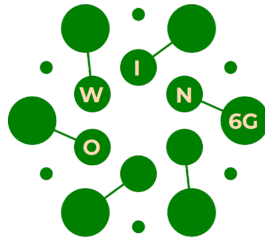


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Project Number: 101119624

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Project title: Optical and Wireless Sensors Networks for 6G Scenarios

Work Package 1: Devices and Subsystems

Deliverable D1.3 (D3): Report on solar panel and battery unit

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Executive Summary

In this report, the progress on Task 1.3 for work package (WP) 1 is presented.

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Work package 1 (WP1) – T1.3 Report on solar panel and battery unit

1. Objectives

As part of OWIN6G network, WP1 objectives are to design, and development a novel sensor networks with (i) distributed biochemical optical sensor for environmental monitoring, and medical diagnostics; (ii) standalone mobile electro-optical sensor nodes for indoor applications; (iii) solar-cell-based power units; and (iv) hybrid radio frequency (RF)-optical transceivers.

To achieve these objectives, the major tasks encompass the development of distributed optical sensor systems, portable electrical/optical sensor devices, high performance flexible solar cells, and radio frequency (RF)-optical transceivers.

During the current reporting period, D1.3 summarises recent progress made in the modelling, simulation, and prototyping of photovoltaic (PV)-based energy-harvesting (EH) and communication modules, with the objective of enabling next-generation energy-autonomous wireless sensor networks (WSNs).

2. General Comments

Deliverable 1.3 reports on the progress of Task 1.3 within WP1, which focuses on the development of PV-based power and communication units for indoor WSNs. The work carried out includes modelling, simulating, and experimentally investigation of PV devices operating as optical receivers (Rxs). In particular, the study applies previously established principles to the prototyping of the dual-function devices capable of simultaneous energy harvesting and reception of visible light communication (VLC) signals. Figure 1 depicts a general view of the system implemented.

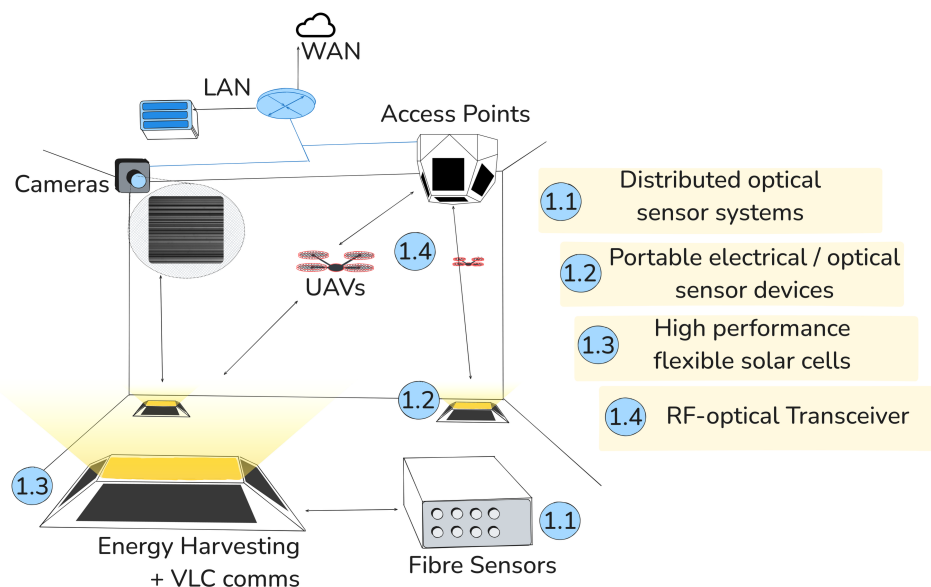


Figure 1. OWIN6G WP1 sensor-network architecture: fibre sensors (T1.1), unmanned aerial vehicle (UAV)-borne electrical/optical sensors (T1.2), PV-based EH and VLC nodes (T1.3), and RF-optical transceivers (T1.4).

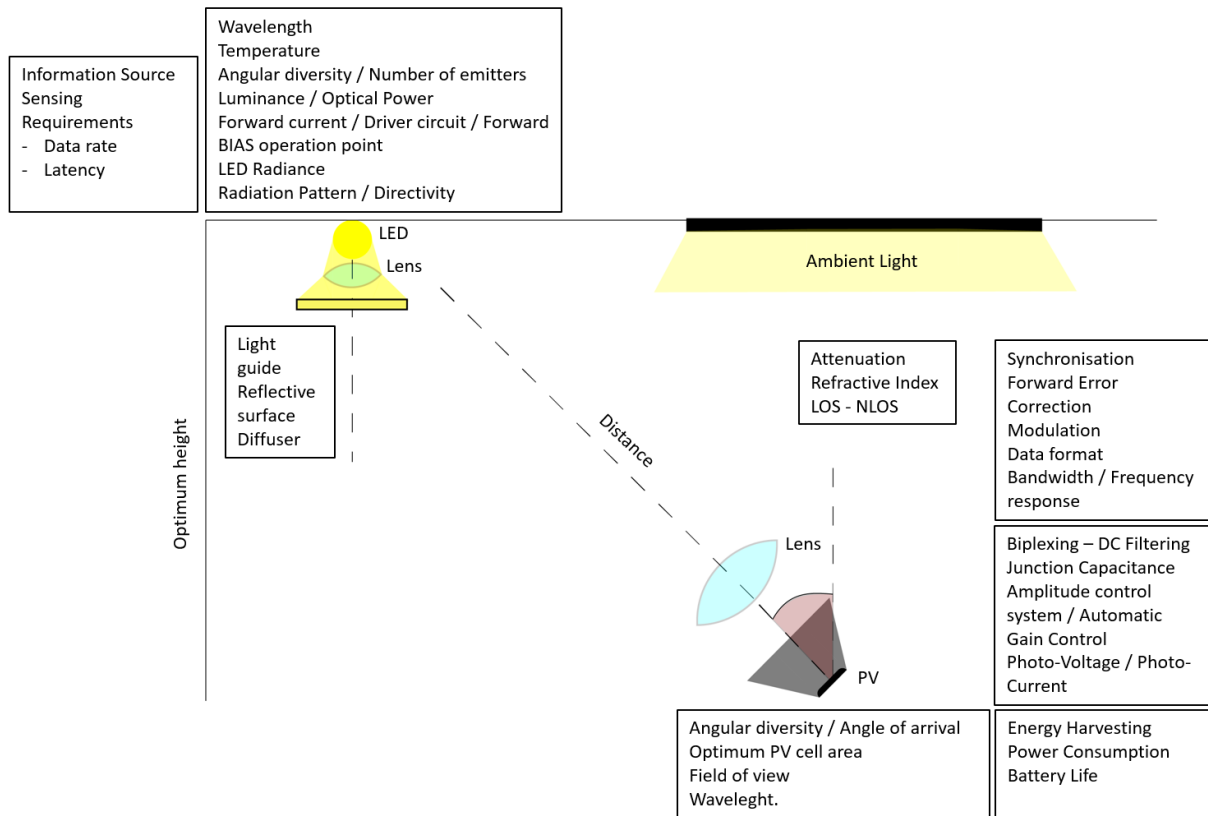


Figure 2. End-to-end VLC link with a PV-based receiver, with the principal design parameters annotated across the light-emitting diode (LED) transmitter, the propagation channel, the PV receiver, the communication front-end, and the energy subsystem.

