Feasibility Study on the Use of Printed OLEDs for Wireless Data and Power Transmission in Light-based Internet of Things (LIoT)

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***Abstract*— Visible light communication (VLC)-based Internet of Things (IoT) designs are rapidly gaining attention due to their unique communication-friendly features such as the ability to support high data rates, free-spectrum usage, and inherent security. In addition, the same infrastructure used by the VLC system can be exploited to support optical wireless power transmission (OWPT). The Light-based IoT (LIoT) concept encompasses both wireless data and power transmission. Recently, the use of printed electronics (PE) technology has been considered as a highly attractive approach to implementing the LIoT concept, as PE will allow manufacturing energy-autonomous, low-cost and sustainable nodes that can be attached to virtually any object. In this paper, we study the problem of communication and power transfer purposes in the uplink direction. In particular, we carry out a feasibility study comparing the use of OLEDs and conventional LEDs for the mentioned tasks. The performance of actual state-of-the-art printed optical components are measured, evaluated, and contrasted with that of similar conventional (non-printed) components. We found that printed OLEDs, though exhibiting sub-optimal performance, offer a robust performance to be used as key components in the implementation of the LIoT concept.**

Keywords—LIoT, VLC, OWPT, Printed electronics, OLED

I. INTRODUCTION

VLC-based Internet of things (IoT) is emerging as a promising solution for many problems currently faced by the radio frequency (RF)-based IoT. According to be operational predictions, with the industry 4.0 – 4th industry revolution, more than 31 billion IoT nodes devices are expected to come worldwide at the end of 2025 [1]. Instead of facilitating this large number of IoTs on the already congested RF spectrum, the visible light spectrum can be effectively used for this bandwidth requirement. The unique features that come with VLC, such as robustness to electromagnetic interference, unlimited license-free spectrum reusability, and physical security, can further enhance the quality of service of the IoT. In addition, since VLC systems use less complex signal modulation and demodulation within the transceivers, VLC-based IoT will not require high processing capable hardware for the implementation [2]. Also, on many occasions, high data transmission rates of the VLC have been demonstrated and proven to be sufficient to support the IoT data rates requirements.

On the other hand, as a sub-technology of VLC-based IoT, energy-autonomous, light-based Internet of things (LIoT) technology promises to deliver environment-friendly green communication in the near future [3]. Since LIoT nodes are designed to rely on harvested energy from indoor illumination, battery-free designs give additional advantages to the IoT nodes. With the addition of printed electronic (PE) technology, low cost, reusable, flexible, low power printed LIoT nodes can be manufactured and integrated with day-to-day IoT applications conveniently [4].

Typically, a VLC system supports full-duplex communications [5]. In the downlink direction, the lighting infrastructure is exploited to generate the optical link to the receiver, e.g., IoT node. The uplink direction is more critical, as, among others, energy in the device, e.g., IoT node, is typically very limited. The uplink can be implemented using retroreflectors, active optical sources (visible or infrared), or eventually radio [6]. In IoT, uplink is typically used to communicate sensor information between the primary data collecting point or to connect a near-by device, e.g. through device-to-device (D2D) communication. In addition, similar to wireless data transmission, wireless power transmission (WPT) between the nodes has become more common in modern IoT device designs [7]. Therefore, it is essential to discover the ability to integrate these two mechanisms for PE-based LIoT in the optical domain. The typical scenario of the proposed LIoT inter-node communication and power-sharing is depicted in Fig.1.

In summary, we foresee the development of energy-autonomous light-based IoT nodes that will fully printed and attached to virtually any surface. There are multiple challenges that need to be addressed before that vision can be realized. In this paper, we focus on the uplink of a LIoT node,

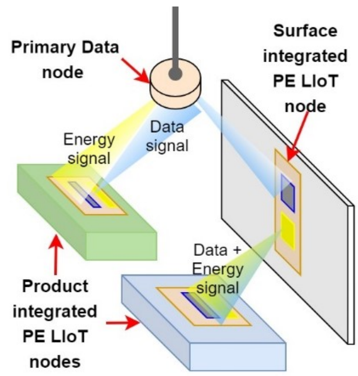

Fig. 1.LIoT inter-node communication and power-sharing

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particularly studying how printed OLEDs can be used as a part of the wireless data and power transfer solution. The paper is organized as follows. Initially, we evaluate the frequency response of the OLED-based and LED transceiver system in Section V (A) and then study the printed OLED's capability of work as a visible light power transmitter in Section V (B).

