WIRELESS NETWORKS USING VISIBLE LIGHT COMMUNICATION: A REVIEW

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ABSTRACT

Provisioning of quality of service (QoS) is a critical issue in visible light communication (VLC) systems and other wireless communication systems. LED lights are becoming widely used for homes and offices for their luminous efficacy improvement. VLC is a new way of wireless communication. Typical transmitters used for visible-light communication are visible-light LEDs, and receivers are photodiodes and image sensors. We present new applications that will be made possible by visible light communication technology. Especially location-based services are considered suitable for visible light communication applications.

KEYWORD

Visible Light Communication, LED, image sensor, photodiode, location-based service

1. INTRODUCTION

The trend of wireless communication systems is the increase in the variety of multimedia applications, which further spreads the traffic load of wireless networks. Among the type of traffic, few classes of traffic e. g., traffic related to security, healthcare, banking, handover calls, etc., are more critical than others. Provisioning of quality of service (QoS) is a crucial issue in visible light communication (VLC) systems as well as in other wireless communication systems. VLC (colloq. Li-Fi) is wireless data communications technology standardized by IEEE 802.15 WPANTM Task Group 7, which uses visible light in the 80 -780 THz frequency range. It is being touted as one of the next generation's most promising wireless communication technologies. VLC research is gaining a growing interest mainly because of the easy implementation of uni-directional broadcasts via visible light using only low-cost and omnipresent LEDs and regular photodiodes (PDs) or image sensors as the receiving device. The basic principle of VLC communications is that the VLC transmitters can modulate the intensities of the used lighting sources (e.g., LEDs) at such high frequencies that the human eye cannot perceive any difference in lighting compared to the situation when there is no modulation. As a consequence of this, VLC transmitters can be used for both lighting and data communication simultaneously.

Figure 1 shows a representative use of visible light communication, where an LED light is used as a data transmitter, and a cellular phone with a visual light sensor is used as a data receiver. The application of this system is the indoor location service, where a user uses a cellular phone with a photodiode, which detects signals from an LED light.

Figure 1: Visible Light Communication using LED Light: NEC, Matsushita Electric Works, Ltd, Keio University, CEATEC demonstration, Japan, 2004

The primary function of a white LED is to provide illumination, which is also why the core advantage of using VLC is the duality in using visible light both for illumination and for wireless data transfer. Other possible light sources to be considered for use in VLC besides existing incandescent lightbulbs, regular LEDs, or halogen lamps include micro-LEDs, phosphorus LEDs, RGB LEDs, resonant cavity LEDs, and laser diodes (LDs). Currently, two types of white LEDs on the market can produce white light. A 3-chip LED that mixes the three primary colors (red, green, and blue) and a 1-chip blue light LED that excites yellow phosphor, resulting in white emission (Cui *et al.*, 2010). Out of these two LED types, the 1-chip is dominant due to its good applicability to mass production. VLC device operates in one or several color bands with peak radiated energy within the visible light wavelength spectrum from 380 nm to 780 nm. Any information transferred by modulating the light waves in this range can be considered a type of Visible Light Communication. It is essential to observe that the radio waves, which include Wi-Fi technology, cover frequencies ranging from 3 kHz to 300 GHz. On the other hand, visible light frequencies vary from 430 THz to 770 THz, which is 10,000 times larger than the entire radio frequency spectrum, as summarized in Figure 2.

