Visible light or infrared? Modulating LiFi for dual operation in the visible and infrared spectra

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***Abstract*—Light-Fidelity (LiFi) has emerged in the last few years as a promising technology for alleviating the stringent demand of wireless data services. Prior works have considered LiFi operating either in the visible light or infrared spectrum. Each spectrum band has its own advantages: visible light allows leveraging existing infrastructure for communication, while infrared is not affected by degradation in presence of light dimming. In this work, we propose a modulation scheme that efficiently uses both spectra, and present a simple, low cost, yet efficient modulation technique that retains the benefits of both bands. We prototype our solution by creating an extended version of OpenVLC, and we experimentally show its robust performance in communication under different dimming conditions. We make the implemented system publicly available to the research community.**

I. INTRODUCTION

In the past few years, there has been an increasing interest in the research, development, and commercialization of Light-Fidelity (LiFi). LiFi is considered a promising solution to alleviate the Radio Frequency (RF) spectrum crunch problem in 6G networks, and to serve Internet of Things (IoT) devices. LiFi systems operating in the *visible light spectrum* (wavelengths between 380 nm and 780 nm) reuse the existing Light Emitting Diode (LED)-based infrastructure, retrofitted for communication purposes. This approach has two advantages: it significantly reduces the infrastructure and deployment costs of LiFi solutions, and greatly reduces the energy required for communication as illumination consumes much higher energy than communication [1]. However, one mandatory requirement of LiFi communication systems operating in the visible light spectrum is to provide dimming support [2], adjusting the brightness of light bulbs during communication according to the users' comfort.

Earlier light communication standards, i.e., IEEE 802.15.7-2011 and IEEE 802.15.13, used the visible light spectrum, targeting short-range optical communications and multi-gigabit optical wireless communication, respectively. Instead, the most recent IEEE 802.11 TGbb standard focuses on achieving high data rates but ensuring the rapid market adoption of LiFi technology. To this end, the standardization effort has focused on enabling existing chipsets such as WiFi to work in the *infrared spectrum* band. According to the IEEE 802.11 TGbb, the uplink and downlink operation of LiFi systems in the infrared band is mandatory with wavelengths between 800 nm and 1000 nm. The advantage of this approach is that dimming does not need to be taken into account in the infrared spectrum, which allows easing the commercialization of LiFi solutions. However, this approach results in losing one of the aforementioned advantages of LiFi systems, which is, to retrofit existing lighting infrastructure for communication.

In this work, we envision that future LiFi systems will operate in *both* visible light and infrared spectra, retaining the advantages of both bands for robust communication. From a technological standpoint, LED bulbs are typically composed of multiple small Surface Mounted Device (SMD) LEDs. In the future, some of these SMDs LEDs could be operating in the visible light band, and others in the infrared band. Therefore, it would be simple to extend the functionalities of LED bulbs to operate in both spectra. Our solution takes also advantage of the fact that the responsivity of typical photosensitive devices covers both visible light and infrared spectra, and thus *no changes are required at the optical receiver*. However, operating in both visible light and infrared spectra requires the design of new modulation schemes that efficiently combine the transmissions in both bands, while taking care of dimming in the visible light band, as we address in this paper.

The trivial solution would be to dedicate visible light LEDs for illumination and infrared LEDs for communication, but this would increase the overall energy consumption, as it will be shown in the results section of this paper. Therefore, a different approach is needed to cover this larger spectrum. Unlike previous works that proposed complex techniques for implementing dimming in LiFi [3], in this paper we propose a *low-power modulation scheme* based on On-Off-Keying (OOK) and Pulse Width Modulation (PWM) that can operate in *both the visible light and infrared bands*, for fulfilling *both illumination standards and required communication performance*. Due to its simplicity, this modulation scheme can be extended to multiple low-end and energy-constrained systems, such as IoT devices for applications in smart homes, offices, and Industry 4.0. We have experimentally validated our proposal by designing

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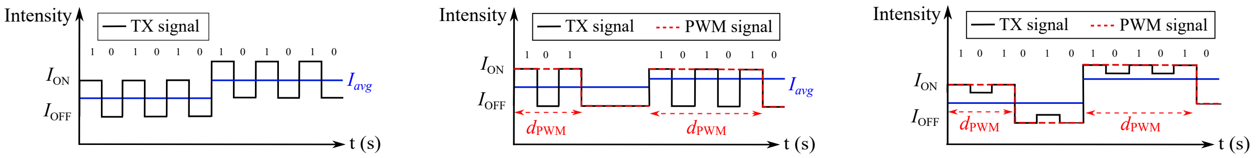

(a) Analog dimming - OOK modulation.

