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LETTER

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The internet of light: Impact of colors in LED-to-LED visible light communication systems

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LED-to-LED communication, in which an LED is used as both transmitter and receiver, is n ubiquitous technology that presents important advantages such as low-cost devices and security enhancement. We investigate the performance of visible light LED-to-LED communication under realistic conditions. We analyze the impact on transmission performance imposed by different colors of LEDs and their combinations. In sum, our results evidence the importance of a correct LED setup. According to our results, lower frequency LEDs such as red and orange are highly efficient when used as receivers, while higher frequency LEDs are less sensitive and therefore more limited in these scenarios. Moreover, we highlight that the pattern created by a wide range of LEDs can be helpful for new visible light communication-based mechanisms.

KEYWORDS
evaluation, internet of light, LED-to-LED communication, li-fi, visible light communication

1 | INTRODUCTION

Recently, visible light communication (VLC) has received great attention from industry and the academic community. In fact, due to the spectrum crunch of Wi-Fi, VLC has been seen as a complementary alternative to radio frequency communication. Moreover, VLC opens a new horizon for several new applications such as indoor localization, vehicle-to-vehicle communication, and underwater communication.

Choosing the proper transmitter (TX) and receiver (RX) for a VLC system plays a key role in the achieved performance. The light emitted by LEDs is modulated to provide both illumination and communication. Several factors such as the type of LED, bandwidth, illumination power, and color have a direct impact on the performance. In this context, choosing the right LED is very important in VLC scenarios, especially when the VLC system supports bidirectional communication between LEDs.

Many parameters and environment conditions can affect LED-to-LED communication performance. For instance, LED illumination varies in terms of distance and field-of-view. Communication using LED also suffers influence from ambient light. In summary, choosing the receiving mechanism is crucial because photodiodes (PDs) are much more sensitive than low power LEDs.

In this paper, we investigate the use of LEDs as both transmitter and receiver in a VLC system. We evaluate the impact of LED color combination and distance in VLC performance, considering realistic environments. We have conducted our analysis using OpenVLC,[1] an open-source Linux-based VLC platform.

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At a glance, our results show that LED color combination and intensity highly impact the quality of communication. For example, the use of red LED outperforms other color combinations. In this case, even when the communication pair uses a distinct color from red, the system performance is significantly better than other pairs. While previous works focus on the evaluation of either physical properties of visible light[2,3] or only consider single LED color (red in this case),[4] our work considers alternative implementations, where the combination of LED colors opens new perspectives to multiple access, modulation schemes, and applications.

2 | RELATED WORK

The impact of colors on VLC has been studied in different manners in literature. The first approaches that explored different colors and communication were related to modulation schemes, such as the Color-Shift Keying presented in IEEE 802.15.7.[5] Since the creation of this standard, other color-based modulation mechanisms were proposed, such as generalized color modulation (GCM).[6] The present work differs significantly from those approaches, because many of the previous works explore cameras or PDs as receivers, while in the present we explore LED-to-LED communication.

Bi-directional communication between LEDs is possible because LEDs can act as selective photosensors and are capable of receiving light above the emitted frequency.[2] There are works in the literature whose objective is to define and analyze such properties of LEDs. Shin et al analyze the emission and reception spectrum of different colored LEDs and their applications as absorption sensors in the context of chemistry. Kowalczyk et al brought the application to the field of VLC, but limited only in choices of red and amber LEDs as receivers and transmitters.[7]

Studies involving the bi-directional use of LEDs in a VLC scenario date from 2003.[8] Dietz et al were the first to consider using LEDs as receivers in a bi-directional VLC system. Giustiniano et al have also implemented a low-complex VLC system, focusing on bi-directional communication between LEDs.[9] The authors presented the first ideas of the impact of different LEDs on a VLC channel by performing the experiments considering only two scenarios: red-to-red and blue-to-blue LEDs, which achieved better performance. After that, Schmid et al proposed a bi-directional system between LEDs and evaluated the performance considering factors such as the range of communication and energy consumption.[4] Although the results were considered advanced compared to the previous ones—distances greater than 2 m and flow of 800 b/s—the system considers only a pair of LEDs of the same color. Wang et al introduced the OpenVLC, a research platform capable of bi-directional communication, using LEDs or PDs as receivers.[1] LED-to-LED communication has been evaluated using only red-to-red LEDs. In this work, we explore the OpenVLC platform and go further by evaluating the impact of different LED colors on LED-to-LED communication.