Figure 2 depicts the multiple design variables involved in developing a PV-based VLC link, spanning the LED transmitter (Tx), free space channel, and the PV Rx. These considerations range from device-level characterisation to the communication-level performance metrics, such as bandwidth B and load-impedance implemented, and extended to the design of integrated sensor-node prototypes, which are further described in Section 4.

3. Specific Progress Made

3.1. Integration of PV Panels in Indoor WSNs

To date, our research efforts [OW1, OW2, OW3] have focused on investigating the feasibility of integrating silicon PV panels into indoor WSNs to support both EH and optical wireless communication (OWC). This objective has been addressed through comprehensive and experimentally validated modelling frameworks that jointly characterise the optical, electrical, and communication behaviour of the system under realistic indoor operating conditions.

3.1.1 Modelling of a Hybrid EH-RF/OWC Network

In our first study [OW1], we proposed a hybrid EH-RF/OWC architecture deployed within a $10 \times 10 \times 3 \text{ m}^3$ indoor environment. In this framework, sensor nodes (SNs) transmit data over an RF uplink while receiving acknowledgments via a VLC downlink. System-level performance

was evaluated using a custom-developed, open-source Python simulator that models both the physical and the medium access control (MAC) layers, implementing an unslotted carrier-sense multiple access with collision avoidance (CSMA/CA) protocol.

The modelling framework places particular emphasis on accurately characterising the energy harvesting process under realistic constraints. Energy acquisition at the SN is realised using PV panels parametrized according to a commercial monocrystalline Voltaic P121 PV cell, featuring an active area of 27 cm². The electrical behaviour of the PV device is modelled using the five-parameter equivalent-circuit model [1], enabling simulation of current–voltage (*I*-*V*) characteristics across a wide range of indoor illumination conditions, as shown in Fig. 3. The model, shown schematically in Fig. 4(a), incorporates key physical parameters, including photocurrent, reverse saturation current, series and shunt resistances, and diode ideality factor.

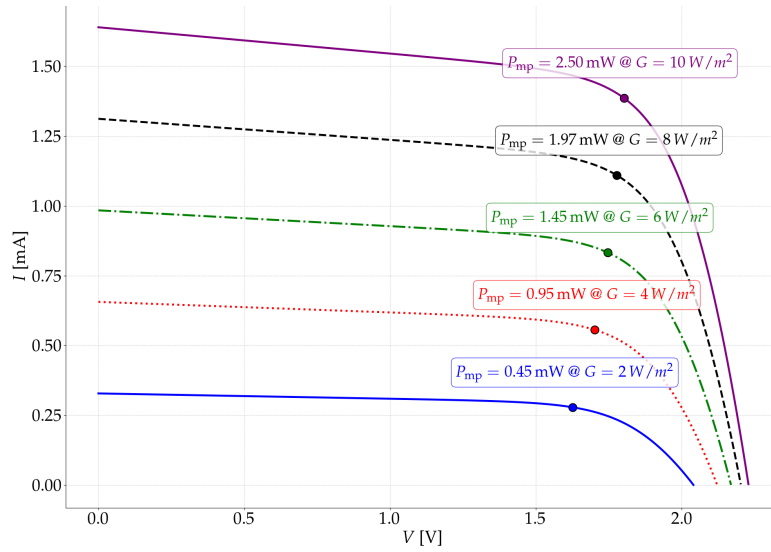


Figure 3. Simulated *I*-*V* curves for different indoor irradiance levels (*G*), where P_{mp} denotes the power at the maximum power point (MPP).

The incident optical power at the PV surface is computed by jointly accounting for natural sunlight entering through windows and artificial illumination provided by ceiling-mounted LED luminaires. To accurately capture the spectral characteristics of indoor lighting, a spectral mismatch factor [2] is introduced to compensate for differences between the emission spectrum of artificial light sources and the reference spectrum used during PV characterization. Furthermore, the optical channel model includes an angular-dependent coefficient [3] to capture the relationship between absorbed power and the incidence angle at the PV surface. To maximize the harvested energy under these constraints, a particle swarm optimization algorithm is employed to identify near-optimal tilt and azimuth angles of the PV panels.

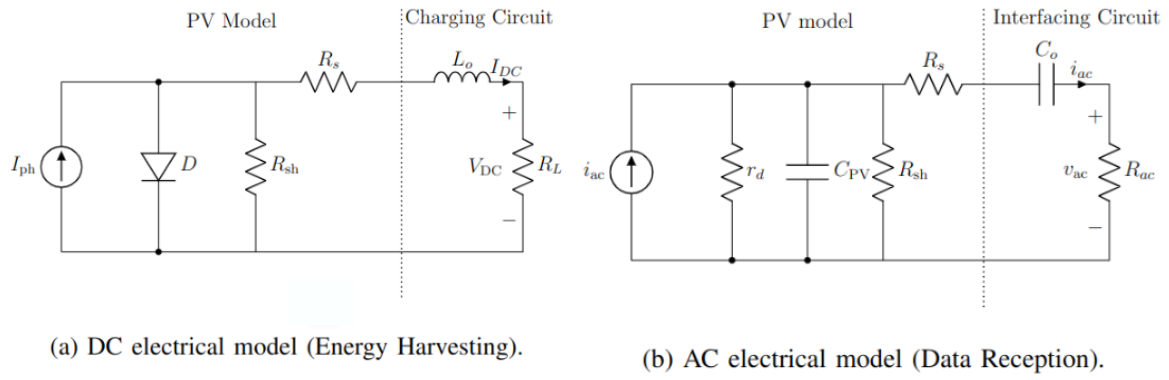


Figure 4. Equivalent circuits for the PV-based receiver separated into: (a) direct current (DC), and (b) alternating current (AC) domains.

Power management and energy storage are modelled using a 3 V, 250 mAh coin cell battery interfaced with the PV panel through an SPV1050 power management circuit operating in buck-boost mode. The system assumes maximum power point through an enhanced maximum power point tracking (MPPT) controller, enabling efficient energy extraction with an overall conversion efficiency of approximately 80%.

The viability of the proposed energy-harvesting subsystem is assessed through detailed energy-consumption profiling of SNs across all operational states, including sleep, sensing, channel assessment, and data transmission. System-level self-sustainability is evaluated under three representative lighting scenarios. In environments where natural sunlight supplements artificial illumination, the harvested energy consistently exceeds daily energy consumption of SNs, enabling energy-neutral operation with only 30-60 minutes of harvesting for most deployment locations. By contrast, in windowless environments relying exclusively on artificial lighting from 6 W LED luminaires, the harvested energy is substantially lower, typically ranging between 0.45 J/h to 0.7 J/h. Nevertheless, energy-neutral operation remains achievable by increasing the PV active area to approximately 75 cm², provided that artificial illumination is available for an average of 8-hour per day. These results demonstrate that energy-autonomous WSN operation is feasible under realistic indoor conditions, even in the absence of natural daylight, given appropriate system-level design and optimisation.

3.1.2 Modelling of a Hybrid EH-OWC Network

Building on this foundation, our second study [OW2] extends the role of the PV panel beyond energy harvesting device to a dual-function component that simultaneously supports energy harvesting and VLC signal reception. In the proposed architecture, the downlink is implemented via VLC, while the uplink utilizes infrared transmission to ensure reliable operation in RF-sensitive environments. This progression enables a unified hardware platform, reducing system complexity and enhancing integration potential for compact, energy-autonomous WSNs.

