D4.3 Demonstrator 3: Printed Limited-capability IoT Node

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Executive Summary

This document presents a project-level summary of the implementation and outcomes for the demonstrator based on printed electronics technology.

The primary objective is to show, at laboratory scale, that this technology is feasible and could advance to higher levels of technological maturity through ongoing development (Technology Readiness Level 3, Horizon projects). For SNS Phase 1 Stream B projects, the intended TRL is "low to medium". The demonstrator node has been created using reverse offset printed transistors and gravure printed organic solar cells, supporting the concept of minimal IoT nodes. The technology is ready for further development, with no fundamental problems identified, confirming its scientific feasibility. Key features of the demonstrator include energy autonomy and the capability to receive, send, and display information. This node does not rely on battery power; instead, all energy is harvested from printed solar cells, which also act as both energy and information receivers. Information is transmitted to the node using three light wavelength bands (red, green, blue), pulsed to encode signals. The printed transistors are tested to determine how much energy is required from the solar cells, and the solar cell modules are designed to deliver this output. Optical filters are integrated to enable selective responsiveness to different colours. Output information takes the form of a voltage pulse, which can be connected to an indicator such as a printed display element, an e-paper display, or used to modulate the response of a backscattering antenna..

In summary, the demonstrator was developed to validate SUPERIOT's potential for utilizing printed electronics technologies. It consists of a node that can be addressed by the green, blue, and red components of a light signal, with one colour serving as the system clock. The node generates a voltage output signal, making it energy autonomous and capable of both receiving and displaying or sending information.

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Editions

Version	Date	Modified by	Modification
0.1	2025-12-01	Henrik Sandberg, VTT	First draft outline
0.1	2025-12-12	Marcin Drzewiecki, MPICOSYS	Added section 3.6 Access point for the printed IoT node with backend system/UI
0.2	2025-12-20	Juha Häkkinen, UOULU	Final assembled lab demo experimental results added
0.3	2025-12-21	Henrik Sandberg, VTT	First full draft version for review
0.4	2025-12-22	Marcin Drzewiecki, MPICOSYS	Fixed issue with references to figures in the text in Section 3.7 Access point for the printed IoT node with backend system/UI
1.0	2025-12-29	Henrik Sandberg, VTT	Clean version after internal review
1.1	2026-05-08	Henrik Sandberg, VTT	DRAFT - Revised version based on request from the project officer
2.0	2026-05-22	Henrik Sandberg, VTT	Clean revised version

1 Acronyms

6G	The sixth-generation mobile communication system
a-Si	amorphous Silicon
AES	Advanced Encryption Standard
ALD	Atomic Layer Deposition
AP	Access Point
BBB	BeagleBone Black
BLE	Bluetooth Low Energy
CS	Channel Sounding
CVD	Chemical Vapor Deposition
EMI	Electromagnetic Interference
EPD	Electronic Paper Display
ERs	Emergency Rooms
GUI	Graphical User Interface
ICT	Information and Communication Technologies
IoT	Internet of Things
LED	Light Emitting Diode
MQTT	Message Queuing Telemetry Transport
MRI	Magnetic Resonance Imaging
OPV	Organic Photovoltaic
OTA	Over-the-air
PCB	Printed Circuit Board
PE	Printed Electronics
PIL	Python Imaging Library
QoS	Quality of Service
RF	Radiofrequency
RFID	Radio-Frequency Identification
RIoT	Reconfigurable IoT

RSSI	Received Signal Strength Indicator
SLIPT	Simultaneous Light Information and Power Transfer
SUPERIOT	Project no 101096021 (Truly Sustainable Printed Electronics-based IoT Combining Optical and Radio Wireless Technologies)
SWIPT	Simultaneous Wireless Information and Power Transfer
UWB	Ultra-wideband
VLC	Visible Light Communication

2 Introduction

2.1 Motivation

The Internet of Things (IoT) has the potential to significantly improve various areas of society, but for large-scale utilization using current technology, the cost and environmental impact are high. Both issues are efficiently addressed by employing printed electronics technologies and simplifying the application case to the absolute minimum.

Unlike the other demonstrators of this project, the printed node doesn't address a specific use case. Instead, the objective is to set a benchmark for creating a fully printed IoT node using printed electronics technologies, as laid out in the grant agreement of SUPERIOT [1]. To cover the minimum requirements of an IoT node, the printed node should be energy autonomous, i.e. battery-free and energetically sustainable, so that the energy harvested from light or radio is sufficient for normal operation of the node.It should be capable of communicating with an access point (AP), either using the SUPERIOT dual RF/light communication approach in part or employing both modes, and it should be made by printing or compatible techniques to ensure low environmental impact and low overall cost.

The SUPERIOT Opportunity

Demonstrator 3 is positioned to illustrate how printed devices developed in SUPERIOT can fit in an IoT network environment, and communication can be established between the access point and the node via RF and/or light modes. The project specifically addresses the development of printed transistor devices, organic printed solar cell technology, charge storage components such as printed supercapacitors, and other electronic components as reported in Deliverable D2.3 [2] and other reports from Work Package 2.

As our life and surroundings are increasingly monitored and measured, the amount of electronic devices will continue to rise sharply, posing challenges for the environment and access to natural resources. The cost and ease of manufacture must be improved. Printed electronics technology can, in the future, address these challenges by leveraging the key capabilities of the SUPERIOT concept:

- **Dual-Mode Communication and Reconfigurability**: The dual optical-radio (VLC/RF) communication system provides the opportunity to select the design and mode of operation depending on the requirements of the application to meet only the specific need while keeping cost and other negative impact low.
- **Sustainable Implementation and Energy Autonomy:** By utilizing printed electronics (PE) and aiming for energy autonomy, the demonstrator seeks to provide eco-friendly, cost-effective solutions for components. The design philosophy aims to replace conventional batteries by harvesting and storing energy from light and RF sources, leading to reduced cost, maintenance, and environmental impact. The demonstrator aims to maximize the utilization of printed technologies and materials to showcase state-of-the-art in this field.

2.2 Summary

The demonstration was designed to build upon the hybrid node and other demonstrators of SUPERIOT, and to design a system based on the node itself from a printed electronic standpoint, rather than a use case as in the other demonstrators. The components developed in WP2 were carefully characterized, and a system was designed so that ideally only printed devices were used. Thus, the capabilities of the node are reduced to the bare minimum, but with the essential properties expected of an IoT system, namely being addressable, receiving information, and sending information.

3 Demonstrator 3: Printed Limited-capability IoT Node

3.1 General requirements

A specific project objective unique to this demonstrator is the development of a sustainable implementation of the IoT node. To achieve this the use of printed electronics (PE) technology is maximized, e.g. by developing printed components and substrates specifically for this project. A "Less is More" philosophy has been adopted: using resources more efficiently and wisely, while implementing only the necessary properties instead of creating multifunctional devices the goal can be reached. Since PE is a sustainable manufacturing technology and the printed components are more sustainable than conventional ones, an IoT node or device using this technology will be more sustainable. This means that less energy is needed in its manufacturing process. In many cases, more abundant and less problematic elements or materials would have been used. Moreover, the use of PE would result in less problematic e-waste and a lower environmental load. As PE technology advances, the share of PE in IoT node implementations will increase, making nodes more sustainable. The technology readiness level (TRL) target for the printed electronics-based IoT node is three, i.e., a proof-of-concept model is constructed. In other words, results from experiments/tests support the initial idea, and the technology is ready to go to the development phases, and one can conclude that the new technology is feasible from a scientific point of view.

In the spirit of the SUPERIOT project, the node will receive data via an optical interface based on organic photovoltaic (OPV) cells/modules. From these, also the required energy will be harvested. The optical signals will identify the node as well as function as a trigger. The nodes will be "hard coded" with an identity using optical filters. A back-scattering part of the node will send the information as a "ping" reply over radio frequency for the node that is addressed using the optical signal. Alternatively, feedback from the node can be provided visually by an indicator or electrochromic device which can be made by printing.

To demonstrate the addressability, two channels will be used for addressing; thus, three nodes can be identified. However, depending on the application needs, the number of channels can be increased.

All the components developed in the project have been reported in Deliverables for WP2, including TFTs (thin film transistors), diodes, OPVs, and others. The back-scattering module requires the use of an inductor and a capacitor, and while these can be made by printing, the development of such components are not included in the DoA. Thus, if the components cannot be made with the required specifications based on VTT or NOVA.id.FCT background technology, the components will be sourced externally, if needed. The circuit is described in Figure 1.