New perspectives arise for VLC systems when considering the bi-directional communication of LEDs and their properties as photosensors. For example, Li et al implemented a MIMO-VLC system using RGB LEDs, and addressed the reception and emission capacity of LEDs, when developing a system capable of multiple communications.[10] The authors analyzed the data transfer performance considering different color combinations and concluded that channels such as red-red and blue-green do not suffer interference from each other.

In this paper we expand the ideas presented in the following directions: first, we perform a study in which the diversity of LEDs is larger, so that the visible spectrum has been widely explored, according to each color. In addition, the most common colors (RGB) have been studied in more detail in the transport layer of the TCP/IP model, in order to explore the impact on the performance of a real-world VLC scenario. Finally, this work opens space for discussions related to determining factors in the future of VLC systems, such as channel allocation and medium access mechanisms.

3 | BASIC ARCHITECTURE OF VLC

VLC is the name given to systems that use the modulation of light waves to communicate. In general, any system in which information can be transmitted using some type of light detected by human eyes can be called VLC. However, the idea of this type of communication is to use existing light infrastructure (eg, light bulbs, semaphores, etc.) to transfer data in an imperceptible way to human eyes.

The architecture of a VLC system consists of two main components: transmitter and receiver. The idea of a VLC system is to provide lighting and communication simultaneously. Most of the existing works consider LEDs as transmitters. On the other hand, photo-sensors are often used to capture light, and converting it into current, as shown in Figure 1.

LEDs are often used as VLC transmitters. Off-the-shelf LED light bulbs can contain several LEDs. These light bulbs also contain a driver that controls the current supplied to the LEDs, directly influencing the illumination intensity. In other words, transistors control the current arriving at LEDs, and as consequence, one can manipulate LEDs at a high frequency, performing

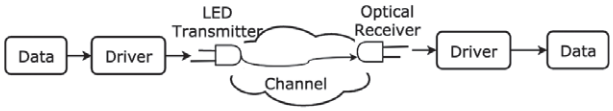


FIGURE 1 Basic visible light communication system architecture

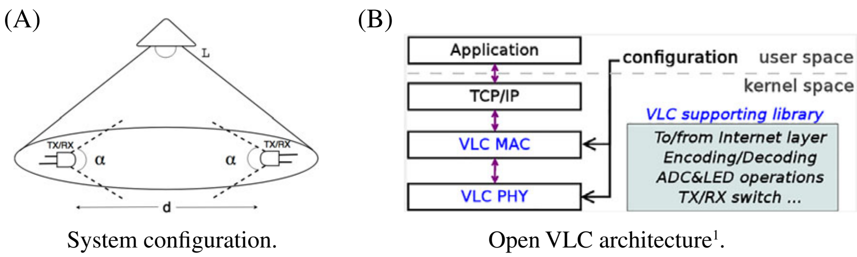


FIGURE 2 System organization and software architecture

communication that is undetectable to human eyes.[11] Typically, VLC employs PDs as receivers. However, PDs are more sensitive, and capture waves beyond the spectrum of visible light, such as ultraviolet and infrared. Thus, in an outdoor environment exposed to sunlight, the PD usually fails to receive the data due to high interference. Some works propose alternatives to overcome this issue, for example, LEDs can be used as receivers due to their photosensor characteristics.[1] The use of LEDs as both transmitter and receiver allows a greater flexibility of VLC systems and applications.

LEDs can act as sensor due to a phenomenon known as photocurrent. When the light is received by an LED, a small current is generated.[3] The magnitude of this current is related to the intensity of light received. While a PD has a broader spectral response, LEDs can be considered a selective PD. They detect a narrower wavelength range and, in general, an LED of a certain color can detect signals from an LED with the same color or higher frequencies. For example, red LED detects signals from red, green, and blue LEDs; and a blue LED is only capable of detecting signals from the same color.