The EH behaviour is again characterised using the five-parameter PV model, while the corresponding communication model [4] is shown in Fig. 4(b). For practical implementation, the PV panel is assumed to operate close to its maximum power point. Nevertheless, it is acknowledged that an inherent trade-off exists between energy-harvesting efficiency and communication B , as operating at higher operating voltages (favourable for energy extraction) typically leads to a reduction in the effective communication B .

To enable simultaneous EH and signal detection, a bias-tee circuit, consisting of an inductor and a capacitor, as shown in Fig. 4, is incorporated into the Rx design to separate the generated photocurrent into its DC and AC components. The DC component is directed to the MPPT controller for battery charging, while the AC component is applied to a transimpedance amplifier for subsequent signal amplification and data demodulation. The AC response of the PV panel is modelled using experimentally derived impedance spectroscopy data obtained from a commercial Al-BSF-1 device [4]. This enables accurate representation of frequency-dependent capacitive and inductive characteristics associated with the panel's internal junctions.

A comprehensive noise analysis is performed to account for the non-idealities arising from the use of PV panels as optical Rxs. The model includes contributions from ambient light-induced shot noise, thermal noise from the transimpedance amplifier, and intrinsic thermal noise associated with the series and junction resistances of the PV device [5]. This empirically grounded approach ensures that the communication performance evaluation reflects realistic operating conditions.

The complete dual-function system is evaluated within the same indoor environment under practical constraints. Although the use of PV panels as optical Rxs introduces higher noise levels compared to conventional photodiodes (PDs), the communication link demonstrates strong robustness. In particular, the signal-to-noise ratio (SNR) consistently exceeding 70 dB across the evaluated conditions, ensuring error-free communication within standard forward error correction limits. From an energy perspective, the system maintains full energy-neutral operation across all evaluated scenarios. Even under the most challenging conditions, corresponding to a SN located in a poorly illuminated area of a windowless environment, a zero-energy deficit is achieved with 8 hours of artificial illumination, provided that the transmission duty cycle is appropriately configured.

3.1.3 Pyenlight Simulation Library

To consolidate these component-level models and support the systematic design and evaluation of complex indoor environments, our subsequent work introduces Pyenlight, an open-source Python library dedicated to simulating heterogeneous hybrid optical wireless and RF networks [OW3]. The Python library provides a scalable simulation framework for the systematic evaluation of the dual-function PV panels, enabling large-scale joint analysis of data reception performance and EH. It integrates a comprehensive five-parameter DC electrical model for energy extraction and an AC equivalent-circuit for data reception. Leveraging vectorised computational techniques, Python effectively evaluates channel gains, noise variances, and SNR across extensive 3D spatial grids, facilitating the realistic assessment of heterogeneous hybrid optical wireless and RF network deployments. Furthermore, the library incorporates spatial discretisation techniques to model ambient optical interference arising from both natural and artificial light sources, while translating physical-layer communication activity and MPPT efficiency into battery-level energy metrics. By continuously tracking the net daily energy balance, this tool allows network designers to assess the long-term energy sustainability of PV-equipped SNs across a wide range of deployment scenarios and system configurations.

Overall, the presented results demonstrate that PV-based dual-function devices can support self-sustaining and maintenance-free indoor WSNs while simultaneously enabling reliable OWC. These findings highlight a promising pathway toward fully integrated and energy-autonomous sensing infrastructures suitable for long-term indoor deployments.

3.2 Experimental approach for communication and energy harvesting

Following the theoretical and environmental analysis presented previously, an experimental campaign was conducted to validate the dual-function PV-Rx concept using practical implementations. The investigation began with laboratory-fabricated copper zinc tin sulfide-selenide (CZTSSe) solar cells, where initial tests revealed pronounced non-linearities and limited communication performance. This was followed by a comprehensive characterisation of both laboratory-made antimony selenide (Sb₂Se₃) cells and a commercial silicon PV reference, which enabled reliable optical links and supported the use of higher-order modulation schemes. Flicker-mitigation challenges were subsequently addressed to ensure the coexistence of VLC with human-centric lighting conditions. Through the parallel connection of multiple PV devices, the achievable throughput was increased to 2 Mbps using the most basic non-return-to-zero (NRZ) modulation. Finally, simultaneous EH and data communication were demonstrated on a single device, albeit with a B trade-off that limited the supported data rate R_d to 9.6 kbaud in the configuration presented.

The first experimental stage evaluated laboratory-fabricated CZTSSe PV cells, made by the PV team at NU, configured as 3×3 arrays on a soda-lime substrate. The device stack comprises Mo / CZTSSe / CdS / i-ZnO / indium tin oxide (ITO) layers, and the cell were systematically characterised both in their conventional role as PV generators and in their additional function as VLC rxs. NRZ data transmission tests conducted at R_d of 10, 25, 50 and 100 kbps with using a load impedance Z_{load} of 50 ohms, as presented in Fig. 5, reveal the performance limitation of the CZTSSe PV devices when used as optical Rx. As R_d increases, progressive eye-diagrams closure is observed, accompanied by high noise levels and pronounced non-linear distortion. These effects are particularly evident under total-darkness conditions and ultimately constrain the achievable R_d , thereby motivating a more carefully optimised testbed design in the subsequent experimental stages.

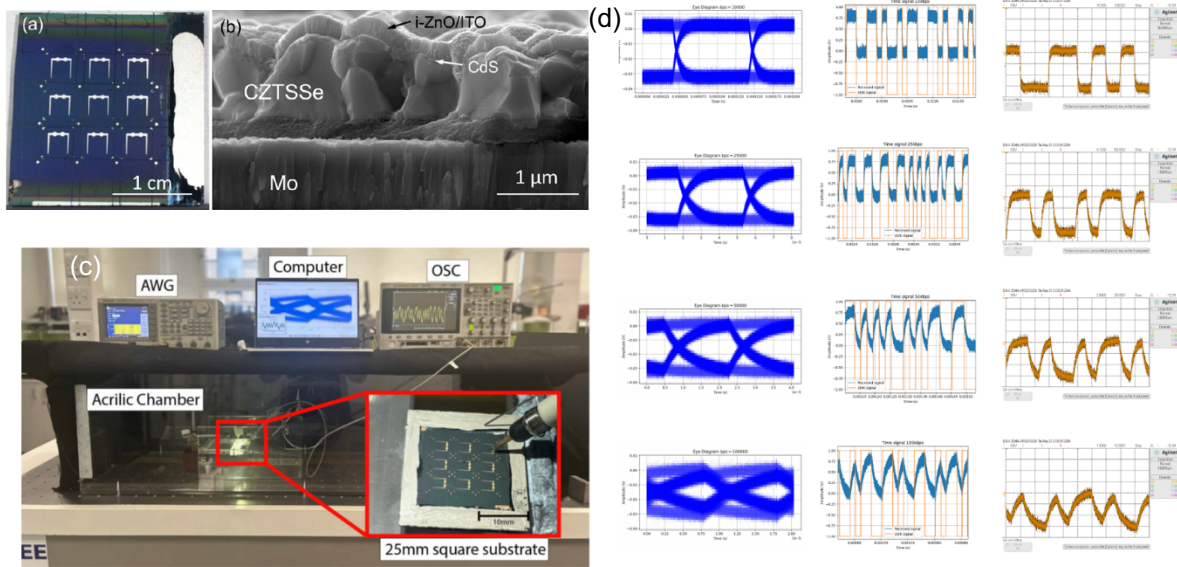


Figure 5. Fabricated CZTSSe thin-film solar cell sample: (a) top view of the 3×3 cell array on substrate, (b) scanning electron microscopy (SEM) cross-section showing the Mo / CZTSSe / CdS / i-ZnO/ITO layer stack, and (c) NRZ communication eye diagrams at 10, 25, 50 and 100 kbps using $Z_{load} = 50 \Omega$.

