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Work Package 2: Physical and MAC Layer

Deliverable D2.1 (D6) : Optimized Energy-Efficient IoT Concept

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Executive Summary

In this report, the progress on Task 2.1 for the work package WP2 is presented.

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1. Work Package WP2 - Physical and MAC Layer

The deliverable 2.1 is part of the WP2, which involves the technical research on physical and media access control layers.

2. Objectives

The WP objectives are shown in Table I. Highlighted in bold are the items covered in this report that are related to T2.1 activities.

Table I. Task 2.1 main objectives.

#i	WP2 Objectives
1.	Develop optical wireless for sensing and communication by creating opportunities for reducing power consumption in WSNs.
2.	Explore opportunities for optical frontends, such as using solar cells to collect energy during idle time and lasers and switched-mode drivers at higher baud rates with on-and-off-keying and sectorized transmitters to save energy in optical links.

3. General Comments

As we transition into an era of unprecedented connectivity, energy efficiency emerges as a cornerstone objective for the design and deployment of sixth-generation (6G) wireless networks. Among emerging communication technologies, visible light communications (VLC) stands out, leveraging existing light emitting diode (LED) lighting infrastructure for dual purposes of illumination and data transmission.

For wireless sensor networks (WSNs) energy sustainability becomes a challenge when addressing mobile nodes. In many cases, the lifetime of individual battery-powered nodes directly dictates the longevity and reliability of the entire system. In remote or inaccessible deployments, battery replacement or recharging may be logistically unfeasible or prohibitively costly. Consequently, future 6G-based WSNs must prioritize extreme energy efficiency, and ideally, aim for full or partial energy autonomy.

Achieving energy efficiency requires advances across hardware, resource management, MAC protocols, and energy harvesting. Among various methods, light-based harvesting is most viable due to its higher energy density [1]. Despite challenges like low indoor light and spectral mismatch, we focus on using commodity silicon photovoltaic (PV) panels for their affordability and availability, even though newer materials like Organic PVs (OPVs) offer better low-light performance [2].

We have developed a simulation-based model for energy efficient hybrid radio frequency (RF)/VLC, which utilizes photovoltaic panels for EH. The research is added under the section of list of publications.

Okomentoval(a): [FG1]: Full words.

4. Specific Progress

4.1 Outcomes from Task 2.1

- Energy consumption reduction strategies in optical fiber sensing (OFS) systems: Outlines key methods for reducing energy consumption in OFS. It emphasizes passive sensing architectures, multiplexing techniques, and low-loss optical design. Task lead: CTU and all beneficiaries are involved. The Task duration was 2 months (M7-M8).
- Quantization of energy harvested from solar panels for powering a hybrid VLC/RF system. Task lead: CTU and all beneficiaries are involved. The Task duration was 4 months (M8-M11).

Those results are summarised in the following section.

4.2 Energy Consumption Reduction Strategies in OFS Systems

OFSs offer several advantages for sensing applications, including high sensitivity, compact size, and resistance to electromagnetic interference [3-6]. One important feature of many OFSs is their ability to operate with minimal power consumption, especially when designed as passive devices. Here, we present the key strategies for reducing energy consumption in OFS, focusing on passive sensing architectures, multiplexing, low-loss optical design, and efficient signal interrogation.

4.2.1. Passive Sensor Architectures

Many OFSs do not require electrical power at the sensing point. For example, fiber Bragg gratings (FBGs) [7] and Fabry–Perot interferometers [8] reflect or modulate light in response to environmental stimuli, such as strain or temperature. These sensors are interrogated using external light sources and detectors located at a central unit. For example, we developed a dynamic refractive index sensing system based on tapered U-shaped singlemode–multimode–singlemode (SMS) interferometer structure, as demonstrated in Fig. 1, which can be potentially used for remote environmental monitoring. The light source and photodetectors are integrated into the interrogator, while the sensor head is immersed in the liquid to be measured. Because no electrical power is needed at the sensor node, passive OFSs are especially suitable for long-term deployment in remote or inaccessible areas.

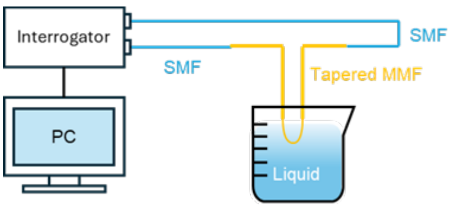

Fig. 1. Schematic diagram of the proposed refractive index sensing system. SMF: single-mode fiber, MMF: multimode fiber.