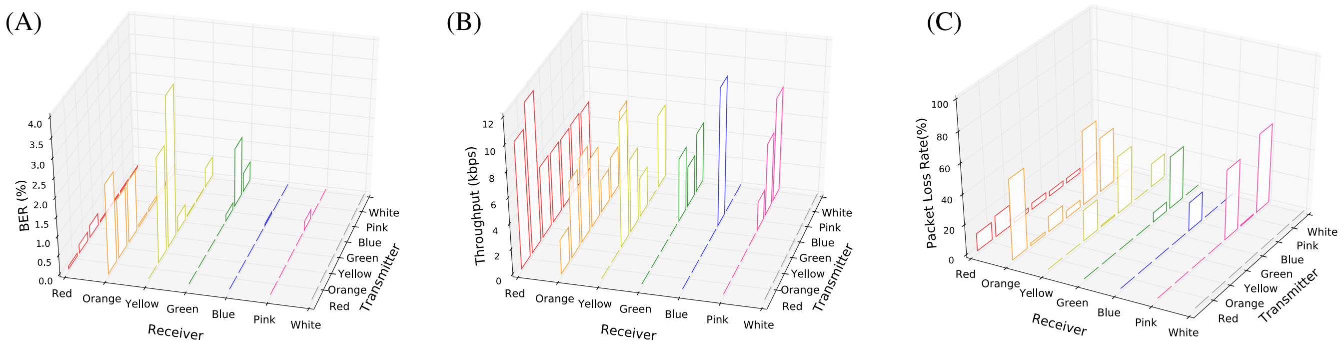
4 | EXPERIMENTAL SETUP AND EVALUATION METHODOLOGY

We use two OpenVLC 1.0 devices to perform the experiments, organized in a point-to-point topology. OpenVLC is a software-defined open-source platform for research in the VLC area.[1] It allows the use of LEDs and PDs as *front-end* and it is based on Linux network stack. OpenVLC 1.0 is composed of three components: BeagleBone Black (BBB), OpenVLC cape and, finally, a driver. The first component, BBB, is a low-power open-source platform for embedded systems. The OpenVLC cape (front-end transceiver) includes three optical components: a low-power LED, a high-power LED, and a PD. The low-power LED can be configured as both transmitter and receiver. The last component is the OpenVLC driver, a software defined PHY and MAC layer, implemented as a Linux driver (kernel module). In OpenVLC, the VLC interface is set up as a new communication interface (shown in Figure 2) that can take advantage of the vast range of Linux tools. By default, OpenVLC driver implements OOK (on-off Keying) as the modulation technique.

Figure 2 presents the environment setup we consider in this work. We place two OpenVLC devices lined up at a distance *d*. We use off-the-shelf LEDs with a 30° field of view. We have conducted the experiments under the influence of ambient light. We keep the incident light at 212.5 ± 14.8 Lx, which is a common value for light intensity on indoor environments.*

In order to make a comprehensive and complete analysis of LED properties as sensors, we consider multiple LEDs, going from lower frequencies (red, orange, and yellow) to higher frequencies (blue). It is important to note that some colors are compositions of others, such as the white LED, for example, which is made of a material whose emission is a mixture of blue and yellow colors. The environment dimensions we evaluate are compatible with indoor environments, such as offices, which are prone to future VLC systems due to the existing infrastructure.

The experimental evaluation was performed considering two different layers: (a) MAC layer, where we set simple frame payloads of a fixed size (800 bits). The aim of this scenario is to evaluate the bit error rate (BER) after the decoding process due to the different colors used as both sensors and transmitters. We transmit the fixed-sized frame 50 times, and collect the data related to the difference between original bits and received bits. We also evaluate the scenario at (b) The Network layer, where performance is evaluated based on the following approach: we configure VLC devices using fixed IPs. We use *iperf* tool to evaluate network performance. Unless we tell otherwise, we setup iperf to evaluate network performance using UDP packets with packets size of 0.8 kb, which are optimal values for the OpenVLC 1.0 platform.[12] The duration of each experiment is 1 m, which is repeated five times for each combination, for a 90% confidence interval.