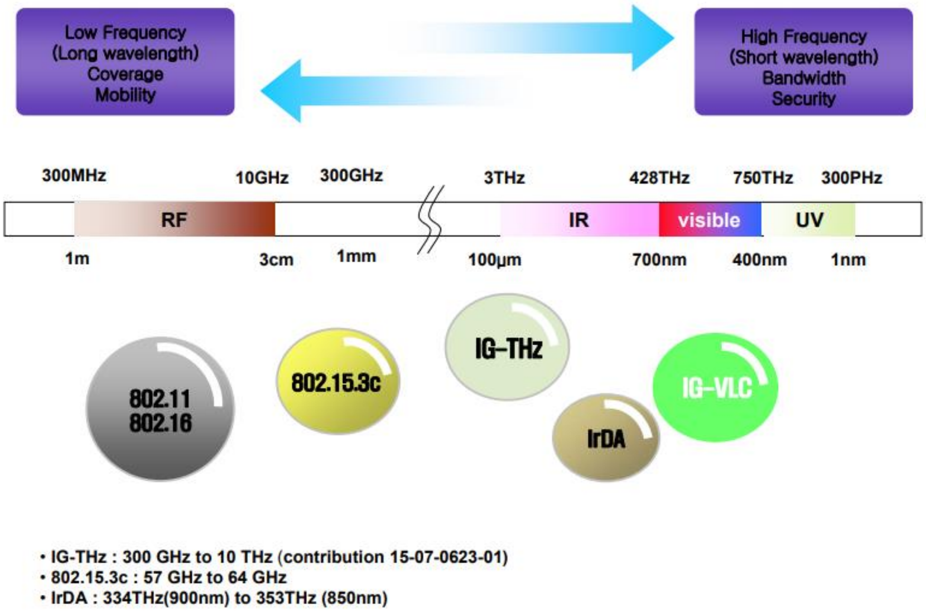

Figure 2: Electromagnetic Spectrum or VLC frequency spectrum (Pathak *et al.*, 2015)

Yun and Kavehrad (1992) reasoned that an LED would be ideal for a VLC network because it has a large bandwidth, high output power, and a coherent (and monochromatic) wavefront.

Notably, the coherent wavefront makes it possible to have a well-collimated beam, which means no restriction on the size of the diffusing spot. RGB-LED system was tried and tested in practice successfully by Komiyama *et al.*, 2011.

The authors analyzed the characteristics of the color variation and the intensity change of each RGB LED and RGB sensor. The slow response of the phosphor limits the modulation bandwidth for white emission. However, improved modulation bandwidth is achievable using only the blue emission component (e.g., by placing a blue optical filter at the receiver). This has the drawback of blocking a significant amount of the emitted energy. As an alternative, a receiver equalizer can be used to compensate for the source. For the equalized case, there is an SNR penalty of approximately 18 dB due to the equalizer. For blue filtering, about 10% of the power is in the blue-emitted component (Zeng *et al.,* 2009). Through simulations, the authors also noted that the blue channel could be better suited to MIMO at high speeds, as the power in the blue component, filter losses, and low responsiveness lead to huge receivers collecting enough power for the correct detection.

The equalized and white components have comparable receiver size and data rate performance. Still, the white LED-based system requires more channels for a specific data rate as the individual channel rate is lower. Regarding performance in terms of data rate, the equalized channel has the potential to provide Gbit/s rates, albeit with a large receiver array. Imaging diversity and multi-beam transmitters were discussed (Kahn *et al.,* 2002). The authors of the article successfully designed a 100 Mbit/s infrared-multi-beam link, quite similar to an earlier article (Spot-diffusing and fly-eye receivers for indoor infrared wireless communications 1992), where the authors coined the term ’fly-eye for representing multi-receiver configuration.

Generally speaking, two photodetectors can be adopted in an indoor LOS VLC system design – the PD and the image sensor. The PD has been widely adopted in optical communication systems with relatively large received optical power. The advantages of the PD include its low price and possible high reception bandwidth. The bandwidth of the PD is usually inversely proportional to its active receiving area due to the internal capacitance along this area. Compared with the PD, the image sensor can provide receiver spatial diversity to enhance the detection performance and supply additional source location information for location-aware services. For application scenarios where multiple LED arrays in a room send different signals to multiple users, using a large field-of-vision PD may lead to large interference that degrades received SNR. In this case, an image sensor would better serve as a light detector that could effectively discriminate different LED arrays and reduce inter-array interference (Cui *et al.,* 2010).

