Novel Data and Energy Networking for Energy Autonomous Light-based IoT Nodes in WPAN Networks

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***Abstract*—As internet of things (IoT)-based wireless personal area networks (WPAN) get more popular, visible light communication (VLC) offers unique advantages over radio frequency (RF) communication, such as unrestricted reusable spectrum and high security. Additionally, visible light can carry both signals and optical power, making it a useful medium for exchanging information and energy between network nodes. A VLC-based wireless personal area network (WPAN) concept for light-based energy autonomous IoT is proposed in this paper, which can share both data and energy between nodes. The network uses photovoltaic (PV) based energy harvesting for operation while sharing excess energy between nodes to increase efficiency. Performance of the main concept of the network is evaluated and discussed in the paper. In the future, this kind of network will enable self-sustaining IoT networks.**

***Index Terms*—internet of things, energy harvesting, visible light communication, power sharing, sustainable IoT**

I. Introduction

The rapid growth of smart IoT technologies is leading to a massive deployment of sensors and nodes all over the world. Moreover, wireless sensor networks are key enabling technologies of current 5G and future 6G networks. These technologies pose several fundamental challenges as more and more wireless IoT devices are deployed for various applications. It is expected that hundreds of billions IoT nodes will be globally deployed in the next decade [1]. In addition to the conventional wireless communication challenges such as providing reliable connectivity, energy- and spectral-efficient operation, low cost, and others, environmental challenges need also to be considered, particularly considering the massive number of connected devices. These latter challenges include the need for batteries to power up IoT nodes, associated maintenance costs and the huge infrastructure costs required to connect these nodes. In order to address these challenges, techniques such as Simultaneous Wireless Information and Power Transfer (SWIPT), energy harvesting (EH), Optical Wireless Power Transfer (OWPT) can be used [2].

Applications for sensor nodes include automation, health sector, industrial monitoring, logistics, wireless personal area networks (WPANs) and wireless body area networks (WBANs). Z-wave and Bluetooth low energy (BLE) WPAN technologies are popular for their ability to facilitate low data rate communication, thereby enabling low-power sensor nodes that can communicate with each other [3]. In both BLE and Z wave, data can be transferred through multi-hops by using mesh topology [4]. Typically in a mesh network, one main controller acts as the primary coordinator of the network while all other sensor nodes act as routing and data communicating nodes.

Visible light communication (VLC)-based IoT is emerging as a promising solution to the problem of moving new IoT applications from already congested radio frequency spectrum (RF). An approach to address communications, sustainability challenges and take advantage of the VLC technology is light-based IoT (LIoT), in which existing lighting infrastructure is used to provide both wireless connectivity and energy to the nodes being served [5]. Earlier work [6] demonstrated that LIoT has the potential to communicate and operate energy autonomously with photovoltaic cells-based indoor energy harvesting from the visible light illumination. Since these LIoT designs are battery free, these nodes are expected to have theoretical unlimited life time without requirement for frequent maintenance. Typical LIoT nodes can be manufactured using sustainable electronics technologies such as printed electronics (PE), making future IoT designs more environmentally friendly, as shown in [7]. In the future, as PE technology develops, the LIoT nodes could eventually be fully implemented with PE technology, resulting in a highly sustainable, very low-cost solution.

Based on the idea that IoT nodes exploit light to both communicate and harvest energy, this research work proposes a novel LIoT-based data and energy networking concept for mesh-type sensor networks (e.g., WPAN) followed by proof-of-concept results. In the proposed network structure, the energy-autonomous nodes communicate with VLC while sharing the harvested energy with other nodes using OWPT. Due to the fact that the same optical transmitters can be used for both VLC and OWPT, there is no need to integrate separate circuits for the nodes [8]. Generally, in PV-based energy harvesting IoT nodes, after a point where the energy storage unit of the node becomes fully charged, the additional generated energy by the PV panel will not be utilised due to the lack of energy storage. As a solution, this proposed concept can be exploited to make the most of each node's maximum photovoltaic energy generation to improve the entire network's performance. One of the advantages of this approach is that the indoor illumination infrastructure fully supports the operation of the IoT-based WPAN network through efficient data and energy networking. In addition, this LIoT network will be capable of operating reliably and energy autonomously, under relaxed requirements for the lighting infrastructure.

The rest of the paper is organised as follows. In Section II, we introduce the model of the proposed system and the key data and energy networking concept. In Section III, we present the performance evaluation of key functionalities of the network. Finally, in Section IV, we discuss the results and present the conclusions.