4.2.2. Multiplexing Techniques

Multiplexing allows multiple sensors to be deployed along a single optical fiber, reducing the number of light sources and detection units required. In wavelength-division multiplexing (WDM), each sensor reflects a unique wavelength, enabling parallel sensing. In time-division multiplexing (TDM), optical pulses are sent down the fiber, and sensors are identified by the delay in the reflected signal. Both techniques improve energy efficiency by reducing the number of active components. Hybrid WDM–TDM systems can further expand sensor count while maintaining low power requirements.

4.2.3. Low-Loss Optical Design

Minimizing optical losses reduces the required power from the light source. This can be achieved by using low-attenuation fibers, high-quality connectors, and efficient splicing methods. In resonator-based sensors, such as whispering gallery mode (WGM) devices, maintaining a high-quality factor (Q) reduces the input power needed to observe clear resonances. Proper packaging and mechanical alignment also help reduce insertion loss and unwanted signal degradation.

4.2.4. Smart Interrogation and Processing

Energy use can be further reduced through adaptive or event-driven interrogation strategies. For example, the system may increase sampling rates only during significant environmental changes or events. In addition, edge processing units can be used near the sensing site to perform initial signal analysis, transmitting only relevant data to the central processor. This reduces power consumption associated with continuous data transmission, especially in systems with wireless communication links.

4.2.5. Summary

OFS systems can be made highly energy-efficient through a combination of passive operation, multiplexing, low-loss design, and intelligent interrogation. These strategies make optical fiber sensing a strong candidate for scalable, low-power, and long-term monitoring applications in a wide range of environments.

4.3 Towards Energy Autonomous WSNs

As the paradigm shifts from the Internet of Things (IoT) to the Internet of Everything (IoE), an unprecedented number of low-data-rate devices will be interconnected, shaping future communication networks [9]. This evolution presents two major challenges: increasing congestion in the RF spectrum and the constrained energy budgets of battery-powered sensor nodes. Optical wireless communication (OWC). OWC networks - particularly hybrid OWC/RF architectures - are emerging as promising solutions to address RF spectrum congestion and energy constraints. Among these, VLC stands out for its inherent energy efficiency, as it leverages existing lighting infrastructure to perform dual roles - illumination and data transmission. Recently, there has been a growing focus on enabling energy - autonomous WSNs through energy harvesting techniques, including solar, RF, vibration, thermal, and wind energy harvesting [10]. In this context, we investigate the feasibility of powering next-generation hybrid OWC-based WSNs using commercially available, low-cost single-crystalline silicon PV.

4.3.1. PV Technologies

Commodity PV panels are primarily designed to efficiently harvest energy under outdoor conditions. Silicon is the most used material in commercial PV technologies, available in various forms such as single-crystalline, multi-crystalline, and amorphous silicon. Among these, single-crystalline silicon panels offer the highest efficiency under standard outdoor illumination.

However, under indoor conditions - where irradiance is significantly lower and the spectral distribution differs - these panels exhibit a sharp decline in efficiency. This is a well-documented limitation of silicon-based PV technologies [11].

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Some emerging PV technologies, such as dye-sensitized solar cells (DSSCs) and OPVs, are being developed specifically for indoor applications, as they demonstrate better performance under low-light conditions [12]. However, these technologies are still relatively immature, are not yet widely adopted, and tend to be more expensive compared to silicon-based alternatives. Thus, we focus on single-crystalline silicon PVs.

4.3.2. PV Model

The one-diode and two-diode electrical equivalent circuit is mostly used for describing the electrical characteristics of PV panels. The one-diode model (also known as 5-parameters model) is a good compromise between accuracy and computational complexity as it has been shown to be accurate even in low-light conditions [13]. Five parameters should be calculated: the photocurrent, the diode reverse saturation current, the series and shunt resistors values and the diode ideality factor. There is a plethora of way to calculate those. A straightforward approach is that proposed in [14], as it relies solely on parameters provided by PV panel manufacturers under standard test conditions (STC). Once these parameters are extracted, they must be scaled to account for the irradiance level present in the indoor environment of interest.