BER (%) at 10 cm. Throughput (kbps) at 10 cm. Packet Loss Rate (%) at 10 cm

FIGURE 3 Bit error rate, throughput and packet loss rate for the combination of LEDs at a distance of 10 cm

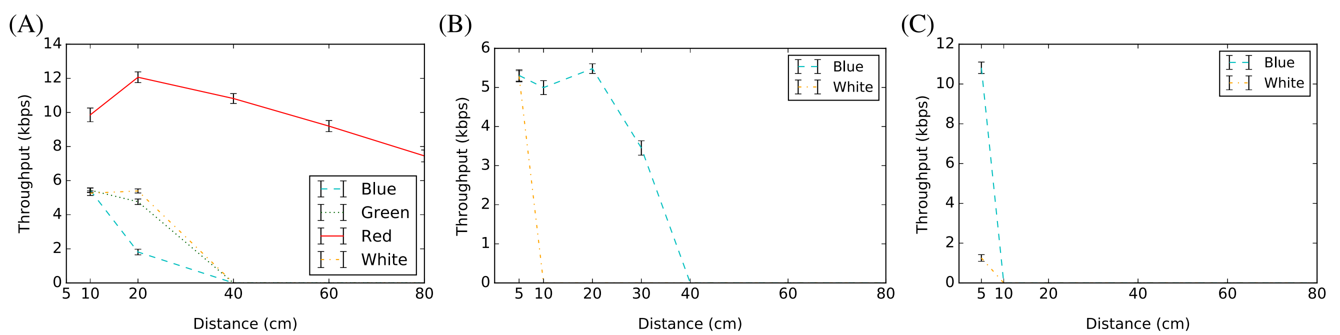
5 | RESULTS

In this section, we first analyze the results regarding the combination of different LED colors at the MAC layer. Figure 3A presents the BER for the setup explained in the previous section and a distance of 10 cm. The first aspect to be observed is the low BER found in all combinations, which reaches a limit of approximately 4% yellow to yellow combination. This happens because in general bits are sent correctly, with very little errors. However, there are bursts moments in which the payload decoded has many errors. These moments are caused by external factors, such as noise, ambient light, and LED light intensity.

Figure 3B presents the mean throughput between the combinations of all seven LEDs as both receivers and transmitters at a distance of 10 cm. At this distance, it is possible to analyze almost all LED color combinations and extract good insights from the performance of throughput and packet error rate. As shown in this figure, lower frequencies LEDs are better choices as receivers due to its wide spectral response. In this case, lower frequencies LEDs, such as red and orange, are able to cover the whole visible spectrum. On the other hand, higher frequencies LEDs, such as the blue LED, tend to be less sensitive to other frequencies. Figure 3C also evidences a common LED property, which has been empirically studied only in a few works[2,3]: LEDs are able to detect frequencies equal to and above to the frequency it emits. Practically, all LEDs present the same behavior.

