LED-to-LED based VLC Systems: Developments and Open Problems

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ABSTRACT

Visible light communication (VLC) is an emerging short-range wireless communication technology using the unlicensed light spectrum. Light Emitting Diode (LED) is used as VLC transmitter, while photodiodes or image sensors are used as receiver, depending on the applications and hardware constraints. However, LEDs can be used not only as a transmitter, but also as a receiver in applications where cost is of primary concern. LED as a receiver is sensitive to a narrow band of wavelengths, it is robust to sunlight interference and widely available as compared to other light detectors. This paper surveys the potential and limitations of LED-to-LED communication. It also contributes to identifying the challenges and potential research directions in this rising area of interest.

CCS CONCEPTS

• **Hardware → Emerging optical and photonic technologies**.

KEYWORDS

LED-to-LED, visible light communication, LED as receiver, taxonomy, opportunities

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1 INTRODUCTION

The global market for lighting based on light-emitting diodes (LEDs) has experienced significant growth in the last decade. In parallel, the exponential growth in Internet-of-Things (IoT) devices has raised the demand for energy-efficient connectivity and data handling. In this scenario, visible light communication (VLC) has been proposed to provide connectivity to IoT devices leveraging the pervasive lighting infrastructure, and as alternative or complementary to Radio Frequency (RF) solutions. A typical VLC system requires: i) a lighting source based on LEDs, and that can provide simultaneous illumination and data transmission; ii) a photo-detector, typically a photodiode (PD) or an image sensor, to receive optical data. However, in practical scenarios, not every device is equipped with a PD or an image sensor for reasons such as cost efficiency. This hinders the vast deployment of VLC solutions.

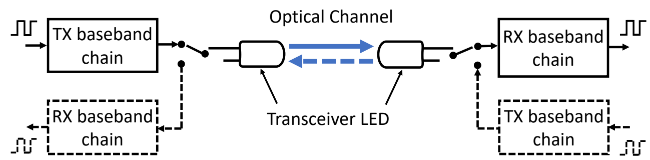

Figure 1: LED-to-LED communication: The line of research reviewed in this work.

LEDs have emerged as a power-efficient, low-cost, longer lifetime, highly reliable, and dimensionally small alternative to conventional fluorescent light. LEDs are well known to emit light of different colors. However, another key feature of LEDs with enormous research potential is their usage as photo-receivers, a property that is known and has started to be studied already in 1998 [16]. In simple terms, LEDs operate as light emitter when forwarded biased, and as light receiver when zero or reversed biased. LED as a light receiver has certain advantages:

- LEDs are sensitive to a much narrower band of wavelengths compared to PDs. On the contrary, PD requires expensive filters for wavelength selective detection;
- LED as a receiver in outdoor applications is orders of magnitude more robust to sunlight interference than PDs [24];
- The LED's sensitivity is very stable over time, similar to PDs, but the optical filters used with PDs have limited life;
- LEDs can be set up as both transmitter and receiver, which capacitates a bi-directional VLC link using only a single LED on each end;
- LEDs are widely available around us compared to PDs, which enables a vast deployment of LED-to-LED based VLC systems.

Despite the progress of LED technology and its potential to be used as both transmitter and receiver, there is a lack of overview of research conducted in LED-to-LED based VLC. As it will be shown in this contribution, this area has been studied by different research communities, such as optical, electronic and networking. This paper presents the first survey on LED-to-LED communication (Fig. 1),

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detailing the fundamentals, state of the art, research challenges and opportunities.

2 FUNDAMENTALS

LED-to-LED communication is an area of VLC that utilizes the LED both as transmitter and receiver. It offers low cost, power efficiency and a simple design for implementing a communication link. We can leverage the ubiquitous presence of LEDs that can be found in cellphones, ceilings, traffic lights, etc., to perform as transmitter and receiver for LED-to-LED communication.

