Visible Light Communication for Intermittent Computing Battery-less IoT Devices

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Abstract. Eliminating the dependency on batteries as primary energy sources boosts the Internet of Things (IoT) to scale up to billion devices. New low power communication technologies combined with new energy harvesting techniques can significantly improve the energy efficiency of IoT battery-less devices. We present a communication system based on Visible Light Communication (VLC) embedded in a lighting system that enables data transmission and energy harvesting. The transmitter is a powerful LED light source. We avoid light variation and flickering of the source while transmitting data. Moreover, we embed the receiver in a cheap and compact solution by using only a single MCU and very few external components such as small-size photovoltaic cells. Experimental results show that our approach is a viable solution for powering the IoT battery-less devices of the future.

1 Introduction

The omnipresence of lighting systems in indoor environments makes Visible Light Communication (VLC) a noticeable solution for Internet of Things (IoT) applications. LED-based systems can be adopted to improve the lighting system efficiency [1] and enable communication over battery-less devices [2]. Avoiding battery dependencies as the primary energy source means overcoming the hard limit to the growth of the billion devices trend [3]. However, to consolidate the spread of battery-less devices, several aspects must be considered. First, the alternative energy source should exploit various energy harvesting technologies relying on the surrounding environmental energy sources (such as light and solar [4], radio-frequency (RF) [5], bacteria species [6]). As the energy source is not always available and can be considered as sporadic, the battery-less device must deal with frequent power failures and so intermittent operations [7, 8]. The operation is cycled through waiting for energy availability and the very action moment, when the energy is sufficient [9, 10]. Exploiting light energy to power IoT devices is a viable solution [11], even with indoor lighting systems where visible light is used as a communication channel [12, 13]. Communication over visible light is achieved by modulating the light. The challenge for lighting systems is to maintain a certain comfort level, so the modulation process must be “invisible” to human eyes. Thus, meaning the absence of light flickering and variations during data transmission.

1.1 The state-of-the-art

IoT devices claim to communicate information towards the Internet. In battery-less devices, communication is crucial due to the ultra-low power constraints. Intermittent computing battery-less devices drastically reduce the power consumption thanks to optimized power management [4, 6, 8]. Reliable communication under ultra low power constraints is still an open challenge. One of the challenges to tackle for battery-less devices is the synchronization over the sensing network [16, 17]. In this scenario, we believe light communication would be a promising solution. Thus, we focus our preliminary investigation on VLC. LED lighting systems are suitable to achieve data transmission [18] even with high data rates [14, 20]. The second challenge to overcome is related to battery-less device communication between nodes [7]. Nowadays, light communication is enabled only between a specific illuminator and the end node even with complex modulation [13]. Furthermore, bidirectional communication is achieved thanks to visible light backscatter [15, 19]. Finally, hybrid systems combining different communication technologies are gaining momentum. Different sensors exploit different communication channels such as RF backscatter [11]. Others combine the technologies to allow devices to communicate between nodes and achieve tag-to-tag communication [12].

1.2 The Problem Statement and Contributions

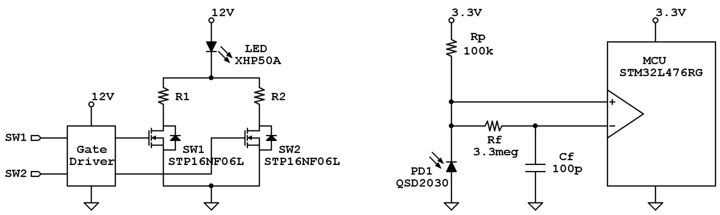
Eliminating batteries brings IoT devices to new applications fields. Communicating information with light is an appealing solution to reduce the IoT device's power consumption, thanks to low power receiver circuit, and harvesting energy directly from the light communication channel. We present a system design composed of a LED transmitter (i.e., the illuminator) emulating a light bulb, and an all-in-one receiver solution based on a single microcontroller unit (MCU) and few external components such as a photodiode, or alternatively a small size photovoltaic cell, and a RC network. To accomplish this result the first task to do is to run the MCU in low power mode and reduce the overall system power consumption to the lowest 28.4 mW (i.e., 8.6 mA @ 3.3 V). Thus, allowing the system to be powered entirely with super small sized photovoltaic cells (46 mm x 15 mm). However, in dark conditions the system can still experience power failures as the only power source comes from light. The introduction of a small energy buffer (i.e. a supercapacitor) and the use of intermittent computing architecture can solve this further issue, allowing the system to be operated with memory consistencies even in the case of an intermittent power failure. Our approach covers the preliminary measurement to support communication and energy harvesting from the light communication channel. Moreover, we focus on the light modulation and coding technique to ensure a quality of service in the lighting system, avoiding light flickering and variation due to data transmission.

