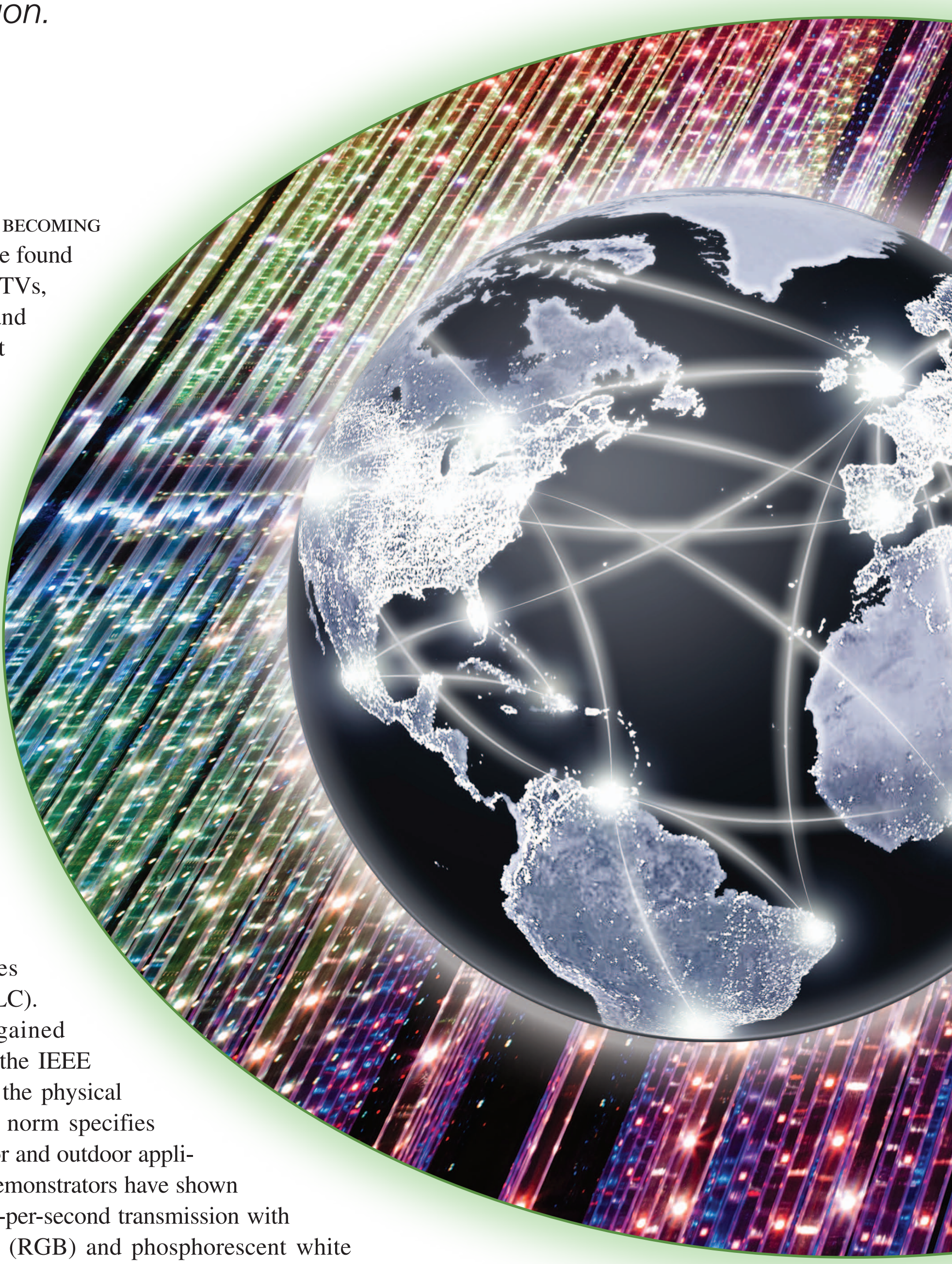
Lighting the Wireless World

By Monica Figueiredo, Luís Nero Alves, and Carlos Ribeiro

The promise and challenges of visible light communication.



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Light-emitting diodes (LEDs) are becoming increasingly ubiquitous. They can be found in illumination appliances, phones, TVs, advertising panels, dashboards, and traffic signals, among others. Most illumination applications are becoming LED based, mainly due to their long operational lifetime and high energy efficiency, which is nowadays higher than 100 lm/W [1]. Other benefits include enhanced sustainability, a compact form factor, easier maintenance, and lower cost. For these reasons, LED lighting is expected to have a market share of 84% in the general illumination market by 2030 [2]. However, there is another characteristic that is not being fully exploited: LEDs are capable of switching their light intensity at a rate that is imperceptible to the human eye. This property has been used for dimming purposes but can also be utilized in the opportunistic deployment of value-added services based on visible light communication (VLC).