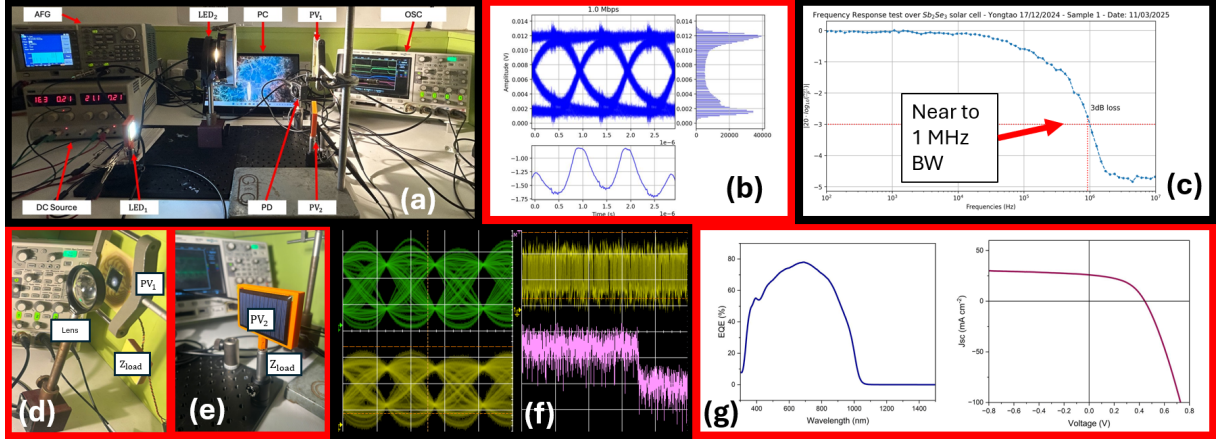


Figure 6. Sb2Se3 PV-based VLC testbed: (a) bench setup with two LEDs and two PV receivers, (b) 1 Mbps eye diagram obtained from the Sb2Se3 PV, (c) frequency response showing 1 MHz 3 dB B, (d–e) Laboratory-made PV1 and commercial silica-based PV2 used at the experiments using different Z_{load} , (f) both links eye diagrams and frequency response when applying root raised cosine filter, and (g) external quantum efficiency (EQE) and J-V curves for the Sb2Se3 PV.

A second testbed enabled a more comprehensive characterisation of the optical communication link and the PV front-end. This redefined setup significantly reducing the system noise and incorporated a laboratory-fabricated antimony selenide (Sb2Se3) PV cell (PV1) alongside a commercial silicon reference (PV2). Both devices were evaluated as optical Rxs under illumination from two LED TxS selected to match their respective spectral responsivities, as depicted in Fig.6. This enhanced experimental analysis enables a substantially improved evaluation of communication performance. In particular, the Sb2Se3 PV-based Rx exhibits a 3 dB B of ~1 MHz, while its external quantum efficiency and $I-V$ characteristics confirm stable and well-behaved PV operation. Building on these results, the application of pulse-shaping techniques employing a root-raised-cosine filter demonstrates robust signal transmission within the linear operating regime for both optical links. This advancement enables the use of higher-order modulation schemes that were not feasible before in earlier experimental configurations.

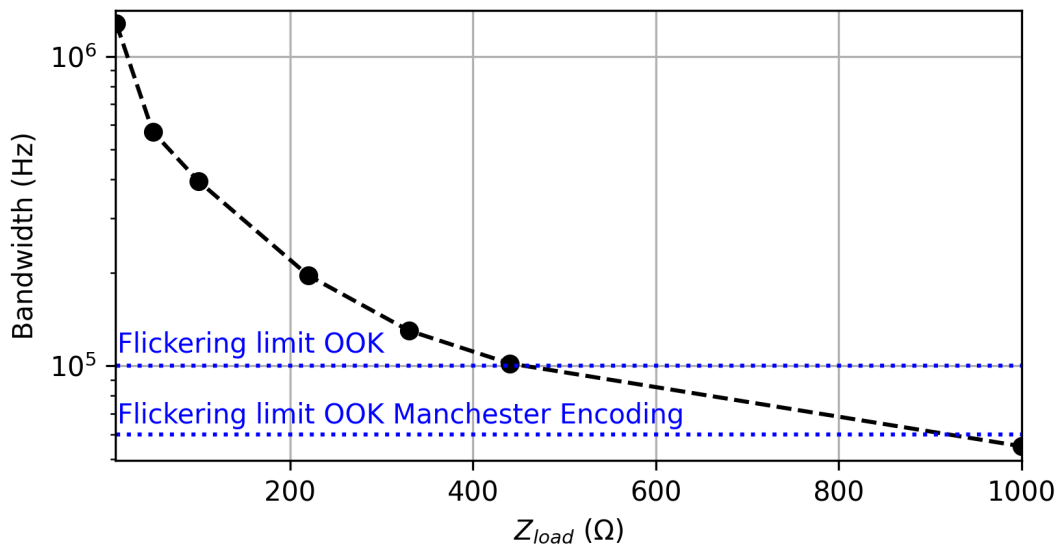


Figure 7. Measured PV-Rx B as a function of Z_{load} , with on-off keying (OOK) and OOK-Manchester flickering limits indicated.

For practical deployment in indoor environments, a VLC link must operate at sufficiently high modulated speeds to ensure that illumination fluctuations remain imperceptible to human occupants. In PV-based Rx's, the achievable B is fundamentally limited by the RC time constant at the PV junction, and therefore depends strongly on the selected Z_{load} . The 3 dB B was measured across a range of different Z_{load} while explicitly considering the minimum data rate requirements for flicker mitigation under both on-off keying and Manchester-coded modulation formats. The resulting analysis reveals an ell-defined operating window in which B exceeds the flickering-perception thresholds for both schemes. This operating region also informs the selection of the transimpedance amplifier gain used in future prototypes, ensuring compatibility with indoor flicker constraints while maintaining reliable communication performance.