II. Model of the Proposed System

A. Data - Energy networking

The proposed data - energy networking structure is depicted in Figure 1.

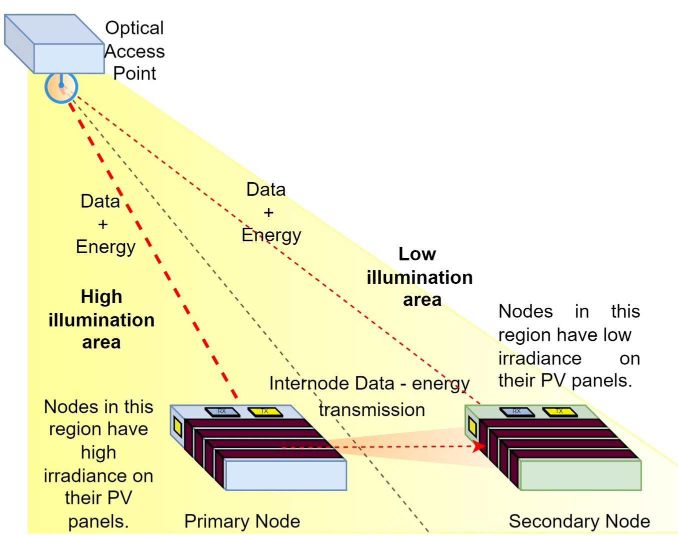

Fig. 1. Data - Energy networking structure.

In this proposed WPAN network, an optical access point (OAP) provides optical illumination and serves as a control centre for all nodes within the coverage area. Depending on the illumination levels received by nodes from the OAP, nodes under OAP can basically be classified as primary or secondary nodes. Primary nodes are located closer to the OAP, whereas secondary nodes are located further away (or their associated optical channel, despite the node being close to the OAP, may not be favorable, e.g., NLOS is prevailing). This allows primary nodes to receive more light illumination for efficient energy harvesting while maintaining strong SNRs for communication with the OAP. However, secondary nodes will receive considerably less illumination, which will have an impact on the quality of the optical signal as well as on the energy harvesting performance of the node. A primary node can therefore be configured to activate its optical transmitter when it is not in active (communication) mode to create optical energy links to secondary nodes, improving the energy harvesting performance of these nodes. Basically, this concept can be called "energy spilling", as primary nodes harvest more energy than they need in order to share their excess energy with neighbouring nodes. Note that a secondary node could eventually repeat this energy procedure to a third node, resulting in an energy relying scheme working in an analog manner as data relaying.

B. Data - Energy transfer enabled LIoT

To operate this proposed WPAN, LIoT nodes with data and energy transfer capability will be required. To maintain energy autonomy, the following requirement needs to be satisfied at the node.

$$E_{Input+Storage} > E_{Electronics+Leakage}, \quad (1)$$

where, $E_{\text{Input + Storage}}$ is the combination of energy input to the system from the source and the stored energy in the storing unit at a given time. $E_{\text{Electronics + Leakage}}$ is the combination of energy consumption for the operation of the node and the energy leakage of the system. A typical block diagram of a LIoT node is shown in Figure 2.

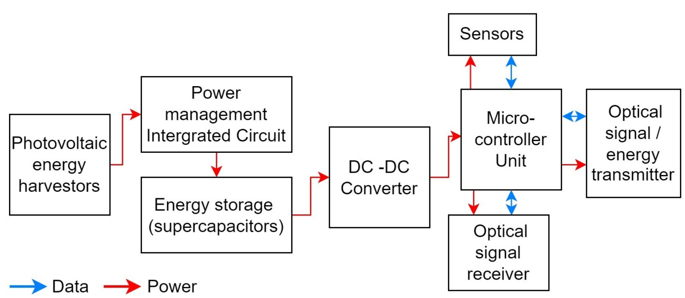

Fig. 2. Structure of LIoT Node.

The LIoT node is expected to be energised by the incident illumination on the photovoltaic energy harvesters. Generally, PV cells or optical rectenna can be used for this purpose. Utilising technologies such as maximum power point tracking (MPPT), the power management integrated circuit increases the energy generation efficiency from the PV harvesters. Thereafter, the generated power is stored in the energy storage unit. Using a DC-to-DC converter, the stored energy will be fed into the microcontroller unit (MCU) at a steady voltage compatible with the device requirements. The MCU controls the optical/energy transmitters, the signal receiving units, and the sensing units of the node.