There are multiple types of LEDs available in the market. They are classified based on their manufacturing process, semiconductor material and characteristics [9]. The most widespread LED type for VLC is Phosphor Converted (PC) LED, which is a blue-colored LED coated with phosphor to generate white light. They are low-cost but with a limited bandwidth due to the slow response of phosphor. Besides, micro LEDs (μLEDs) are in the form of arrays. They have applications in VLC and can incorporate high density parallel communication for display panels. Finally, multi-chip LED consists of three or more chips within a single enclosure to emit different colors, typically Red, Green and Blue (RGB). The chips can be controlled individually to get various colors and multiple communication channels through Wavelength Division Multiplexing (WDM). RGB LEDs emit a narrow spectrum for each primary color, and the human eye perceives it as white light if correct bias is applied to each sub-LED [6]. RGB LED is not the ideal choice to generate white light due to its high cost and complex drive circuit, but RGB LEDs are optimum for LED-to-LED communication with dual functionality of transmitter and light sensor. Unlike PC-LED, RGB LED has a much faster response, allows WDM to increase the transmission rate and can sense light on their sub-LED chips separately [5].

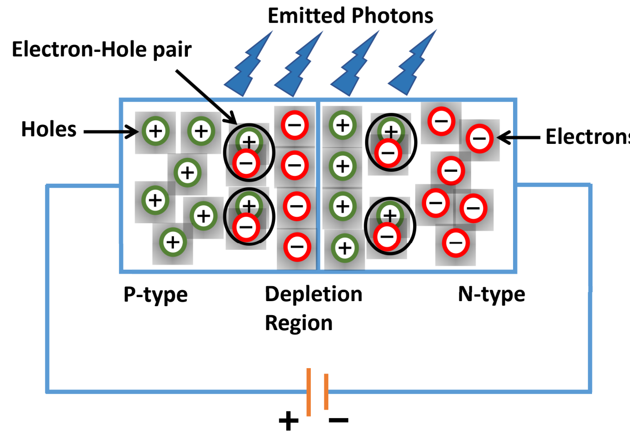
In transmitter mode, LED works as a p-n junction diode which emits lights when electrically activated. Under the forward biased condition, the electrons and holes in the semiconductor recombine to emit light (see Fig. 2a). Differently, in receiver mode, LED can function as a PD to sense light based on the photo-electric effect governed by the following equation:

$$I_{\mathrm{p}} = \int_{\lambda} S(\lambda) \cdot \eta(\lambda) \cdot A_{\mathrm{PD}} \mathrm{d}\lambda, \qquad (1)$$

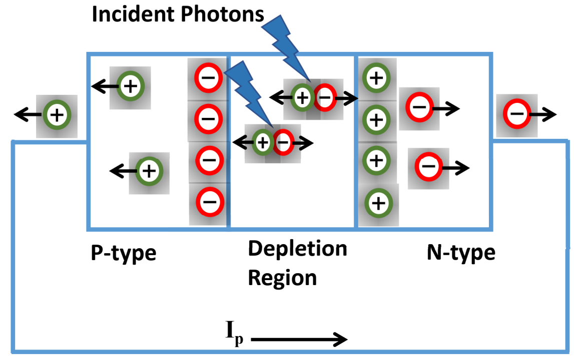
where $S(\lambda)$ is the spectral irradiance ($\mathrm{W/m^{-2} \cdot nm^{-1}}$) impinging on the LED, whereas $\eta(\lambda)$ and A_{PD} are the responsivity (A/W) and area, respectively of the photo-sensitive device. When an incident photon has energy greater than the semiconductor bandgap of the LED, it is absorbed and results in the creation of electron-hole pairs. The electric field across the depletion region impairs them and results in the tiny flow of current I_{p} as shown in Fig. 2b. The resultant current is proportional to the intensity of light incident on LED in receiver mode (see Equation (1)). However, also note that, to generate photo-current, the received spectral irradiance must match with wavelengths where the photo-receivers have a non-zero responsivity.

3 STATE-OF-THE-ART WORKS

After the invention of the first visible light (red) LED in 1962, the experimentation to produce more efficient, bright and colorful LEDs



(a) LED p-n junction at forward bias.



(b) LED as light sensor.

Figure 2: Basics of LED as forward bias (transmitter) and as light sensor (receiver).

continued. Modern LEDs offer high output light, multiple colors, and high switching rates that make them ideal for VLC transmitters. On the other hand, the idea of using LED as a photo-detector began to take root in the 1990s after Miyazaki et al. [16] evaluated the potential of LED as a wavelength-selective photo-detector. They proclaimed the effectiveness of reverse bias voltage on LED responsivity and current gain. Also, they showed the significant overlap of emission spectra and spectral response of red LED, which makes it ideal for bi-directional communication using a single LED at each side. In the following, we detail the most relevant works in the LED-to-LED communication field, which are also summarized in Table 1.