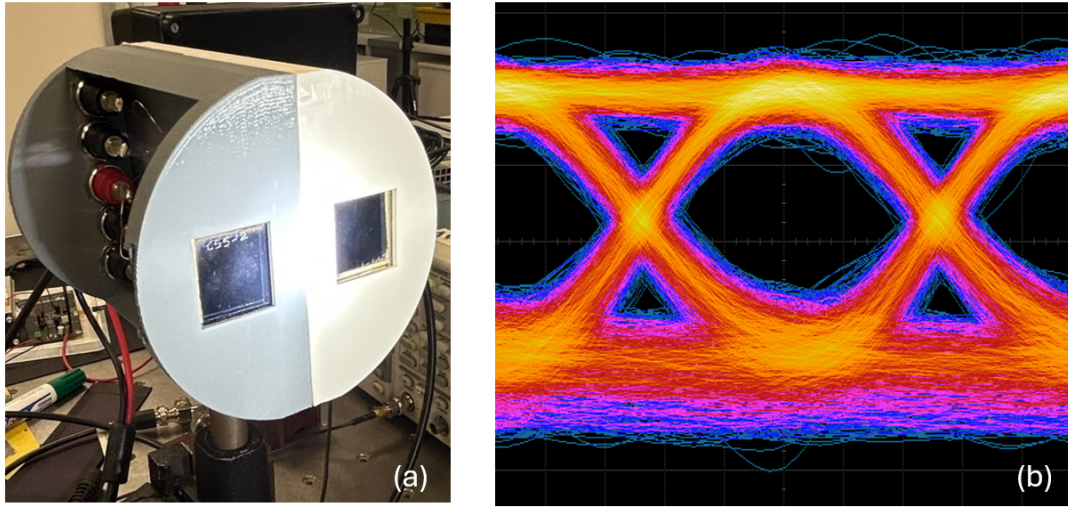


Figure 8. Parallel transmission with two PVs in parallel: (a) receiver assembly and (b) 2 Mbps eye diagram.

With a reliable and flicker-compliant link established, the next step was to further increase the achievable R_d . To this end, two Sb2Se3 PVs were connected in parallel, allowing their photocurrents to be combined within a shared front-end. This configuration effectively doubled the active receiving area without requiring an increase in individual device B , as shown in Fig. 8. The resulting arrangement successfully supports transmission of a 2 Mbps NRZ signal with a clearly open eye diagram, demonstrating a practical pathway for capacity scaling via array-level parallelism rather than device-level enhancement.

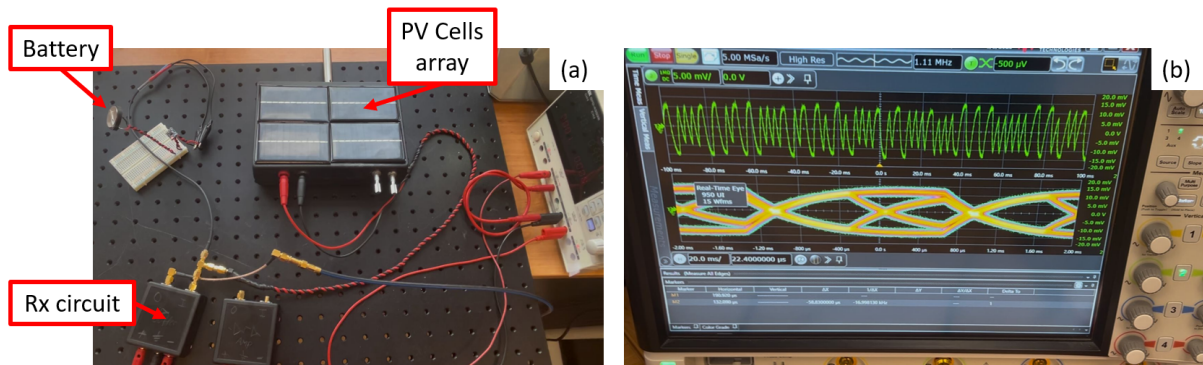


Figure 9. Sensor-node prototype: (a) PV-cell array, battery, and Rx circuit on the optical bench, and (b) distorted Manchester encoded received signal and real-time eye diagram on the oscilloscope.

Finally, the dual-function of the PV devices as both EH and data communications Rx is demonstrated using silica-based PV cells. In this configuration, the PVs simultaneously charge a battery through an MPPT circuit and while receiving the data carrying VLC signal. The complete prototype, including the PV array, energy-storage battery, and Rx front-end electronics, is integrated into a single platform, as displayed in Fig. 9. Diverting the generated photocurrent between the MPPT circuit and the communication Rx inherently reduces the effective B available for signal detection. Consequently, in the demonstrated implemented of the optical link, it is operated with a Manchester-encoded waveform at 9.6 kbaud, while subsequent optimisation in later experiments enabled R_d of up to 115.2 kbaud. These R_d enable the reliable reception of activation signals, allowing the prototype to switch dynamically between battery-charging and data communications-only operating states. This mode switching enhances data communication capabilities by leveraging stored battery energy when required. The resulting behaviour clearly illustrates the fundamental trade-off that defines the dual-function operating point, and validates the complete end-to-end system chain ahead of the system-level prototypes demonstration presented in the following Section 4.1.5.

3.3 Prototyping of PV-based VLC links

At a system-level, integrated prototypes have been developed that combine the PV-based Rx front-end with the necessary amplification and signal-conditioning stages to enable operation over realistic communication spans and within full network architectures. The system-level validation begins with a 15 m long line-of-sight link designed to assess the achievable range and R_d of the PV Rx. This is followed by integration with an Internet-of-Things (IoT) server architecture that acquires, processes, and visualises bidirectional data link under vehicular-style operating conditions. The platform is then extended to support mobile SNs streaming real-time gyroscope data to an access point (AP). Building on this foundation, the same platform is adopted to a wearable health-monitoring use case and subsequently extended to incorporate a polarisation-orthogonal parallel-channel optical link, enabling higher-order modulation schemes and, therefore, increased data throughput [6].

To assess the operational range of PV cells when used as an optical Rx in VLC in conjunction with dedicated amplification stages on the Rx side, an initial prototype targeting vehicular communications scenarios was developed at Northumbria University (NU) in UK. This system successfully demonstrated a unidirectional, line-of-sight VLC link over a transmission range of 15 m. A high-power LED Tx, driven by an arbitrary signal generator, illuminates both a reference PD and the PV Rx, enabling a direct comparison between the two detector technologies under identical channel conditions. When combined with Rx-side amplification chain, the link supports R_d of up to 115.2 kbaud, as shown in Fig. 10, confirming that the PV-based Rx remains viable at outdoor-scale communication distances.



Figure 10. VLC link testbed at NU, LED transmitter with signal generator and PD/PV-based Rx's at 15 m line-of-sight for a proof of concept vehicular to infrastructure communications.

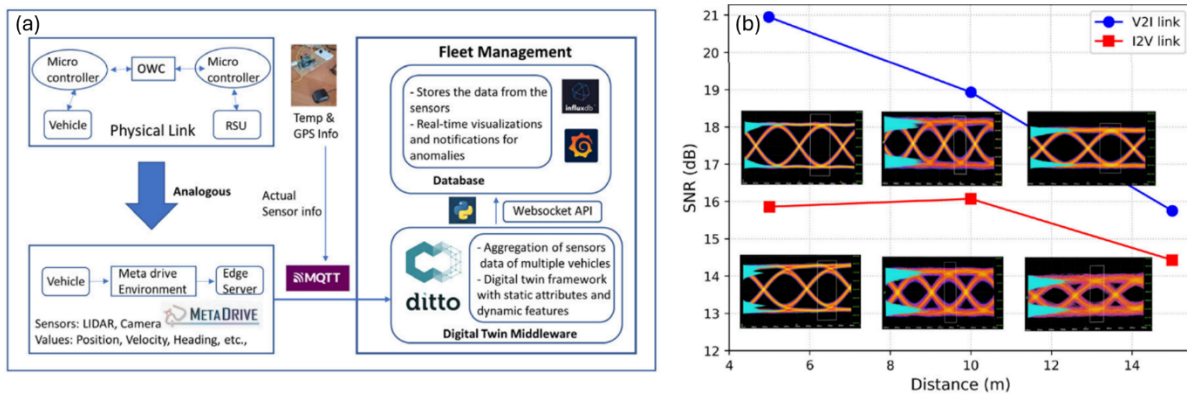


Figure 11. (a) Description of the platform, and (b) eye diagrams for the communication performance.