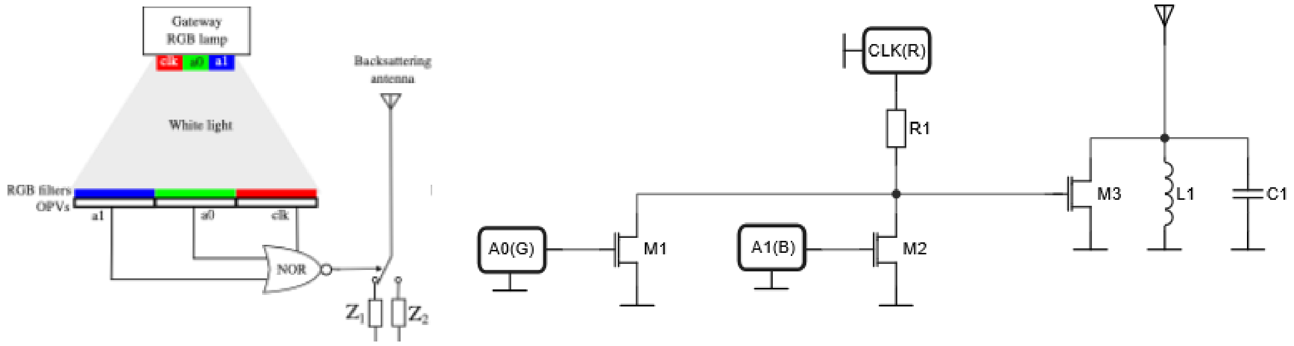


Figure 1. The principle of operation and the schematic design of the fully printed node.

The circuit design for the fully printed node will be applied and experimentally validated after the circuit has been verified using the final versions of the printed components. Transistors are manufactured in various dimensions, leading to a variety of specifications, so that suitable components can be found experimentally. Additionally, the OPVs have been made using layouts that allow them to be combined and connected in various ways to obtain the required voltage and current levels. A circuit board will be printed on thin polyethylene terephthalate (PET) sheets using screen printing, which allows the formation of sufficiently thick layers to yield high conductivity, thereby forming the carrier of the lightweight and flexible node design. The PET sheet will feature landing patterns for reverse offset printed (ROP) transistor "chips" based on polyimide (PI), containing all required transistors for the node in one small area. VTT has also developed a "flip chip" type process to combine ROP printed flexible "chips" with other printed components and modules. To make the different structures on different materials using different printing techniques, based on their dimensions and other criteria, is the most efficient method for combining very small-features and large structures in one system.

The node, as shown in Figure 1, will communicate with the SUPERIOT network using a specially designed access point with a supporting backend system and user interface (UI). The access point is not part of the node design nor development, but MPICOSYS which is responsible for the access point implementation, has been involved in the node design and development throughout the process to ensure compatibility.

3.2 Demonstrator proof-of-concept

To demonstrate the concept, initially two node circuits were implemented, combining both light and RF communication. Simplified nodes that combine RF and optical information pathways have been demonstrated as proof of concept using conventional electronics but possible to realize using printed components. Two options have been made where both utilize the backscattering channel for uplink information, with a solar cell functioning as the downlink channel to steer the function of the backscattering module.

The proof-of-concept version of Demonstrator 3 depicted in Figure 1 was presented experimentally using discrete components at a technical meeting of the project and is shown in Figure 2.

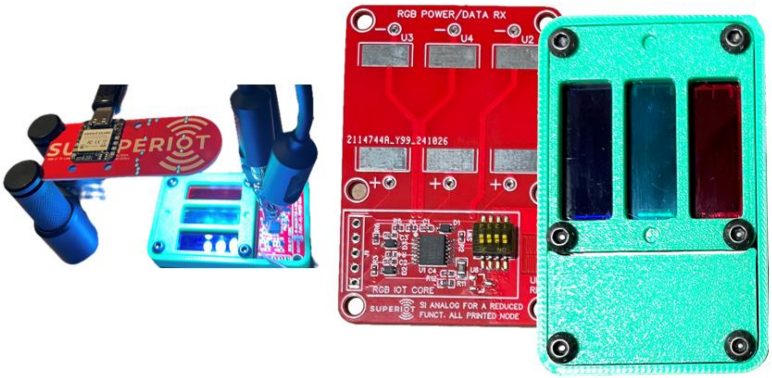


Figure 2. Proof of concept realization of the Demo 3 using traditional discrete components (non-printed version).

A more capable demonstrator was made and presented as a scientific publication and at scientific conferences [3]. This work demonstrates a hybrid platform that integrates Simultaneous Wireless Information and Power Transfer (SWIPT), Simultaneous Light Information and Power Transfer (SLIPT), and RF backscatter to power battery-free IoT nodes while providing localization capabilities. A schematic and photo of the experimental setup of the hybrid node are presented in Figure 3.

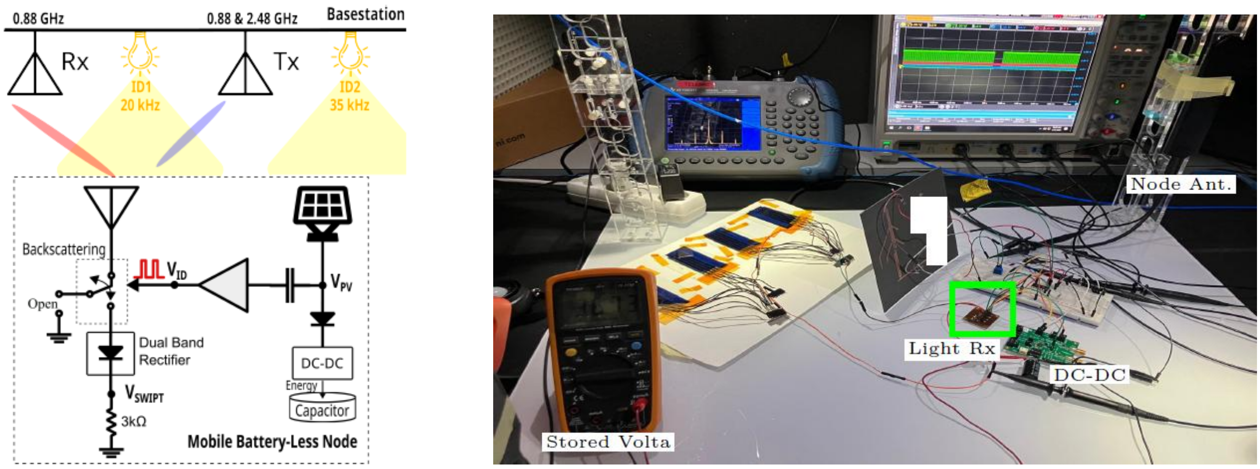
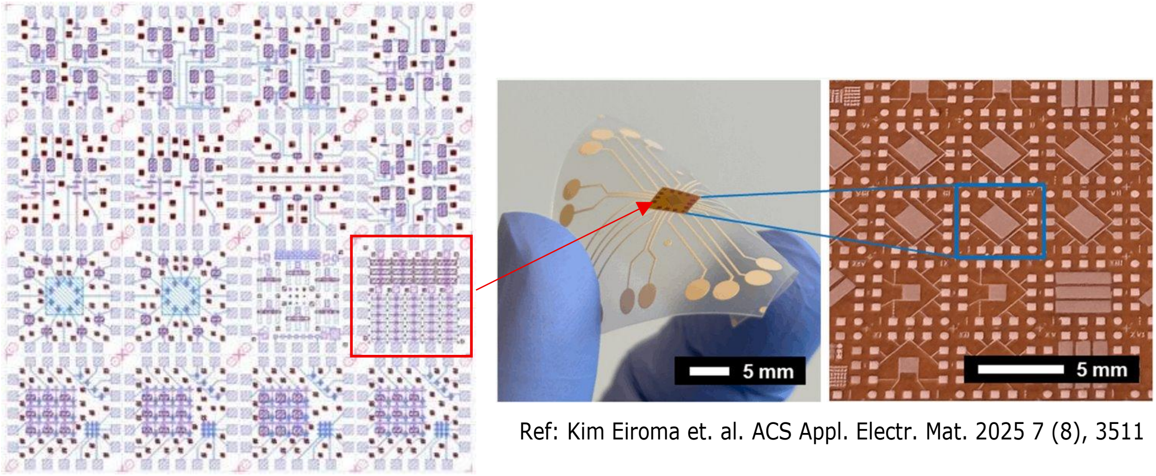


Figure 3. Hybrid RF and light localization system concept for battery-less IoT applications (left) and implementation using OPVs and discrete components (right).

The node was initially made using some printed components (OPV), and it was further developed towards printed implementation by attempting to replace conventional components with printed components one by one; such as capacitors, diodes, and antenna structures.

3.3 Printed components

One of the main individual components developed in the project is the thin-film transistor, a central and critical component in all modern electronics. ROP has been used to create transistors of various dimensions corresponding to a variety of specifications. Of these, the most suitable TFTs can be selected for the final demonstrator. The TFTs and logic gates made from interconnected TFTs can be connected using external wiring or using another printed flexible sheet with, for example, screen printed conducting traces utilizing a flip-chip type process. (see Figure 4, with detailed description in the reference [4]).