Since 2011, VLC technology has gained momentum, supported by the release of the IEEE 802.15.7 draft standard [3] that defines the physical and medium-access control layers. This norm specifies data rates of up to 96 megabits/s for indoor and outdoor applications [3]. Since then, several research demonstrators have shown that VLC is capable of achieving gigabits-per-second transmission with commercial off-the-shelf red-green-blue (RGB) and phosphorescent white LEDs [4]. This is the result of the increasing attention that this technology has

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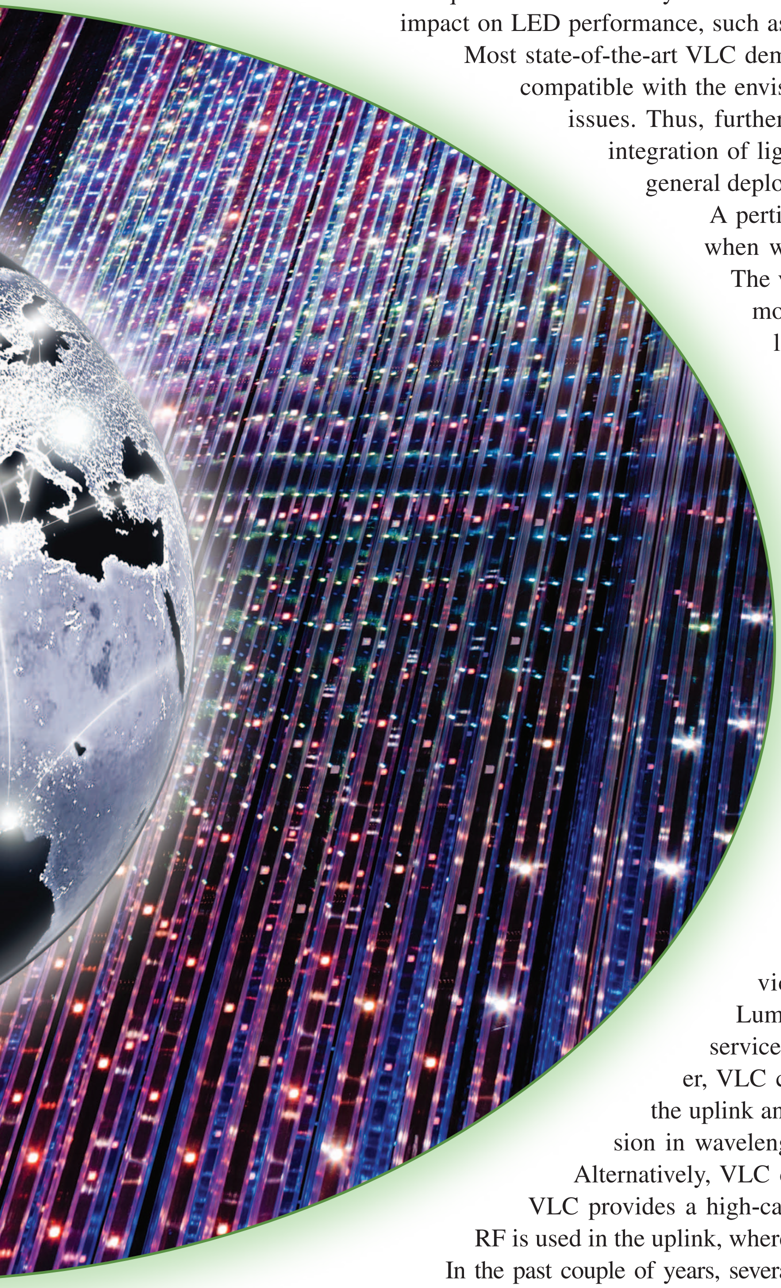
attracted in both the research community and global society in recent years. Figure 1 illustrates this trend over the last five years by depicting the number of results for the search term *visible light communication* conducted using the IEEE *Xplore* online library and Google search engine.



A key VLC requirement is that it must be based on illumination-grade LEDs and comply with the illumination requirements and safety recommendations [5]. Also, data transmission should have minimal impact on LED performance, such as color temperature, color rendering index, and lifetime [6]. Most state-of-the-art VLC demonstrators have already proved they can achieve data rates compatible with the envisioned applications, but they do not address lighting quality issues. Thus, further investigation is still necessary to guarantee the seamless integration of lighting and communication services, which is crucial for the general deployment of this technology [7].

A pertinent question that one might ask is, “Why use light signals when we can use radio-frequency (RF) signals to communicate?” The visible light spectrum can be used synergistically with common radio technology. First, as the available RF bandwidth is limited, highly regulated, and increasingly congested, it may be helpful to use a portion of the spectrum that is unlicensed, currently largely unused, and amenable to spatial reuse. This is especially relevant in the realm of technologies beyond fifth generation (5G), where the density of users and devices with communication needs is predicted to scale up exponentially. Second, there are many application scenarios where the use of radio signals raises concerns related to e-smog, privacy, and security. Third, in scenarios where line of sight (LOS) and locality are important and the illumination infrastructure is already deployed (e.g., offices, stores, or vehicles), VLC can be a complement to current RF communications. Finally, light can be a good medium for low-cost and/or low-latency short-range links for near-field communications or high-bandwidth download links. Table 1 shows the most relevant visible light and RF signal characteristics, highlighting their complementarity.

Broadcasting content to end users is the most natural service envisioned for directional technologies such as VLC. Luminaires are supposed to transmit a low- [8] or high-data-rate service [9] for end users located in their illumination area. However, VLC can also be used for full duplex communication, as long as the uplink and downlink can be separated [10]. This can be done by division in wavelength, in time, or in code or by resorting to spatial isolation. Alternatively, VLC can be combined with RF in heterogeneous networks [11]; VLC provides a high-capacity, uncongested, and unregulated downlink path, while RF is used in the uplink, where congestion is less likely.