RGB LEDs as transmitter and receiver: Kashima et al. [10][11] evaluated the performance of red, green and blue LED as transmitter and achieved the data rate of 100 kb/s up to 55 cm range using red LED at both ends. The work is extended to demonstrate 6 MHz TV analog transmission using super luminosity LEDs.

Signal demodulation by evaluating capacitance discharge of LED: Researchers proposed the LED-to-LED communication based on the charging and discharging time of LED's parasitic capacitance. In receiver mode, the capacitance is fully charged by a short pulse and then exposed to the modulated light signal for the discharge.

Table 1: Summary of previous work on LED-LED communication

System	Modulation	Deployment			Data rate	Range	Evaluation scenario
		TX	RX	RX Mode			
Super Luminosity LEDs [10]	Direct modulation with sinusoidal signal	Red LED	Red LED	No biased voltage	100 kb/s	55 cm	BER=10^{-2}
High-speed transmission [11]	Pseudorandom binary sequence	Red LED	Red LED	No biased voltage	30 Mb/s, 25 Mb/s	5 mm, 15 mm	BER=10^{-8}
iDroppers [4]	PWM	Red LED	Red LED	Reverse biased	250 b/s	3 cm	Bidirectional using LED internal capacitance
VLC Network [7]	OOK	Blue or Red LED	Blue or Red LED	Reverse biased	870 b/s	90 cm 30 cm	CSMA/CD protocol for networking
OpenVLC1.0 [22]	OOK with Manchester	HP White and LP red LED	Red LED + PD	Reverse biased	15-20 kb/s	≈5 m	Variable lighting and payload length
Real-VLC [23]	OOK with Manchester	White LED	Red LED + PD	Reverse biased	15 kb/s	≈3.5 m	PD/LED as RX at noise floor = 10 lux
Bi-directional VLC [2]	OFDM	Red from RGB LED	Red from RGB LED	No biased voltage	110 Mb/s	1 m	BER≈2x10^{-3}
Full-Duplex [8]	32-QAM DCO-OFDM	Green LED	Yellow LED	Reverse biased (5 V)	49 kb/s	15 cm	BER=2.5 x 10^{-4}
Gb/s VLC [14]	OFDM	Laser diode	2 x Yellow LEDs	Reverse biased (3 V)	3.1 Gb/s	2 m	BER≈2.3x10^{-5}
Transmission Beyond 100 Mbit/s [20]	2-PAM	Red LED	Red LED	Reverse biased (0-30 V)	50 Mb/s, 100 Mb/s	4-5 cm, 1 cm	BER=10^{-3}
Self Powered [13]	OOK and PPM	Red LED	Red LED	No biased voltage	10 Mb/s	30 cm	16-PPM and TX power 100 μW
Two-way VLC [12]	OOK with Manchester	Red from RGBW LED	Red from RGBW LED	No biased voltage	2.4 kb/s	18 cm	Dark room conditions
Indoor VLC [3]	OOK-NRZ	Red LED	Red LED	Reverse biased	1 Mb/s	20 cm	SNR = 11 dB using MOSFET driver

OOK: On-Off Keying, PWM: Pulse Width Modulation, HP: High Power, LP: Low Power, RX: Receiver, TX: Transmitter

The discharge time is longer for bit '1' than bit '0', enabling the successful data transmission with proper synchronization between transmitter and receiver. Dietz et al. [4] achieved bi-directional communication at 250 b/s with 3 cm range in a keychain-sized device.

Higher layer protocols with LED-to-LED communication: Authors of [7] explored the networking and flickering issues using low-power LEDs. The network architecture with a software-based physical and medium access control layer was evaluated using a low-cost microcontroller and various types of low-power LEDs. The system guaranteed constant illumination and communication at 870 b/s with a range above 2 m. Wang et al. [22] developed multiple access communication protocols to ensure a reliable VLC link in a network scenario made up of nodes with different field-of-view (FOV). Authors of [23] proposed an adaptive VLC receiver design (REAL-VLC) based on a white LED as transmitter and complementary photo-detectors (Red LED and PD) as a receiver. The receiver dynamically configures itself to maintain the link in different lighting conditions. The system was implemented in the open-source OpenVLC platform consisting of the BeagleBone Black as processor and an external cape as front-end transceiver. A data rate of 20 kb/s with the range of 5 m was achieved.