The OWPT can exploit either narrow beam or wide beam transmitters. A LIoT node can be equipped with multiple combinations of both wide and narrow optical transmitters by using compact LED technology to cover the area around the node. Based on the Volterra series, the LED current-optical power conversion can be expressed as follows.

$$P_{Optical}(t) = P_{DC} + \sum_{n=1}^{\infty} \frac{1}{n!} P_n(t), \quad (2)$$

where P_{DC} is the DC component of the optical power and P_n(t) is the nth order component of $P(t)$, this can be expressed as follows [9].

$$P_n(t) = \int_{-\infty}^{+\infty} ... \int_{-\infty}^{+\infty} h_n(\tau_1, ..., \tau_n) \prod_{k=1}^{n} I(t-\tau_k) d_{\tau_k}, \quad (3)$$

where h_n(t1, ...,tn) is the nth order Volterra kernel and $I(t)$ is the driving current.

Whenever the energy storage level of the primary node reaches a minimum level, the node is expected to go to a deep sleep mode which consumes ultra low power and recovers the energy quickly by using the high illumination on the PV surface. There can be several cycles of optical power transfer before the secondary nodes have collected sufficient energy to operate. Figure 3 shows the expected energy storage voltage variation during a cycle period when the sensor node is configured to have maximum energy transmission time.

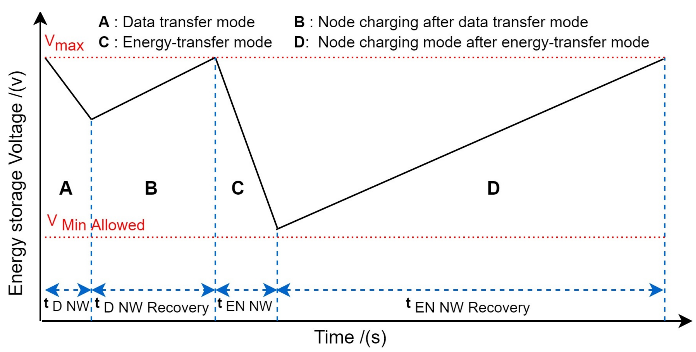

Fig. 3. Data - Energy networking structure .

Where $t_{D\ NW}$, $t_{D\ NW\ Recovery}$, $t_{EN\ NW}$ and $t_{EN\ NW\ Recovery}$ are, respectively, data networking time, voltage recovery time after data networking, energy networking time, and voltage recovery time after energy networking. V_{max} and $V_{Min\ Allowed}$ are maximum voltage level of the energy storage and the minimum voltage that the node is allowed to reach in order to continue operation of other sub components.

C. Energy-Data Relay Nodes

In order to address the low quality optical signal at the secondary nodes (OAP-secondary node), the Data Relay mode operation is introduced. In this way, the primary node can act as an intermediate data routing node - "data relay", to communicate between the OAP and a secondary node. Nodes that are far away from the OAP or have non line of sight (due to shadowing/blockage) with the OAP can use multihop data transfer via node-to-node communication. Similarly, the intermediate nodes involved for energy transfer can be named as Energy Relays. Energy relays can operate in a multi-hop manner similar to data relays. Thus, a single node can act both as an energy and data relay. The concept of energy and data relay is depicted in Figure 4.

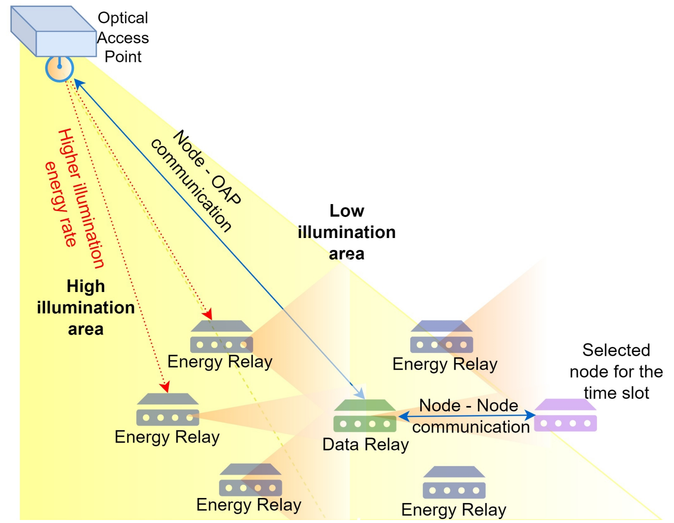

Fig. 4. The concept of energy and data relay.