An On-Edge IoT server architecture was integrated on top of the communication link to support real-time data acquisition and visualisation, as shown in Fig. 11. The platform retrieves the recovered signal from the Rx and stores it for further analysis. Fig. 11 also reports the communication performance of the link under vehicular operating environments. The eye diagrams captured at the Rx output for both vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) transmission directions show clearly open eyes in both cases, quantifying the available system margin and confirming that the PV detector supports reliable bidirectional vehicular-style communication on a single physical platform.

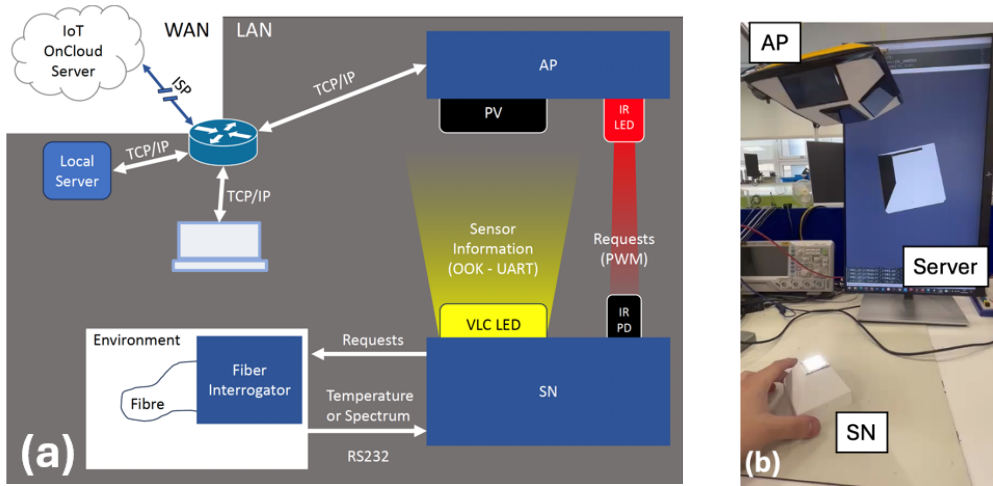


Figure 12. Indoor sensor-network demonstrator: (a) network architecture with fibre interrogator, SN, AP, and VLC/infrared (IR) links to a local server, and (b) photo of the AP, SN, and server visualising real-time gyroscope data.

As depicted in Fig. 12, the next prototype targets mobile SNs streaming sensing data to a fixed AP. In Fig. 12(b), a wireless SN equipped with a gyroscope transmits its readings over a VLC uplink to an AP, which forwards the data to a local server for real-time visualisation and monitoring. The operation and duty cycle of the SNs are managed through infrared-based activation signals, enabling controlled communication periods and efficient energy utilisation. This configuration validates the feasibility of a PV-based node as a mobile end-point in a WSN rather than being limited to fixed-station detector constraints.

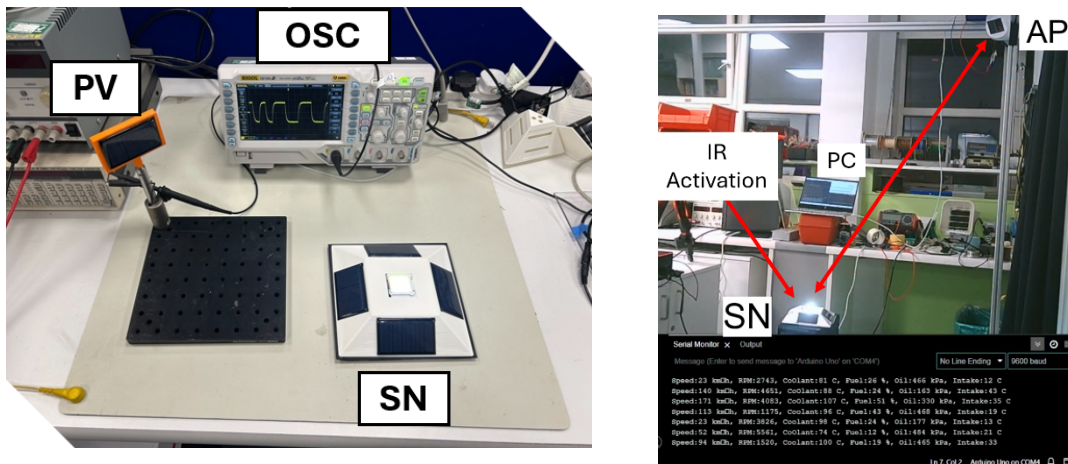


Figure 13. Bench-top demonstration of the PV-equipped sensor node receiving the VLC signal, monitored on the oscilloscope.

Figure 13 shows the activation process and the VLC uplink for the SN, where the AP successfully recovers the VLC signal transmitted by the PV-equipped SN. The oscilloscope trace captured at the Rx front-end output confirms reliable reception. Battery charge is performed by a commercially available MPPT circuit, as well as the infrared activation mechanism. Figure 13 depicts the real-time decoded sensor data at the AP side, corresponding to a R_d of 9.6 kbaud.

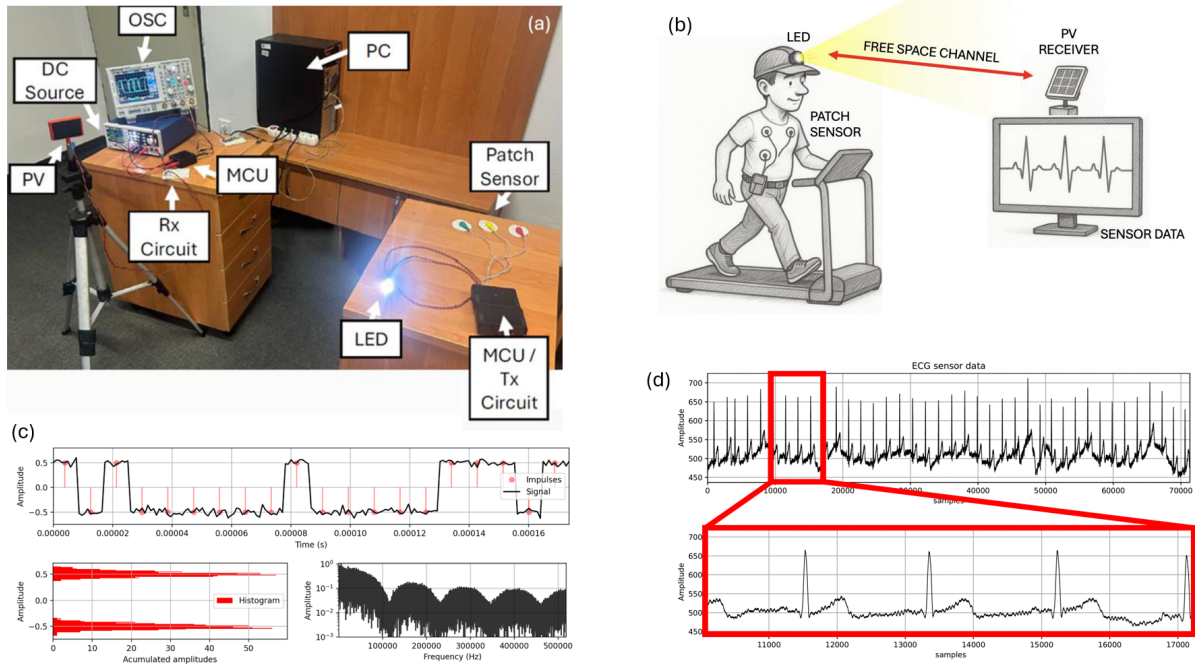


Figure 14. Wearable patch-sensor demo over VLC: (a) Tx/Rx bench with PV, microcontroller unit (MCU), LED, patch sensor, (b) treadmill use-case schematic, (c) recovered OOK signal with histogram and spectrum, and (d) ECG trace captured through the link.