Another important factor to consider is the difference between the reference spectrum used in STC and the spectral distribution of the indoor ambient light, which can significantly impact the accuracy of performance predictions.

4.3.3. Charging Circuit

PV panels exhibit a non-linear voltage–current (V–I) characteristic. For each level of irradiance, there exists a unique operating point - known as the maximum power point (MPP) - at which the output power is maximized. At the same time, charging a rechargeable battery typically requires supplying current at a constant voltage. To meet both requirements, we use an integrated circuit that combines a buck-boost converter with an embedded maximum power point tracking (MPPT) controller. This ensures that the PV panel operates at its MPP while delivering the appropriate voltage and current to the battery. The efficiency of these converters is around 80 %.

Several MPPT algorithms exist, varying in complexity and performance. One of the simplest is the fractional open-circuit voltage method, which estimates the MPP voltage as a fixed proportion of the open-circuit voltage. While this method is easy to implement, it provides limited accuracy and adaptability under changing environmental conditions. A more sophisticated and commonly used technique is perturb and observe, which continuously perturbs the operating voltage and observes the effect on output power to dynamically track the MPP.

4.3.4. PV Panels as OWC Receivers

Recent studies have investigated the integration of PV panels into VLC - enabled systems, taking advantage of their dual functionality as both optical receivers and energy harvesters. This approach enables simultaneous data reception and power generation, making it particularly attractive for self-powered IoT devices and other energy-constrained applications. By using the same optical signal for both communication and energy harvesting, system complexity and hardware costs can be significantly reduced.

However, challenges remain in balancing the trade-off between maximizing energy conversion efficiency and maintaining reliable data transmission, particularly under varying lighting conditions and different modulation schemes. This trade-off is especially relevant because energy harvesting and data reception often require different optimal operating points [14-17]. Nevertheless, in many IoT applications, the required data rates are relatively low - often limited to intermittent transmission of sensor readings

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or control signals. As a result, it is possible to prioritize energy harvesting without severely compromising communication performance. In such cases, even modest communication bandwidth is sufficient to meet application requirements, enabling the design of VLC systems that are both energy-efficient and functionally adequate for typical IoT use cases.

4.4 Optimization of EH OWC-RF Systems for IoT-use Cases

We developed a simulation model for an energy harvesting optical wireless RF (EH-OWRF) WSN, in which sensory data is transmitted via the RF channel, while acknowledgments (ACKs) are communicated through the VLC channel, as described in [OW3]. The developed open-source Python simulation tool, along with a detailed start-up guide, is available in [18]. In our design, we assume the use of commercial white LEDs; thus, in practice, VLC is used for the downlink. Our simulation tool can be easily adapted for other types of LEDs in the general OW scenario.

This hybrid approach addresses RF spectrum congestion by offloading part of the traffic to the VLC channel, enhances energy efficiency at the master node by reusing LEDs for data transmission, and reduces power consumption at the sensor node during the ACK reception phase. The block diagram for the system representation is shown in Fig.2. Our simulations incorporate realistic models of the communication subsystems, medium access control (MAC) mechanisms, and energy harvesting processes at both the sensor and master nodes. The results reveal the significant potential of EH-OWRF technology for future IoT and 6G networks, particularly in achieving system self-sustainability. In the analysed scenarios, we showed that a zero-energy deficit can be achieved daily. When sunlight is available, just one hour of energy harvesting per day is sufficient. In the absence of sunlight, a zero-energy deficit is still attainable with larger PV panel areas, provided room lighting is available for at least eight hours per day.

To further optimize energy harvesting, we employed particle swarm optimization (PSO) to determine the optimal placement of PV panels for indoor environments. Our results show that this method can, in some cases, nearly double the harvested energy. We also provide a detailed methodology for selecting the appropriate PV panel size based on specific application requirements. Since VLC links are susceptible to blockage and shadowing, we also considered scenarios where the line-of-sight (LOS) connection is interrupted. Our analysis showed that even under such conditions, the signal-to-noise ratio (SNR) from diffused light remains sufficient to maintain successful communication. This highlights the robustness of the VLC channel in real-world indoor environments.