Ref: Kim Eiroma et. al. ACS Appl. Electr. Mat. 2025 7 (8), 3511

Figure 4. Printing plate design for manufacturing polyimide flexible "chips" with TFTs and logic gates (left) and method for integrating polyimide chips on larger flexible (and optionally, stretchable) substrates (right).

The OPV manufacturing process has been developed over a long period through various projects, and resources in this project are used only for modifying the material, layouts, and processes for the specifications needed in this project.

To serve multiple circuits in this project, other printed components, such as diodes based on solutionprocessable ZTO (Zinc Tin Oxide) and TFT-connected diodes used as rectifying or switching elements, as well as printed backscattering antennas, were developed. A PCB connector board (shown in Figure 5 a) was specifically produced under the project to allow for component integration. To increase the chances of success of the circuits, passive printed components, not initially intended on the DoA, were being fabricated, such as thin-films resistors based on sputtered Molybdenum films for lower resistance (R ~800 Ohm to 30 kOhm) and printed resistors based on Carbon inks for higher resistance (1 MOhm to 22 MOhm). Resistors based on thin films or commercially available carbon-based inks were evaluated for different demonstrators. At this stage, standardised inks were chosen over those used for micro-supercapacitor electrodes, despite the former exhibiting higher resistivity. Capacitor based on Al/Parylene/Al layers with different overlapping areas and therefore different capacity values were developed according to the circuit requirements. All these components are dimensioned to be compatible with the connector board for PCB, as depicted in Figure 5 during development.

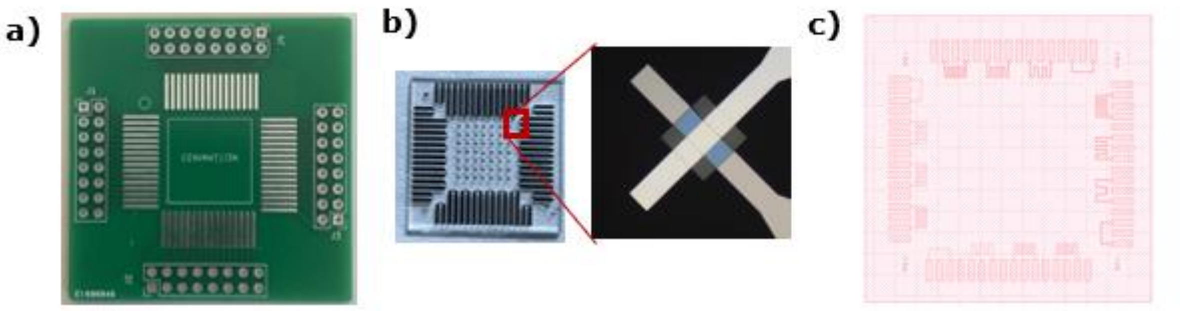


Figure 5. a) Connector boards able to receive extended pad components; b) printed diodes and c) resistor design masks.

The printed components developed in the project were reported separately in Deliverable 2.3 [2].The components available for integration in Demo 3 are listed in Table 1, although in the end, not all were required for the final demonstrator.

Table 1. Printed components to be implemented.

Component	**Description**	**Responsible partner**	**Risk assessment and mitigation plan**
Transistor	ROP-printed TFT	VTT	Tested in PoC and new print layout and plates are in manufacturing
OPV	Printed using various methods, e.g. screen	VTT	Tested in various configurations
Resistor and Photoresistors	Printed and thin films	VTT or NOVA.id.FCT	Can also be implemented using a diode-connected TFT. Resistor development is not in DoA.
Inductor	Needed for backscattering, can be printed but no resources in DoA.	NOVA.id.FCT	As resources not available in DoA, may have to fall back on discrete component if required specifications require printing process development.
Capacitor	Needed for backscattering, can be printed but no resources in DoA.	NOVA.id.FCT	As resources not available in DoA, may have to fall back on discrete components if required specifications require printing process development.

Antenna	Printed	NOVA.id.FCT	Printed structures are under investigation at KU Leuven.
Diode	Printed	NOVA.id.FCT	Printed structures are under investigation at KU Leuven.
μSupercapacitor	Printed	NOVA.id.FCT	Tested in different arrangements and configurations

3.3.1 Reverse offset printed transistors

The critical and most central component of the circuit is the transistor. These were manufactured using the ROP printing technique as indicated above and with an example shown in Figure 6. The TFTs produced for the demonstrator are based on metal oxide as the semiconductor. Electrode material is a metal which is patterned using ROP.

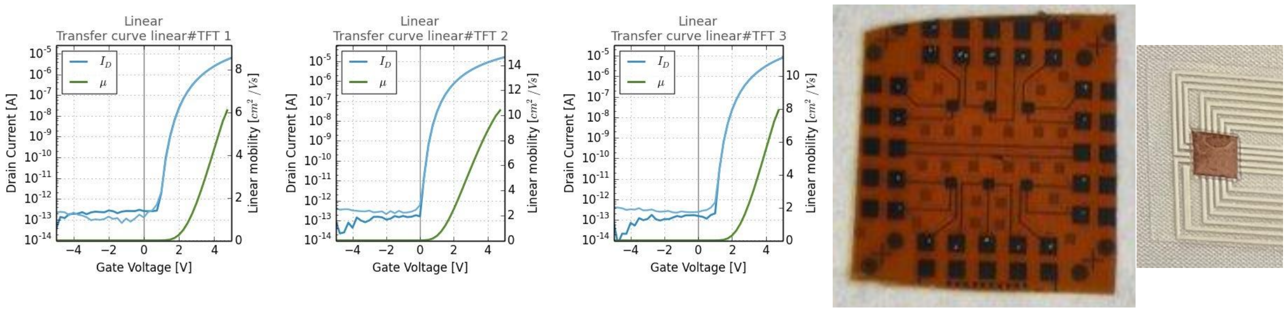


Figure 6. Each ROP printed chip contains six transistors, two sets of three identical transistors as required by the circuit. The transfer curves display the performance of the top row of transistors in the chip shown on the right, while the photograph on the far right shows the PI transistor chip integrated onto the PET carrier substrate.

Five chips were selected based on initial characterization and sent to the flip-chip integration onto flexible PET circuit board.

3.3.2 Printed organic solar cells manufacture and characterization

The OPVs (Figure 7) used simultaneously as a photo-sensors and for generating the required power, were made in accordance with procedures described in Deliverable D2.3 of WP2 [2]. The photoactive material in these devices is NF3000, and the gravure printed modules can produce an open circuit voltage (Voc) of around 4.5 V and 200 µW when illuminated at 1000 lx.

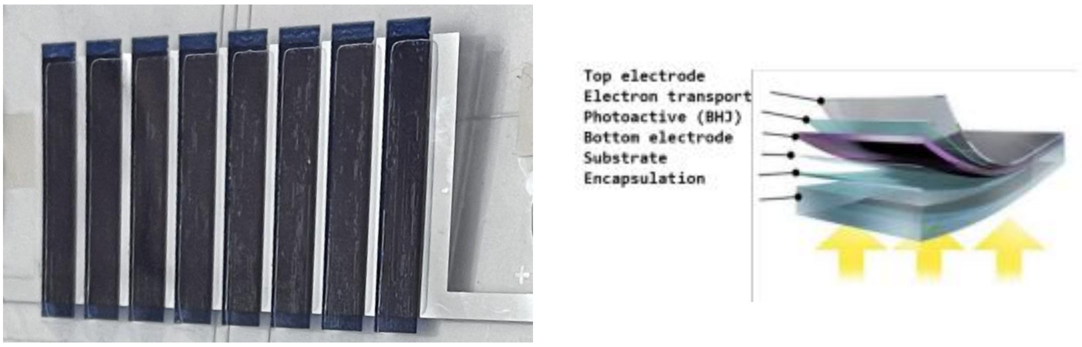


Figure 7. OPV module consisting of eight cells manufactured for the hybrid and the printed demonstrators. The modules are encapsulated for maximum durability and lifetime.

3.4 Backscattering Design and Operation

The preferential backchannel for the printed node is a backscattering RF system. A more advanced backscattering arrangement is implemented in Demonstrator 2 in the SWIPT & RF scenario (see report D4.2 [5]), where the proposed node supports both SWIPT and backscatter communication using a dual-band circuit that operates at 880 MHz and 2.48 GHz. Due to the completely different frequency and power range where the printed node operates, the back channel cannot be readily transferred to the printed node but would require extensive modifications. All required elements, however, can potentially be made using printing methods.

3.5 Integration of components

Screen printing is used to create a plastic main circuit board where the transistor "chips" and the OPV modules will be integrated and connected with the other components to make up the flexible printed node. The design is shown in Figure 8.