Modern smartphones and comparable mobile devices can receive visible light communications via the camera. However, the technology is still relatively immature, and because of that, VLC lacks a steady standard to back it up. With VLC, high-order wireless MIMO transmissions (of X-resolution * Y-resolution) are possible due to the spatial separation of multiple light sources in a digital camera (Roberts, 2013). One main challenge for VLC is the limited modulation bandwidth of the light sources, which limits the achievable data rates.

As the room or coverage space would typically be illuminated by an array of LEDs anyway, the potential for parallel data transmission becomes increasingly apparent – this is also why using optical MIMO techniques is potentially attractive for achieving high data transfer rates, as noted by the authors of (Zeng *et al.,* 2009). The authors also compared non-imaging and imaging MIMO approaches. They pointed out a non-imaging optical MIMO system performs poorly at every receiver position due to symmetry. Still, an imaging-based system can operate under all foreseeable circumstances. The authors also ran simulations and showed how such systems can work at several hundred Mbit/s and even at Gbit/s in many circumstances.

The parallel free-space optical interconnects between the source and detector arrays typically require precise alignment to map a source to a particular detector or a group of sensors, and they can achieve this by the design of the physical system. MIMO allows the alignment required for such an interconnect to be performed in hardware, as in Lightroom, a source is not necessary to strike a specific single detector precisely. Also, because the source and detector are typically in motion relative to each other, it is, as a result, only sometimes possible to precisely align the detector and receiver array. MIMO techniques can be used to learn the channel matrix, thus quantifying the crosstalk between the channels created by each source and detector – this can subsequently be used to estimate the transmitted data.

Hence, the motivation for using MIMO is not to increase the wireless capacity but rather to reduce the difficulties in achieving optical alignment physically by using electronic signal processing (Zeng *et al.,* 2009).

Once deployed, possible benefits of VLC can include:

- High security due to the possibility of utilizing optical lenses to form a narrow beam for the link or obscuring the communication within the ambient visible light, thus hiding the communication entirely in the overall illumination.
- Immunity to RF interference and RF band congestion.
- Low additional cost when compared to using the LEDs purely for illumination purposes.
- VLC technologies do not, as of yet, require any licenses to use, unlike many RF bands do.

- VLC can be implemented where radio waves cannot be used (e.g., in hospitals or near sensitive precision equipment). High-speed wireless VLC transfers do have their challenges as well due to the following items recognized by (Pisek *et al.*, 2012):
- Ideally, the channel between the light source and the light detector must be in LOS, or it should use reflections or both. The channel should also be short (up to a few meters).
- The light from the source has to be focused directly on the light detector due to the light detector’s low sensitivity at a high transfer rate.
- Light detectors are typically sensitive to ambient light and interference from adjacent light resources.
- Channel bandwidth can be increasingly high, increasing power consumption.

There are, however, ways to limit the channel bandwidth, namely with the help of line coding. Several different modulation schemes can be used to send data over the visible light spectrum:

- On-Off Keying (OOK)

As the name implies, the data in OOK is carried by switching the light source(s) on and off. In its simplest form, a digital ’1’ is represented by the light power-on state, and a digital ’0’ is represented by the light’s power-off state. The elegance of this method is that OOK is simple to generate and decode. Regardless, this method is still not optimal regarding illumination control and data throughput.

- Pulse Width Modulation (PWM)

This modulation method transfers information encoded into the duration of the light pulses. More than one data bit can be transferred within one pulse, but the pulses may have to be longer than for OOK, so this scheme lacks a particular finesse. It is also possible to transmit data in an analog format using this scheme. Like OOK, PWM is also a relatively simple modulation scheme to implement.

- Pulse Position Modulation (PPM)

The transferred data is encoded in PPM using the pulse position within a frame. Again, more than one bit can be transmitted within each pulse, and the frames’ duration should be longer than a single OOK-bit, so again, it is less efficient per se. It does have the benefit of containing the same amount of optical energy within each frame, however.