In the past couple of years, several interesting surveys have been published on VLC. Some are focused on physical-layer techniques [12], while others cover medium-access protocols [13], networking techniques and sensing [14], and lighting requirements [15]. A survey on more general optical wireless communications can be found in [16]. In this article, we provide a brief state-of-the-art overview of the technology and the main upcoming challenges.

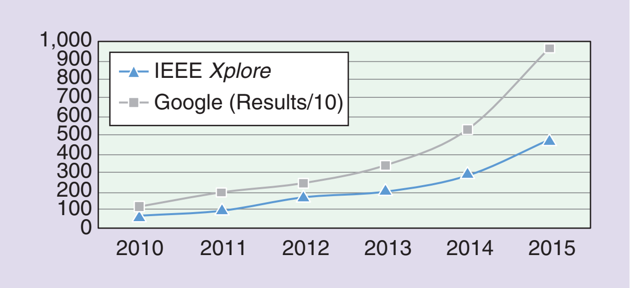


FIGURE 1. The search results for "visible light communication" using the IEEE *Xplore* online library and the Google search engine.

VLC APPLICATIONS

The particular characteristics of VLC systems, highlighted in Table 1, and the potential synergy of lighting and communication make it a viable solution in a broad spectrum of applications. We divide these applications into five main categories according to the field of application, which are illustrated in Figure 2.

PERSONAL AREA NETWORKS

For high-density wireless scenarios, such as conference halls or transportation hubs, VLC can provide indoor wireless Internet access and support real-time bandwidth-intensive applications, easily enabling the spatial reuse of the lighting resources, i.e., LEDs, to support crowd demands. In this kind of indoor heterogeneous scenario, RF and VLC are complementary technologies; RF is advantageous to support mobility and uplink transmissions, while VLC can provide a low-cost solution for Wi-Fi spectrum relief. Smart home and office networks can also exploit the benefits offered by VLC by using the existing lighting infrastructure to enable safe wireless Internet access (visible light is harmless to the human body).

Table 1. A comparison between visible light and RF signal characteristics.

Property	Visible Light	RF
Bandwidth	Large, unlicensed	Limited, licensed
Produces e-smog	No	Yes
Produces flicker	Yes	No
Requires LOS	Yes (mostly)	No
Technology maturity	Medium	High
EMI plus hazard concerns	Low	High
Susceptibility to eavesdropping	Low	High
Range	Short	Medium
Supports mobility	Limited	Good
Data density	High (spatial reuse)	Limited

Another envisioned application is related to localized high-rate optical data spots that can boost the speed of wireless communications.

INTELLIGENT TRANSPORTATION SYSTEMS

LEDs are increasingly being adopted in vehicles (headlamps, brake lights, and signal lights), street lamps, signage, and traffic lights. Based on these new lighting systems, many VLC application opportunities have been envisioned and prototypes developed. This technology can be used for both vehicle-to-vehicle and vehicle-to-infrastructure communication in high-traffic-density scenarios to avoid traffic accidents, increase road safety, and improve traffic management systems. However, it is still an early-stage technology for outdoor applications, and further research is needed to increase its robustness, range, and coverage. Also, street lighting solutions employing VLC must comply with the same energy efficiency and environmental adaptability requirements (daylight and traffic/occupancy adaptive illumination) that provide the cost-saving opportunities necessary for municipalities to modify their lighting infrastructure [17]. Finally, other solutions to support the network availability during daytime are required, as lighting is mostly needed at night.

NON–RF-FRIENDLY ENVIRONMENTS

There are several environments where the use of RF-based wireless technologies is not feasible and/or not desirable. In these environments, LEDs can provide safe and secure lighting, communication, and localization services. Some examples are areas where there is a risk of explosions, such as mines, petrochemical plants, and oil rigs; environments where RF technologies may raise some health concerns, such as nursery schools; applications where LEDs' light signal isolation and nonomnidirectional properties can be used to prevent eavesdropping and ensure secure communications (e.g., military, defense, industrial, or corporate secure communication applications); underwater scenarios where RF is not feasible and acoustic communication has a limited data rate; and spaces with equipment that requires isolation from electromagnetic interference (EMI), such as airplanes and hospitals (though the deployment of VLC systems in hospitals must be considered carefully, as pulsed light may interfere with some light-sensitive health equipment, such as oximeters).

SMART LIGHTING

This category includes applications that can increase energy efficiency and human comfort by integrating multiple services in the lighting infrastructure. The most popular VLC application in this category is indoor positioning, enabling navigation, augmented reality, and e-commerce services. Some examples are VLC positioning in the following places:

- supermarkets for shopping assistant purposes, as implemented by Philips in Lille Carrefour
- museums, to guide the public and trigger audio or video guides, as in a pilot light-fidelity (Li-Fi) project rolled out by Philips at the Boerhaave Museum in Leiden, The Netherlands
- unfamiliar indoor environments, to help visually impaired people or tourists (now being deployed in the Paris Métro).

