieces of HW**, known as CIM, can be a viable solution
- Micro/Nano technologies, i.e., Water-like solutions, can provide relevant contribution in overcoming the mentioned issue
- The scientific community is also investigating **unprecedented approaches to computation**, stepping beyond the “0” and “1” digital states
- Analogue computation principles, known as **soft computing**, can be powered by Micro/Nano technologies and materials

CIM – An Example

- Neuromorphic system called **receptron** opens to complex networks of reconfigurable elements
- Nanostructured Au films (gold clusters; gas phase) have non-linear non-local conduction properties
- It generates a complete set of Boolean functions of *n* variables
- It enables classification of non-linearly separable functions without previous training of the device



Reference G. Martini, et al., "The Receptron: a device for the implementation of information processing systems based on complex nanostructured systems," Japanese Journal of Applied Physics, 2022, doi: 10.35848/1347-4065/ac665c

January 2023 | Volume 111 | Number 1

Proceedings of the IEEE

Machine Learning for Emergency Management: A Survey and Future Outlook

Efficient Acceleration of Deep Learning Inference on Resource-Constrained Edge Devices: A Review

Technology Prospects for Data-Intensive Computing

Point of View: A Perspective Vision of Micro/Nano Systems and Technologies as Enablers of 6G, Super-IoT, and Tactile Internet

Scanning Our Past: The Information Age and Naval Command & Control

IEEE

POINT OF VIEW

A Perspective Vision of Micro/Nano Systems and Technologies as Enablers of 6G, Super-IoT, and Tactile Internet

By JACOPO IANNACCI, *Senior Member IEEE*
Fondazione Bruno Kessler (FBK), 38123 Trento, Italy

I. INTRODUCTION

Modern research in technology fields, such as electronics, distributed networks of sensing/functional nodes, and wireless and wearable devices, is relentlessly converging around wide application paradigms, such as Internet of Things (IoT) [1] and Internet of Everything (IoE) [2]—Table 1, at the end of section, offers a full list of used acronyms. From a different perspective, recent advances in electronics, hardware (HW) technologies, information technology (IT), and artificial intelligence (AI) for telecommunication networks, standards, and protocols look to unavoidably fall under the umbrella of fifth generation of mobile communications (5G) [3]. Even though they appear orthogonal to each other, IoT, IoE, and 5G are closely linked together. In a nutshell, IoT and IoE target pervasivity of services, while 5G is the pillar upon which transmission of massive amounts of data and information should lay [4]. As brief recap, 5G poses on the three cornerstone drivers of enhanced mobile broadband (eMBB), massive machine-type communications (mMTCs), and ultrareliable low latency communications (URLLC) [5], to enable data-centric applications such as machine-to-machine (M2M), vehicle-to-vehicle (V2V), and vehicle-to-everything (V2X) communications, along with virtual reality (VR), augmented reality (AR), and extended reality (XR).

Date of publication 19 December 2022; date of current version 12 January 2023.
Digital Object Identifier 10.1109/JPROC.2022.3223791

Reference Literature (Selection)

General vision	**J. Iannacci, "A Perspective Vision of Micro/Nano Systems and Technologies as Enablers of 6G, Super-IoT and Tactile Internet," Proceedings of the IEEE, 2023, https://ieeexplore.ieee.org/document/9991880/** J. Iannacci, H. Vincent Poor, "Review and Perspectives of Micro/Nano Technologies as Key-Enablers of 6G," IEEE Access, 2022, doi: 10.1109/ACCESS.2022.3176348
WEAF Mnecosystem	J. Iannacci, "The WEAF Mnecosystem: a Perspective of MEMS/NEMS Technologies as Pillars of Future 6G, Super-IoT and Tactile Internet," Proc. IEEE SmartIoT, 2021, doi: 10.1109/SmartIoT52359.2021.00018
HW-SW Divide	J. Iannacci, "Towards Future 6G from the Hardware Components Perspective – A Focus on the Hardware-Software Divide, its Limiting Factors and the Envisioned Benefits in Going Beyond it," Proc. IEEE 5GWF, 2021, doi: 10.1109/5GWF52925.2021.00008

Conclusion

- Full deployment of 6G, Super-IoT and FNs from the bottom-up perspective of low-complexity miniaturized hardware components, requires a **reformulation of the concept of HW**, widely leveraging Micro and Nanotechnologies
- Considering this target, the **WEAF Mnecosystem was conceived** and introduced