SUPERIOT

SUPERIOT project

Project presentation

Co-funded by the European Union

6GSNS

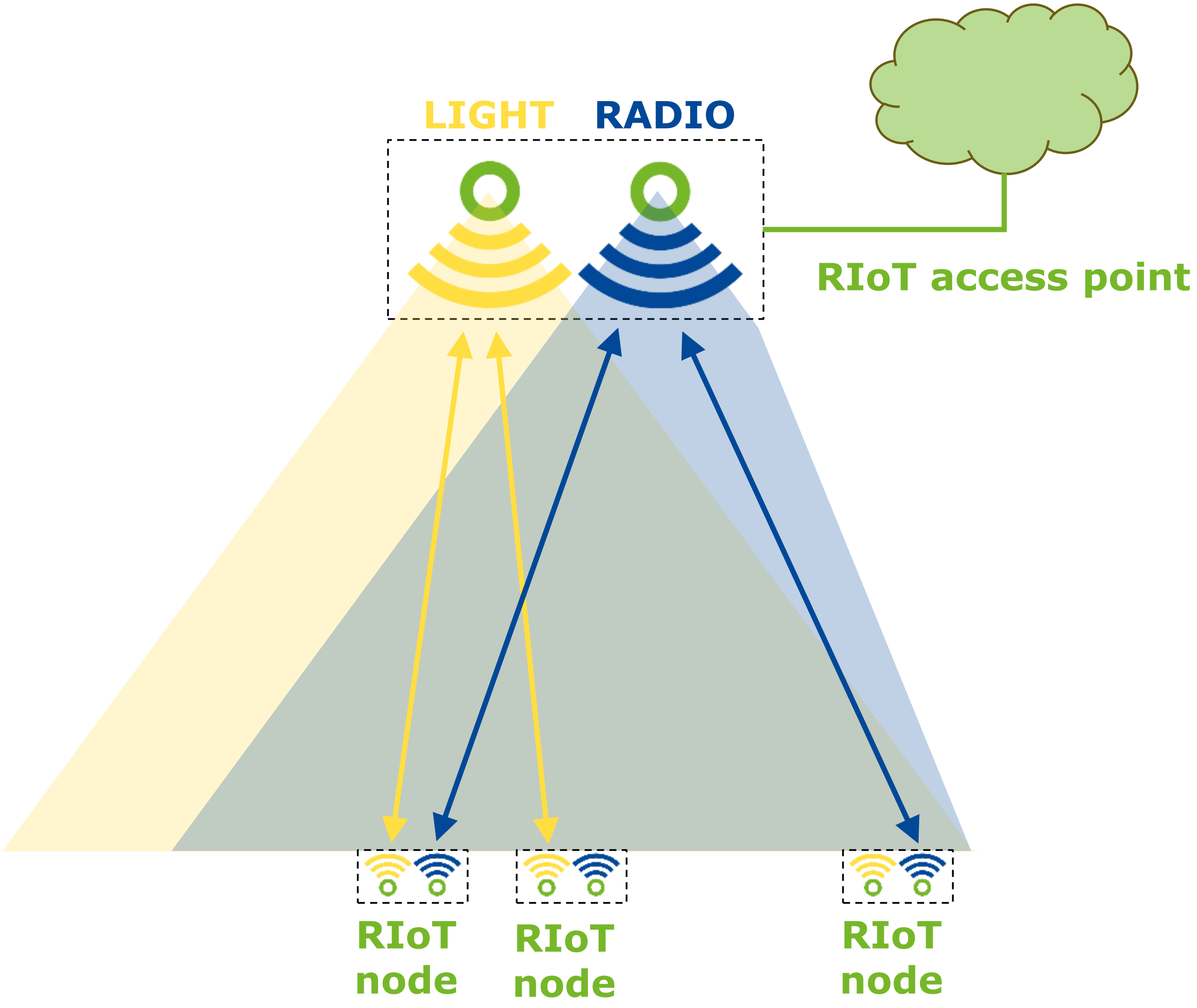
SUPERIOT

Presentation overview

- **SUPERIOT concepts**
- Printed electronics
- RIoT nodes
- Energy management
- Reconfigurable networks
- Applications
- Conclusions

SUPERIOT dual-mode concept

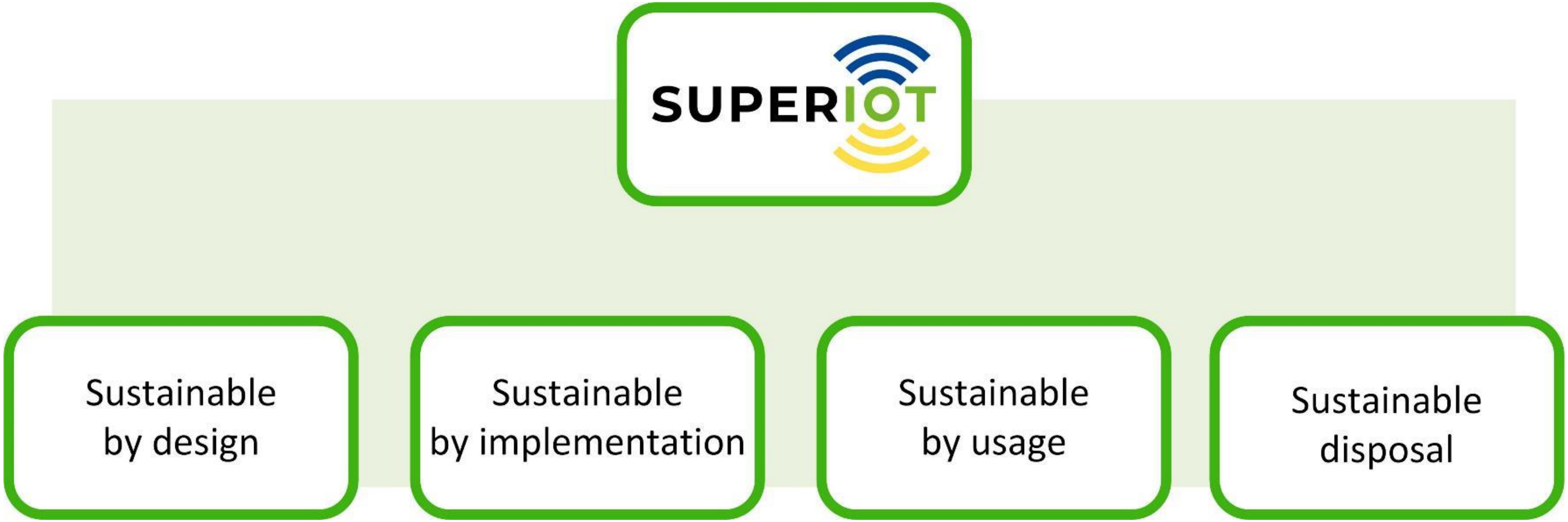
- **Dual-mode wireless connectivity**
  - Connected by both radio and/or light
- **Dual-mode energy harvesting**
  - From radio and light
  - Battery-less node operation
- **Dual-mode positioning**
  - Enhanced and robust performance
- **Sustainable implementation**
  - Printed electronics (PE)
- **Reconfigurability**
  - IoT (RIoT) nodes
  - Network levels
  - Dynamic selection of light/radio



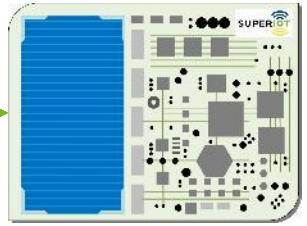
Overview of the project in J. Phys. Phot. (2024)
https://iopscience.iop.org/article/10.1088/2515-7647/ad1c6a

Towards truly sustainable IoT

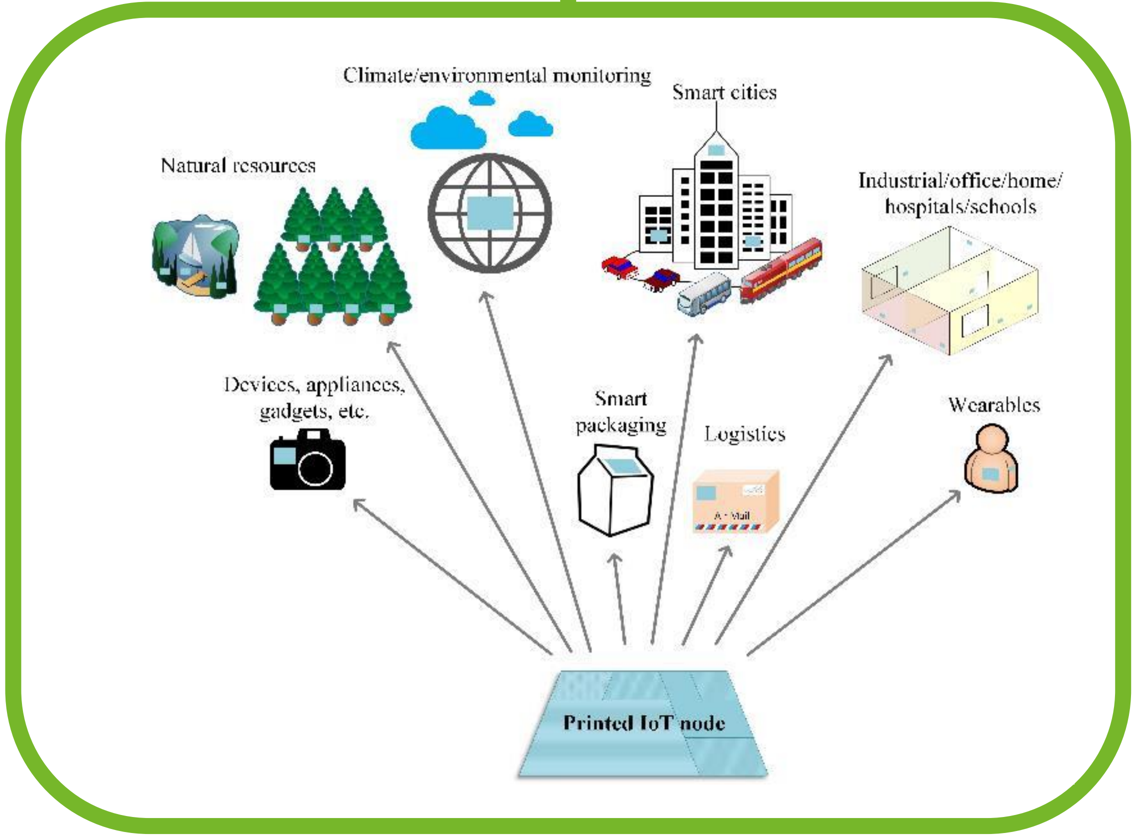
- The SUPERIOT project will develop an IoT communication system following a unique holistic approach to sustainability.