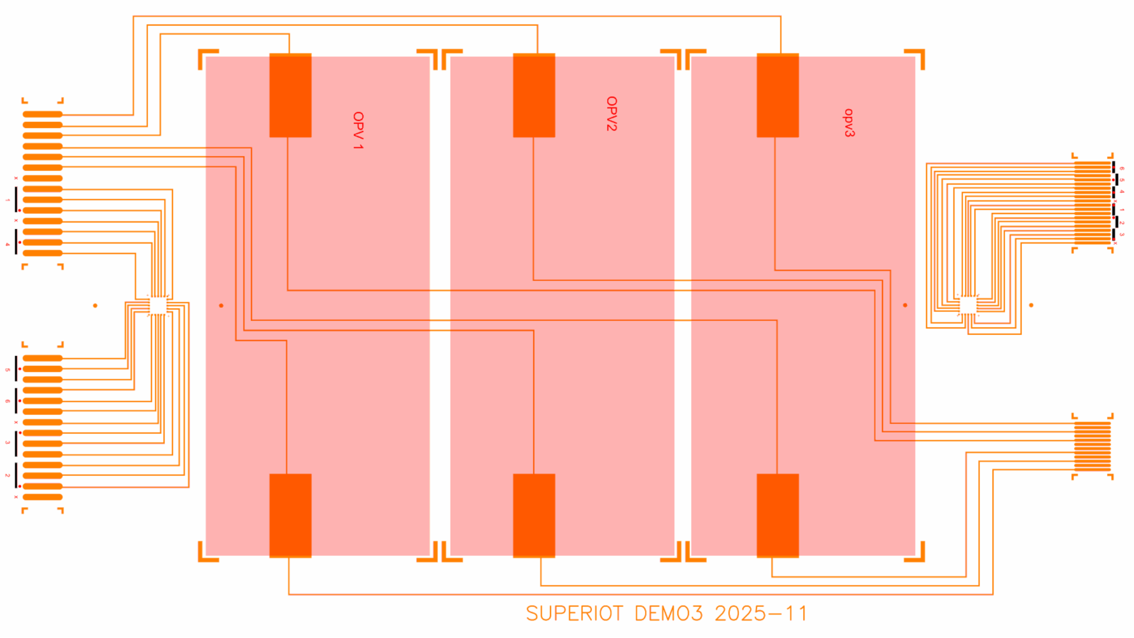


Figure 8. The small chip with the transistors as well as the OPV modules will be integrated using a screen-printed flexible circuit board. The conducting traces are based on a silver particle ink for optimized conductivity printed onto a 125 µm thick film of PET.

The TFT chips are bonded to the landing patterns in the layout. There are two positions for the TFT chips, to allow for either smaller or larger connection pads. Only one TFT chip is connected to form the demo circuit.

3.6 Proof-of-concept laboratory demo

3.6.1 Node implementation

As shown in Figure 9 (a), the demo node was implemented by three OPVs, two printed TFTs (M1 and M2), and three traditional resistors. These were connected to the demo circuit using a wiring bard shown in figure 9 (b). *Lee Colour Filter PAR64*[1] gel filters were attached to the OPVs to provide RGB separation of clock and address signals.

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[1] 106 - Primary Red, 139 - Primary Green and 120 - Deep Blue

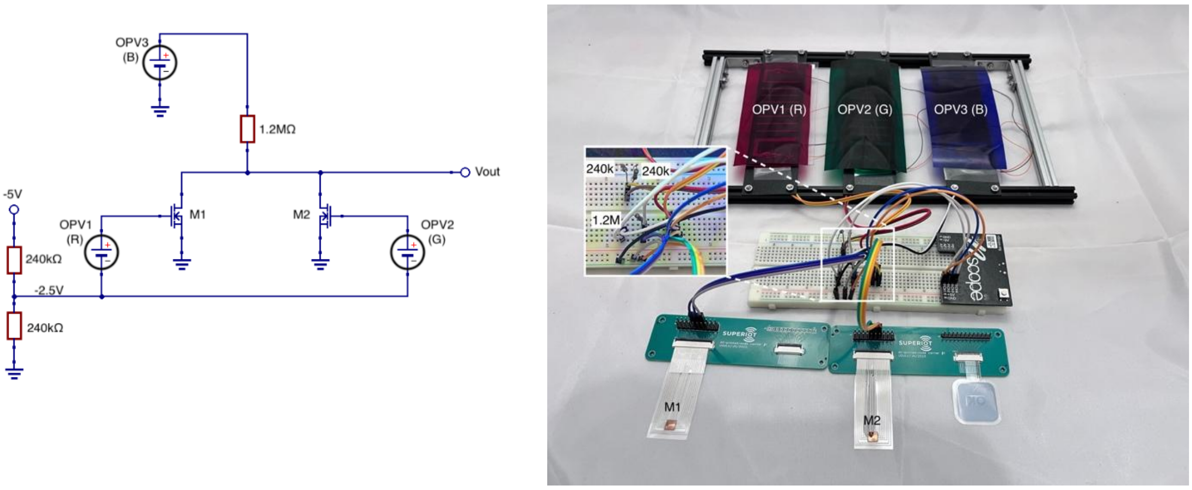

Figure 9. (a) Schematic and (b) implementation of the node.

All materials and components used in the demonstrator node implementation are listed in Table 2. The table also indicates which of the items were included in the sustainability evaluation performed in Work Package 1 and reported in Deliverable report D1.5. The sustainability evaluation was focussed on fully printed components; therefore, the traditional resistors that were introduced for signal fine-tuning were not included. The main circuit board is based on the same substrate material as the solar cell. An evaluation of the sustainability of the combination of silver ink on PET is reported by VTT and Lappeenranta Univ of Techn. In the paper by Nassajfar et al 2023 Flex.Print.Electron. 8 025015.

Table 2 Components and materials used in the printed node demonstrator. The SUPERIOT components/modules evaluated in D5.1 are indicated. Evaluation of other materials have mostly been reported in other projects.

Component/material	Comment (incl evaluation in D1.5)
Printed transistor chip	2 chips (only two transistors are connected) [**D5.1**]
Printed organic solar cell	3 modules [**D5.1**]
Colour filter film	3 pcs (red, green, blue), could also be printed [not evaluated in D5.1]
Resistor	3 pcs (traditional, could also be printed) [not evaluated in D5.1]
Main circuit board	Test layout, could be minimized to exclude test contacts and reduce the use of materials [not evaluated in D5.1]
Conductive adhesive	For integration of modules [not evaluated in D5.1]

3.6.2 Test setup

As shown in Figure 10, three Senrise 10W LEDs[2] were used as test light sources, one for the clock and two for the address signals. Daylight white (6000-6500K) versions of LEDs were used to create strong signals also in the blue side of the spectrum. To create the required colours for each signal, RGB filters matching those used in front of the OPVs were placed in front of each LED. Hence, separate channels were created between similar-coloured lamps and LEDs. It is

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[2] SENRISE HA1828A:ZC217303334

worth noting that the full brightness (10 W) of the LEDs was not used in the experiments; rather, the current through each LED was about 400 mA, which gave roughly 1.2 W of power.

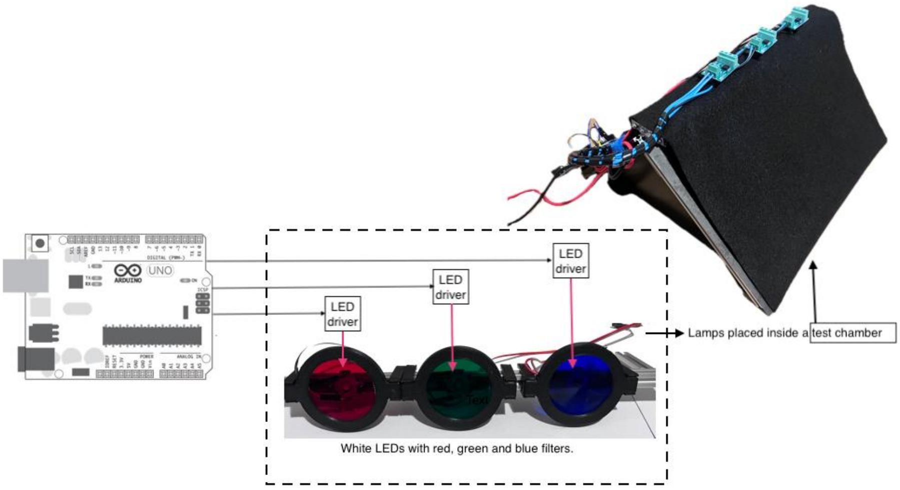

Figure 10. Lamp control, RGB lamp rig and test chamber.

As shown in Figure 10, The lamps were attached to the roof of a light-proof measurement chamber, and the LED lamps were controlled individually by an Arduino Uno microcontroller board.

Finally, the OPVs of the implemented node were placed under the RGB lamps inside the test chamber as shown in Figure 11. The NScope[3] wiring board and NLab application running on a personal computer were used to take measurements of the OPV output signals and the circuit output (Vout).