D. Node Prioritisation

Generally, wireless nodes consume more power at the transmission state than other states. As the receiving illumination on the PV cells is equivalently correlated with the node recharging times, the nodes in the low illumination areas will require to have longer sleep modes to recharge up for communication. However, this could be disadvantageous when the network follows a time schedule-based communication. To overcome this, Node Prioritisation can be used. Inter-node energy transfer can thus be prioritised to a particular node in accordance with the schedule in this way. For this purpose, nodes in between the OAP and the end or destination node can act as relay nodes and transfer energy to fill up the energy storage at the end node. As a result, prioritised nodes will have more average light illumination on the PV area during the sleep phase. The concept of node prioritisation is depicted in Figure 5.

In this network the OAP is responsible for scheduling tasks for other nodes in the network, such as wake-up, sensing, and data transmission. The network nodes are expected to report important operating parameters to the OAP, which will then use this information to schedule wake-up times and prioritise tasks. The OAP may also assign data/energy relay tasks to other nodes.

III. Performance Evaluation

For the performance evaluation, LIoT nodes with temperature sensors were used. The nodes consisted of PV cells, an MPPT tracking unit, and a super capacitor-based EH unit. The IR and VLC bi-directional communication system used

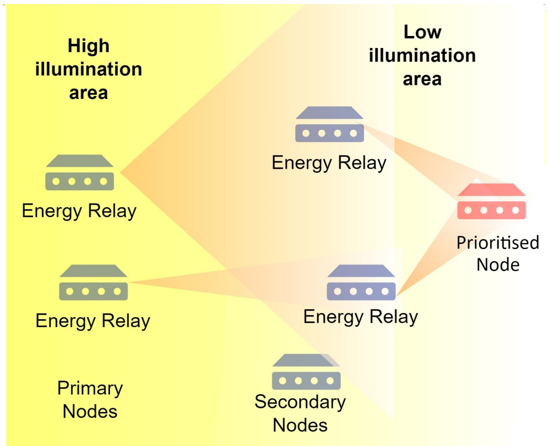

Fig. 5. The concept of node prioritisation.

the same transmission, receiving circuitries, and data encoding protocols as in our previous work [6]. Temperature information from nodes was transmitted at 1.4 kbps data rate. Table 1 shows the components of the prototype LIoT nodes used for the measurements.

TABLE I
LIoT Node components

Item	Component
Photovoltaic harvesters	Epshine LEH3 50 x 50 x 4 PV cells
Wide beam transmitter (Half intensity angle (100))	VAOL-5701WY4 White LEDs
Narrow beam transmitter (Half intensity angle (15))	LW514 White LEDs
Node MCU	Atmega 328P (AVR)
Energy storage	GA230F 400mF supercapacitor
PMIC	AEM10941
Temperature sensor	TMP36GT9Z
DC - DC converter	TPS62740
Optical sensor	Silicon 525 nm (Peak WL) PD

During sleep, data transmission, and energy transmission, LIoT nodes consumed an average power of 0.06 mW, 16.6 mW, and 42.6 mW, respectively.

A. *Effect of energy relay*

In order to measure the performance of the internode energy transfer under node prioritisation, the following experiment was carried out. For the experiment, a scenario of two energy transmitting nodes (primary energy relay nodes) and one energy receiving node (secondary - prioritised node) were considered, see experimental setup in Fig. 6 (a). The receiving node was kept in a low power sleeping mode during the experiment. The internode distance was kept at 25 cm throughout the experiment since no special optical lenses or reflector arrangements were used to enhance the gain of optical transmission. The two primary - relay nodes were configured initially to sense and transmit temperature data. After that, the nodes were put into a short sleep time to recharge the energy. The nodes were then put into energy-transmitting mode in two separate slots. When the stored energy of the relay nodes is depleted, they are forced to sleep for energy recovery. Initially, the secondary node was recharged by only using the OAP illumination. Then, the experiment was repeated for different indoor illumination levels and different settings of light beams. Figures 6(b) and 6(c) depict the modules used for narrow- and wide-beam transmissions, respectively.