The same end-node concept was then adopted to a wearable health-monitoring use case, in which an electrocardiogram (ECG) patch sensor streams physiological data over a VLC link, as illustrated in Fig. 14. On the Tx side, the patch sensor side uses the microcontroller universal asynchronous receiver-transmitter (UART) communication interface to generate the data stream for intensity modulation of the LED via a current driver circuit. On the Rx side, a PV-based Rx serves as the VLC AP, recovering the transmitted data stream and forwarding it to the IoT platform for further processing and visualisation.

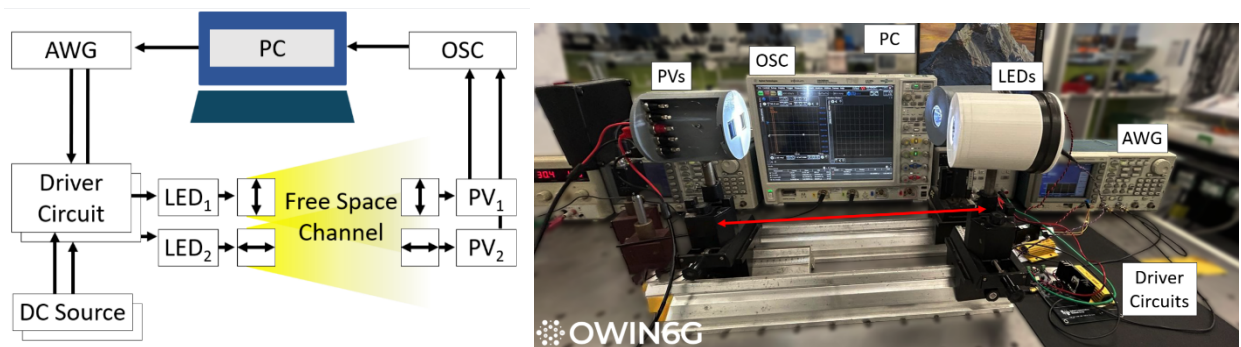


Figure 15. A polarised orthogonal visible light communication link using two LEDs for parallel transmission and Sb₂Se₃ PVs-based receivers: schematic block, and the experimental testbed.

To further improve spectral efficiency and enable parallel communication channels, an advanced prototype implementing a polarisation-orthogonal VLC link was developed. In this configuration, two LEDs Tx's operate on mutually orthogonal linear polarisations states, while two Sb₂Se₃ PV Rx's, each equipped with matched polarisers, independently recover the corresponding optical channels information. This arrangement enables simultaneous,

interference-free data transmission over parallel optical paths, thereby enhancing overall link capacity without increasing bandwidth or optical power. Figure 15 shows the schematic block diagram together with the implemented optical testbed.

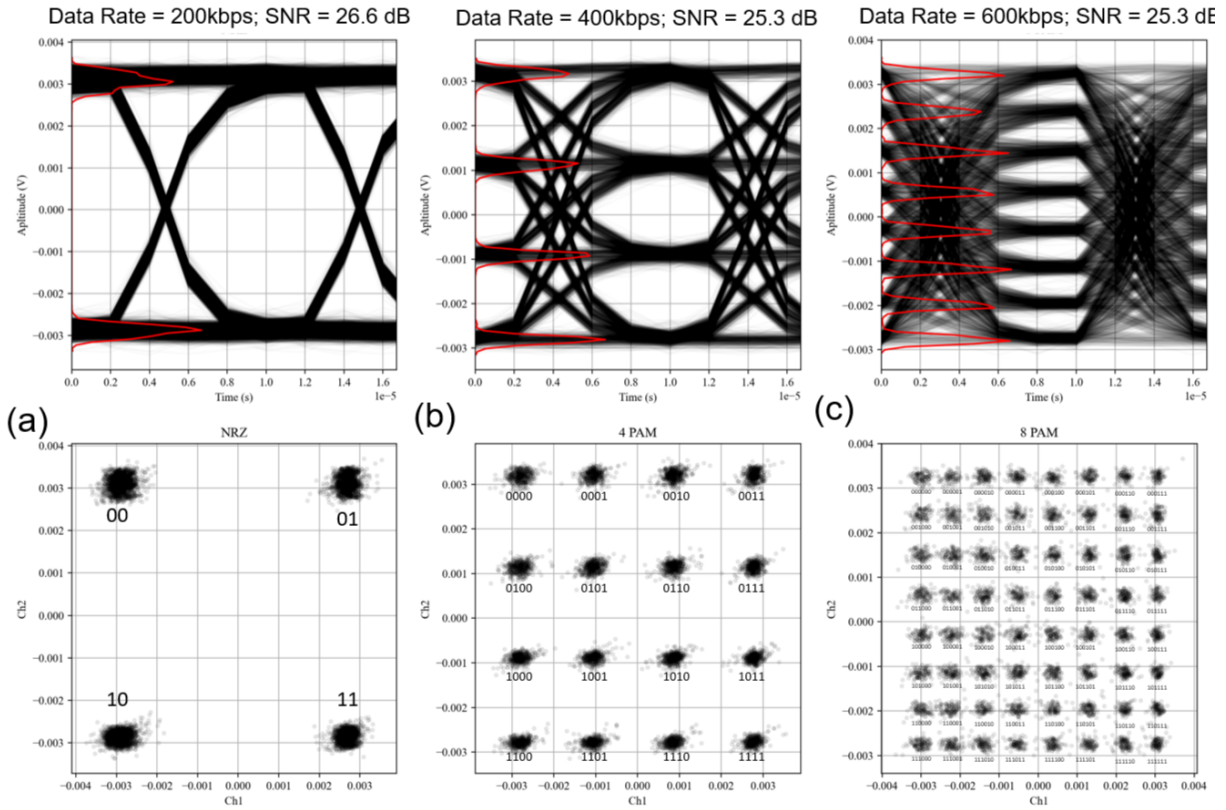


Figure 16. The implementation of: (a) NRZ, (b) 4-, and (c) 8-pulse amplitude modulation (PAM) communication links is shown through eye diagrams obtained on a single channel, with histograms and the calculated SNR for each case, as well as the constellations obtained by the intersection of the amplitude values of both channels [7].

When operating within the linear region of the system, the polarisation-multiplexed VLC platform supports the implementation of multiple modulation formats, including NRZ, 4-PAM, and 8-PAM. The eye diagram measurements conducted for the cases presented in Fig. 16 enable quantitative evaluation of the SNR, complemented by corresponding amplitude-histogram analyses. Furthermore, the joint constellation, formed by combining the amplitude samples from the two orthogonally polarised channels, illustrates how the parallel transmission scheme distributes symbol points across both modulation dimensions, effectively exploiting polarisation diversity to enhance link capacity.