SUPERIOT vision



- Widespread implementation of IoT devices using hybrid technologies
  - *I.e.* PE combined with silicon-based technologies
- Future expectations include:
  - Fully-printed reconfigurable optical-radio IoT nodes
    - *I.e.* Sticker-like RIoT nodes
  - Very low-cost nodes (*e.g.* one cent node)
  - Environmentally-friendly IoT nodes
    - Use of biodegradable materials *etc*.
- Novel scenarios/use cases:
  - Massive sensing and massive actuation
  - Inside the human body
  - Underwater
  - Mining *etc.*



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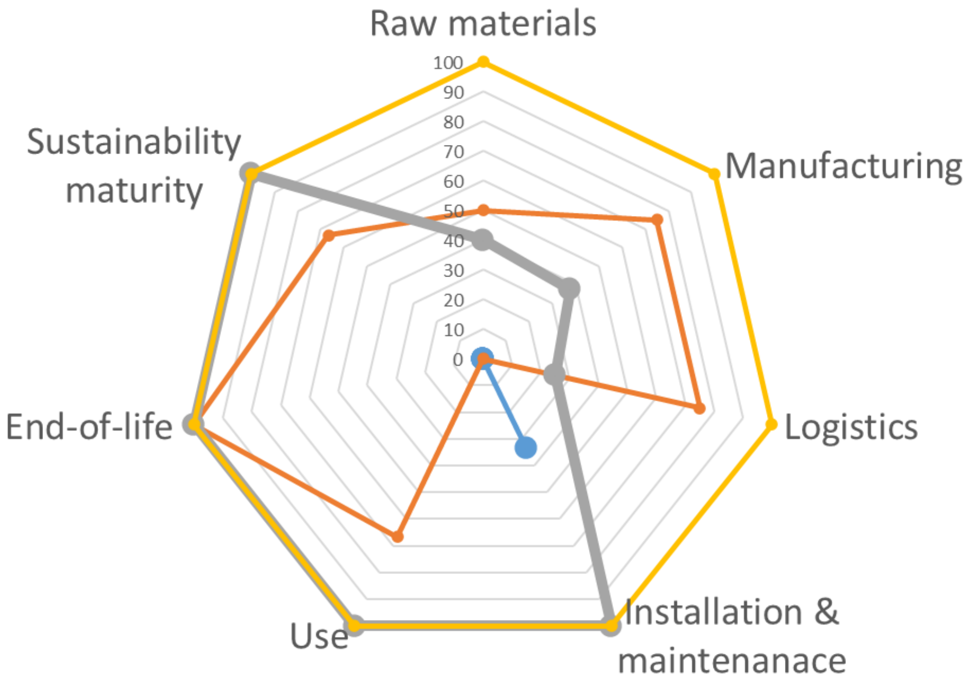
Printed electronics for sustainable manufacturing

- **New types of electronic products** which are thin, flexible and lightweight
- **Eco-design and circular design** for circular economy
- **Material and energy savings** during production
- **Compatibility with sustainable materials**: bio-based, renewable, abundant

➡ **Sustainable printed and hybrid integrated components, devices and functionalities**

Hakola et al. 2020
https://doi.org/10.1007/s00170-021-07640-z
Naji Nassajfar et al. 2023
https://doi.org/10.1088/2058-8585/acd650



Smart label concepts

- Existing label based on traditional electronics
- Printed label with flexible batteries
- Printed label with energy harvesting
- Printed label optimized for sustainability

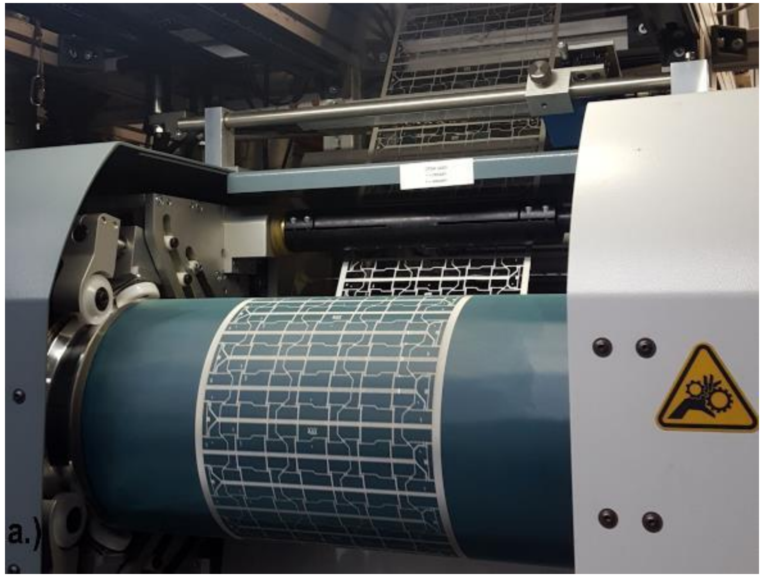
Hakola et al. 2023
https://doi.org/10.1007/s43615-023-00280-3

Sustainable substrates for PE

Printed and hybrid electronics S2S and R2R processing

- Biobased & recycled polymers
    - *e.g.* PLA, regenerated cellulose, CAP, Bio-PET, rPET
- Papers and other wood-based materials
    - *e.g.* nanocellulose, cardboard, veneer.

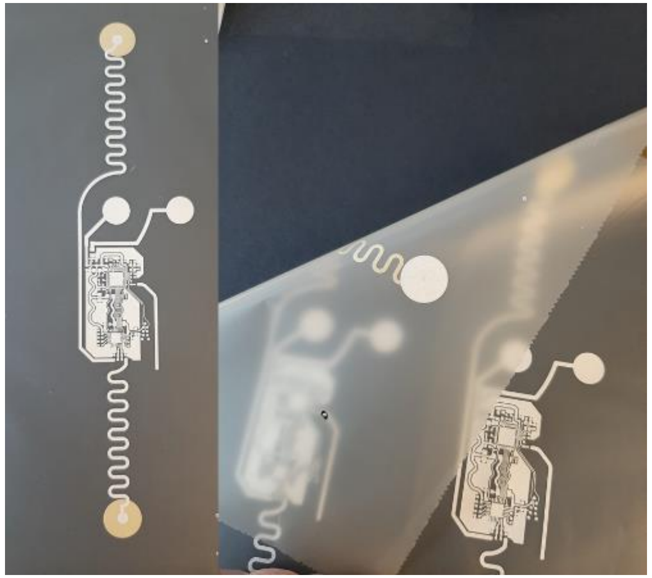
Conductor patterns on PLA



Overmoulded hybrid electronics on PLA

Conductor patterns on paper

Conductor patterns on nanocellulose substrate

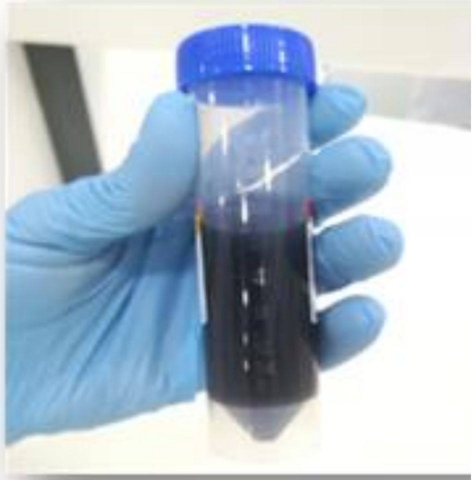


Välimäki *et al.* 2020 https://doi.org/10.1007/s00170-020-06029-8
Luoma *et al.* 2021 https://doi.org/10.1177/875608792098856
Luoma *et al.* 2022 https://doi.org/10.3390/polym14091863
Luoma *et al.* 2023 https://doi.org/10.1002/app.53414