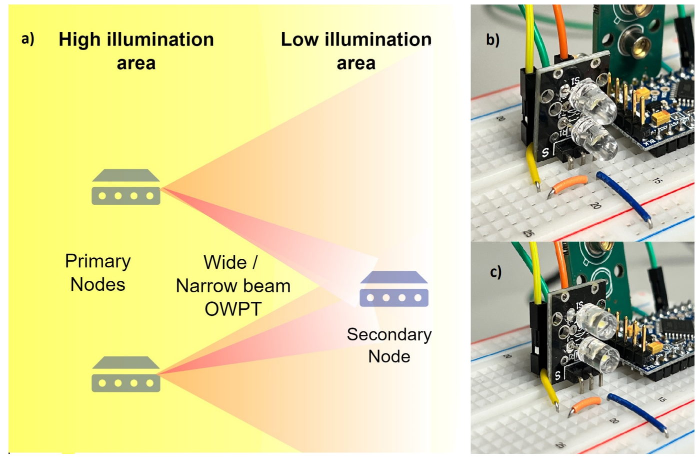

Fig. 6. (a) Narrow/Wide beam OWPT scenario used for experiment. (b) LW514 narrow beam transmitting module. (c) VAOL-5701WY4 wide beam transmitting module.

The obtained results for the average node recharge time performance in the experiments are plotted in Figure 7.

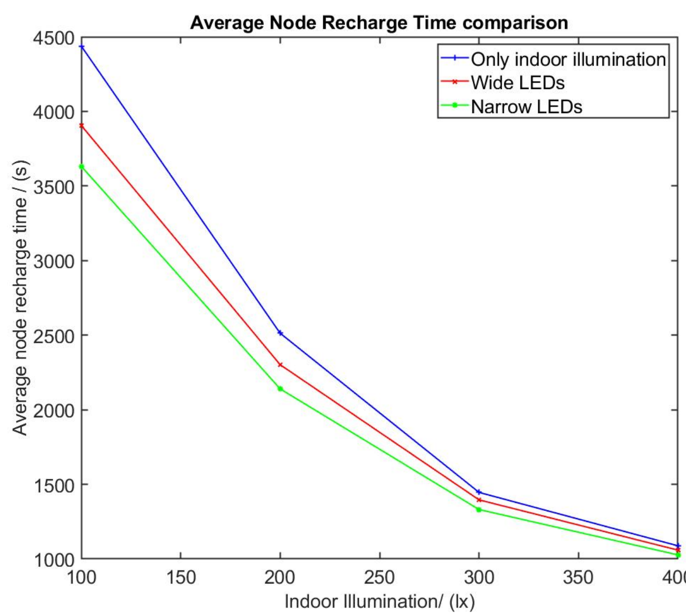

Fig. 7. Sleep LIoT node average recharge time comparison with and without OWPT.

Results show that narrow beam energy transmission could improve secondary node recharge by 18.2% under 100 lx low ambient illumination, while wide beam transmission could achieve 12% improvement. However, when the indoor illumination is stronger, the gain of energy transmission decreases, as expected. Thus, the proposed concept is more effective at lower illumination levels. Therefore, LIoT nodes located in low illumination areas could benefit from nodes located in high illumination areas in order to increase the recharging speed and thus increase the up time of the overall LIoT node network.

B. Analysis of Energy Profile of a Node

In order to analyse the energy fluctuation during the energy storage of the primary-energy relay node, the voltage variation during a one duty cycle was studied in detail. In the energy harvesting unit of the LIoT node, the minimum voltage of the capacitor is limited to 3.3v in order to keep the DC-DC converter powered on. The measurements were obtained from the multi-meter through a serial communication link. The obtained voltage level and power level variation at the energy storage of the relay node is plotted in Figure 8.

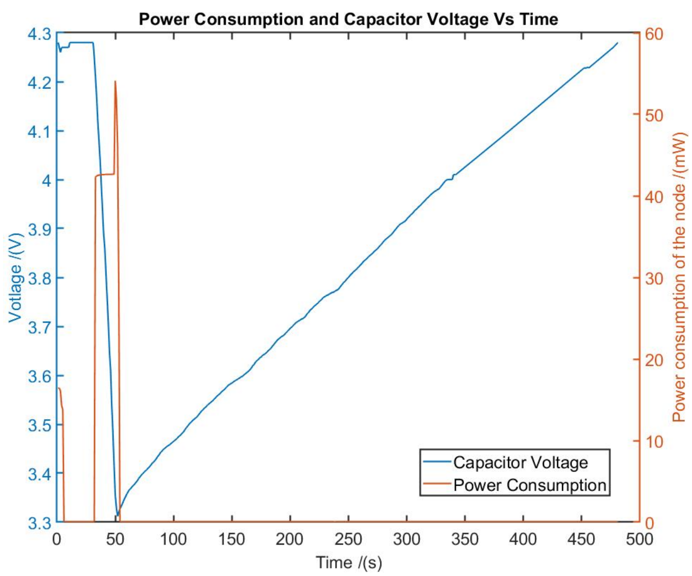

Fig. 8. Relay node capacitor voltage and power consumption variation.