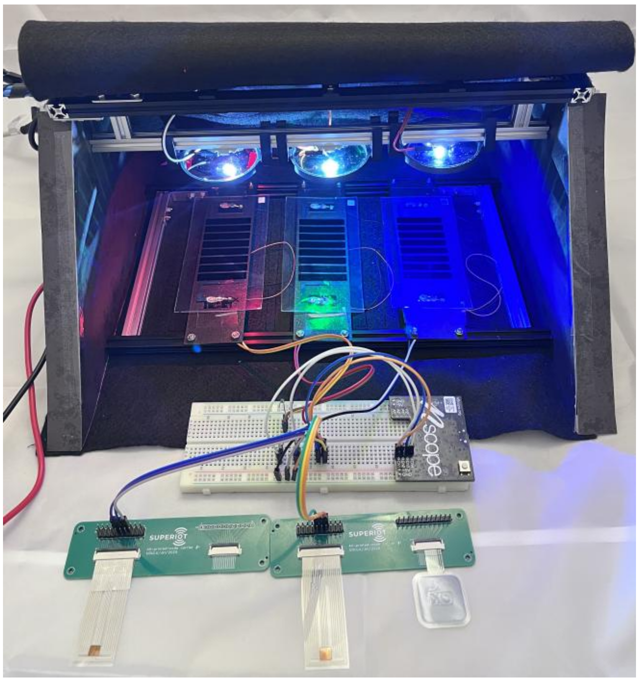

Figure 11. Final test setup with node (without filters on OPVs) partially placed inside the test chamber.

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[3] https://getnlab.com

3.6.3 Measurements

In all measurement plots below the signals are assigned as follows; yellow curve = Vout, red curve = clk (R channel), blue and green curve = address0 and address1(B and G cannel), respectively. Fclk = 62.5 Hz (i.e. no visible flicker in lighting inside the test chamber) or fclk = 6.25 Hz (to show high-quality signal waveforms well below the -3 dB bandwidth of the system).

Address0 and address1 were defined to be HIGH (1) when they are in the same phase as the clk, and LOW (0) when 180° out of phase.

Table 2 shows signal waveforms without filters (i.e. all lamps and OPVs without filters, lamp-OPV pairs in their own compartments leading to no leak between channels, hence, mimicking ideal R, G and B filters).

Table 2. R. G and B (clk, address0 and address1) signals for different addresses – no filters used.

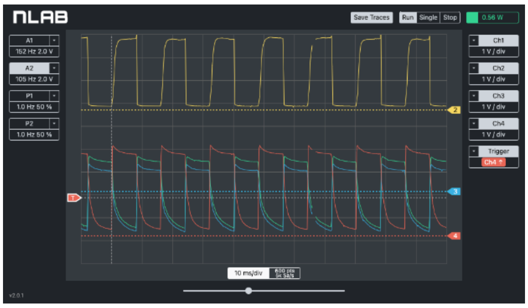
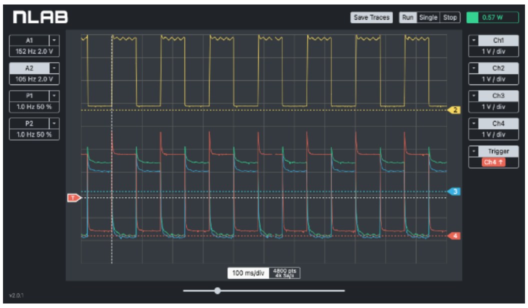
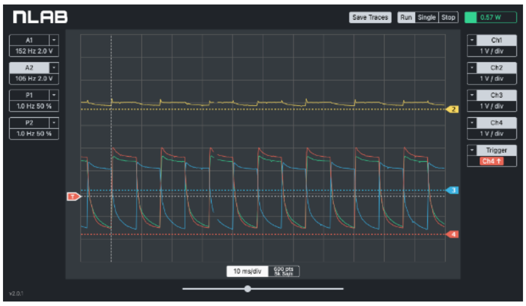
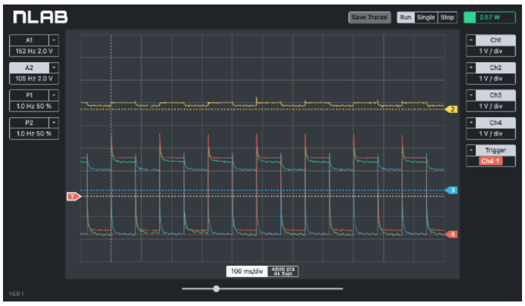
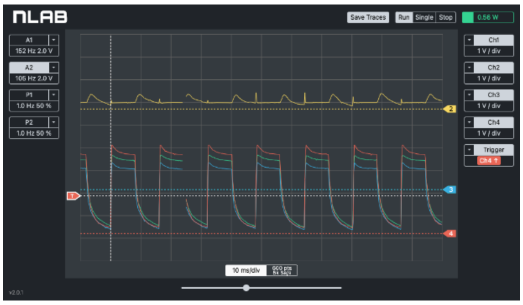
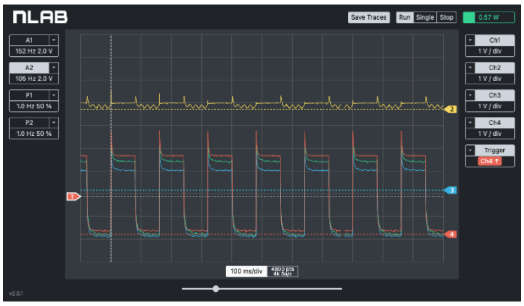
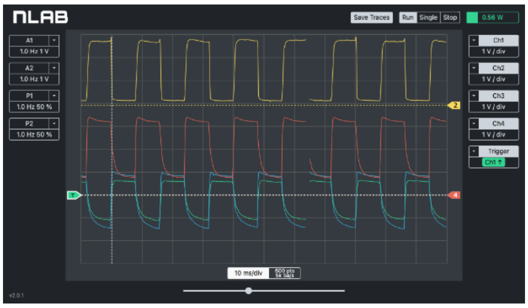
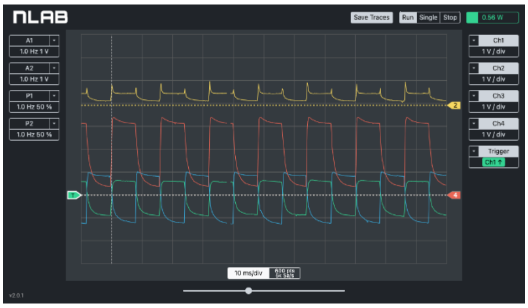
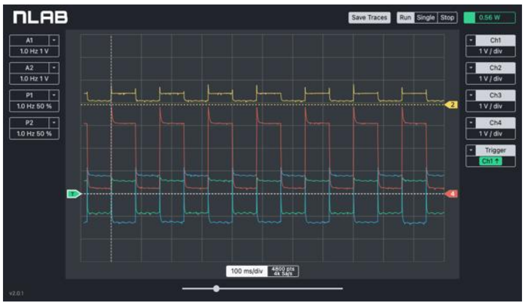
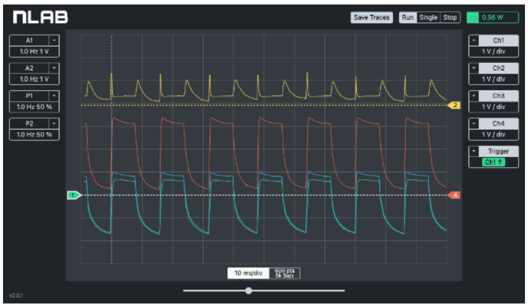
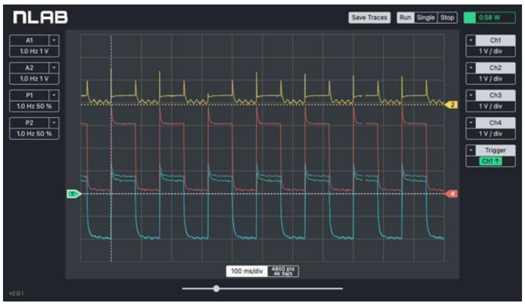
Address	Signals at 62.5 Hz	Signals at 6.25 Hz
00 (addressed)		
01 and 10		
11		

Table 3 shows signal waveforms with OPVs in the same space and cannel separation provided by R, G and B filters in front of both lamps and OPVs.

Table 3. R. G and B (clk, address0 and address1) signals for different addresses – colour filters used.

Address	Signals at 62.5 Hz	Signals at 6.25 Hz
00 (addressed)		
01 and 10		
11		

Results show that the node is addressable when addresses (Addess0 and Address1) are both zero. For this address, the output Vout is a square wave. For all other addresses, the output is LOW. The output signal could be used to power a printed indicator such as an electrochromic element, or to modulate a back-scatter response of an RF signal. Thus, the demonstrator on TRL 3 level show in an experimental fashion that a node with minimum functionality can be realized by printing and to advance the technology from the lab scale proof of concept to a practical implementation can be made by further tweaking of the component dimensions and material choices using the methods and principles demonstrated in this work. The flexible electronics implementation is shown in Figure 12.