(b) Digital dimming - OOK modulation.

(c) Combined analog/digital dimming - OOK modulation.

Fig. 1: State-of-the-art OOK dimming techniques.

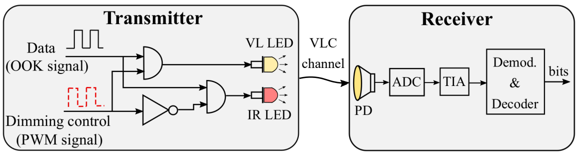

Fig. 2: Block diagram of the proposed LiFi system.

a Printed Circuit Board (PCB) that is an extension cape for the BeagleBone Black (BBB), and the firmware required to control it[1].

II. RELATED WORK

Existing techniques to adjust the brightness of an LED are classified into *analog dimming* and *digital dimming*. The former consists of decreasing the radiated optical flux of the LED by adjusting the amplitude of the forward current through it, while the latter is based on a digitally modulated pulse train whose duty cycle (d_{PWM}) determines the dimming level (i.e., a PWM signal) [4]. In the past years, these dimming techniques have been combined in many different ways with existing modulations schemes to convey data while providing dimming control in LiFi systems. Fig. 1 represents an example of these dimming techniques where OOK modulation is used, though any other modulation scheme can be employed.

Analog dimming with OOK (Fig. 1a) ensures low computational complexity and simple implementation, but directly changing the forward current through the LED alters the emitted wavelength of the light [4] and degrades the spectral efficiency [5]. *Digital dimming* with OOK [3] (Fig. 1b) shows limitations in terms of achievable data rate [4]. To solve the limitations mentioned above, different dimming techniques combining both *analog and digital dimming* with existing modulation schemes have been proposed. This is the case of the solution depicted in Fig. 1c and proposed in [6]. However, most of existing dimming proposals present the following drawbacks: (i) limited dimming precision; (ii) constrained dimming range; (iii) increased complexity when trying to guarantee a balance between communication performance and illumination [7]; and (iv) poor communication performance under high dimming conditions [8]. Moreover, most of current solutions can only be applied to specific scenarios (only to multi-carrier [9] or only to multi-LED systems [10]), and have not been experimentally tested.

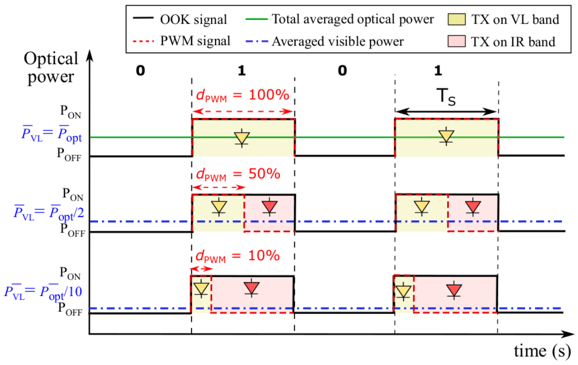

Fig. 3: Proposed modulation scheme.

III. PROPOSED APPROACH

Fig. 2 presents the block diagram of our proposed LiFi transmitter and receiver for dual operation in both the visible light (VL) and infrared (IR) spectra. As it can be observed, from two input signals (i.e., OOK signal and PWM signal) and after some logic gates, we determine the two signals transmitted by VL and IR LEDs. Fig. 3 represents some examples of the signals emitted by each LED for different dimming levels. As it can be observed, it combines OOK and PWM modulations for communication and dimming purposes, respectively. Specifically, when sending the OOK symbol '1', the transmitter switches between the VL and IR bands following a PWM signal whose duty-cycle (d_{PWM}) determines the provided dimming level. As depicted in Fig. 3, when the PWM signal is 'ON', the transmitter operates on the VL band, sending out a VL signal that contributes to illumination purposes. In turn, when the PWM signal is 'OFF', the sender works on the IR band generating an IR signal that contributes to dimming. In this way, the higher d_{PWM}, the lower the dimming level is. In Fig. 3, $\overline{P}_{\mathrm{VL}}$ and $\overline{P}_{\mathrm{opt}}$ denote the averaged visible light optical power emitted for each dimming case, and the total averaged optical power, respectively. Note that the proposed technique could also be extended to other modulation schemes by alternating VL and IR LEDs. We consider OOK in this paper for simplicity.