- Variable Pulse Position Modulation (VPPM)

VPPM is similar to PPM but allows the pulse width to be adjusted to dim the lights.

- Pulse Amplitude Modulation (PAM)

As the name implies, the information in PAM is carried by the amplitude of the pulse.
Several data bits could be conveyed in a single pulse (e.g., off = 00, 1/3 amplitude = 01, 2/3 amplitude = 10, full amplitude = 11). This example uses four different amplitude levels to carry two bits of information. PAM can have more data in each pulse than OOK, but it is more complex and susceptible to noise or interference on the optical channel.

- Colour Shift Keying (CSK)

CSK can be used if the lighting system uses RGB-type LEDs. Using the combination of different light colors, the output data can be carried by the color of the light itself, so the intensity of the output can be left constant. The drawback of this system is the inherent complexity of both the light transmitter and the receiver.

- OFDM

This modulation scheme has been widely deployed in digital TV, radio, and Wi-Fi. OFDM can be modified for use in optical communications, and it uses a set of sub-carriers, each at different but harmonically related frequencies. OFDM has several advantages, including good spectral efficiency, but as a consequence of this, this modulation method is also quite complex to implement.

- Spatial Modulation (SM)

Several techniques could allow one to determine the source of an optical signal. In SM, if one can determine the optical signal source, one can either use the multiple sources of information to transfer multiple streams of independent data (one from each source) or use the source of the signal as part of the information encoding itself. For instance, the optical signal sources could be multiple LEDs within a fixture.

The electrical drivers for an LED are often used together with an optical amplifier (a particular lens) located on top of the LED that would increase the intensity of the emitted light towards a specific direction (which is, in a sense, optical beamforming). In addition, the optical filters (or color lenses) could be used on top of the LEDs to filter only specific colors to be transmitted or, for instance, on the PDs to filter data from only particular LEDs. Different optical filters could share different colors with the channel, thus creating a Coarse Wavelength Division Multiplexing (CWDM), a solution to increase the transmitted bit rate significantly. The receiver must also be designed to support receiving the multiple transmitted data channels in many colors (Chou *et al.*, 2010).

The VLC systems assume free space between the light-emitting source (LED/LD) and the light detector (PD). Usually, this channel is considered to be LOS. Still, there are many cases in which LOS could be attainable, and due to this, the light received into the light detector is essentially only a reflection coming from its surrounding materials. These reflections can also be caused deliberately (i.e., adding aluminum foils or mirrors to reflect the light from CWDM enables the combination of different wavelength signals onto a single transmission channel without the signals interfering (Walls and barriers) to increase the reflected light intensity at the receiver. Figure 2 shows one example of VLC in the outdoor environment. Free-space optical communication (FSO), one kind of visible light communication, is an optical communication technology that uses light propagating in free space to transmit data for telecommunications. In the highway road, train line, or subway line, the FSO communication networks can be installed. The FSO access point (AP) is established every 2 km or 3 km. The FSO AP is connected to the optical fiber backbone. Optical transceivers are installed outside a vehicle. WLAN, femtocell (Chowdhury et al., 2011), and other indoor wireless networks are installed inside the car. The users are connected to these networks.

However, for backhauling the traffic for these networks, the FSO network is used. This application of VLC can support a vast number of users in vehicles.

Figure 3:VLC outdoor application scenario where FSO communication is used for the users in train

The distance of the channel primarily depends on the transmitted power from the light source driver. However, the channel is not intrinsic other than real barriers and reflections. There are, therefore, many different types of interference that can be treated as noise and, as such, can reduce the SNR. The receiver is burdened with defeating these interferences and equalizing the signal to its intended form. The light receiver must be carefully designed to maximize signal detection with minimum noise contributions to the overall receiver noise figure. The characteristics of the light receivers are crucial to the receiver's overall performance since they are logically at the front of the receiver, and they are, therefore, the first part that processes the light received from the channel. Like any other RF receiver, the noise figure of the first receiver stage is the most crucial, and it can define the receiver's quality as a whole (Pisek *et al.*, 2012).