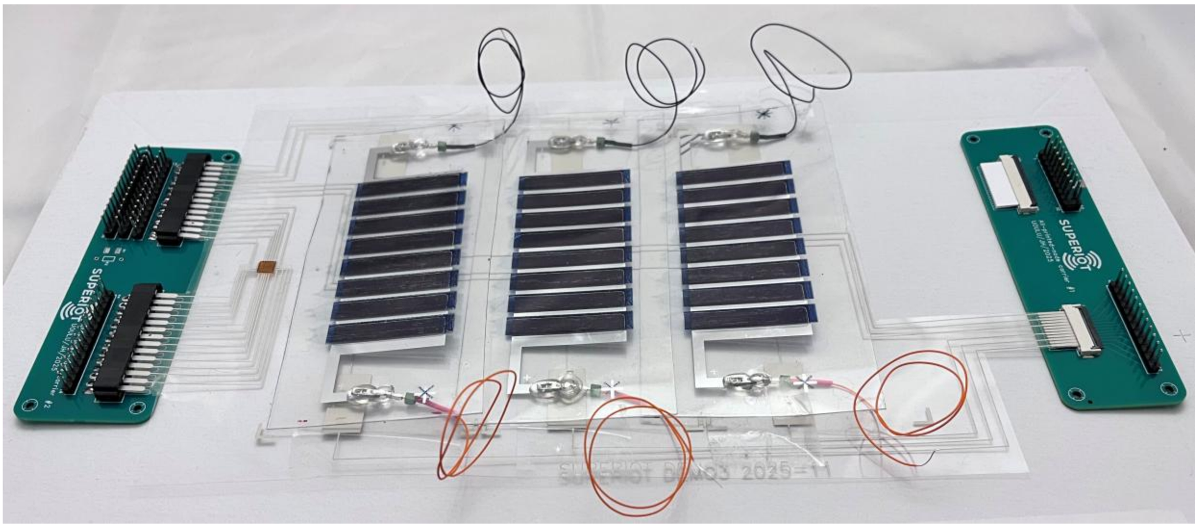


Figure 12 Flexible electronics implementation of the node with extra wires connected for probing the OPV modules and external connection test boards at the flat cable interfaces to allow the connection of various TFT components during testing.

3.6.4 Energy requirements for the node

Sustainable electronics also address the energy requirement of the system during operation. This node is significantly minimized in functionality, mainly to facilitate the limitations of printed electronics, but simultaneously for minimizing the energy needs. The implementation of printed electronics in this demonstrator is limited to the node functionality; thus, the power requirements of the access point is not considered. As described above, the up-link is also not implemented, but reference is made to the other demonstrations with back-scattering channel and e-paper modules. The most power efficient uplink would be based on a visual indicator such as the e-paper display technology. The power requirement for an e-paper display is in the range of 1 μW/cm^2.[4] Energy is required mainly for changing the state of the indicator and scales with the surface area. Only 1,5 V is required for switching and the speed of change of state depends on the current available. Maintaining the ON-state requires 1,1 μA/cm^2 and thus the switching current needs to be higher, but the energy required to make one switch from OFF state to ON state is 1 mJ/cm^2. The power requirement is for maintaining a specific state, thus, to maintain the state a refresh is needed with a few seconds (5-10) but this operation only requires energy in the μJ range per cm^2 of indicator area.

Of more relevance to the power requirement consideration is the minimum voltages and currents available in the node, to be able to function. Since the node is powered by the OPV modules, the threshold for node function relates to the light intensity of the light signal. The use environment envisaged for the node is indoors with lighting where the pulse code / drive of the node is masked by the continuous white light. Thus, the light for powering the device is fairly strong and there will be sufficient voltage generated in the OPV modules. However, the power consumed by the TFTs and the resistors in the circuit under operation can still be calculated in order to further optimize the device.

For a theoretical analysis a few assumptions are required; the TFTs are all identical (same turn on voltage, mobility, channel resistance, and the Gate current is assumed to be zero and no drift is assumed in the devices over time). In practice there is a variation, which is why there is a margin in the values the circuit is based on. The TFTs are not of a pure "enhancement type", meaning that the turn on voltage is not positive, a small negative bias is required to completely turn the TFT channel off. This is the reason a bias divider is required. (see the left part of Figure 9a) The current implementation uses a bias divider resulting in a -2,5 V bis a the two signal TFTs

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[4] See https://www.ynvisible.com/e-paper-displays?datasheet-popup-filled=1 (visited 20260507)

to make sure they stay in the OFF state. This bias divider consumes a power of ~52 µW. When considering the power consumed by the current thorough the transistors, there are three distinct cases depending on the switching state of the circuit. When both transistors are in the OFF state there is no current running through, i.e. ~0 W is used. Since the load resistor is much larger than the channel resistance in the transistors, the power requirements are similar regardless of whether one or both transistors are in the ON state, i.e. 13.3 µW. But the light is pulsed also for the clock signal, and the duty cycle is 50%, cutting the power requirement in half. Thus, the worst case scenario for power requirement is P_{total} = 52 µW + ½*13,3 µW = 58,9 µW. Considering a simple use case where the node is used for identification and an indication for 1 s is required in the e-paper pixel, the energy requirement is correspondingly ~60 µJ. This is significantly lower than the energy required to switch the state of the indicator. The light intensity will determine the level of current that is available to switch the indicator state, but in any case the most energy is consumed by the e-paper pixel.

3.7 There are a few strategies to further reduce the power requirement to take into account in further development of the technology. This is the most relevant for cases where the transistor circuit accounts for a larger portion of the power requirement. First, further development of the printed transistor and the printable materials could result in enhancement type transistors. In this case, since the transistor channel is then in the OFF-state when not biased, the power contribution will be only that of the current through the transistors and the load resistor. In the case of a 50% duty cycle the power requirement will be 6,67 µW. It's not un-likely that TFTs with a positive threshold voltage could be developed by utilizing new oxide materials or optimizing the structure and manufacturing process even further. If enhancement mode transistors cannot be achieved another solution would be to increase the resistance of the bias divider resistors as this will significantly reduce the power consumed by this part of the circuit. Using resistors in the range of ~20 MOhm will already reduce the contribution to the power requirement to only ~10% of the overall power requirement. Furthermore, the circuit could be additionally modified so that diode-connected transistors are used instead of resistors. This will achieve a self-stabilizing circuit that can account for variations in the device performance from one batch of printed devices to the other. On the other hand, this require more printed TFTs and the need for bias to fully close the TFT channel requires an additional OPV module to make the node fully self-powered. The main benefit of minimizing the power requirements is that the OPVs can be made smaller in size as lower currents are required. The number of cells in the OPV module cannot be changed as the voltage must still be sufficient to switch the transistors.Access point for the printed IoT node with backend system/UI

The Demonstrator 3: Printed Limited-capability IoT Node, incorporating the printed electronic components determined to be implemented and listed in Table 1, needed the suitable Access Point (AP) and backend system (BS) with User Interface (UI), ensuring proper data exchange with the MQTT cloud server (MQTT broker) and communication with the SUPERIOT network. It was needed to design and create such AP with BS and UI. The process included hardware and software integration and development. This process and results are detailed in the following subsections.

3.7.1 Access Point for the printed IoT node

The AP needed to be integrated into the existing SUPERIOT network, developed and delivered in WP3. The SUPERIOT network structure with the fully printed limited-capability IoT node and suitable AP is presented in Figure 13.

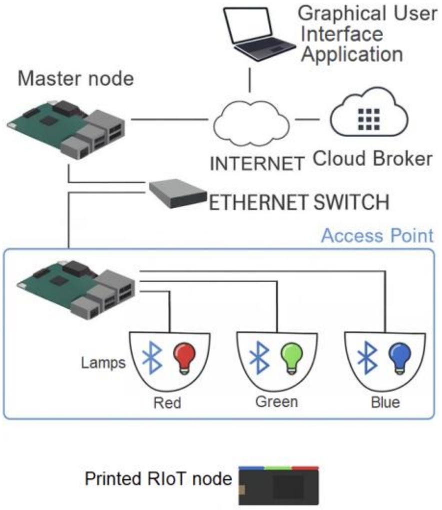


Figure 13 The SUPERIOT network structure with the fully printed limited-capability IoT node and dedicated Access Point.