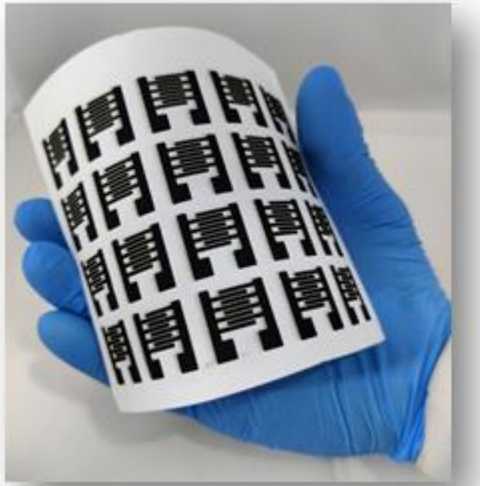
Jansson *et al.* 2020 https://doi.org/10.3390/ma15030957
Immonen *et al.* 2022 https://doi.org/10.3390/ma15072679
Jaiswal *et al.* 2023 https://doi.org/10.1002/aelm.202201094
ECOtronics Project https://www.ecotronics.fi (2019-2022)

Sustainable materials for printable electronics

- Green nanomaterials inks formulation and sustainable substrates
- Nanomaterial-based inks will be developed by liquid phase exfoliation and sol-gel methods
- Ink liquid carriers will be selected according to their environmental footprint
  - Priority to water and other eco-friendly options to replace commonly used solvents *e.g.* NMP



Graphene dispersion in 2-Propanol



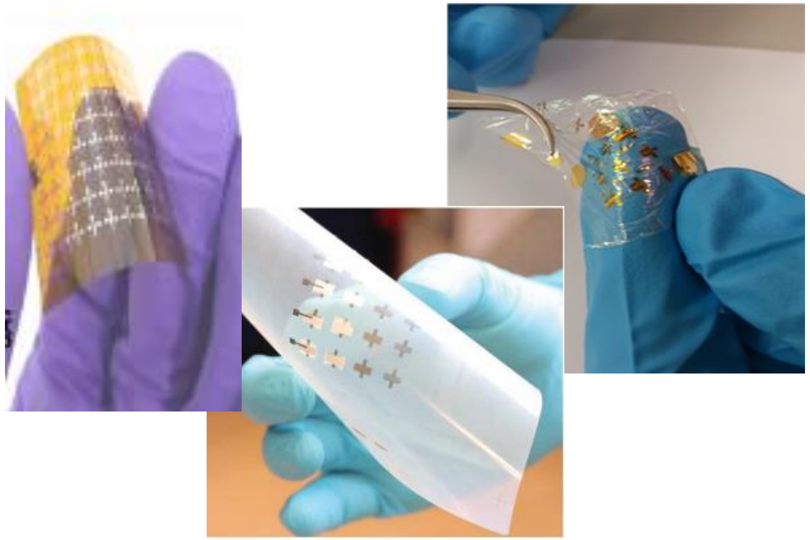
Micro-supercapacitors deposited on paper

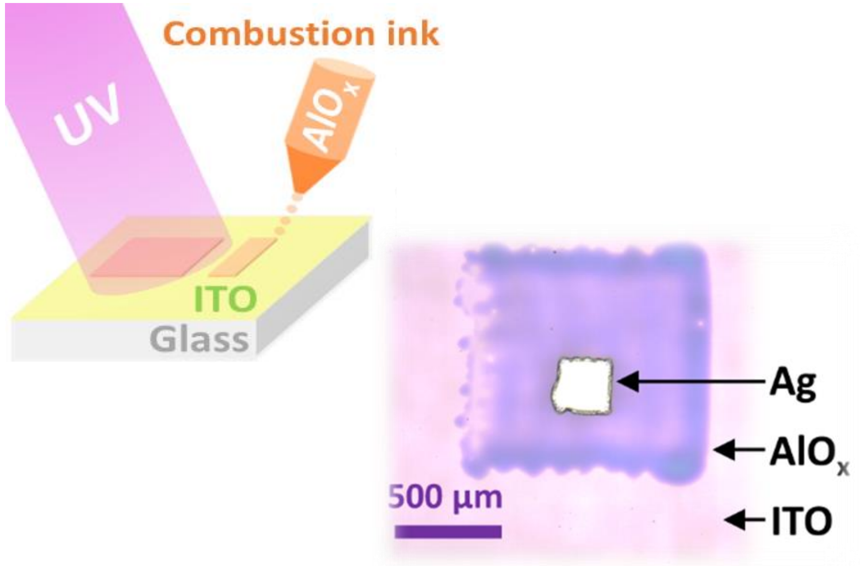
- Where possible devices will be printed on parylene, paper or other sustainable substrates.

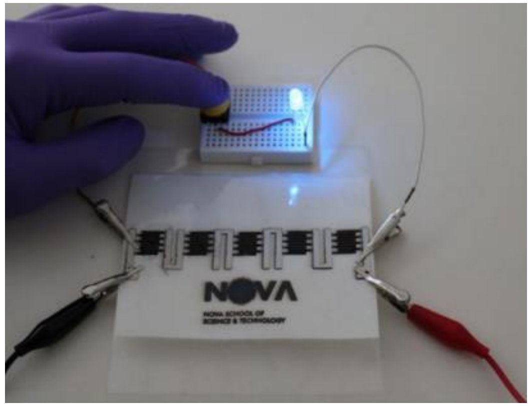
E. Carlos *et al.* 2022
https://iopscience.iop.org/article/10.1088/2058-8585/ac4bb1/meta

J. Coelho *et al.* 2022
https://doi.org/10.1038/s41578-022-00448-7

PE device fabrication and characterisation







Substrates

- PEN, PET, paper, cork
  - Thickness 1-10 µm
- Parylene-C and polyamide

Methodologies

- Inkjet printing
- Flexographic printing
- PVD
- Photolithography
  - If required for high resolution

Devices

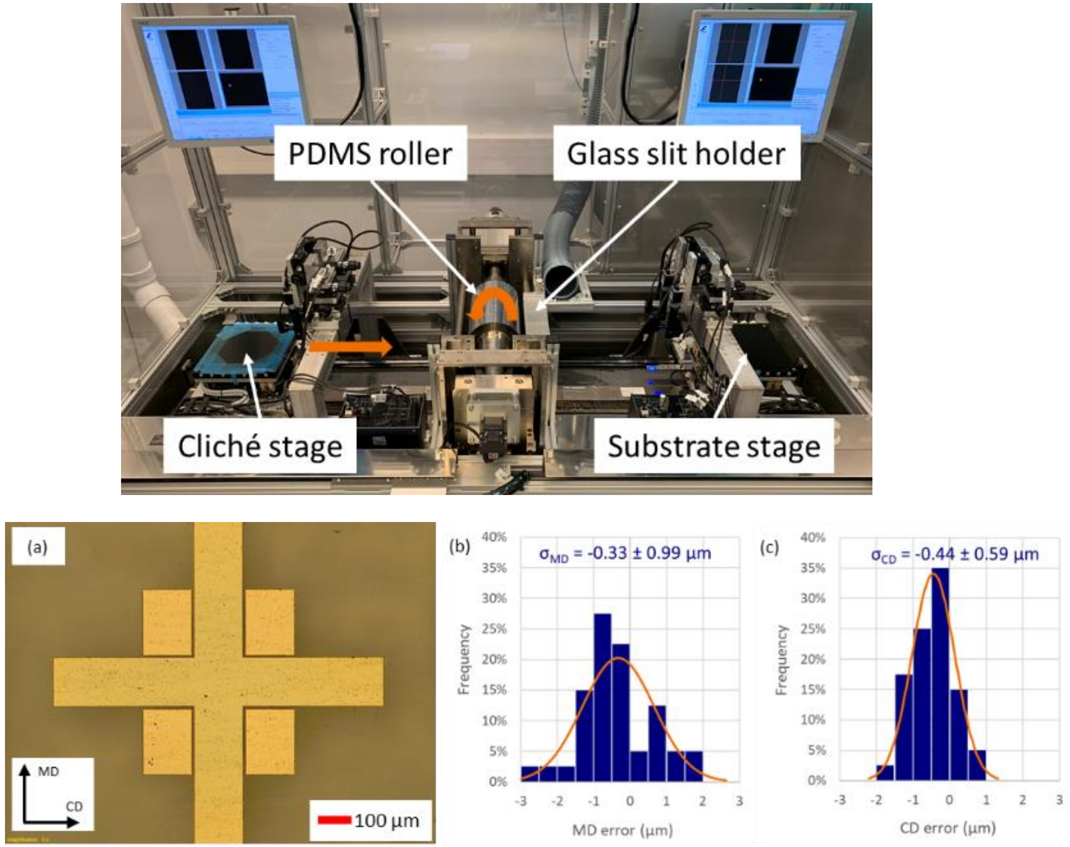
- Photo-responsive sensors
- Diodes
- MSCs
- Memristors.