In LiFi networks using the transmitter we propose here, any photodiode (PD) with sensitivity in both the VL and IR bands can be employed as receiver. If we look at the responsivity of photosensitive devices, as long as the power received at IR and VL bands are the same, we find that PDs provide better performance when operating in the infrared band (800 nm to 1,000 nm band). This is

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[1] https://github.com/openvlc/OpenVLC/tree/master/OpenVLC_VL_IR

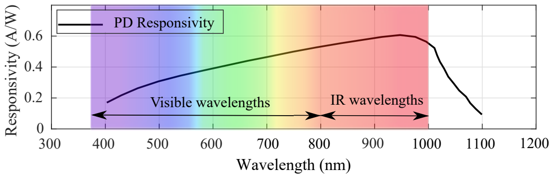
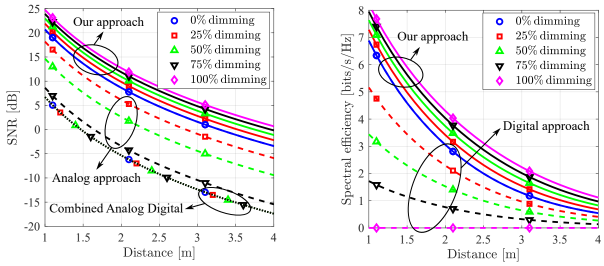


Fig. 4: Responsivity of the ‘VTP4085H’ PD at the receiver.



(a) SNR against distance for our proposal, analog dimming and combined analog/digital dimming.

(b) Spectral efficiency against distance for our proposal and digital dimming.

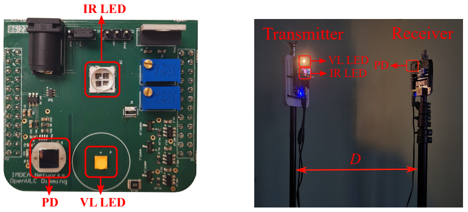
Fig. 5: Performance comparison between our proposal and state-of-the-art OOK dimming techniques.

represented in Fig. 4, which depicts the responsivity curve of the ‘VTP4085H’ PD. In this paper, we take advantage of this not only to implement a dimming technique that provides dimming ranges wider than traditional approaches, but also to ensure high-quality communication links even under extreme dimming conditions. As shown in Fig. 2, the signal reception process consists in a TIA, an ADC, a demodulator with a threshold to decide between bit ‘1’ and ‘0’, and the decoder.

IV. IMPLEMENTATION AND RESULTS

First, Fig. 5 shows some simulation results of our proposal against state-of-the-art solutions: analog, digital and combined digital-analog, as depicted in Fig. 1. These results are obtained using well-known equations derived in [11] and the following simulation parameters: an optical power when LED is ON of 1 W, sampling frequency of 10 MHz, absolute temperature of 300 K, receiver load 50 Ω, LED models XHP35B-00-0000-0D0HC40E7 and LZ4-00R708 for VL and IR LEDs, respectively, and PD VTP4085H. Note that the larger the dimming level, the larger are the gains of our proposal with respect to the state-of-the-art solutions in terms of SNR and spectral efficiency, due to the gain obtained by the PD in IR wavelengths.

To confirm these simulation results, we implement the proposed transmitter and receiver in a PCB designed by ourselves which is compatible with OpenVLC, an open source and open hardware project for LiFi communication [12]. Our prototype and the experiment's setup are shown in Fig. 6, and the transmitter schematic is detailed in Fig. 7. The firmware for transmission is design to be running at the Programmable Real-time Unit 0 (PRU0) of the BBB and it has three main functionalities: (1) generate the modulating signal to the selected LED (the OOK signal in Fig. 2), (2) create the PWM signal whose duty cycle (d_{PWM}) determines when to switch between the VL and IR bands and thus the provided dimming level, and (3) switch between the VL and IR LED by enabling the proper General Purpose Input Output (GPIO) to control each LED (B1 or B2 in Fig. 7). From Fig. 7, note that the MOSFET enabling each LED is managed by a different GPIO from the BBB. Also, note that our approach is easily implemented by including an additional line of code in the firmware of OpenVLC to enable/disable B1 and B2 pins depending on the configured duty cycle (illuminance). Then, the prototyping complexity is similar to a system that uses a single LED for transmission. Fig. 8 shows actual signals transmitted through GPIO1 and GPIO2 to control VL and IR LEDs, respectively, for providing communication at dimming levels of 25% and 75%.



(a) Fabricated PCB.

(b) Setup for experiments.

Fig. 6: Hardware and setup used for experiments.

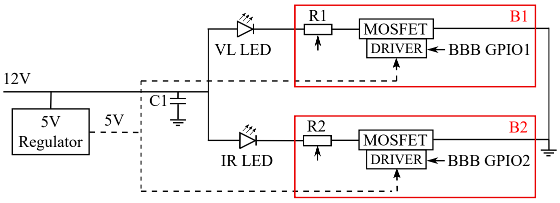


Fig. 7: Schematics of the designed transmitter.