The access point consisted of:

- Three NB VLC mini lamps LED modules delivered by UOULU in WP2 and further developed with UOULU and LIGHTBEE SL in WP4, each lamp equipped with the red or green or blue passive optical filter, in such a way as to obtain three independent channels: red, green, blue for RGB downlink communication.
- One Raspberry Pi Single Board Computer (SBC) equipped with Debian OS and running python scripts, controlling above-described RGB lamps via serial COM ports, and properly handling the network traffic and cooperating with the Master Node and SUPERIOT network, delivered and developed by MPICOSYS in WP4 on the basis of the SUPERIOT network software delivered by UOULU in WP3.

The RGB lamps equipped with the RGB optical filters and integrated together connected to Raspberry PI SBC are presented in Figure 14.

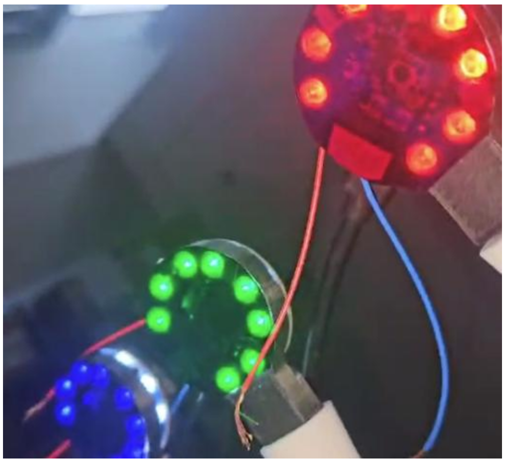


Figure 14. The RGB lamps are equipped with passive optical filters: red, green, and blue, enabling three independent channels for RGB communication with the Printed RIoT node.

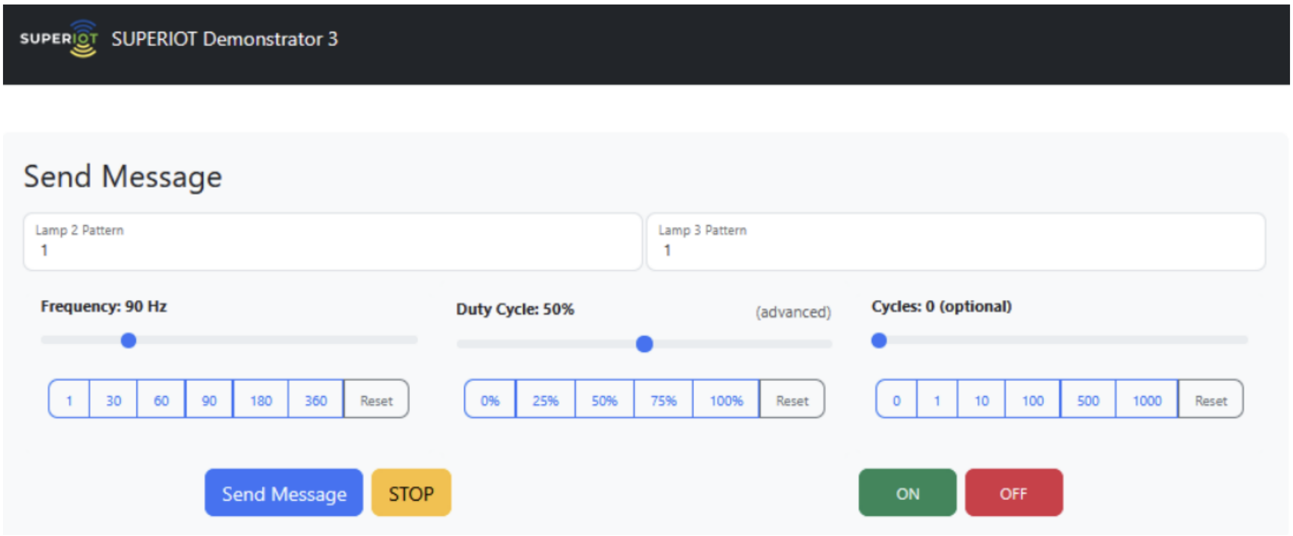
The AP's SBC properly handles the commands received over the SUPERIOT network with the Master Node and controls the RGB lamps, i.e. the data send over three independent RGB channels in form of the bit states High or Low.

It enables the printed IoT node to receive data via an optical interface based on OPV cells, also equipped with the corresponding RGB optical filters. Such optical signals actuate the printed IoT node according to the principle of operation resulting from the printed electronic design. According to the design presented, the red channel is used as a digital clock signal, while the green and blue channels are used as two independent digital data signals (High or Low bit state). Consequently, the printed transistors can be switched between conducting and non-conducting states depending on Gate-Source voltage and Drain-Source voltage. Functionally, it corresponds to the logic gate with three inputs and one output. Such RGB inputs control the logical output state to be High or Low and thus can switch what impedance is to be connected to the backscattering antenna. Then the backscattering antenna can be tuned. Moreover, the printed surface – e.g., indicator or electrochromic film – for the visual feedback from the node, can be used to be voltage-controlled from the output of the logic function – complementary or alternatively to the antenna. The AP for the printed IoT node is presented in Figure 15.

Figure 15. Access Point for the printed IoT node – RGB lamps on the left and Raspberry Pi SBC on the right.

3.7.2 Backend system and User Interface

In addition to the above-described design and creation of the AP for the printed IoT node, there was a need to develop the backend system and the frontend system with the Graphical User Interface (GUI). It has been done in the form of a webpage application available at https://superiot.mpicosys.com/demo/project_demonstrator3/browser/ . The Demonstrator 3 GUI webpage application, designed and created for the access point and printed IoT node, is presented in Figure 16.



SUPERIOT Demonstrator 3

Send Message

Lamp 2 Pattern: 1

Lamp 3 Pattern: 1

Frequency: 90 Hz

Duty Cycle: 50%

Cycles: 0 (optional)

Figure 16. The main view of the Demonstrator 3 GUI webpage – available at https://superiot.mpicosys.com/demo/project_demonstrator3/browser/ .

The webpage application realizes both functions:

- User Interface function that allows the user to enter the data in a convenient way,
- The backend system is properly processing the entered data.

The GUI webpage allows sending the message containing the logical states: 1 or 0, which corresponds to High and Low. The logical states can be set on both digital data channels described above as green and blue. It can be set in *Lamp 2 Pattern* and *Lamp 3 Pattern* corresponding fields. The logical values can be additionally set to be a logical sequence, i.e. not only 1 or 0, but also as a sequence(s) of subsequent logical values, e.g. 00001111 in *Lamp 2 Pattern* and 01010101 in *Lamp 3 Pattern.* According to the view presented in Figure 15, the following parameters can be defined by the user; the frequency of logical signals (field *Frequency:*), their duty cycle (field *Duty Cycle:*) and number of cycles (field *Cycles:)* . The digital clock signal related with the frequency, duty cycle and number of cycles is distributed with the use of the red channel described above. All communication is held by the SUPERIOT network.

The SUPERIOT network architecture was developed and implemented in WP3 and further developed and integrated with Demonstrators in WP4. The data entered by the user at the above presented Demonstrator 3's webpage is processed into the form of JSON structure and published to the MQTT broker superiot.mpicosys.com . It is published in the proper structure and with the proper content, allowing the SUPERIOT network to control the traffic with the Master Node and between the APs to be finally received by the fully printed IoT node in the downlink. The JSON structure and content for the exemplary data entered with the GUI and further processed are presented in Figure 16. The presented message is published to the *"cloud_broker/command"* topic of the MQTT broker when the "Send message" button is pressed in the GUI. The values for the keyword "exact command": in line 16 in Figure 17, correspond to the user-defined parameters visible in Figure 15.

```json
{
  "cloud_broker": {
    "commands": {
      "message_type": "command",
      "message_header": {
        "message_id": 1765560340,
        "message_timestamp": "2025-12-12T17:25:40.057Z",
        "message_destination_address": "MASTER_NODE",
        "message_destination_subelement": "D8:3A:DD:48:88:9A",
        "message_source_address": "SUPERIOT_CLOUD",
        "message_source_subelement": "UserApp",
        "message_acknowledgement_requested": false
      },
      "command_payload": {
        "command_category": "cloud_to_master_command",
        "exact_command": "{\"lamp2\":\"1\",\"lamp3\":\"1\",\"frequency\":90,\"duty_cycle\":37,\"cycles\":null}",
        "destination_type": "AP",
        "ap_address": "D8:3A:DD:48:88:9A",
        "node_address": "D8:3A:DD:48:88:9A",
        "expected_result": 1
      }
    }
  }
}
```

Figure 17. The JSON structure and content for the exemplary data entered with the GUI and processed by the backend system – the format is published to the MQTT cloud broker.