E. Carlos et al. 2021
https://doi.org/10.1039/D0TC05368F

J. Coelho et al. 2022
https://doi.org/10.1007/s00604-022-05610-0

Printable electronics

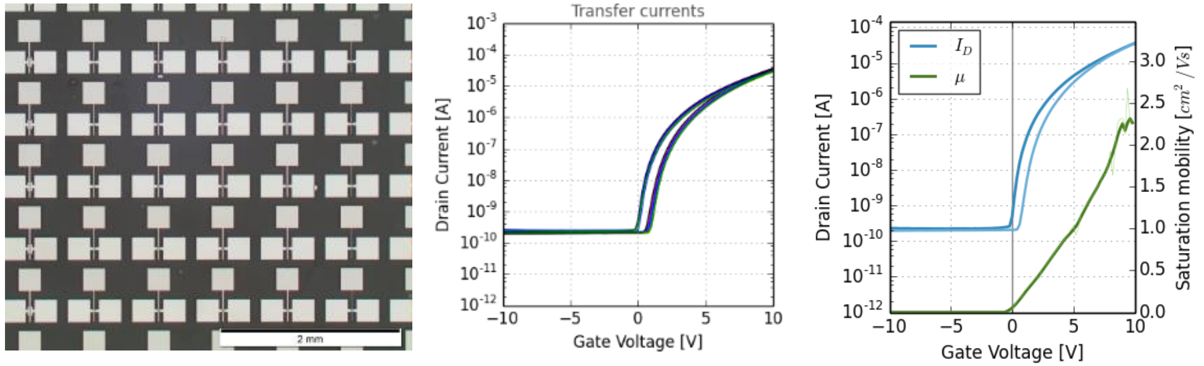
- High-resolution printing



A. Alastalo, J .Leppäniemi, A. Sneck, K. Eiroma, "Taking the accuracy of printed electronics beyond 1 µm," OPE-Journal, **37**, p. 17-19 (2021). https://www.coating-converting.com/epaper/c2com/212/epaper/9086/17/index.html

Metal oxide TFTs

- Patterning of metal oxide TFTs at µm-level using high-resolution printed resists
- Targeting device yields >99 % for enabling circuits in limited-capability printed IoT nodes.

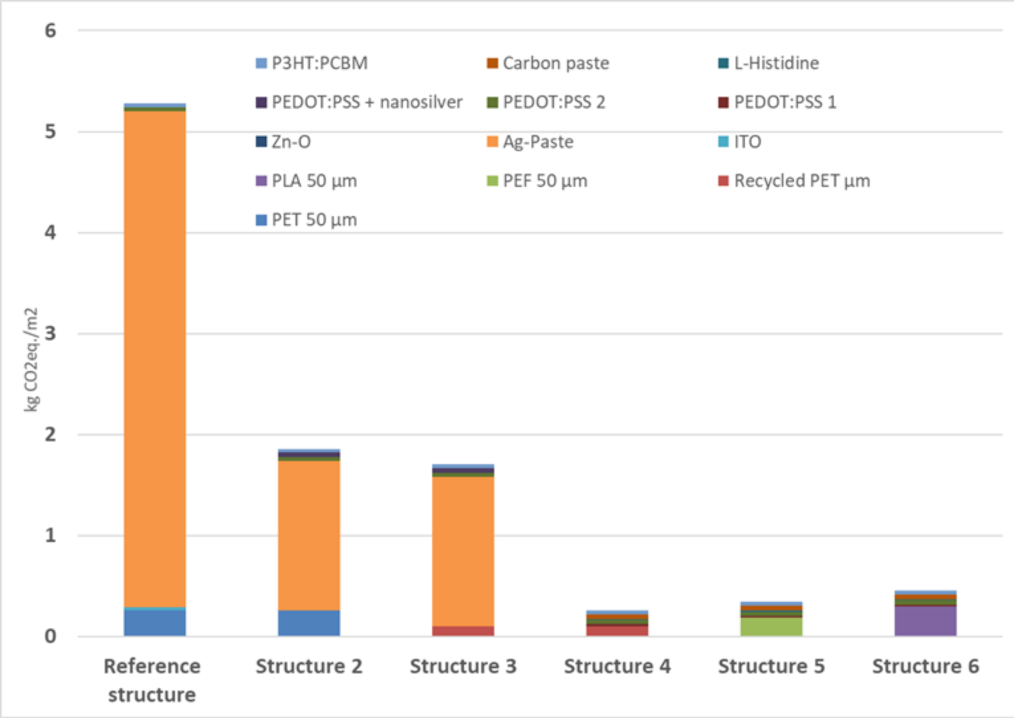


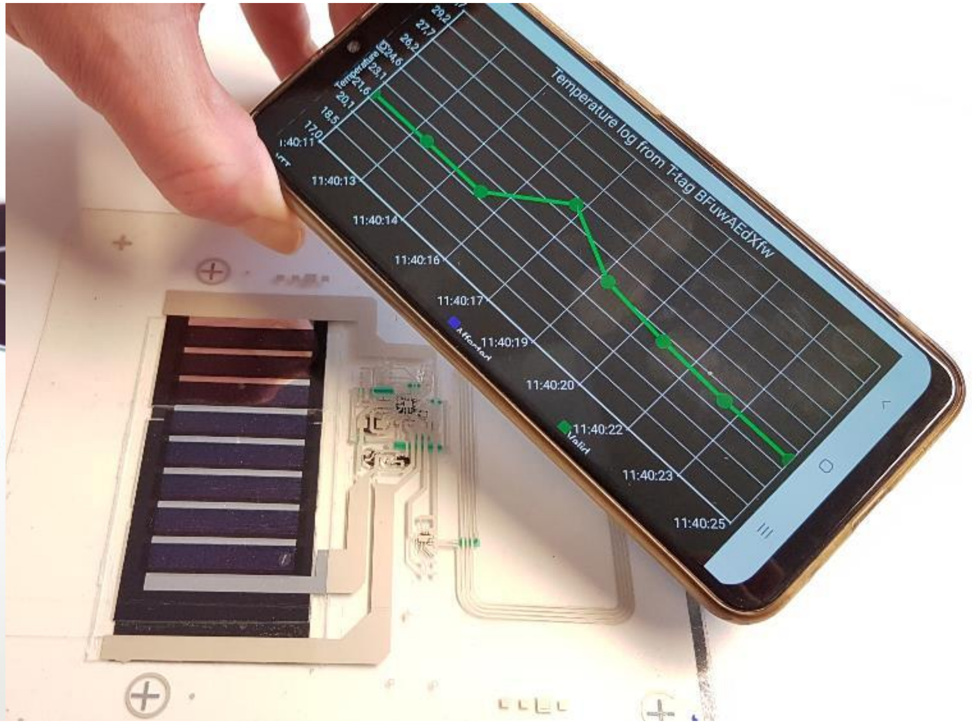
A. Sneck, H. Ailas, F. Gao, J. Leppäniemi, "Reverse-Offset Printing of Polymer Resist Ink for Micrometer-Level Patterning of Metal and Metal-Oxide Layers", ACS Applied Materials & Interfaces **13**, p. 41782–90 (2021). https://dx.doi.org/10.1021/acsami.1c08126

F. Liu, A. Sneck, A. Alastalo, J. Leppäniemi, "Oxide TFTs with S/D-contacts patterned by high-resolution reverse-offset printed resist layers," Flex. Print. Electron. (2023). https://dx.doi.org/10.1088/2058-8585/acbf65

Energy harvesting and storage with PE

- Greener materials and technologies for self-powering systems
  - Biobased, earth-abundant, non-hazardous materials in OPV
  - Material and energy-efficient, ambient atmosphere fabrication.





Välimäki *et al.* 2020
https://doi.org/10.1007/s00170-020-06029-8
Luoma *et al.* 2022
https://doi.org/10.3390/polym14091863

Välimäki *et al.* 2022
https://doi.org/10.1007/s00170-022-08717-z
Ylikunnari *et al.* 2020
https://iopscience.iop.org/article/10.1088/2058-8585/ab6e73

ECOtronics Project (2019-2022)
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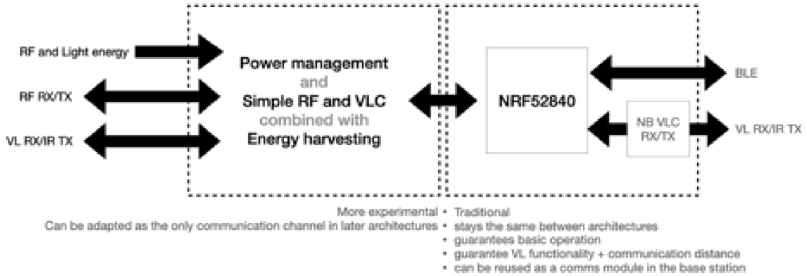
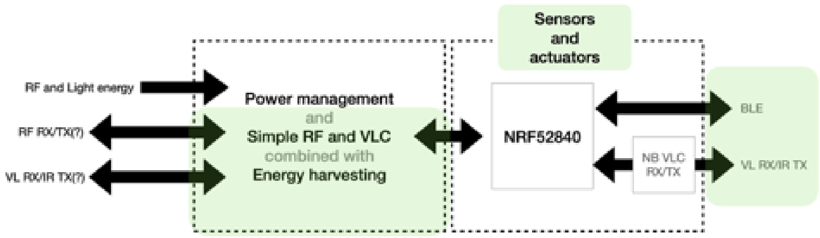
RIoT node designs in SUPERIOT

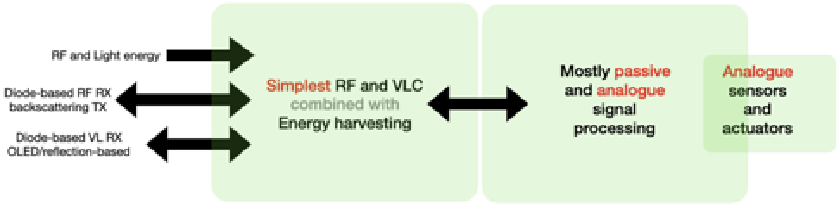
Node architectures



Reference node architecture



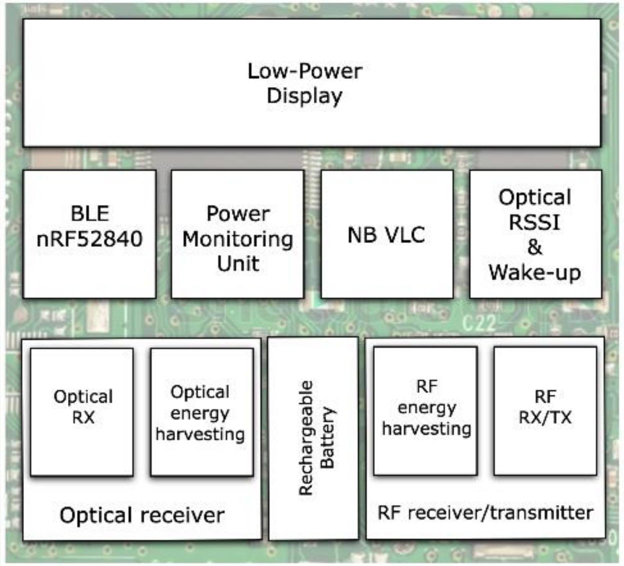
Hybrid node architecture



All-printed node architecture

- A reference node will be built using conventional Si-based components and manufacturing methods
- The primary node developed in the SUPERIOT project is a hybrid node using traditional and printed components, such as OPVs, supercapacitors, and antennas
- The third and most experimental node will attempt to make a complete (reduced capability) all-printed node using only printed components.