Multicarrier modulation schemes with LED-to-LED communication: To overcome the low data rate and vulnerability to nearby lighting sources, a multi-carrier approach using orthogonal frequency-division multiplexing (OFDM) modulation was proposed. Chun et al. [2] showed a bi-directional VLC link using red light from RGB LED both as transmitter and receiver. The author reported uni-directional and bi-directional data rates of 155 Mb/s and 110 Mb/s for 1 m link, respectively. Jung et al. proposed in [8] a quadrature amplitude modulation (QAM) based OFDM scheme for full-duplex LED-to-LED communication using Green LED as transmitter and Yellow LED as receiver to achieve a data rate of 49 kb/s with 15 cm range. Data rate in the order of Gb/s was achieved in [14] by replacing the transmitter LED with a laser diode. Two yellow LED-based receivers were used along with intense processing using digital signal processing (DSP), analog-to-digital converter (ADC) and digital-to-analog converter (DAC) components.

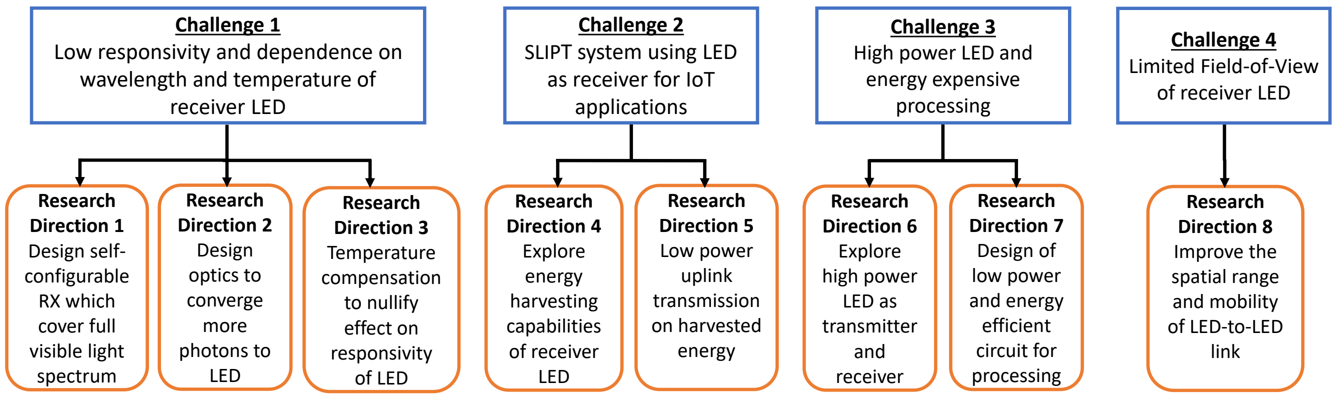


Figure 3: Open research challenges in LED-to-LED communication.

On top of the previous categorized works, there are some other works previously published that experimentally showed advancements in the LED-to-LED communication domain: Stepniak et al. [20] proposed a simple low-cost receiver using the same red LED as transmitter and receiver without reverse biased. A 2-Pulse Amplitude Modulation (PAM) scheme was implemented with equalization at the receiver to achieve a throughput of 100 Mb/s at a very short range of around 1 cm. A self-powered LED-to-LED link was investigated by Liang et al. in [13]. In the proposed system, red LED for communication is driven by the photo-current produced by the array of white LEDs illuminated with artificial sunlight. A bit rate of 10 Mb/s with range 30 cm is achieved by invoking a 16-Pulse Position Modulation (PPM) scheme with a transmitted optical power lower than 100 μW. Li et al. [12] proposed the two-way using the same red chip from a RGBW LED in a transceiver configuration. The best results for data rate and constant illumination are achieved by combining OOK and Manchester coding. The system achieved 2.4 kb/s with a range under 18 cm. Dahri et al. [3] developed the system with a simple transistor-based LED transmitter and a resistor driver-based LED receiver operating in photo-conductive mode. The system achieved a throughput of 1 Mb/s at the range of 20 cm under indoor lighting conditions.