As shown in the graph, the node consumes approximately 16mW of power during data networking and small voltage fluctuations can be observed at the beginning. Then, the node returns to the fully charged stage after data networking recovery time, before energy networking/discharge begins. In the voltage graph, sudden voltage drops can be observed during discharge time as the node consumes an average of 42 mW power. The graph shows that the node switched to sleep mode once its stored energy had been depleted, which involved 0.06 mW of power consumption during recharging. From the graph, It can be clearly observed that the voltage of the energy storage gradually increases during the recharging time.

C. Interferences analysis

During internode wireless power transfer, the most common Si photodiode (PD) based VLC receivers could get saturated and decrease the performance level of the communication link. When energy transfer between nodes occurs, the highly illuminated light beam can interfere with communication between the OAP or neighboring nodes. To analyse this behaviour, the following experiment was carried out. Initially, the main transmitter illumination level was kept low (100 lx) while the distance between two nodes was kept at a maximum. Then, the distance between the nodes was reduced until the SNR ratio dropped to a weak level threshold (20dB). The process was repeated for different indoor illumination levels. The obtained results are plotted in Figure 9.

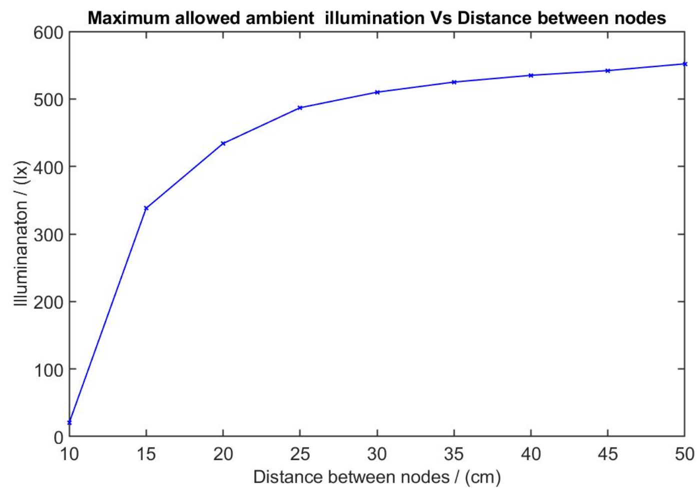

Fig. 9. Maximum allowed ambient illumination vs internode distance.

According to the results, minimum allowed inter-node distance varies with the indoor illumination levels. The minimum distance is small and increases linearly at low illumination levels. The minimum distance limit needs to be considered when selecting the data communication links "between node-to-gateway" and "node-to-node" according to the indoor illumination. The illumination of the room may need to be adjusted adaptively if the distance between the nodes changes. For a fixed room illumination, (a typical case) a given (minimum) node distance can be supported.

IV. Conclusion

This paper proposes a novel data and energy networking concept for mesh WPAN networks using energy-autonomous LIoT devices. Nodes can share both data and energy. Using OWPT, this WPAN concept allows the nodes capable of harvesting energy at a higher rate to share their energy with other nodes, improving the network's overall energy harvesting efficiency. This paper discusses concepts such as energy relays and node prioritisation in order to minimise operation outages due to insufficient energy at the nodes. Using prototype nodes made up of general purpose hardware components, the performance of these concepts was evaluated, and 18% faster recharge times were achieved. In addition, interference phenomena that can occur on PD receivers during OWPT were examined and results indicated that a minimum distance between modes is necessary to minimise PD saturation. In the future, optical transceiver-specific collimators, reflectors, and lenses can be utilized to enhance the efficiency of this network. Collimators, reflectors, and lenses designed for optical transceivers can further enhance the range of the communication. Sensor network applications for indoors where people are present, distractions caused by visible light can be mitigated by using optical wavelengths that are less visible to the human eye. It is possible to use OAP to observe human presence on the indoor premises and switch to a different optical spectrum as necessary by optimising the trade-off between energy harvesting efficiency and eye discomfort.

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