Reference Node



The reference node uses the nRF52840 microcontroller from Nordic Semiconductor for Bluetooth Low Energy. It also has new communication channels, power monitoring, and power harvesting circuitry.

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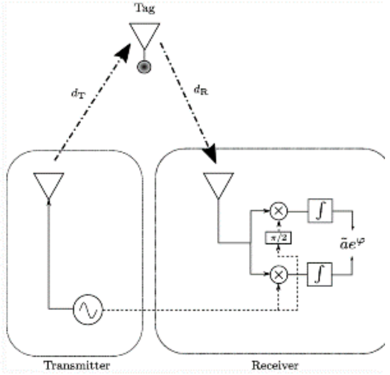
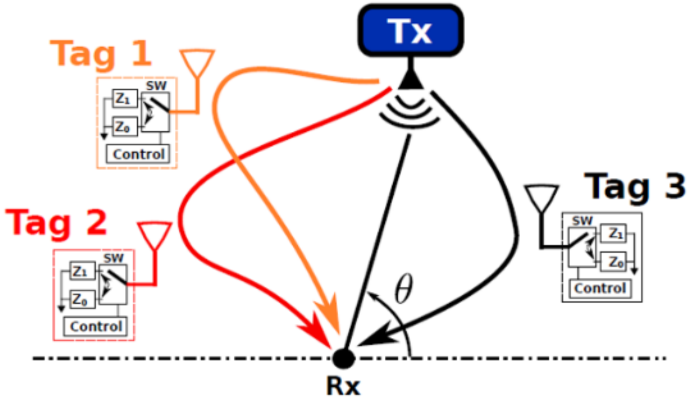
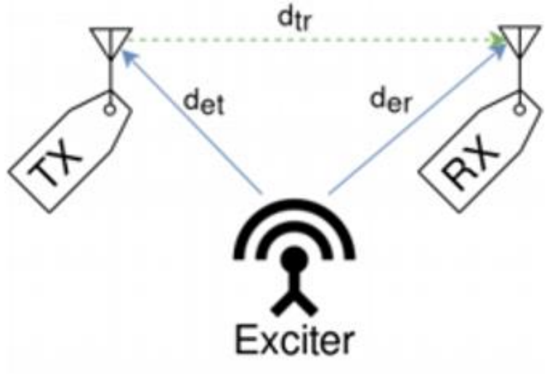
Localisation using dual-mode RF/optical 1

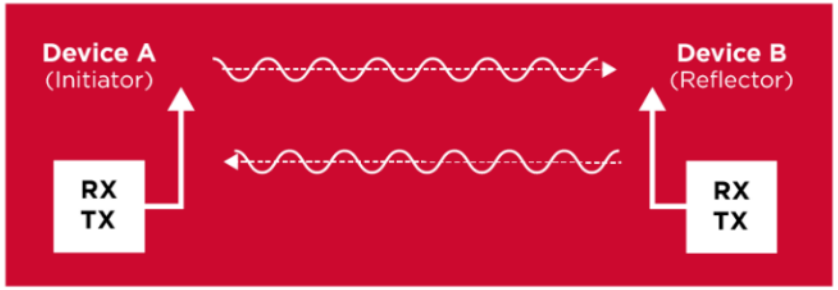
- RIoT Nodes Printed RF - **Backscatter Phase Response**

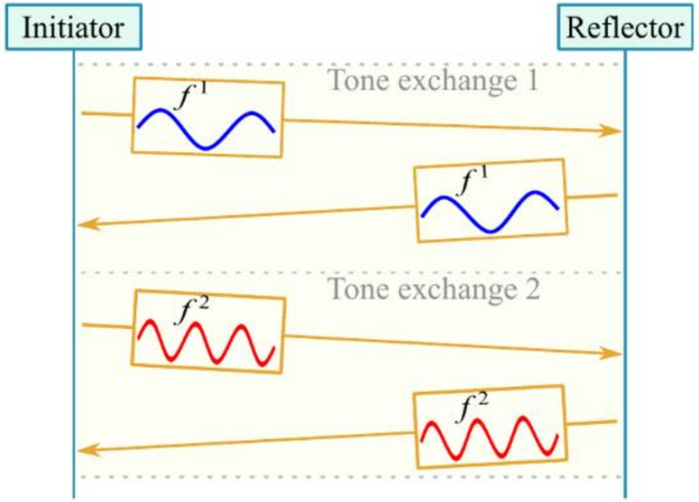






- RIoT Nodes Hybrid / Electronics RF – **Bluetooth Channel Sounding**

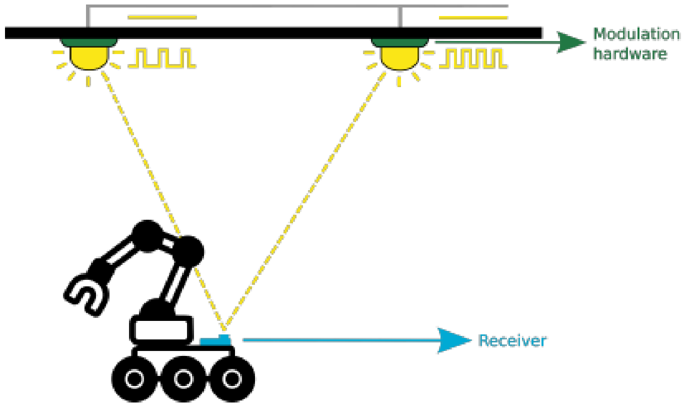


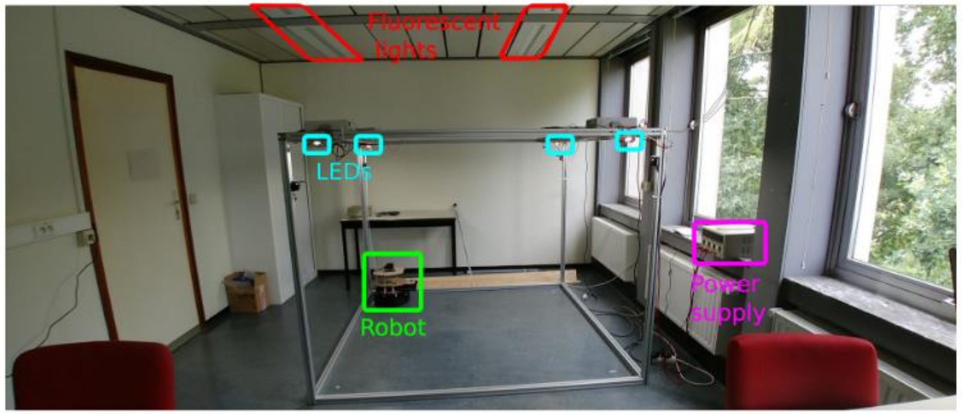


Bluetooth® ESL – The Global Standard for the Electronic Shelf Label Market

Localisation using dual-mode RF/optical 2

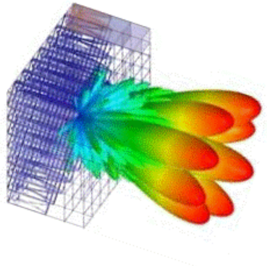
- RIoT Nodes Printed Optical – **Ranging**