The authors (Komine and Nakagawa, 2004) provided a fundamental theoretical analysis of VLC systems in an indoor environment. A basic indoor VLC service scenario is shown in Figure 4. Several LEDs provide lighting and communication sources.

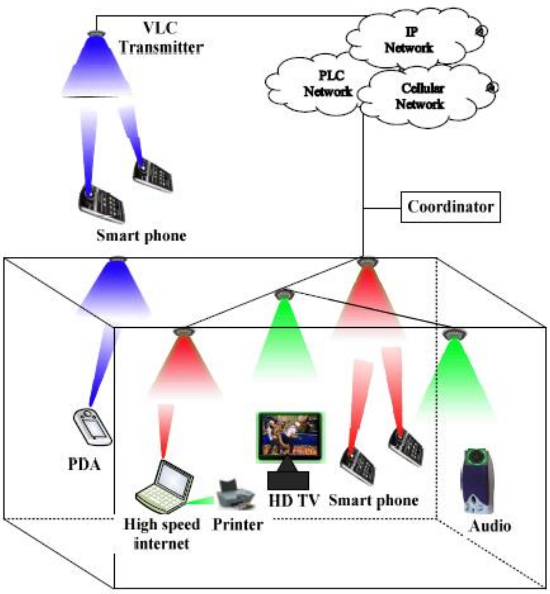

Figure 4: A basic network architecture and indoor service scenario for visible light communication

The authors noted that reflection and inter-symbol interference can severely impede and degrade communication performance. Using more advanced optical techniques and modulation schemes, the VLC link speeds can be increased. In (Minh *et al.*, 2008), a VLC link speed of up to 80 Mbit/s by using per equalized white LEDs was successfully demonstrated, and in (Vuˇciˊc *et al.*, 2009), the authors presented a 200 Mbit/s VLC link with phosphorescent white LED lamp modulated by a discrete multi-tone modulation signal link in various lighting conditions. The authors of (Pisek *et al.,* 2012) proposed and described novel optical/electrical VLC frontend and baseband systems to enable parallel processing that could achieve a 1 Gbit/s bit rate over free space. The authors also detailed the implementation issues of the low-power VLC communication system for an MT. Also, simulation results were brought up for a Low-Density Parity-check-coding-based VLC system that did provide a high level of parallelism for an energy-efficient gigabit rate baseband system. VLC also has an advantage over some other short-range free space wireless standards, such as 60 GHz WiGig, because it uses a simple low-power front-end scheme rather than high complexity, high-power RF front-end that usually involves phased-array antennas to support beamforming, where each antenna is chained and equipped with a low-efficiency PA. The 60 GHz WiGig system also uses high-power Digital-to-Analog Converters and Analog-to-Digital Converters to help the high modulation schemes (64 QAM, etc.) to achieve gigabit communication (Pisek *et al.,* 2012). Also, VLC does not penetrate thick materials such as walls – which can, in turn, be seen as a security advantage over RF-based wireless transmission standards – but as a handicap from a mobility standpoint. Also, the communication distance with VLC is typically only between 1 to 100 meters, which can be again seen as a limitation or, on the other hand, as an enabler for more accurate location-based services, such as customer flow analysis in the supermarket, or indoor navigation system for the visually impaired (Haruyama, 2013). The article's authors (Hyun-Seung *et al.*, 2011) studied the applicability of VLC to an indoor positioning system with the help of an intercell interference mitigation system that the authors also devised.

In a paper by (Deqiang *et al.,* 2007), the authors analyzed the relationship between the optimal indoor (white) LED layout and the received power of the VLC system, whereas in (Cui *et al.*, 2010), the authors demonstrated and optimized a practical indoor LOS VLC system. A typical indoor optical wireless communication receiver front-end typically consists of a concentrator, an optical filter, a photodetector, a pre-amplifier, a post-equalizer, and an electrical filter.