II. PRINTED OLED FOR LIOT

OLED technology is receiving considerable attention due to its unique characteristics over other light sources. Unlike traditional point/line lighting sources, which require multiple units to cover up a larger illumination area, OLED can light an entire area using a single appropriately scaled-up unit. Therefore, it will require a less complex driver unit to modulate for data transmission in VLC systems [8]. Moreover, in [9], researchers managed to manufacture single-layered OLED, producing 10,000 cdm^{-2} by only using 2.9 forward voltage on the diode. This type of diode is ideal for IoT applications, as IoT nodes are energy limited, and therefore OLED diodes lend themselves to be used in the LIoT concept. According to [10], researchers have developed and evaluated printed IR emitting diode for medical applications similar to the printed OLED structure. This type of printed IR-OLED can replace traditional IR LEDs in IR communication, enabling more compact, flexible designs of IoT/LIoT. Furthermore, unlike the more concentrated Lambertian radiation pattern emitted by traditional light-emitting diodes (LED), OLED has higher emitting angles, which causes a non-Lambertian radiation pattern on the illuminated surface. The structure of layered printed OLED is illustrated in Fig. 2.

Moreover, exploiting the unique characteristic of OLED, the printed LIoT nodes illuminating part can be customizable according to the requirement. This will help to increase the printed node's compactness while saving more area to place other printed sub-circuits on the node.

There are several approaches to manufacturing printed OLED. Gravure printing, inkjet printing, slot-die coating technologies can be used to fabricate these units [11],[12]. Industrial printing mechanisms such as sheet to sheet (S2S) and roll to roll (R2R) are vastly used for manufacture these components. However, in all these mechanisms, initially, the anode material is placed on a flexible substrate. Then organic materials according to the layered structure will be deposited on top of the anode layer. After that, the cathode layer and finally the top encapsulation layer will be placed respectively.

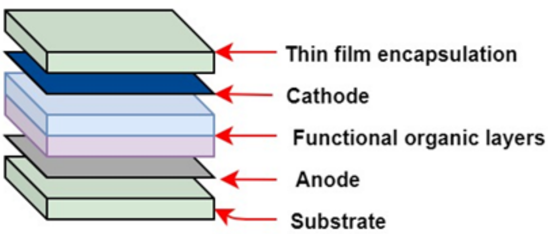

Fig. 2. Structure of printed OLED

III. PRINTED OLED AS UPLINK FOR LIOT

In many communication systems, data transmission can be considered one of the most power-consuming processes. This will be more crucial when it comes to the battery-powered, hence energy-limited, device nodes. Similarly, for printed LIoT nodes, a suitable low power consuming uplink approach needs to be carefully selected. For this requirement, the previously discussed low-power consuming printed OLED technology can be considered. In this way, the nodes are expected to transmit data between the primary data collection point or neighbor nodes using VLC.

According to [8], due to the layered structure of the OLED, the optical source tends to follow a plate capacitor-like behavior, resulting in capacitance fluctuations at high-frequency signal transmission. Typically this will act as a low pass filter with a cutoff frequency given by (1). The equivalent circuit of the OLED is depicted in Fig. 3, where R_d and R_p are contact and leakage resistance of the OLED, respectively.

$$f_{cutoff} = \frac{1}{2\pi RC} \tag{1}$$

where R is the total effective resistance of the OLED, C is the OLED plate capacitance, which can be described by (2).

$$C = \frac{A\epsilon_0\epsilon_r}{d} \tag{2}$$

where, A is the photoactive area of OLED, $\in_0$ is the permittivity of free space, $\in_r$ is the relative dielectric constant of the organic layer, and d is the thickness of the OLED.