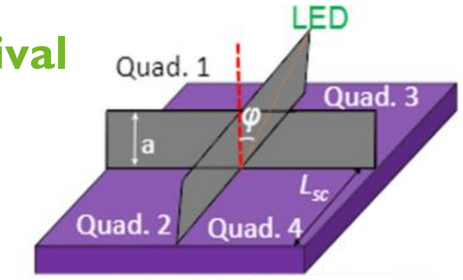


- RIoT Nodes Hybrid / Electronics Optical – **Angle of Arrival + Beamforming**

Optical beamforming



Optical angle of arrival



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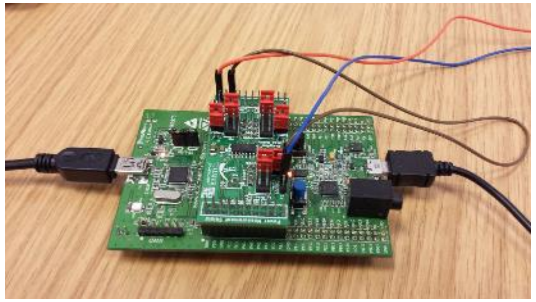
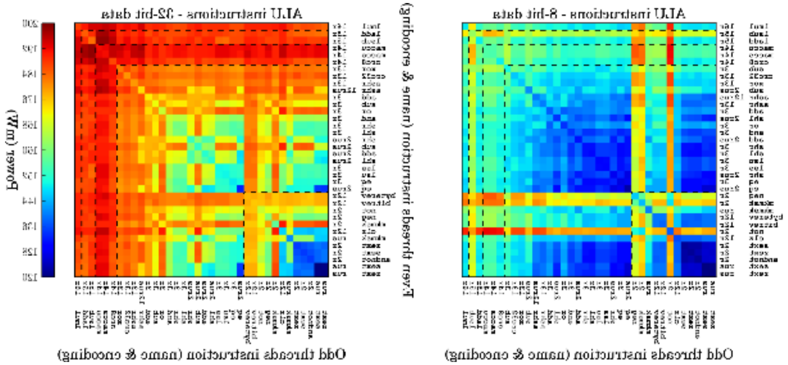
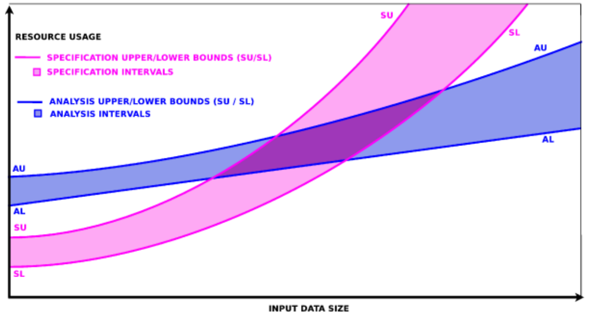
Energy analysis for sustainable IoT

- **Measurement** of power dissipation and energy consumption at node and network level
- **Power and energy modelling** at node and network level to estimate or predict the resource usage during design and at runtime
- **Validation** of the models with respect to the actual hardware to ensure accuracy of predictions
- **Power and energy analysis** to enable resource optimisation at node and network level.

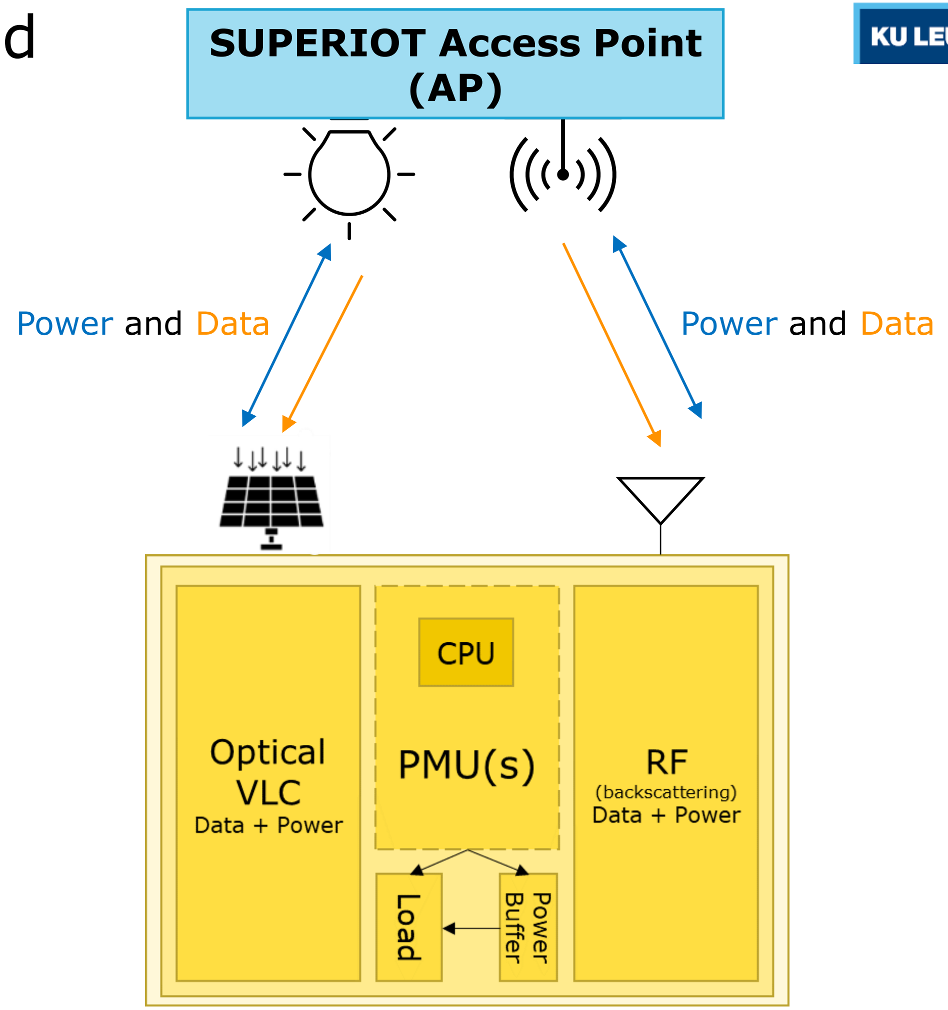






Energy management

- A power management unit (PMU) will be used to exploit both light- and RF-based energy harvesting
  - Si-based reference node
  - Hybrid node
  - All-printed node
- Use of a single PMU or multiple PMUs will be investigated to ensure maximum power efficiency
- For RF-based harvesting, both ambient RF and intentional RF will be explored.



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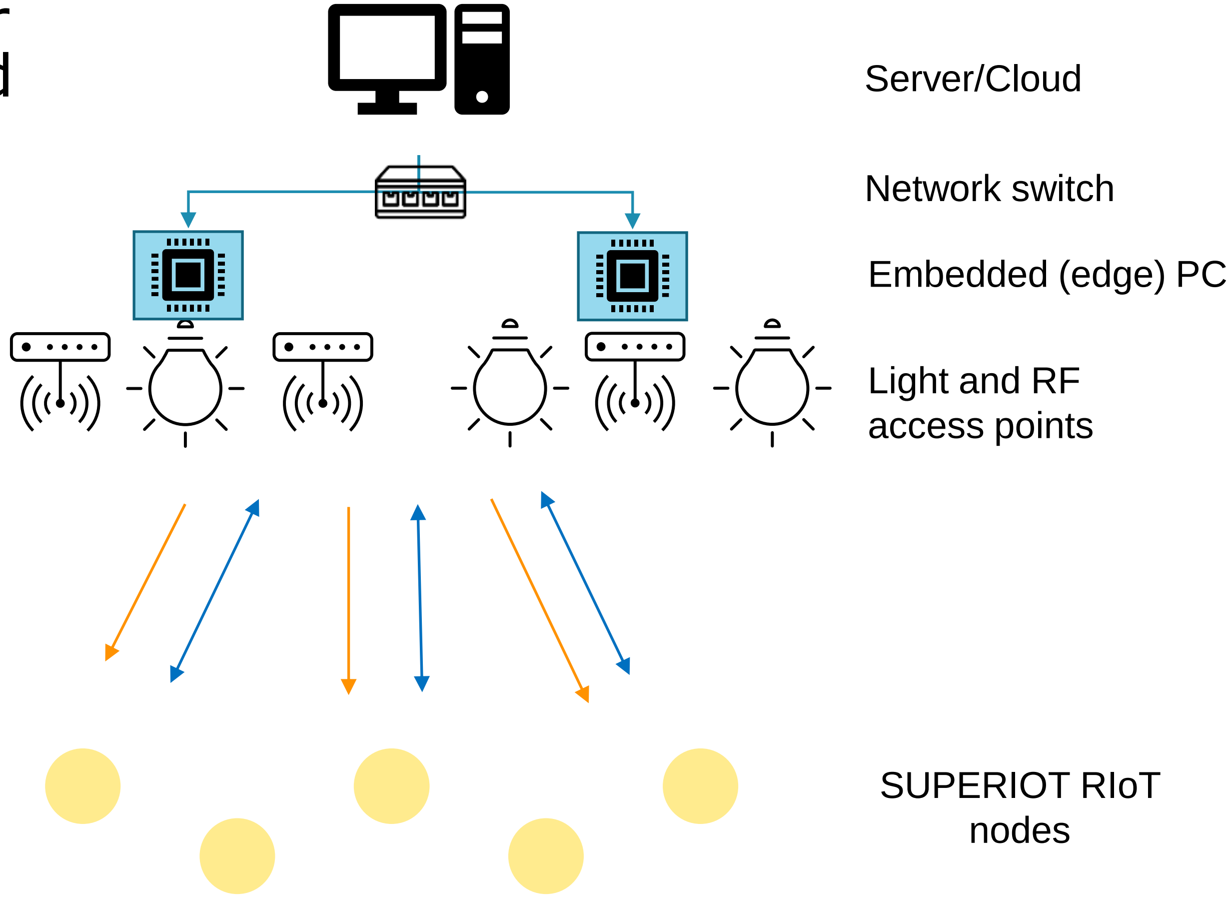
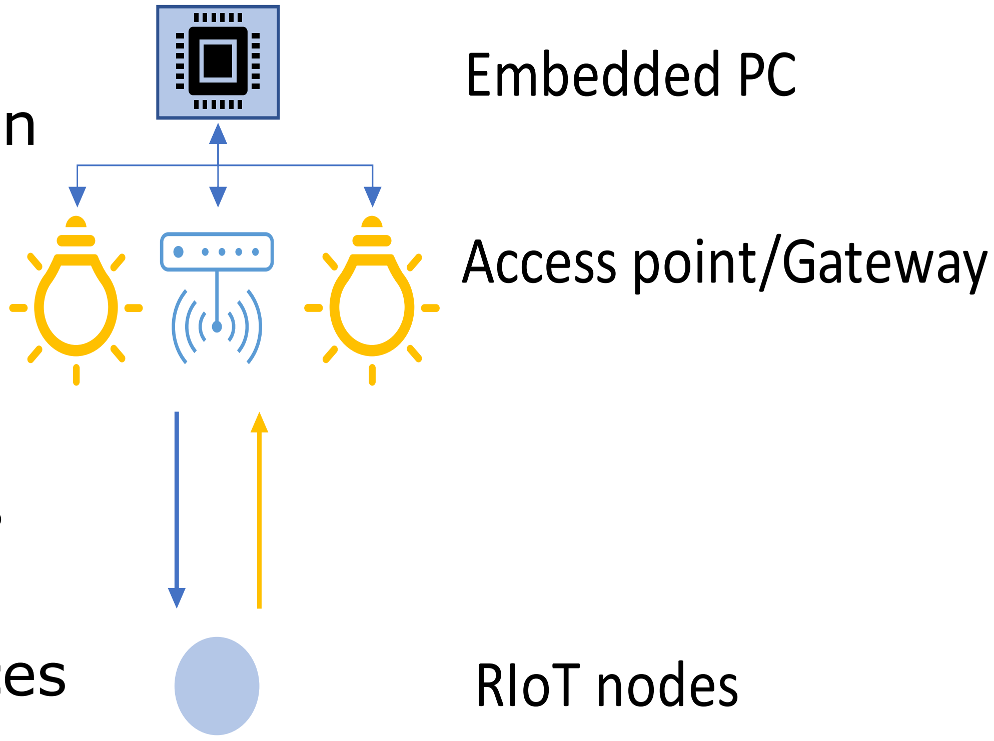
Network architecture