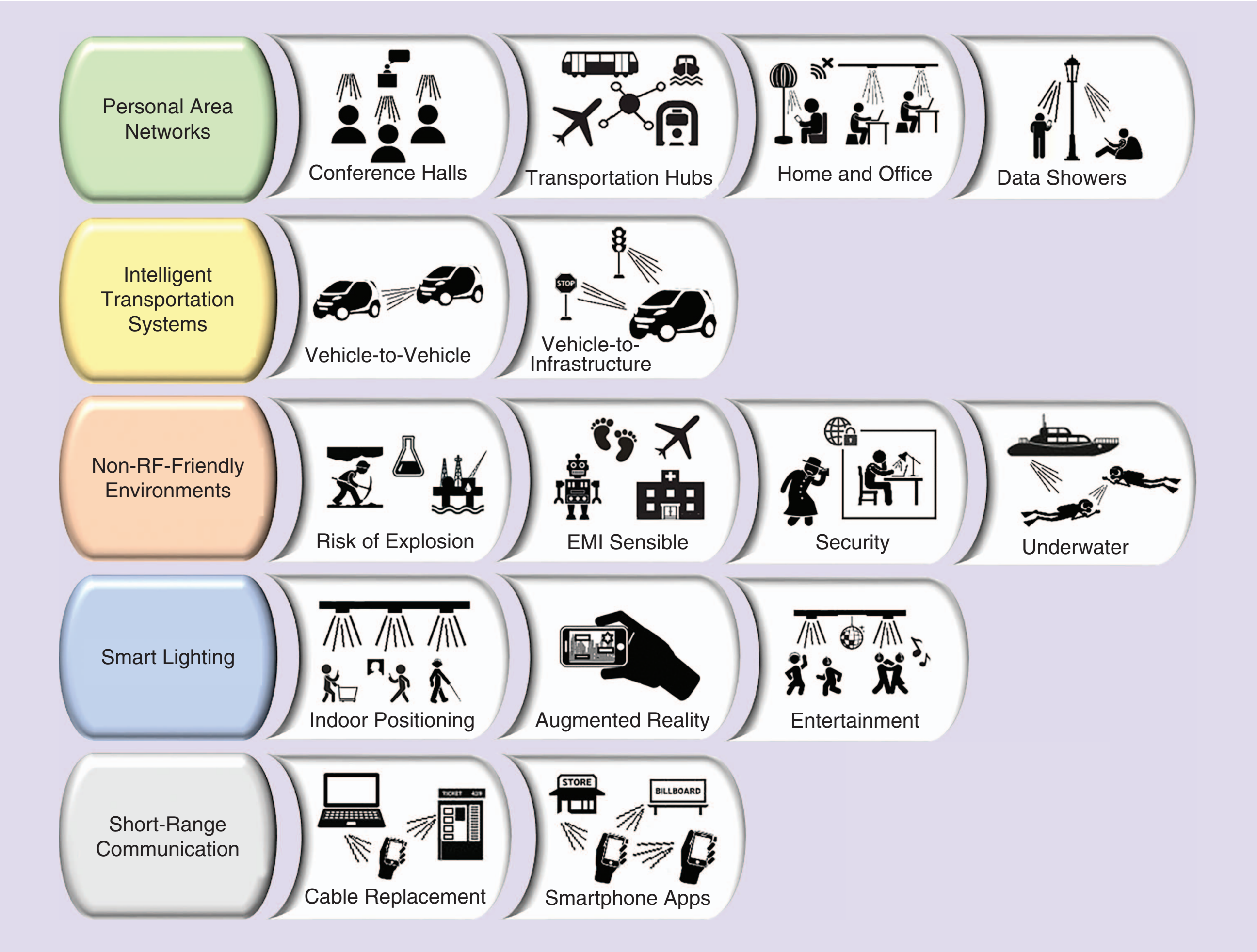


FIGURE 2. The main applications of VLC by category.

LED communication can also be used to improve coordination between luminaires (without the need for physical links in every one) [18] or to enable the deployment of entertainment and advertising applications. Several of these applications have been proposed over the years and implemented in demonstrators. Some examples include the following:

- localization-based music streaming, so people can choose to listen to different types of music depending on their localization, as showcased by Sony and Agilent Technologies
- smart lighting of buildings and art objects, where light can transmit music sounds to the public, as demonstrated in the Yokohama National Gallery
- advertising services using light-based Quick Response (QR) codes embedded in the lighting infrastructure, as exhibited by Fujitsu and Panasonic
- a merchandise information distribution system, as showcased by NEC and Matsushita Electric Works.

More information on these and other proposed applications and demonstrators can be found in [19].

SHORT-RANGE COMMUNICATION

Visible light has proven to be an interesting solution for safe, low-cost, short-range communications with low risk of signal jamming, data snooping, or modification. In the high-data-rate end, it can be used to enable low-cost multigigabit/s data transmission among devices, thus replacing high-speed cable connections, such as universal serial bus 3.0 and HDMI, similar to high-speed infrared data association. On the other end, multiple applications for smartphones have been proposed, where the display is used as a VLC transmitter and the camera is used as the receiver. Most of these applications are focused on social-media interaction, entertainment, and advertising and include mobile-to-mobile and mobile-to-infrastructure application scenarios. The infrastructure may be advertising billboards, TVs, or any other display where small pieces of information can be embedded as a watermark. Both Fujitsu and Panasonic have demonstrators to showcase these applications.