Our experimental results show that our solution can provide different illuminance values as represented in Fig. 9. To make a fair comparison, we adjust the potentiometers R1 and R2 in Fig. 7 to ensure the same amount of received power in the VL and IR spectra. Fig. 10 represents the experimental results of UDP throughput and packet loss ratio for two different distances $D = 0.6$ m and $D = 1.2$ m, and for different dimming levels. This test is done with the *iperf* command transmitting data from our LiFi transmitter to a LiFi receiver. Note that, as expected, the UDP throughput achieved with higher dimming level is larger than the one obtained with lower dimming level, although the illuminance is lower due to the fact that the VL LED is OFF during a time period longer than the IR LED. For example, at a distance of 1.2 m, the option 100% of dimming provides the maximum UDP throughput of the OpenVLC platform (400 kb/s), whereas 0 kb/s is obtained when only the VL LED is ON, i.e., with 0% of dimming. This is because, as discussed in Section III, photosensitive devices provide better performance when operating in the infrared band. On the other hand, notice that 100% of dimming means no visible

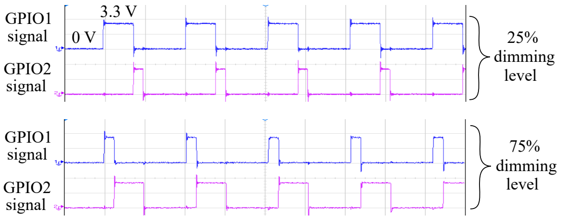


Fig. 8: Oscilloscope screenshot of signals transmitted through BBB GPIO1 (VL LED) and BBB GPIO2 (IR LED) for dimming levels of 25% and 75%.

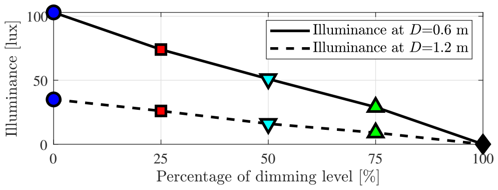
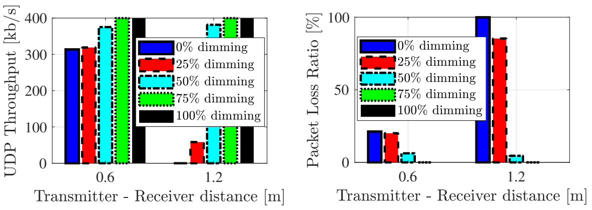


Fig. 9: Illuminance for different dimming levels and distances.



(a) UDP throughput results.

(b) Packet loss ratio results.

Fig. 10: Experimental results.

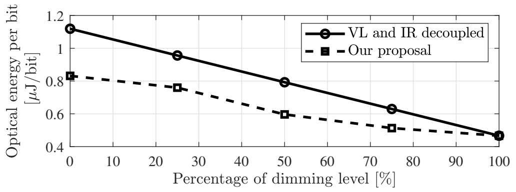


Fig. 11: Optical energy per bit transmitted for each dimming level when the VL and IR LEDs are decoupled. Distance between transmitter and receiver is 0.6 m.

light for illumination and that the *dimming level is selected by the user based on comfort and not on communication performance*. A similar effect happens with the packet loss ratio metric, i.e., the larger the dimming level, the lower is the number of packets lost. Note that larger data rates could be achieved with a more complex hardware design such as one based on FPGA. However, the comparison between the under-discussion techniques would be relatively equal.

We also compare the performance of our proposed solution against the case where IR and VL LEDs are decoupled for communication and illumination purposes, respectively. If LEDs are decoupled, we increase very much the power consumed per bit, as VL LED is uniquely dedicated to illumination (*and its energy is not used for communication*) while IR LED is in charge of communication. Fig. 11 shows the results of optical energy per bit for both cases. Note that, the larger the dimming level, the lower the optical power per bit due to the increased achieved throughput. For the case where both LEDs are decoupled, the maximum 400 kb/s UDP throughput, but the extra power consumed by the VL LED increases the optical energy per bit transmitted, achieving consumptions that are around 30% larger than the ones obtained with our proposed system.

V. CONCLUSION

In this paper, we have proposed a low-power solution for joint illumination and communication using visible light and infrared spectra. We have validated the proposal with simulations and experimental results. We have designed and implemented a new PCB integrating the suggested approach and extending the functionalities of OpenVLC. We have also shown that our approach provides robust communication and illumination, outperforming existing solutions.

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