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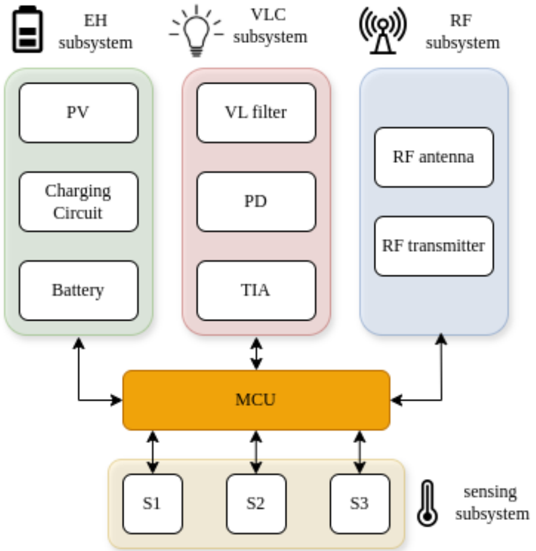

Fig. 2. Block diagram of hybrid EH-OWRF system [OW3].

4.4.1. Summary

Next-generation 6G WSNs aim to be energy-efficient and, ideally, energy-autonomous. VLC offers a strong complement to traditional RF communication, helping to ease RF spectrum congestion while reusing lighting energy for data transmission. Using solar panels as indoor optical receivers is a promising approach in this context. They can simultaneously harvest energy and receive data, making them well-suited for low-power, low-data-rate applications such as IoT devices. This dual functionality helps reduce system complexity and supports self-powered operation. However, some limitations must be considered. Solar panels have lower data rate capabilities compared to dedicated photodetectors, and there is an inherent trade-off between energy harvesting and communication performance. Additionally, indoor environments offer limited energy for harvesting, and the PV efficiency also tends to drop under these conditions. Despite these challenges, integrating solar panels into VLC systems remains a promising step toward sustainable and efficient 6G networks.

4.5 List of OWIN6G Publications Related to Deliverable

[OW1] Y. Shen, Z. Wang, Z. Wang, et al. "Enhanced Force Sensing Utilizing a Glass-Supported WGM Microbubble Resonator". Journal of Lightwave Technology, 2025.

[OW2] Y. Shen, et al. "Two-dimensional force-sensing whisker based on a WGM microbubble resonator." 29th International Conference on Optical Fiber Sensors. Vol. 13639. SPIE, 2025.

[OW3] A. Aslanidis, T. Kamalakis, S. Zvanovec, R. Zamorano-Illanes, Z. Ghassemlooy, Modeling of an Energy Harvesting Hybrid Radio Frequency Optical Wireless Sensor Network, Applied Optics, accepted...

5. Summary

The report outlined the contributions made towards the optimized energy efficient IoT concept as a constituent part of the technical WP 2 physical and Mac layer.

6. Future works

At present, our work is well-balanced around theoretical analysis, modelling, and simulation of VLC-enabled energy-harvesting systems. Future efforts will focus on experimental validation to corroborate our findings in practical scenarios. Additionally, we aim to extend our investigation to pure OWC-based WSNs, which are particularly advantageous in environments with high levels of RF interference. In this context, we also plan to explore the dual use of PV panels—not only for energy harvesting but also as optical receivers—further enhancing system integration and sustainability.

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Annex A. ACRONYMS

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6G	**Sixth-generation**
CTU	**Czech Technical University**
D i.i	**Deliverable i.i**
DSSC	**Dye-sensitized solar cell**
EH	**Energy harvesting**
EPL	**Eblana Photonics**
FBG	**Fibre Bragg grating**
HUA	**Harokopio University**
IoT	**Internet of Things**
LED	**Light emitting diode**
LOS	**Line-of-sight**
MAC	**Medium access control**
MPP	**Maximum Power Point**
MPPT	**Maximum Power Point Tracking**
OPV	**Organic photovoltaic**
OFS	**Optical fiber sensing**
OWC	**Optical wireless communication**
PSO	**Particle Swarm Optimization**
PV	**Photovoltaic**
RF	**Radio frequency**
SNR	**Signal to Noise ratio**
SMS	**Singlemode-Multimode-Singlemode**
STC	**Standard Test Conditions**
T i.i	**Task i.i**
TDM	**Time-division multiplexing**
VLC	**Visible light communication**
WDM	**Wavelength-division multiplexing**
WGM	**Whispering gallery mode**
WP i	**Work package i**
WSN	**Wireless sensor network**