We previously described several VLC application scenarios, but most of them are currently not commercially available. They resulted from different research activities conducted over the years, and, although some demonstrators exist, the technology is still in its first steps toward industrialization. Some companies, such as Oledcomm and pureLiFi, have already introduced some VLC demonstrators into the market for wireless Internet access (showcased in the 2016 Mobile World Congress), which is

> The most popular VLC application in smart lighting is indoor positioning, enabling navigation, augmented reality, and e-commerce services.

commonly known as *Li-Fi* technology. Fraunhofer HHI also has commercially available solutions and demonstrators for 1-gigabit/s and 3-gigabits/s light communication. Other companies are focused on low-data-rate applications for localization, augmented reality, and advertising purposes. Their commercial demonstrators are shown in Table 2. Although these are still not mainstream consumer electronics (CE) products, they are the precursors of future light-based CE communication products.

VLC PHYSICAL LAYER

The VLC channel comprises wavelengths ranging from 390 to 700 nm, between ultraviolet and infrared (IR). In terms of available bandwidth, this corresponds to frequencies from 440 to 700 THz. Broadly speaking, the channel can be classified according to the relative position of the emitter and receiver. This classification was inherited from the IR channel and consists of six major configurations (Figure 3), depending on the existence of LOS [20].

LOS and non-LOS configurations can be directed, hybrid, or nondirected, depending on the emitter and

Table 2. VLC commercial demonstrators (as of the second quarter of 2017).

	Company	Products		
Hardware	OLEDCOMM	GEOLi-Fi for geolocation • Modules using LED lighting • Accessories for the IoT: smartphones and tablets • SDK/API to enable clients to develop applications that are using GEOLi-Fi geolocation services		
		Li-FiNET can be used with any kind of LED lighting for Internet connection between an LED light and a laptop equiped with a Li-FiNET receiver. • Full duplex up to 2 megabits/s • Equipment is compliant with the international standard IEEE 802.15.7		
	Luciom	Li-Fi TAG for geolocation • ID can be decoded by a camera or audio jack receiver, both indoors and outdoors		
		Boadband Li-Fi • Internet access mode and tracking mode • Full duplex up to 20 megabits/s downlink and 5 megabits/s uplink • Li-Fi Internet reception via autopowered USB key		
	pureLiFi	Li-Fi-X • Full duplex up to 40 megabits/s downlink and 40 megabits/s uplink • Full mobility (a portable, USB-powered station) • Multiple users per Li-Fi access point • Handover control for seamless switching between APs • Support for power over Ethernet or power line communications		Legacy Products: • Li-first Full duplex up to 11.5 megabits/s Range: 3 m • Li-flame Full duplex up to 10 megabits/s Range: 3 m Handover capability
	Fraunhofer HHI	1 gigabit/s transceiver • High-speed VLC links up to 1 gigabit/s using ordinary visible LED light	3 gigabits/s transceiver • High-speed optical wireless local links up to 3 gigabits/s using up to a bandwidth of 180 MHz	
	Others	EldoLED ECOdrive • MCU-based driver that supports Lumicast	Acuity brands, GE lighting and Philips lighting • Partnership with Qualcomm to provide light-based localization services	
Smartphone Apps	Casio Qualcomm Fujitsu Panasonic Basic6	Casio PicapiCamera • An entertainment application for smartphones using VLC	Qualcomm Lumicast • Light-based indoor positioning	Fujitsu • Transmit and receive light-based ID data
		Panasonic • Transmit and receive light-based ID data • (light-based QR codes)	Basic6 GeoLi-Fi • Light-based indoor positioning system	

MCU: microcontroller unit; USB: universal serial bus.

receiver types. The emitter and receiver types depend either on the physical aspects of the devices—such as the beam angle of the emitter and the field of view of the receiver—or the possibility of tracking mechanisms (where both emitter and receiver can be adaptively aligned to maximize the signal-to-noise ratio). Nondirected configurations are based on reflections. Unlike to the IR channel, which is focused on a single wavelength, the VLC channel is wavelength dependent [21]. This dependency is implicit in the emitting and receiving devices and also in the reflectivity of the environment. For indoor channels, where reflections may exist from walls and moving objects (people), wavelength-dependence effects may induce penalties on the link performance, affecting both the signal-to-noise ratio and signal distortion. Distortion effects induced by wavelength dependence are of particular relevance for multiwavelength VLC systems employing transmitting devices with multiple emission peaks, such as RGB-LEDs. Nondirected links are also affected by multipath induced intersymbol interference (ISI). This results from the existence of multiple paths with different lengths between the emitter and receiver [22]. As a consequence, non-LOS links offer low potential for high data rates and reduced link performance when compared to LOS configurations. Nevertheless, nondirected links, where the emitter has large beam angles, are the most favorable configurations when combining communications and lighting requirements.

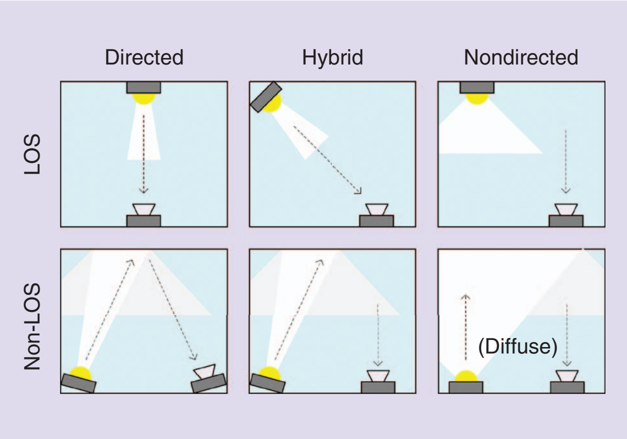


FIGURE 3. The link configurations of VLC.