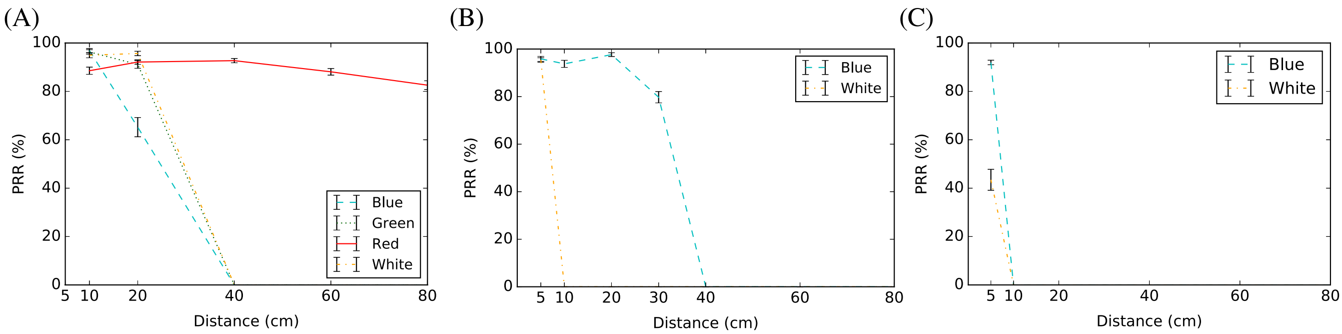
In addition, Figure 3C presents the packet loss rate (PLR) for the LEDs color combinations. According to the PLR values obtained from experiments, except for the red LED which presented very low PLR values for many combinations, the LED works better as a sensor on its own frequency but can present significant PLR for other transmitters. For example, yellow and orange LEDs have a better PLR when sensing from the same source (1.77% and 0.89%), while maintaining a good PLR for white LEDs as transmitters (0.33% and 15.61%). In the following, we describe other combinations of LEDs that were capable of communication in distances below 10 cm (and, consequently, are not shown in the pictures). Blue and white LEDs detect signals from each other because the white LED emission peak is around the same wavelength of blue LED. Moreover, pink LED presents an uncommon behavior by detecting the light from orange LED, which can be explained due to the fact that this LED presents one or two layers of phosphorus above of a blue LED. The first layer of phosphor is yellow, and the second layer may be red or orange.[†] As a consequence, the pink LED is able to detect the yellow and orange LEDs signal.

Next, we discuss the performance of the following LED colors combination: red, green, blue, and white as both receivers and transmitters, considering the communication at different distances. Figure 4A shows the data rate (and confidence interval) when a red LED is used as a receiver. The red-to-red scenario presents similar performance found in previous works.[12] In this



Red as Rx. Green as Rx. Blue as Rx.

FIGURE 4 Throughput for LEDs of different colors as Rx



Red as Rx. Green as Rx. Blue as Rx.

FIGURE 5 Packet reception rate for LEDs of different colors as receivers

case, throughput varies from 8 to 12 kbps, depending on the distance between VLC devices. Clearly, the red-to-red configuration outperforms all other combinations, suffering less impact from devices distance. Although, for short distances, other color combination may still present acceptable performance. For example, when we consider devices located at a 20 cm distance, it is possible to observe a 6 kbps throughput between green/white transmitters and red receiver.

We can also use green and blue LEDs as receivers[‡], as shown in Figure 4B,C. As we previously discussed, a given LED color should be able to detect signals from its own color and higher frequencies. For example, green LED should receive data from other green, blue, and also from white LED. However, according to Figure 4B, a green LED based receiver is not able to detect the green color from a transmitter. This behavior has already been reported in literature.[2] According to Figure 4B,C, green and blue LEDs have limitations when used as receivers. For both receivers (green and blue LED), the blue LED transmitter presents the best throughput performance. Curiously, this is just the opposite when using a red LED as a receiver.

We evaluate reliability in terms of packet reception rate (PRR). PRR decreases with the distance between devices and is highly correlated to the throughput, as shown in Figure 5. The red-to-red combination, which presents the best throughput, seems to be less impacted by distance. For short distances, PRR for other combinations may be slightly higher than red-to-red performance, as shown in Figure 5A. Again, results indicate one may explore different color combinations in a VLC system.

6 | CONCLUSION AND FUTURE WORK

Here, we physically evaluated the impact of different colors in LED-to-LED VLC systems. We have shown that, beyond red-to-red configuration, other color combinations can efficiently be used. Depending on the distance, these color combinations may present better performance than the traditional combination. Our results may be used as a substrate for the development of new VLC approaches. In special, we believe that the evaluation we have conducted may foment (a) multiple access protocols; (b) new perspectives on color-based modulation schemes (GCM, CSK); and (c) channel allocation protocols.

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NOTES

∗ Recommended Light Levels for Outdoor and Indoor Venues—https://goo.gl/mW8D2Y, 2017.
† Light Emitting Diodes—http://www.emred.fi/htmls_en/leds_en.html, 2017.

‡ We have omitted results regarding white LED as a receiver since it is only able to react to its own color, at a very short distance (≤5 cm).

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