4 LED CHARACTERISTICS FOR LED-TO-LED COMMUNICATION

LEDs are mainly designed for illumination, not for photo-detection. Therefore, the manufacturers do not provide the information related to spectral sensitivity, FOV and the effect of temperature on responsivity. For this reason, it is essential to study the mentioned characterization of LEDs when they are used as receivers. This section details the most crucial characteristics of an LED acting as receiver and how to measure them:

Optical spectrum: To specify the photo-detector's spectral sensitivity, the light impinging into the photodetector must emit a narrow optical bandwidth, i.e., a monochromatic light. This way, the photocurrent generated can be measured, then obtaining the corresponding responsivity of the photo-detector for such specific wavelength [21]. In [16], the spectral overlap of the LEDs as a photo-detector is measured. The authors of [1] showed that the peak wavelength and the bandwidth of the LED as a transmitter are higher and shorter than the central wavelength and the Full Width at Half Maximum (FWHM) of the spectrum of LED as a detector, respectively. The authors of [21] demonstrated that the spectral efficiency calculations for the yellow-red regime are giving 56% to 63% concerning overlapping peaks; whereas only 7% to 18% for the blue-green range.

Field-of-view (FOV): The FOV can be determined based on the measurements varying the angle of incidence (AOI), which is an important parameter in optical systems. Authors in [21] measured the sensitivity of an LED as a function of AOI from 0 to 90°. Another important spatial measurement is how the polarization of received light affects the responsivity of LED as a receiver. However, authors of [21] computed the influence of the polarization direction as a function of the sensitivity and determined that the variation of the polarization does not affect the sensitivity.

Temperature of LEDs: The temperature property is an essential parameter from a practical viewpoint that affects both the responsivity and emission power. In [11], authors measured the photocurrent generated and the output power of the red LED by using an optical power meter, and then calculated the responsivity measured in A/W. In their work, the temperature of LED is varied from 0 to 50°C. The results showed that the emitted power shifted to the longer wavelengths by increasing the temperature, and the peak photo-detecting wavelength shifts to the shorter wavelength. Therefore, the measured responsivity and the emitting power changed accordingly.

5 RESEARCH CHALLENGES

Despite the number of published works presented before, LED-to-LED communication is still in its infancy. There are multiple challenges to deploying a low-cost yet reliable link in real-life scenarios. The main research challenges are summarized in Fig. 3 and discussed below:

Research Challenge-1 LED performing as a receiver is considerably less sensitive than PD, which may limit the communication range. Also, LED as a receiver is only sensitive to a certain band of wavelengths normally equal or lower than their primary emission wavelength. For example, if a yellow LED ($\lambda \in [585 - 600]$ nm) acting as receiver is illuminated with a red light ($\lambda \in [640 - 690]$ nm) no photo-current is generated. On the contrary, if it is irradiated by yellow, green or blue light, it generates a photo-current due to a good match between emission and responsivity spectra. As shown in Table 1, the red LED shows a maximum overlap between the emission and responsivity spectra in most cases, which makes it an ideal choice for LED-to-LED communication. Furthermore, LED as transmitter and receiver are sensitive to temperature variations, which produces a wavelength variation in the emitted power spectrum and spectral response [11] [18]. Therefore, LEDs must be carefully studied when used as photo-sensitive receivers, as they may be excited at different wavelengths than its homologous transmitter and considering minor variations in spectra due to temperature. More research for characterizing LEDs as receivers and studies to increase their responsivity is required.

Research Challenge-2 In wireless sensor networks (WSN), VLC is proved to provide reliable communication links while maintaining the illumination standards. The sensors can be powered from the wired connection, but it is more costly and less practical. The power through batteries require replacement and add to the waste, which increases the carbon footprint. Simultaneous Information and Power Transfer (SLIPT) systems can explore the communication and harvesting potential of LEDs to meet the requirements of WSNs and enabling a vast deployment.

Research Challenge-3 The received signal at LED is typically very noisy and low-powered. Thus, a multi-stage amplification is required before feeding into the comparator circuit. These amplification stages are power-hungry which lowers the lifetime of battery-operated devices or diminish the chance of autonomous operation on harvested energy. Also, in most of the systems presented in Table 1, off-the-shelf 5 mm LEDs are used for LED-to-LED communication. These LEDs do not fulfill the requirement of illumination in practical scenarios. Thus, high-power LEDs are required to provide more illumination and higher range, but taking care of the thermal management and high junction capacitance issues. Those issues establish a significant research challenge with the focus on power consumption and the optical power emitted.