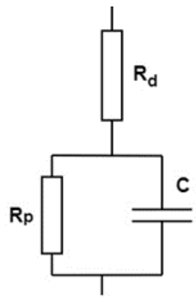

Fig. 3. Equivalent circuit for OLED

Therefore, from the above equations, it can be observed that the physical dimensions of OLED directly impact the bandwidth that the diode can handle. This can cause intersymbol interference when the transmit signal exceeds the cutoff frequency. Moreover, a method to bring down the C value of the OLED using a highpass filter-based pre-equalization method is described in [13]. However, according to [14], in this approach, the RC filter will introduce Baseline Wandering (BLW) phenomena that could affect the performance of several VLC modulations, particularly those with more power spectral density (PSD) at DC level, such as on-off keying (OOK) modulation. However, modulation schemes such as pulse position modulation (PPM) and digital pulse interval modulation (DPIM) tend to be immune to BLW as they have low PSD at DC level [15].

IV. PRINTED OLED AS POWER TRANSMITTER FOR LIOT

In recent years, optical wireless power transfer technology (OWPT) has evolved day by day due to its capability to

outperform typical radio frequency wireless power transmission [16]. There are many studies conducted to combine this technology with VLC links, and their results are promising. In [17], researchers propose a new concept of Simultaneous Lightwave Information and Power Transfer (SLIPT) for VLC links, which optimize the trade-off between energy harvesting and SNR performance of the solar panel-based receiver system. Therefore, integrating OWPT with printed LIoTs will enable the internode power-sharing, which is common in RF IoTs. Since LIoT nodes are designed to operate on harvested energy from ambient illumination, it is important to use high efficiency power transmitter hardware to minimize the energy loss in the transmitting device. The high efficiency printed OLEDs, and printed PV cells with comparable performance to the conventional PV cells will make this idea more feasible to integrate.
According to [18], the harvested energy of such a system can be expressed by (3).

$$E = f I_{SC} V_{OC} \tag{3}$$

where f is the fill factor of the PV cell, and V_{OC} is the open terminal voltage of the PV cell and I_{SC} is the close-circuit current of the PV cell.

V. PERFORMANCE EVALUTION

For the performance evaluation, OLED and LED-based VLC links were implemented. As the data receiver for both links, an OPT101 analog sensor with a built-in trans-impedance amplifier was used. As the transmitter of OLED VLC link, a printed 4cm x 7cm OLED was used. A conventional 5mm white LED was used as the transmitter of the LED VLC link. In order to evaluate the energy harvesting performance, a printed organic PV cell was used. During the experiments, low power device-friendly transmitting powers were used for both transmitting devices. All used optical components are shown in Fig. 4.

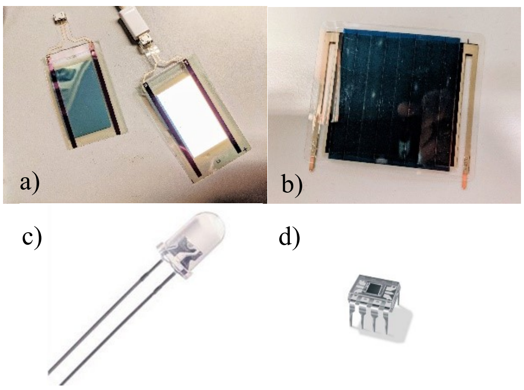

Fig. 4. a). Printed OLED b). Printed indoor OPV c). 5mm LED d). OPT101 analog sensor

A. *Frequency response analysis for the printed OLED-based VLC links.*

In order to compare the frequency response of the LED and printed OLED-based VLC systems, conventional 5mm white LED and printed OLED lighting sources were used. Initially, both transmitters were placed directly above the opt 101 photodiodes (PD) sensor. Then the SNR was measured by varying the operating frequency value of the system. Additionally, to explore the effect of emitting data signals from point and planar light sources, the experiment was repeated after moving PD 10 cm horizontaly, that is, transmitter and receiver were spatially misaligned. The received results are plotted in Fig. 5.