2 Systems Design

First, we focus on the light produced by the LED, which should not flicker during the data transmission. We also focus on simple modulation schemes to keep the receiver side as simple as possible.

2.1 VLC Transmitter

The transmitter embeds light sourcing and data into the same visible light channel. The Manchester coding of the signal prevents the light intensity from varying during data transmission, thanks to the constant average value of the symbols. The symbols are generated by modulating the LED current between a high level and a low level. These two levels must be well separated from each other, as this directly impacts the communication capability and light flickering. Moreover, the LED should always be polarized to speedup switching transients, thus we decide on two current levels different from zero, also reducing the flycker intensity.
The schematic in Fig. 1a reports the LED current modulation circuit (i.e. the VLC transmitter). The transmitter is driven by an MCU STM32L476RG[1], acting on the SW1 and SW2 inputs. The chosen LED is a Cree XHP50A-0S-01-0D0BJ440E[1] with a maximum power of up to 18 W, a forward current of up to 1.5 A and a forward voltage below 11.5 V. By using a 12 V supply in combination with the LED forward voltage the overall power dissipation on the current limiting resistors is kept roughly at 5% to the power reaching the LED.



(a) (b)

Fig. 1. Schematic of the VLC transmitter (a) and VLC receiver (b).

2.3 VLC Receiver

We embed the VLC receiver in a cheap and compact solution using only a single MCU, the STM32L476RG, and very few components (as shown in the schematic Fig. 1b). As a sensing element to receive the light signals, we select a photodiode

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[1] https://www.mouser.it/datasheet/2/810/NewEnergy_XHP50_Modules_DataSheet-2326278.pdf last accessed: June 2021

QSD2030[2]. The MCU internal comparator is used to discretize the analog signal generated by the photodiode. It is important to remark that the inverting input operates as a moving threshold for the comparator. Thus, we can distinguish the modulated signals even in slowly changing light intensity (e.g. due to shadows or surrounding lights turned on or off). It is important to tune the filter cut-off frequency in order to attenuate the modulation frequency. When the illuminator is transmitting data packets, the comparator output produces a sequence of high to low and low to high transitions. Finally, the MCU, through a timer and an interrupt, captures these transitions and reconstructs the message.
To enable energy harvesting, we also test a small sized photovoltaic cell composed of four single elements in parallel[3] of 46 mm x 15 mm in total dimensions. The photovoltaic cell claims to produce up to 44 mW with optimal illumination conditions. We have to consider the possibility of operation with light sporadicity and intermittent operation. With this approach, we have to introduce an energy buffer (e.g., a supercapacitor) that charges when the node is sleeping and provides the proper energy level for the limited time activation.