Research Challenge-4 The application of VLC in autonomous Internet-of-Thing (IoT) devices such as smart lighting, indoor localization, etc., requires the mobility of the device. The directionality of LED is an important parameter for a reliable link in mobile settings. As a transmitter, directional sources have the advantage of a spectrum reuse and collision avoidance. As a receiver, LEDs are only sensitive to the light incident within its FOV. Thus, directional sources are unfavorable for maintaining links in mobile scenarios. The link can easily be broken if the emitted light from the LED transmitter is beyond the FOV of the receiver. The directionality of lighting is normally determined by the illumination requirements which may not favor the communication needs [23].

6 RESEARCH OPPORTUNITIES

The challenges discussed in the previous section open up the research directions for the future. They are shown in Fig. 3 and explained below:

Research Direction-1 The stringent wavelength range matching between LED transmitter and LED receiver may be alleviated by setting up a multi-LED receiver covering the full visible light spectrum. These smart receivers would contribute to the vast deployment of LED-to-LED communication using already installed lighting infrastructure. Besides, the sensitivity of LED as the receiver can be improved by applying the reverse-biased voltage to LED mainly due to the avalanche multiplication effect. The reverse-biased voltage also reduces the junction capacitance and thus increases the bandwidth [20].

Research Direction-2 The optical design of LED receivers was ignored in most of the previous works in this field. A proper optical front-end design can significantly increase the FOV and enhance the receiver gain without increasing the power consumption. Hemispherical lens or optical concentrators can be used in the optical design to converge the input light to the receiver LED as described in [19].

Research Direction-3 The effect of temperature on transmitter and receiver LED is an important phenomenon to consider in LED-to-LED communication. In [18], variation in emission spectra of RGB LED for different p-n junction temperatures is presented. The characterization of this effect can be used either for compensating it at the receiver to achieve a better link performance, or for monitoring different bands with the same LED.

Research Direction-4 While typically solar cells are used for energy harvesting, LEDs can also harvest some energy when they are illuminated with light [13][17]. As explained in Research Challenge 2, a vast deployment of autonomous wireless sensors requires an operation on harvested energy. This research direction is open to increase the harvesting efficiency and efficacy of LEDs.

Research Direction-5 In scenarios with LiFi based mobile nodes (e.g. indoor localization), the power budget available for uplink communication is very small. A significant research potential is available to enable reliable, low-power, long-range LED-to-LED uplink communication.

Research Direction-6 The high-power LEDs, especially RGB LEDs, can be a potential candidate to provide long-range and reliable LED-to-LED links. RGB LEDs can use different combinations of colors for enabling multiple parallel links by employing WDM while providing a target white light for indoor illumination. The communication range can be improved by using the HP LEDs on the transmitter side [15]. On the contrary, the junction capacitance of LED and power consumption increases with size. Consequently, HP LEDs suffer from bandwidth reduction and thermal management issues.

Research Direction-7 The weak modulated signal at the receiver LED is typically processed through a low noise amplification stage followed by voltage amplification and demodulation. Also, the implementation of more robust modulation schemes to achieve higher data rates and longer range require intensive processing. The amplification stages and demodulation stages are energy expensive and hinder the vast deployment of autonomous LED-to-LED communication-based IoT devices. Thus, the research of low-power and energy-efficient post-processing circuitry is necessary.

Research Direction-8 The improvement in the physical and data-link layer can enable seamless coverage in mobility and under various lighting conditions. An important attribute of ideal receiver design is to dynamically adjust the FOV and spectral response as per the operating scenario. A comprehensive study of adaptable receiver design based on LED and PD in complementary configuration is presented in [23]. The design of an LED-based receiver with seamless handover capabilities could be a step forward in pervasive communication systems and mobile scenarios where light is used as the communication channel.

7 CONCLUSION

The significant interest increase in using VLC in IoT applications in the last years has opened up opportunities to explore LED-to-LED based VLC systems for cost-efficient design leveraging the wide deployment of LEDs around us. In this paper, we unified the recent work in the domain of LED-to-LED communication, showing its potential to provide a communication link that does not need photodiodes to work. The main features of LED as receiver were highlighted, and we provided key indications to measure them. We identified the potential challenges in using LED as the light sensor, and multiple research directions in this area. We envision that LED-to-LED communication will contribute to the massive deployment of VLC for IoT devices.

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