Light uniformity is usually a desired lighting characteristic, as it translates into better perception of the environment. It is typically attained with multiple lighting devices uniformly distributed in a room. This uniformity is also a key requirement for VLC systems that are intended to support mobility. However, there are some application scenarios, such as conference halls or airplanes, where light uniformity is not a requirement. In these scenarios, spatially confined lighting footprints can be used to enable the deployment of femtocells, which may provide high-bit-rate access for different users.

Figure 4 depicts the physical layer architecture of a unidirectional VLC communication system. It includes the LED driving circuit front end and the receiving front end. As mentioned previously, full-duplex connectivity can also be achieved, e.g., using light with different wavelengths, thus exploring the features of wavelength division multiplexing for bidirectional communications.

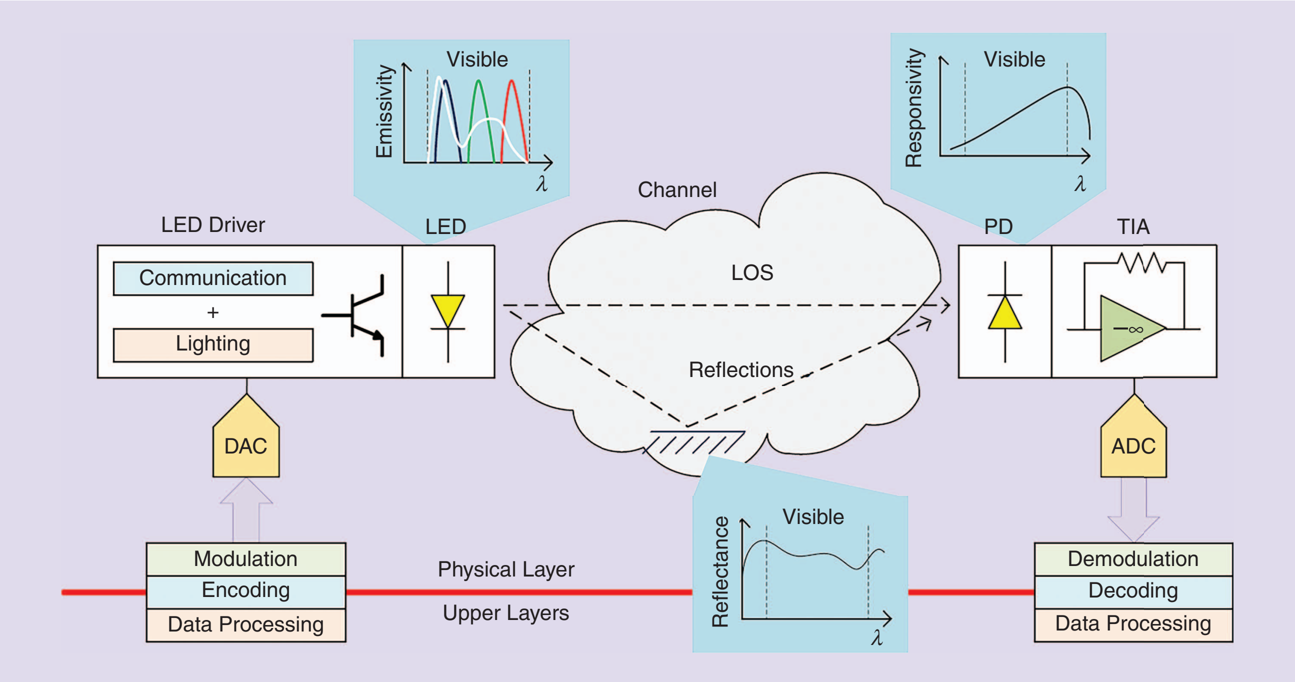


FIGURE 4. The VLC physical layer architecture. DAC: digital-to-analog converter; ADC: analog-to-digital converter; PD: photodiode; TIA: transimpedance amplifier.

Future technologies will have to offer high bandwidth with the same energy efficiency, operation lifetime, light quality, and cost offered by current phosphor-coated LEDs.

TRANSMITTER

VLC systems operate synergistically with lighting systems, in great part due to the sharing of the same lighting devices, i.e., LEDs. For lighting purposes, white light with a given color temperature is often desirable; this is motivated in part by human biology and the way our species evolved since ancient times. Natural light from the sun has always been used as a reference for lighting concerns. LEDs are not able to replicate the same lighting spectrum of the sun, which conforms to Planck's law for black-body radiation. There are two mainstream approaches to LED white light generation: using color combination and phosphor conversion. Color combining usually resorts to the use of multiple devices with different wavelengths, normally red, green, and blue. RGB LEDs can reproduce white light, if the peak emissions for each color are adequately set, and can support wavelength division multiplexing in VLC systems.