3 Result

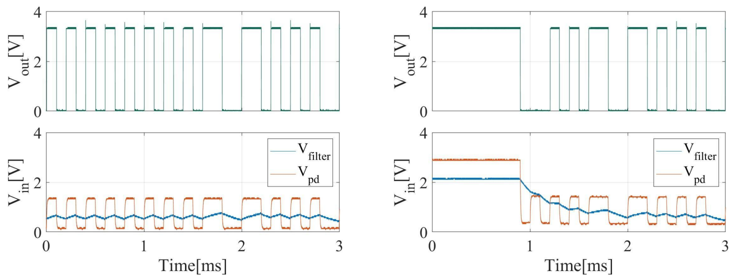
As aforementioned, the Manchester coding of the signal prevents the light intensity from varying during data transmission. Moreover, the higher the light the light modulation, the higher the received signal. However, light intensity can change between idle period and the transmission one. A trade-off between light variations is required so we performed several tests.
First, we have to consider the basic operation, thus having one switch always closed and the other providing the light modulation when data transmission is needed. At this point, it is clear a light variation appears as the average light intensity changes when transmission is activated by reaching a new higher value. The first possible way to solve this problem is to reduce the difference between the two current levels to reduce the light intensity variation between data communication and idle.
Table 1 collects the data for different tests involving different current limiting resistors. Note that during the test SW1 is always closed and SW2 is modulated when data is transmitted. Since we are interested in visual light comfort, we pay attention to light variation recorded by human eyes. Even with the smallest 4.9% current difference, the light intensity variation can be noticed to our eyes. Moreover, this configuration is particularly unfavourable as the two current levels are really close to each other, thus reducing the voltage swing at the receiver side.
A different solution is mandatory to accomplish visual comfort and a sufficient light modulation variation. We propose to send a series of alternated symbols 0 and 1 when the system is idle. Fig. 2a reports the waveforms at the receiver side: V_{out} is the comparator output; V_{pd} is the photodiode cathode voltage; V_{filter} is the voltage after the

[2] https://www.onsemi.com/pdf/datasheet/qsd2030-d.pdf last accessed: June 2021
[3] https://np.micro-semiconductor.hk/datasheet/b4-KXOB22-01X8F.pdf last accessed: June 2021

RC filter. Data transmission with the preamble starts with the first longer pulses. Due to oscilloscope probe connection and loading effect (R_f = 3.3 MΩ, R_{probe} = 10 MΩ), it can be seen that the voltage after the filter is not centered with the photodiode one. Fig. 2b reports evidence of a minor problem solved by the new solution. Due to the time response of the RC filter used for the moving comparator threshold, the comparator loses the first pulses until the filter reaches the steady state.

Table 1. LED currents with different transmitter configurations (supply voltage of 12 V).

R_1[Ω]	R_2[Ω]	I_{R1}[mA]	I_{R1+R2}[mA]	ΔI[%]
4.7	2.2	212	400	+88.7
4.7	4.7	212	319	+50.5
3.3	4.7	267	367	+37.5
3.3	47	267	280	+4.9



(a) (b)

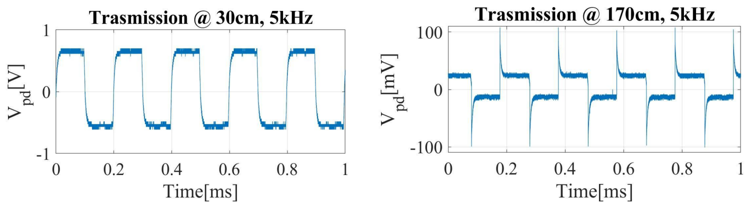
Fig. 2. Data transmission with (a) and without (b) alternated 1 and 0 during idle.

3.1 Characterization: Photodiode

We performed some measurements using the setup with two current levels (high 400 mA and low 212 mA) and a modulation frequency of 5 kHz at different distances in a range between 30 cm and 170 cm (as an upper limit). Fig. 3 reports the voltage waveforms at the receiver side and at the photodiode cathode (AC coupled). The voltage swing decreases as the distance increases. Moreover, when the distance is larger and the voltage swing is smaller, transition spikes appear due to the changes in the input bias current of the comparator.

Fig. 4a reports further experiment parameters such as the received average illuminance and the average photodiode cathode voltage V_{dc}. In particular, when the distance is shorter, the photodiode current is larger, thus the average voltage is lower.

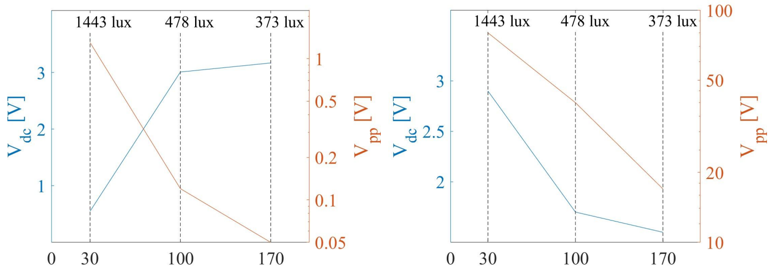
We performed a second test by fixing the distance to the largest 170 cm and using different frequencies. The results are shown in Fig. 5. There are two main problems related to the comparator that limit the maximum distance and frequency: generation of voltage spikes due to changes in the input bias current; large response time (propagation delay) of the comparator due to low overdrive voltage.