- Multi-tier and multimodal (RF/light) network architecture is considered
- Three key network functionalities over multi-modal links are investigated and trialed:
  - Communication
  - Localisation
  - Energy transfer
- Integration and optimisation for sustainability is the goal
- PHY layer is designed to run on the access point (AP) or the edge processing unit
- MAC layer is designed to run on the edge processing unit or on the centralised server.



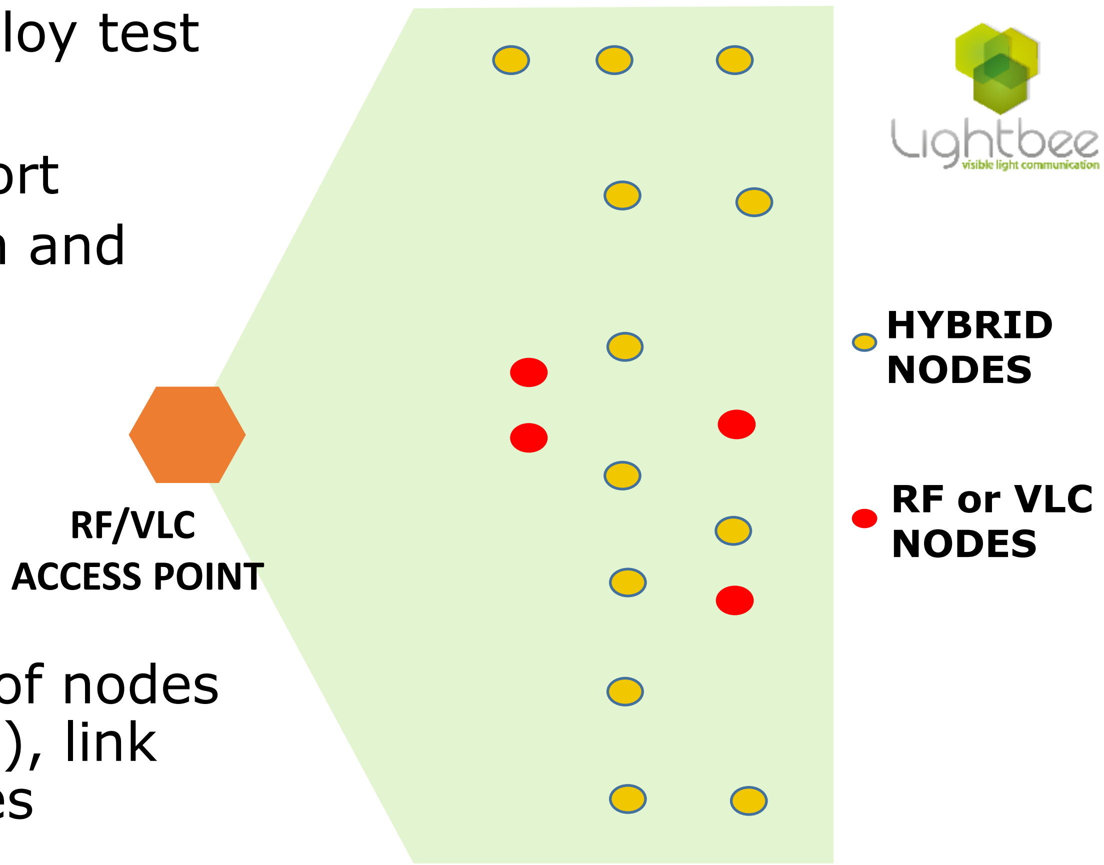
Reconfigurable network protocols

- RF, light and hybrid communication
  - Sustainability-optimal selection of communication modality and parameters
  - Mindful of network topology and application requirements
- RF, light and hybrid localisation
  - Based on signal strength estimation and other principles
- RF and light energy harvesting by RIoT nodes
- Multi-functional optimisation of operations
  - Based on data collected by different services for commercial radio/light access technologies (baseline and scenario).



Network testing

- RIoT network integration and testing will deploy test networks in lab environments
- Integration of new technologies for IoT support
  - *E.g.* positioning, multicast communication and enhanced security.
  - Infrastructure will reach TRL 4
  - TRL 2-3 for system in realistic application



- **Proposed testing**

Congestion	Maximum number of nodes (TDMA, CDMA, etc.), link range, hidden nodes
Latency	Frame transmission time
Network access	Collision strategies
Hybrid mode	RF/VLC communications.

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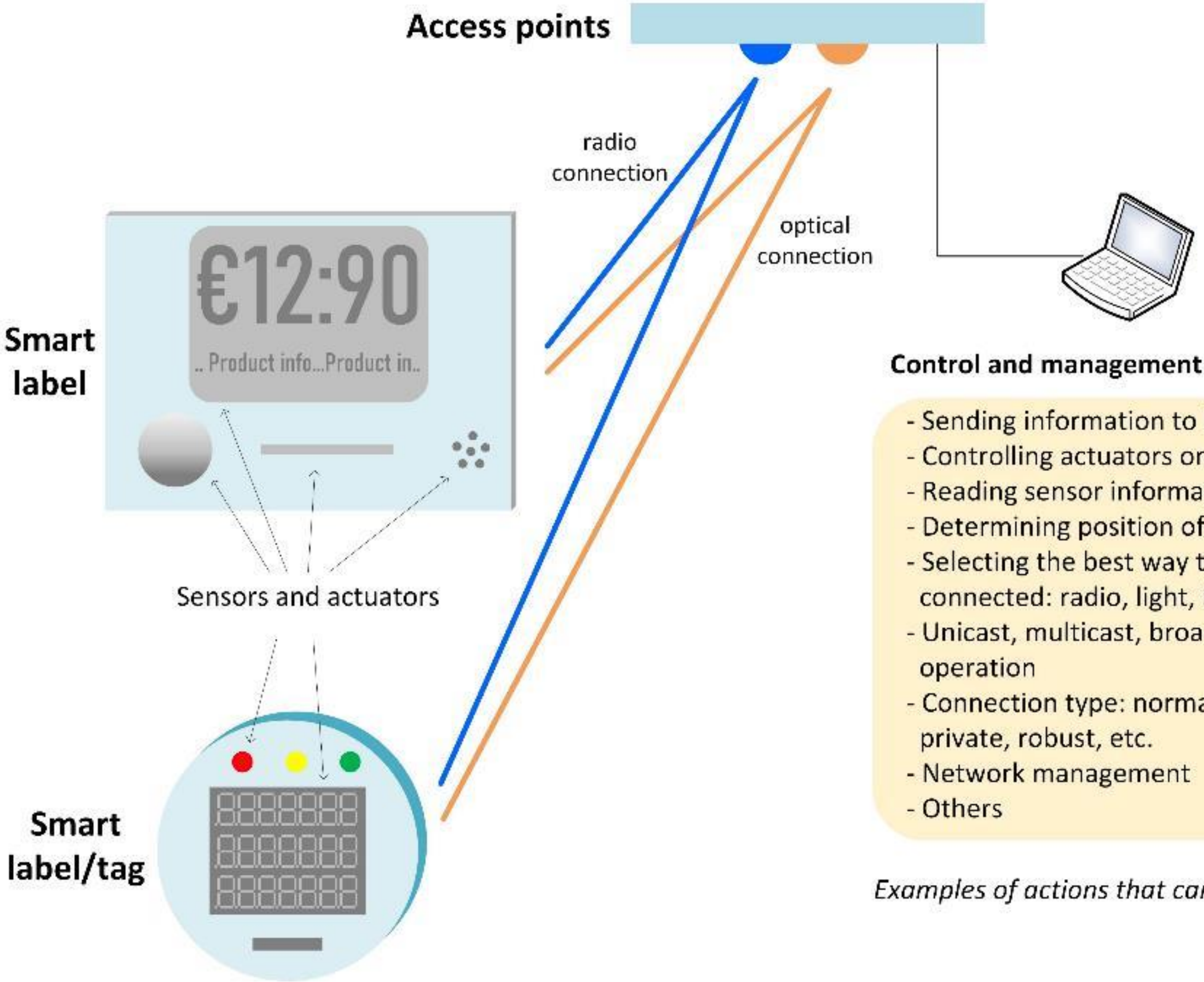
Application 1: Smart tags