On the contrary, white LEDs using phosphor conversion employ a single blue-emission-peak LED chip and a phosphor coating (usually made of cerium-doped yttrium–aluminum garnet Ce^{3+}: YAG). The phosphor absorbs part of the blue-emitted photons and reemits photons of less energy, in the yellow wavelength region. The combined yellow and blue emission is perceived as white light. White LEDs are not able to support wavelength division multiplexing, as they employ a single active device. Furthermore, white LEDs have reduced bandwidth when compared to RGB-LEDs because the phosphor conversion is a slow process (although VLC systems may employ optical filters to cut the yellow part of the spectrum, thus improving bandwidth [23]).

On the transmitter side, the LED driver combines signal transmission with lighting demands. From the lighting perspective, a frequent demand is for light gradation to provide the required lighting level in accordance with environmental demands, which can be accomplished by analog or digital dimming. In analog dimming, light is typically controlled by a dc current, while digital dimming resorts to pulse-width modulation (PWM) to control the light level. Several studies defend the use of constant current against PWM strategies for light control because of the unknown effects that pulsed light may have on humans and also because of interference problems with optically sensitive equipment (e.g., medical equipment for blood pressure and temperature measurement) [5].

The transmitter also has the function of light modulation. VLC systems operate on the basis of intensity modulation/direct detection, where the electrical signal modulates the light generated on the LED. Combining lighting and signal modulation on the same device is not a simple task. Lighting LEDs are usually optimized for illumination purposes, where electrical-to-optical conversion efficiency is of paramount importance. This means that they are not designed to have large bandwidths. On the other hand, there are restrictions on the LED switching speed that limit the use of low-frequency components. Very high switching speed is usually of minor importance for lighting considerations, given that human perception of light-flickering effects is normally below 200 Hz. However, some studies also indicate that modulation of light with frequencies up to 19 kHz can be detected by the human retina [5]. Thus, to attain flicker-free lighting conditions, the modulated signal must be generated with low power content in the low-frequency band.

Research has focused on ways to overcome bandwidth limitations of LEDs. Current trends resort to orthogonal frequency division multiplexing (OFDM)-based modulation formats as a means to compensate for the low bandwidth of these devices. Other approaches resort to pre- and postequalization strategies, as will be discussed in the "Modulation and Coding Schemes" section. On the other hand, LED technology has been improving through a divide-and-conquer strategy, in which instead of a single device capable of handling large luminous outputs, lighting devices are composed of multiple devices arranged in arrays called *chip-on-board* (*COB*)-LEDs. These arrays are able to deliver large luminous outputs while maintaining high electrical-to-optical conversion efficiencies. COB-LEDs can also be used efficiently for communication purposes. On the one hand, they are composed of smaller LEDs, generally capable of handling larger signal bandwidths. On the other hand, they can simplify the transmitter architecture by removing the need for digital-to-analog conversion. This conversion is required when using analog or multiple-amplitude modulation schemes but can be eliminated in COB-LED arrays configured as optical digital-to-analog converters [24].

RECEIVER

On the receiver side, the fundamental building blocks at the physical level are the photodetector, amplifier, and analog-to-digital converter. The remaining tasks of signal demodulation are usually handled by a digital signal processor or field programmable gate array. Visible light detectors usually resort to p-type, intrinsic, and n-type (PIN) silicon photodiodes, as these possess responsivities covering the visible part of the light spectrum. The PIN photodiode converts light into current, which is further processed by the amplifier. VLC systems employ transimpedance amplifiers able to perform the current-to-voltage conversion with reduced penalties on gain, bandwidth, and noise. The gain of the amplifier is set to compensate for the square law loss due to the distance between the transmitter and receiver.

MODULATION AND CODING SCHEMES

The way information can be embedded in light for the purpose of VLC depends on several requirements. These requirements can stem from the following elements: 1) the intrinsic characteristics of LEDs, 2) the envisioned application, and 3) the fact that LEDs must fulfill their primary function, which is to generate high-quality light with high energy efficiency.

Regarding the first set, the requirements are that the transmitted signal must be real and unipolar because the LEDs must be intensity modulated and the light thus produced must be directly detected. Thus, traditional RF modulation schemes must be adapted to fulfill these requirements. Also, the effect of the nonlinear LED light intensity/voltage response must be accounted for in the system if a high modulation order is required. One must be aware that the LED's dynamic range is linear only in a small portion of its characteristic curve, around the operation point. Thus, there is a compromise between communication range, power efficiency, and performance, impaired by distortion.

The second set of requirements depends on whether or not a high-data-rate transmission is required because illumination-compatible LEDs have a limited bandwidth. For low-data-rate applications, on-off keying (OOK) and variable pulse position modulation are the most popular modulation schemes and have been included in the VLC physical layer of the IEEE 802.15.7 standard [3]. However, to achieve a higher spectral efficiency, other schemes are necessary, such as OFDM or multiband carrierless amplitude and phase modulation. Over the last decade, several flavors have been proposed around these schemes, with different power and bandwidth efficiencies, but the most commonly used is dc-biased optical OFDM [25]. Figure 5 depicts the modulation schemes used in VLC demonstrators reported in the last decade's literature. It is clear that the most common are OFDM-based and OOK modulations, with different achievable data rates.