The primary noise sources in an indoor VLC system include ambient light noise (i.e., background solar radiation through windows, incandescent radiation, and fluorescent radiation) signal, ambient light-induced shot noise in the photodetector, and the electrical pre-amplifier noise. The ambient light noise induced by background solar radiation and incandescent lamps represents a DC interference that could be easily eliminated using an electrical high-pass filter. The noise generated by fluorescent lamps must be determined in different application scenarios based on what kind of driving circuit is used (Cui *et al.,* 2010).

The authors of (Liu *et al.,* 2011) examined the critical issues in enabling vehicular VLC networks. They noted that a receiver's narrow field-of-view angle makes vehicular VLC networks resilient to visible light noise from sunlight and legacy lighting sources and to interference from active VLC transmitters. Also, in dense vehicular traffic conditions (*e.g.*, urban highways during peak hours), vehicular VLC takes advantage of multiple available paths to reach vehicles, thus overcoming the effects of packet collisions. In the presence of a visible light blockage in traffic, vehicular VLC can still have many successful transmissions by opportunistically using dynamic inter-vehicle gaps. In (Elbahhar *et al.,* 2005), a new inter-vehicle communication system was proposed based on UWB technology with a comparison of two UWB waveforms: coded Gaussian and monocycle pulses. The coded Gaussian pulse waveform was superior since the obtained BER was lower than for monocycle pulses.

Possible future applications for vehicular VLC include (BMW *et al.*, 2005):

- Traffic signal violation warning
- Curve speed warning
- Left turn assistant
- Stop sign movement assistant
- Lane change warning
- Cooperative forward-collision warning
- Pre-crash sensing
- Emergency electronic brake lights
- and even Internet access

Vehicular VLC also needs built-in security features to prevent any malicious user from deliberately and unnecessarily preventing the aforementioned safety features from triggering (e.g., auto braking from pre-crash sensing). Other potential examples for the use of VLC devices include indoor location-based services, secure point-to-multipoint communication, intelligent transportation systems, information broadcast, cellular phones, portable multimedia players, personal digital assistants, navigation, visible-light APs, signboards, billboards, traffic signals, in-vehicle illumination, street lamps, visible-light IDs, etc. (Won, 2008).

Vehicular VLC was studied by (Kim *et al.*, 2012) from the perspective of implementing a VLC network with the help of a Controller Area Network (CAN) in a vehicle. Once again, the authors had interference problems with sunlight, which were fixed using an optical filter and a lens in the light transmitter and the receiver module. In (Iwasaki *et al.*, 2008), the authors proposed a VLC road-to-vehicle communication system at intersections using LED traffic lights as transmitters and on-vehicle high-speed cameras as receivers. While experimenting with a real-world VLC system, the authors noted that image processing algorithms need further detection speed to improve communication speed. Quite similarly, the authors of (Chinthaka*et al.*, 2010) researched the communication between a vehicle and an LED traffic light. They proposed new, more effective algorithms for finding and tracking the transmitter, which specifically targeted the issues found earlier by the authors (Iwasaki *et al.*, 2008), thus resulting in increased wireless communication speed.

An LED-to-LED wireless network obscures the exchange of messages in the existing illumination. The exchange of visible light messages does not affect the level of brightness (in essence, the LED appears to be switched on all the time). VLC communication was researched by the authors (Schmid *et al.*, 2013), who proposed the use of LEDs both as the transmitters and also as the receivers in place of the PDs, which combined with the notion that the evaluated VLC devices consumed an almost equal amount of power in idle mode, and during receiving or transmitting. The authors noted that the LEDs that are charged in reverse bias can be used to receive incoming light. Depending on the intensity of the incoming light, the LED’s capacitance discharges at different speeds. The stronger the incoming light, the faster the discharge. With an adaptive threshold parameter, the two other ON/OFF symbols can be determined and differentiated by the receiving VLC device at the end of each measurement slot.