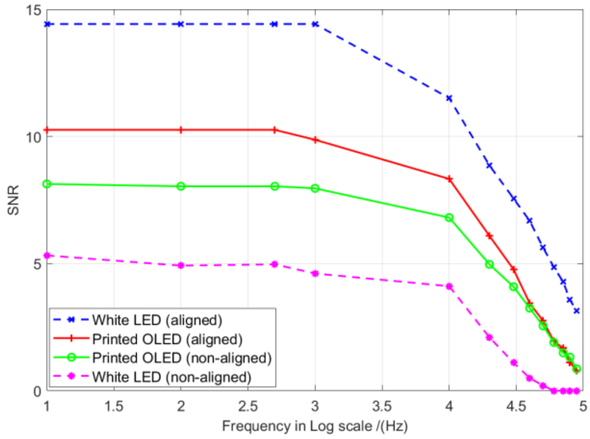

Fig. 5. Frequency response of OLED and LED VLC links

According to Fig.5, it can be observed that the LED technology has a better frequency response compared to the printed OLED when both transmitter and receiver are aligned with each other (Hybrid VLC link). However, when the transmitter and receiver are not directed (non-directed VLC link), the planar printed OLED link has a better frequency response than the LED. Therefore, the results suggest that Lambertian radiation patterned visible light emitters are more suitable for the stationary LIoT's VLC applications while non-Lambertian visible light emitters are more suitable for dynamic VLC applications.

B. *Energy harvesting performance evaluation of the OLED-based OWPT system.*

In order to compare the performance of the OWPT system based on LED and the printed OLED, the following experiment was carried. A printed indoor-optimized organic PV cell was used in the measurements. Initially, the PV cell and transmitters were placed aligned to each other, and then the input power to the transmitter was varied. Then the same experiment was repeated by moving the PV cell 10 cm away horizontally from the initial location. The obtained results from the experiment are graphed in Fig. 6.

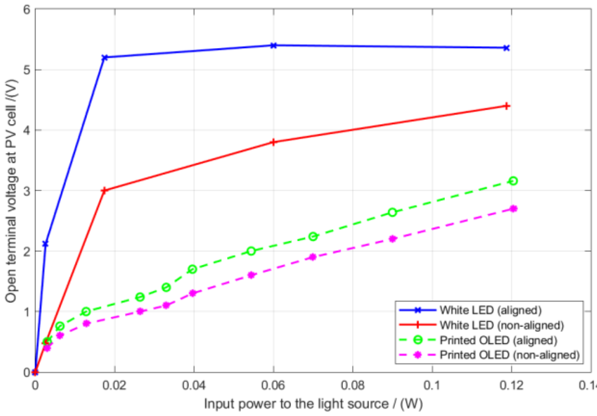

Fig. 6. Energy harvesting performance evaluation of OLED and LED VLC links

According to the graph, the conventional 5mm white LED-based OWPT system manages to create more open terminal voltages compared to the printed OLED system. However, the voltage fluctuation of the OLED seems to be stable compared to the LED for the small PV displacement. Therefore, the results suggest that Lambertian radiation patterned visible light emitters are more suitable for the non-dynamic, ultra low powered LIoT design's OWPT functionality. In contrast, non-Lambertian OLED emitters are more suitable for the OWPT function of dynamic LIoTs and nodes with more power supply capabilities for OWPT.

VI. Conclusion

Based on the experiment results of this research work, we can conclude that the printed OLED has compatibility with low data rate VLC applications while supporting OWPT with suitable efficiencies for LIoT. However, according to the results, conventional LEDs can provide better frequency response and energy harvesting performance when the transmitter and receiver are aligned. With non-Lambertian radiation patterned planar light-emitting design, OLED lighting sources will provide immunity to both power and signal level fluctuation due to the mobility and displacements of the receiving devices. Therefore, with the integration of printed OLED to the node, printed LIoT nodes will be able to communicate between internodes while sharing power between neighbour nodes with stable performance. As future work, a novel power-sharing algorithm can be introduced to energy-autonomous LIoT to optimize harvested power for both own operation and sharing purposes.

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