(a)

(b)

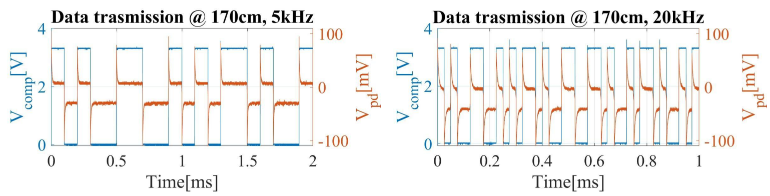
Fig. 3. Voltage waveform at the photodiode cathode at 30 cm (a) and 170 cm (b) with a modulation frequency of 5 kHz (AC coupled).



(a) (b)

Fig. 4. Photodiode (a) and photovoltaic cell (b) average voltages (V_{dc}) and peak to peak AC values (V_{pp}) at different distances with a background of 313 lux.

In Fig. 5b, we can see that when in V_{comp} there is a high to low transition, and vice versa, a spike appears in V_{pd}. Due to the high input impedance provided by the photodiode polarization network, the comparator input bias current generates these spikes. The second problem is related to the propagation delay of the comparator due to the low input overdrive voltage. The comparator tends to become slower when the difference between the two input signals is lower. These two problems combined are shown in Fig. 5b. At high frequency, a large distance and low overdrive voltages, the comparator is too slow to properly translate the signal. For this setup, at 170 cm the frequency limit is 20 kHz. Finally, an important remark is that the peak to peak steady state photodiode voltage remains constant over the frequencies as the distance is fixed and the light intensity is not changing.



(a) (b)

Fig. 5. Voltage waveform at the photodiode cathode and comparator output at 170 cm with different modulation frequencies: 5 kHz (a) , 20 kHz (b).

3.2 Characterization: Photovoltaic Cell

Another set of tests are performed to measure the limits of the photovoltaic cell used to receive the signal and harvest energy. In Fig. 4b results at different distances are collected. The behavior of V_{dc} is the opposite with respect to the one seen for the photodiode. Comparing the distance and peak-to-peak voltage, the photovoltaic cell sensitivity is smaller than the photodiode one. For distances larger than 100 cm V_{pp} is too small to make the signal useful for the comparator.
In Fig. 6, we compare the more comfortable condition for the photovoltaic cell and the limit one. These two measurements are affected by noise but still the signal can be detected properly. The noise contribution at roughly 30 kHz is still present even if the cell is in dark conditions; thus, it is related to the setup environment.
In conclusion, the photovoltaic cell behaves differently with respect to the photodiode, providing an energy source and increasing the output voltage. In opposition, the photodiode reveals a way faster time response, thus allowing for higher frequency modulation. However, the photodiode does not provide any energy. On the contrary, it draws current through the polarization resistor.

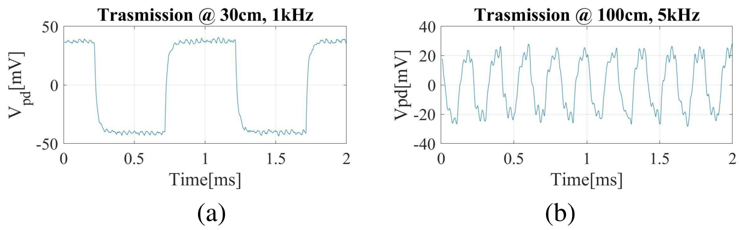


Fig. 6. Voltage waveform at photovoltaic cell: (a) best condition at 30cm, 1kHz, (b) worst condition 100cm, 5kHz

4 Conclusions

We developed a test setup for preliminary measurements on VLC in battery-less scenarios with a valid solution to accomplish the quality of service and visual light comfort. Finally, we develop a compact VLC receiver based only on a few components, comparing the results with a photodiode and a photovoltaic cell.
The future perspective is to combine VLC with other harvesting and communication technology. An example would be an autonomous wake-up system (similar to wake-up radio) to further improve system efficiency and reliability in intermittent operation. These will be the tasks for future work.

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