LED-to-LED wireless communication can be seen as a positive phenomenon from the energy efficiency point of view, as the LEDs typically used purely for lighting can also act as data transceivers without any perceivable impact on the lighting quality. An LED-based VLC ad-hoc network, in which the VLC devices would communicate with each other, might in the future achieve a performance level so high that this approach would help combine smart illumination with low-cost networking, in a sense, eventually becoming a candidate enabling technology for the Internet-of-Things. The authors of (Giustiniano *et al.*, 2012) approached VLC from a practical point of view by building and testing a four-LED VLC network.

The authors implemented a flickering elimination system and a carrier-sense protocol based on free-space optical collision detection to combat the impact of network collisions. The authors also demonstrated that LED sensitivity, physical rate, and flicker elimination are tightly correlated, forcing some compromises in the system design. The authors also noted that using low-cost LEDs to send the light information and detect the transmission reduces the number of components. While resistances, operation amplifiers, etc., can indeed increase the communication rate and range, they also increase the power consumption and cost per device. Also, a typical LED's sensitivity region is only marginally wider than its spectral emission profile, while PDs indiscriminately detect a broad spectrum of visible and infrared light. Therefore, no additional optical filters are needed for LEDs, which makes LEDs more robust against interference from sunlight and any source of man-made interference.

This modulation scheme has been widely deployed in digital TV, radio, and Wi-Fi. OFDM can be modified for use in optical communications, and it uses a set of sub-carriers, each at different but harmonically related frequencies. OFDM has several advantages, including good spectral efficiency, but as a consequence, this modulation method is also quite complex to implement.

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To summarize, some of the possible future directions for VLC research are as follows:

• Standardization of research: During the last decade, we have seen much research related to VLC. However, the lack of experimental testbeds poses a challenge to researchers. Distinct research groups implement our VLC hardware and testbeds; consequently, actual solutions might not interoperate. In this sense, we highlight efforts to standardize VLC research as a future trend. Steps in this direction, as (Zamora *et al.*, 2017), may organize and optimize the research field.

• Popularization through the commercial initiative: The union of academic and commercial VLC-related efforts had its first significant representation during the year 2018, with the official adoption of the Li-Fi technology by Signify (former Philips Lighting), one of the most renowned light companies in the world. In that sense, the future of VLC will be built on top of these commercial movements, while academic efforts will also benefit from the standardization of light infrastructure.

• LED sensing: As discussed in this survey, LEDs have interesting properties when used as sensors. The rapid adoption of VLC by the academy has brought attention to this particular characteristic. Following the guidelines of very recent works (Varshney *et al.,* 2017), (Yang *et al.,* 2017), the use of LED in both VLC and sensing will gather more attention in the next several years.

• Hybrid systems: One of the premises of Visible Light Communication is its adoption as a complementary technology to RF-based mechanisms. In this sense, we suggest developing new hybrid VLC systems as a future trend. Cooperation between VLC and wired-based network devices, concurrent transmission between VLC and RF or Ethernet networks, the use of multiple paths, and the implementation of network coding can enhance the quality of communication.

2. CONCLUSION

The Review is expected to be of considerable interest for future multi-service VLC networks and other wireless networks since the number of new traffic types with different QoS requirements is likely that visible light communication will be widely used as the LED light market expands worldwide. We showed the advantages and disadvantages of visible light communication and explained the effectiveness of location-based services for visible light communication by showing some examples.VLC offers an excellent opportunity to complement the current wireless infrastructure, as it provides increased performance, especially in environments such as offices and homes, where distance is short. In addition, indoor positioning, underwater, vehicular communication systems,the Internet of Things, and Smart Lighting are examples of applications that can utilize visible light. The available studies have shown that VLC can be used in high-data-rate applications in indoor communications. Therefore, VLC is a promising method to meet the ever-growing wireless access and data rate needs. However, well-developed techniques for RF communications can be adapted to the characteristics of VLC.

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