3.3.1 Platform Development

To support the deployment and operation of the prototypes described in Section 4.1.5, a two-tier software platform was developed. This platform combines a cloud-based management layer for SN configuration, monitoring, and administration with an edge-level framework responsible for real-time signal processing of the data received at the APs. Together, these layers enable remote control and configuration of the SNs while allowing low-latency, local handling of the recovered VLC signals, thereby providing the software counterpart to the hardware prototypes presented above.

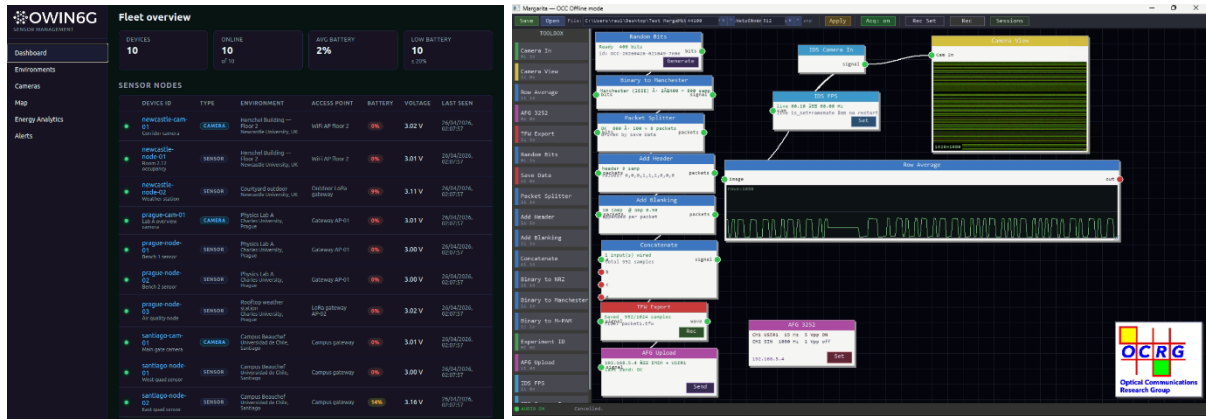


Figure 17. (a) On Cloud platform for SNs management, and (b) framework for the signal processing of the input signals from the access points at On Edge level.

Figure 17 illustrates the two layers of the proposed platform. Panel (a) shows the cloud-side management interface, which enables remote registration, monitoring, and configuration of SNs. This interface provides network-wide visibility, allowing operators to track node status, manage deployments, and access the data streams generated by each SN. Panel (b) illustrates the on-edge processing framework deployed at the APs. Incoming signals from the PV-based RxS are demodulated and decoded locally before being forwarded to the cloud layer. This architecture ensures that latency-sensitive signal-processing tasks are performed close to the physical communication link, while long-term storage, analytics, and network management are handled centrally in the cloud. Together, the cloud and the edge layers form a close loop between the physical communication infrastructure and the application-level services, completing the end-to-end system view of the PV-based SN presented in this deliverable.

4. List of OWIN6G Publications Related to Deliverable

- [OW1] A. Aslanidis, T. Kamalakis, S. Zvanovec, R. Zamorano-Illanes, and Z. Ghassemlooy, "Modeling of an energy harvesting hybrid radio frequency optical wireless sensor network," *Applied Optics*, vol. 64, pp. 6348–6358, 2025.
- [OW2] A. Aslanidis, T. Kamalakis, S. Zvanovec, R. Zamorano-Illanes, and Z. Ghassemlooy, "Performance analysis and modeling of an indoor IoT-oriented energy harvesting optical wireless sensor network," in *Proc. International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, Split, Croatia, 2025.
- [OW3] A. Aslanidis, C. Giachoudis, and T. Kamalakis, "Pynlight: A library for modeling communication and energy harvesting of hybrid optical wireless/radio-frequency indoor networks," in *Proc. International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, Edinburgh, UK, Jul. 2026 (accepted).

4. Summary

This deliverable reported on the progress of Task 1.3 within WP1, which focused on the development of PV-based power supply and data communication units for indoor WSNs. On the modelling side, a hybrid EH-RF/OWC architecture and its dual-function EH-OWC evolution were analysed for a $10 \times 10 \times 3 \text{ m}^3$ indoor environment. The study combined a five-parameter PV model, a bias-tee Rx front-end, and a custom Python simulator encompassing both the physical and MAC layers. The resulting links consistently achieved SNR exceeding 70 dB

while maintaining full energy-neutral operation. These component-level models were subsequently consolidated into Pyenlight, an open-source library that scales the joint communication and energy analysis to large 3D indoor environments. Experimental validation subsequently validated the dual-function concept across a sequence of testbeds, progressing from laboratory-fabricated CZTSSe PV cells to Sb₂Se₃ and commercial silicon-reference RxS. These implementations demonstrated Rx bandwidth of up to 1 MHz, achieved data rate of 2 Mbps using parallel-PV NRZ links, and culminated in the successful demonstration of simultaneous battery charging and VLC reception on a single PV device, supporting a baud rate of up to 115.2 kbaud. At the system level, a series of integrated prototypes embedded the PV-based Rx front-end into diverse application scenarios, including a 15 m vehicular VLC link, an IoT On-Edge architecture supporting bidirectional V2I/I2V communication, mobile SNs streaming inertial measurement data, and a wearable ECG communication patch. The system was further extended to a polarisation-orthogonal parallel-channel VLC link supporting NRZ, 4-PAM, and 8-PAM. All demonstrations were underpinned by a unified two-tier cloud-and-edge software platform that enabled real-time signal processing, remote management, and end-to-end system integration.

Taken together, the modelling, device-level experiments, and system-level prototypes demonstrated that PV-based dual-function devices can simultaneously harvest energy and support reliable optical wireless communication. These results established a credible pathway towards energy-autonomous, maintenance-free indoor WSNs, aligned with within the OWIN6G architecture.

5. References

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Annex A. ACRONYMS

Acronym	Description
AC	Alternating Current
AP	Access Point
BSF	Back Surface Field
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CZTSSe	Copper Zinc Tin Sulfide-Selenide
DC	Direct Current
Di.i	Deliverable i.i
DN	Doctoral Networks
ECG	Electrocardiogram
EH	Energy Harvesting
EQE	External Quantum Efficiency
HUA	Harokopio University of Athens
I2V	Infrastructure-to-Vehicle
IoT	Internet of Things
IR	Infrared
ITO	Indium Tin Oxide
LED	Light-Emitting Diode
MAC	Medium Access Control
MCU	Microcontroller Unit
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSCA	Marie Skłodowska-Curie Actions
NRZ	Non-Return-to-Zero
NU	Northumbria University
OOK	On-Off Keying
OWC	Optical Wireless Communication
PAM	Pulse Amplitude Modulation
PD	Photodetector
PV	Photovoltaic
RF	Radio Frequency
Rx	Receiver
Sb2Se3	Antimony Selenide
SEM	Scanning Electron Microscopy
SN	Sensor Node
SNR	Signal-to-Noise Ratio
Ti.i	Task i.i
Tx	Transmitter
UART	Universal Asynchronous Receiver-Transmitter
UAV	Unmanned Aerial Vehicle
V2I	Vehicle-to-Infrastructure
VLC	Visible Light Communication
WP	Work Package
WPI	Work Package i
WSN	Wireless Sensor Network