3.7.3 The laboratory model of printed IoT node applied

The fully printed IoT node required the completion production process for the printed components. Till this moment, the production of the node was still in progress, and the developed AP with BS and UI could not be integrated with the physical, fully printed IoT node. On the other hand, the development of the AP, BS, and UI needed to be processed. To enable the validation and integration processes, the laboratory model of the printed IoT model was prepared. According to the principle of operation shown in the left-hand part of Figure 1, the physical model of the printed IoT node device has been developed and used in integration. The model consisted of three thin-film amorphous silicon flexible PV cells LL200-2.4-37, laminated with standard PET and foil tape terminals, and for needs of the demonstrator 3, additionally integrated with passive optical filters: red, green, and blue. Such PV cells with RGB filters were used as the light receivers for the needs of downlink communication. The printed circuits were modelled with the use of a logic gate whose structure and logic diagram are presented in Figure 18. The A, B, and C input channels were connected to the PV cells that received red, green, and blue light, respectively. The logic value – High or Low – at the output Y resulted from the states of the A, B, and C inputs. In such a way the principle of operation was modelled logically.

Figure 18. Logic diagram of the gate modelling the principle of operation of fully printed limited-capability IoT node.

The view of the RGB receivers of laboratory model of printed IoT node is presented in Figure 19. The outputs of the receivers were connected to the input channels of logic cate.

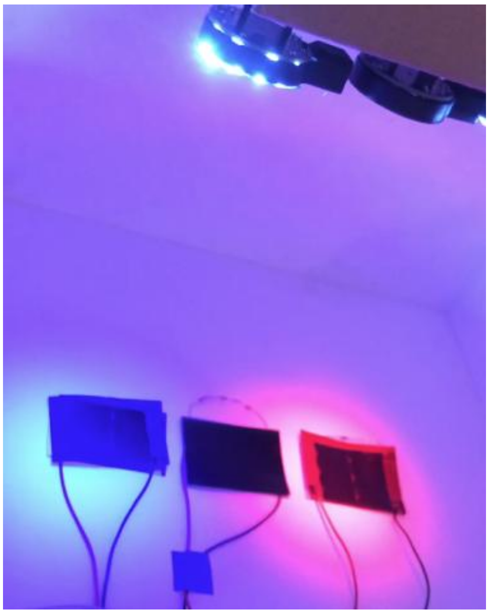


Figure 19 .The view of the RGB lamps (transmitters) on the top of the picture and RGB receivers of laboratory model of printed IoT node on the bottom of the picture.

Such printed IoT node model enabled the laboratory experiments on the integrated AP with BS and UI with verification of the logical output values controlled with the use of SUPERIOT network and GUI presented in Figure 16. The results of the experiment and integration of designed and created AP for printed IoT node with BS and UI is detailed in the following subsection.

3.7.4 Validation of designed and created Access Point for printed IoT node with backend system/UI

The designed and created AP with BS and UI were examined and validated by means of the oscilloscope measurements for the parameters set in GUI. First, the output voltage signals of the PV cells with RGB filters applied to the ABC logical channels input were measured. It was confirmed that for High and Low logic states configured in webpage GUI, the values received over the RGB light is correct and correspond to the expected logical values. It is presented in Figure 20.

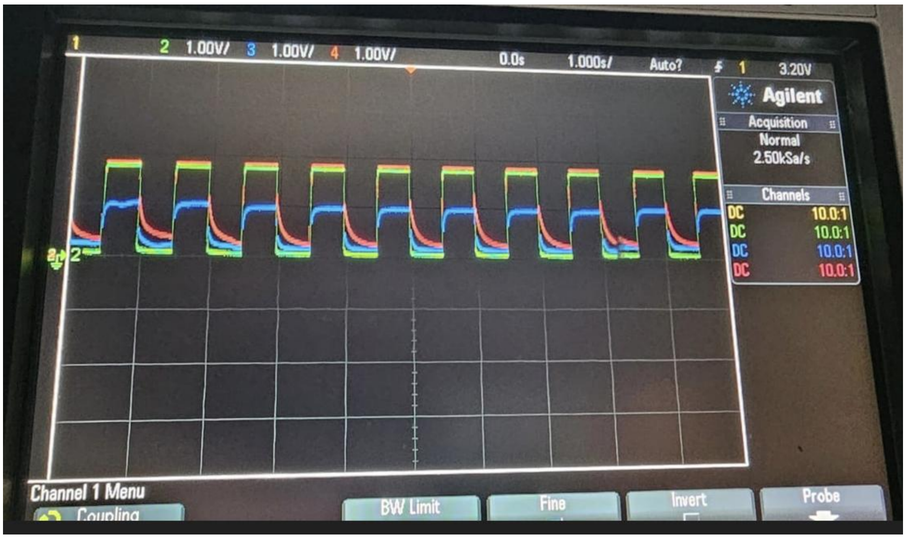


Figure 20. Output signals of the PV cells with RGB filters applied to the ABC logical channels input – the visible red, green and blue colours of the waveforms correspond to the RGB channels.

Next, the output signal Y of the logic gate has been verified as properly corresponding the logic function performed for ABC channels states. It is presented in Figure 21.

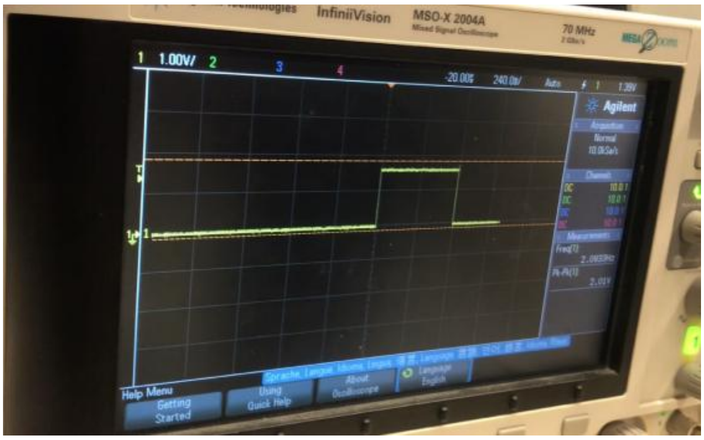


Figure 21. Output signal Y of the logic gate, properly corresponding the logic function performed for ABC channels states.

Oscilloscope testing of the RGB channels revealed that the delay between the red channel (clock signal) and green channel ranged from 200 to 250 microseconds, while the further delay between the green channel and blue channel ranged from 100 to 200 microseconds. The signals were measured on the output of OPV cells, so the test covers the entire chain up to the PV cell outputs, including the delays resulting from switching the NB VLC minilamps with the use of Raspberry Pi SBC Python scripts via serial COM ports.

For a frequency of 30 Hz and a duty cycle of 50%, the signal period was approximately 33.3 milliseconds, of which the High state duration was approximately 16.7 milliseconds.

During this period

- The delay between red channel and green channel was ca. 1.2%–1.5% of the high state duration,
- The delay between the green channel and the blue channel was 0.6%–1.2% of the same period.

This means that, despite the presence of delays, their relative value in the context of the pulse length is small, maintaining synchronization and signal intelligibility in a visible light transmission (VLC) system at low modulation frequencies.

For higher modulation frequencies, such as 120 Hz, 360 Hz, and 1300 Hz, the absolute delays between channels were observed to remain constant. Both the delay between red channel and green channel (ca. 220 μs) and between green channel and blue channel (ca. 270 μs) remained within the same range regardless of frequency.

This means that the delays are constant over time, and their relative impact on transmission depends on the signal period length. It is listed in Table 3.

Table 3 Green and blue channel delays versus red channel clock signal.

Frequency [Hz]	**Period [ms]**	**Green channel delay [%]**	**Blue channel delay [%]**
1300	0.77	28.6	35.1
360	2.78	7.9	9.7
120	8.33	2.6	3.2

30	33.3	0.7	0.8

According to the tests carried out, the system can be considered validated in the range up to 400 Hz, where channel delays do not exceed 10% and allow for robust control of the logical state of the Y output to obtain appropriate backscattering antenna impedance switching to tune it up, and alternatively or complementary to voltage-controlling the printed surface – e.g. indicator or electrochromic film – for the visual feedback from the node.

Such a value of 400 Hz is efficient enough for the considered fully printed limited-capability IoT node.

4 Conclusions

A demonstrator was developed at the laboratory proof-of-concept level aimed at the specific project objective to develop a sustainable implementation of the IoT node by maximizing the use of printed electronics (PE) technology. This was achieved by including the development of printed components and substrates, particularly designed for this project, with a specific focus on the printed transistor and the printed organic solar cell. The objective has been addressed by implementing only the minimum necessary functionality rather than creating multifunctional devices. Since PE is a sustainable manufacturing technology and the printed components are more sustainable than conventional ones, an IoT node or device using this technology as a whole will be more sustainable.

A printed node on flexible PET film was made by utilizing in particular reverse offset printing to reach micrometre-scale features in transistor devices and gravure printing techniques for the solar cells. The node is addressable by using the different colours of the lamps, and the node will reply with an output voltage when the node is addressed, thus demonstrating the minimalist requirements of a IoT node.

5 Bibliography

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6 List of figures

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