Control and management of smart labels

- Sending information to be displayed
- Controlling actuators on the labels
- Reading sensor information
- Determining position of labels
- Selecting the best way to be connected: radio, light, both, etc.
- Unicast, multicast, broadcast operation
- Connection type: normal, secure/ private, robust, etc.
- Network management
- Others

Examples of actions that can be carried out

Application 2: Medical

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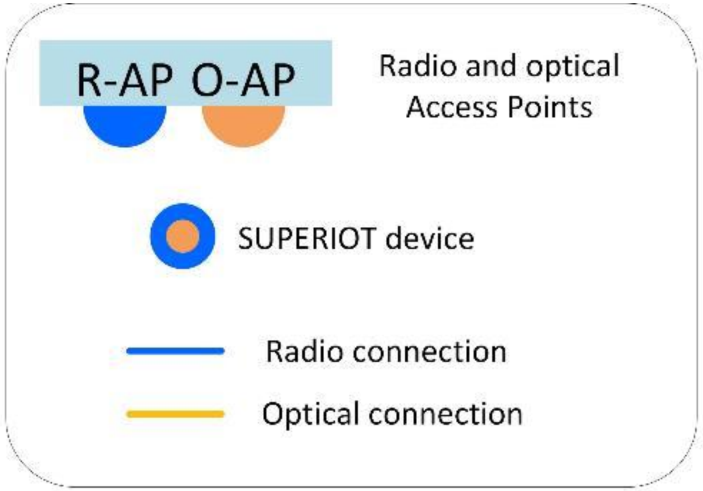
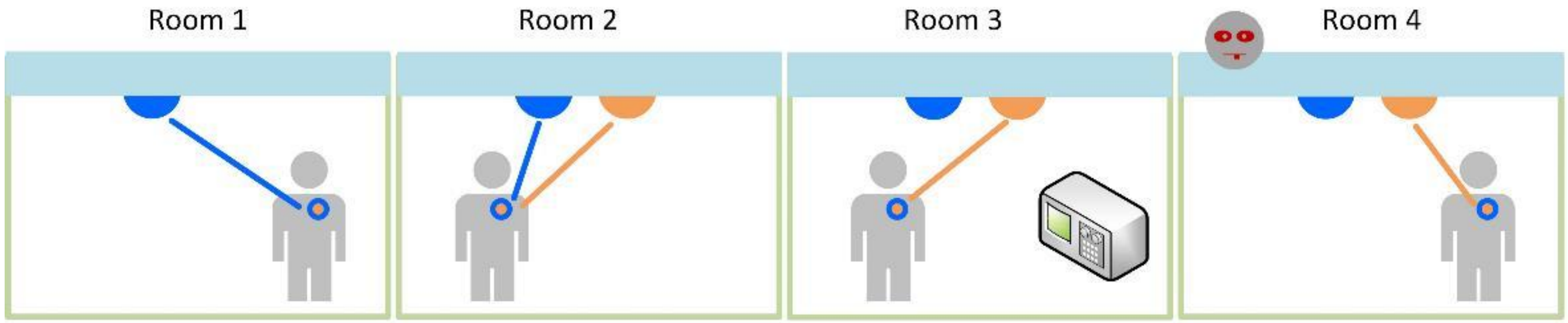
wavecom



Exploiting the SUPERIOT concept in future healthcare applications



Radio Access Point only:
- Connected by radio

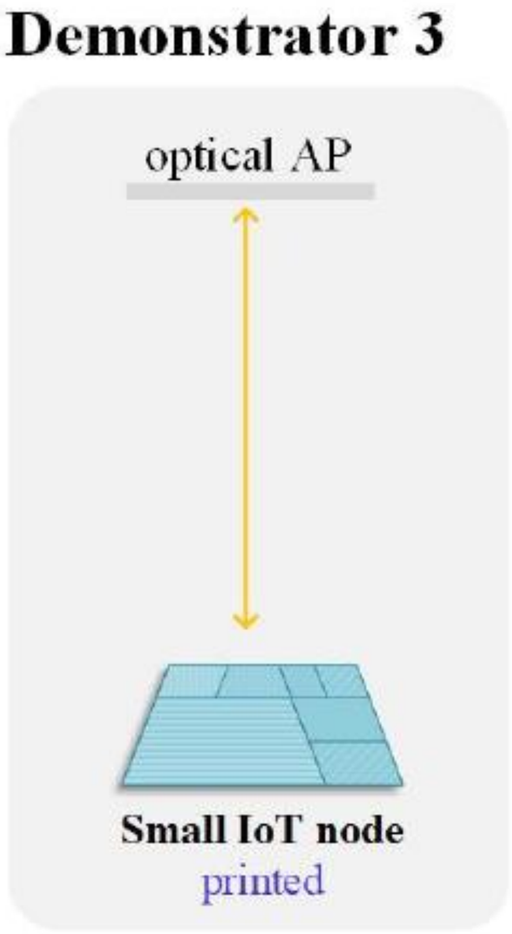
High reliability needed
- Connected by radio and light

Sensitive equipment in the room
- Maximize the use of optical communications

Security and privacy requirement
- Maximize the use of optical communications

Application 3: PE demo

- Fully printed IoT node to address the limitations of printed electronic components
- Truly sustainable implementation
- Energy autonomous
- Planned system:
  - Node receiving and displaying some information: pixels / segments / icons activated from the access point.
  - Node transmitting sensor information to the access point.
- Analog electronics, simple sensors.



Application 4: Large-scale reconfigurable surfaces

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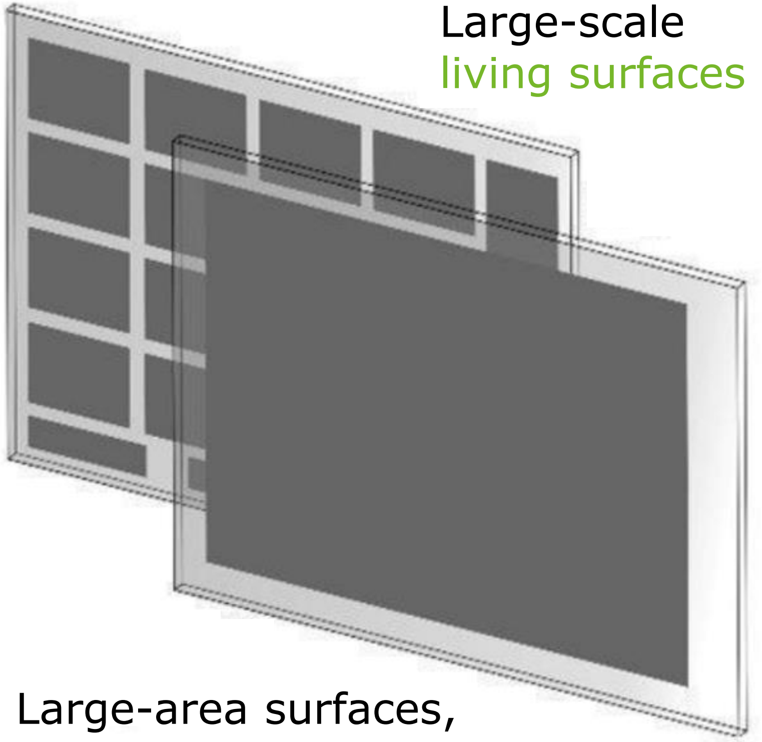
INESCTEC

- *Living surface:* a surface empowered with integrated functionalities *e.g.* wireless connectivity with sensing, actuating and processing capabilities
- A reconfigurable intelligent surface (RIS) enables 3D signal focusing through beamforming suitable for:
  - Relaying signals and power to/from IoT nodes
  - Precise localisation and environment sensing
- An IoT signal repeater at 2.4 GHz is targeted based on a (potentially transparent) printed RIS
  - Will require environmentally friendly substrates and conductors for sustainable large-scale deployment.

Large-scale living surfaces



Large-area surfaces, *e.g.* walls, doors, ceilings, tables *etc.*

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Conclusions

- Dual-mode: radio and/or light
  - Connectivity
  - Energy harvesting
  - Enhanced positioning
- Sustainable implementation
  - Printed electronics
- Reconfigurable
  - IoT (RIoT) nodes
  - Network
  - Dynamic selection of light/radio
- Four applications will be used to demonstrate the potential for SUPERIOT.

- Please check the website for more info and join the SUPERIOT LinkedIn group
- https://superiot.eu
- www.linkedin.com/company/superiot

THANK YOU

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