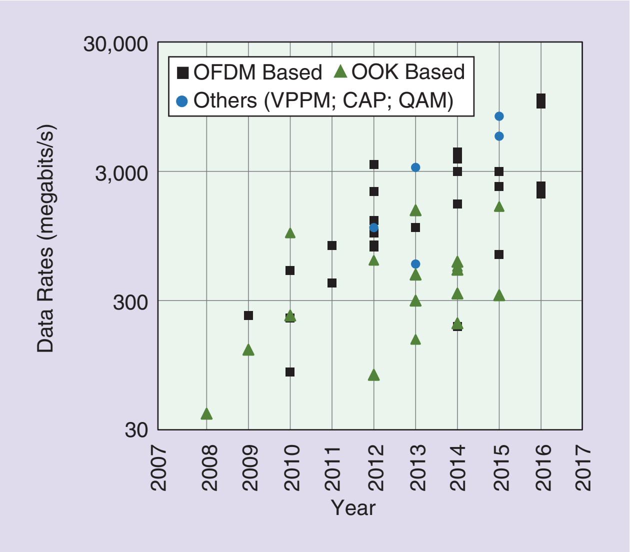


FIGURE 5. The modulations used in VLC demonstrators. VPPM: variable-pulse position modulation; CAP: carrier less amplitude and phase modulation.

For the highest rates, other techniques have also been used, such as high-bandwidth LEDs and lasers diodes, optical lenses and filters, pre- and/or postequalization, multiple-access schemes (e.g., wavelength division multiplexing with RGB LEDs [26]), and parallel communication schemes (e.g., optical multiple input, multiple output [27] and multiuser multiple input, single output [28]). Nevertheless, the underlying modulation scheme is always some flavor of OFDM.

The third set of requirements is probably the least explored by the research community, but it is the one that will ultimately determine the success and penetration rate of this technology. One must be aware why LED technology has been so successful in terms of market share—because it is highly energy efficient, has a long operational lifetime, and enables a more comfortable lighting system for humans. Thus, the functional and aesthetic requirements of lighting also play an important role in the definition of modulation techniques. To meet these requirements, a modulation scheme must achieve the following three goals: 1) support dimming, 2) not introduce perceivable chromaticity shifts, and 3) not introduce perceptible flickering. Although these issues have already been addressed by the scientific community, and both OFDM and OOK modulation were shown to be able to roughly meet these requirements, further investigation is still needed to mature the technology and fuel the practical implementation of VLC in lighting.

Selecting an adequate channel-coding technique is also essential to ensure reliable data communication under the influence of typical VLC impairments, such as the shadow effect, the presence of other light sources, and multipath ISI. Moreover, the code selection should consider the application scenario, which may have specific latency, dimming, and/or flicker requirements. Latency requirements can be met by using different codes (block/convolutional) and techniques (interleaving/puncturing) for different applications or by resorting to codes with adaptive rates. Moreover, coding schemes can be efficiently combined with techniques to guarantee low flicker levels and support light dimming. To this end, several advanced forward error correction schemes for VLC have recently been proposed in the literature, such as low-density parity-check codes [29], Reed–Muller block codes [30], and rate-compatible convolutional codes [31].

CONCLUSION

This article discusses different VLC applications, presents commercially available systems, and describes the technology's key building blocks. The main goal is to provide a broad picture of the nature of VLC and where it stands at the moment. Although some VLC demonstrators are already commercially available, there are still some open issues

Another issue is VLC's coexistence with Wi-Fi in future heterogeneous networks, which is seen as a promising scenario in 5G and beyond-5G networks.

related to the technology's market penetration. One of these issues is LED-to-Internet connectivity, as VLC systems must guarantee compatibility with legacy LED lighting infrastructures. To this end, the most obvious solution is to rely on available network-establishing equipment, such as power line communications (PLC). In PLC systems, data are modulated directly on the power lines, thus reaching all devices. Broadband PLC systems can support data rates in the range of hundreds of megabits per second, which represents a good solution for in-home use. PLC systems, however, are prone to noise on the power lines, which degrades communication performance in outdoor scenarios.

Another issue is VLC's coexistence with Wi-Fi in future heterogeneous networks, which is seen as a promising scenario in 5G [32] and beyond-5G networks [33]. This coexistence between RF and VLC technologies introduces new possibilities. The most immediate is to rely on VLC to broadcast high-data-rate content to multiple users while using radio to manage the network. More evolved scenarios explore the smaller cell size of VLC systems (confined to the luminaires' footprints) to manage spectrum allocation in dense-user cases [34]. VLC systems can also benefit from the wider coverage of radio systems, which could improve user mobility and handover when changing between neighbor cells. VLC systems may also apply concepts already proven in radio technologies. One example is to mimic cognitive radio systems, which are able to adapt to spectrum occupation. VLC systems may sense the channel occupation and optimistically use different wavelengths to provide higher aggregate bandwidths or to mitigate cell interference.

A third issue is related to the ability to produce LED devices compatible with both illumination and communication services. To accomplish this, future technologies will have to offer high bandwidth with the same energy efficiency, operation lifetime, light quality, and cost offered by current phosphor-coated LEDs (typically used for illumination due to their low cost). One of the most promising technologies today relies on arrays of micro-LEDs that can offer optical bandwidths in excess of 800 MHz [35]. However, there is still a long research path before these LEDs can reach the CE market for the purpose of illumination.

Beyond these key challenges, several other subjects are also promising research areas in this field, such as efficient modulation and coding schemes for VLC, transceiver design and energy efficiency, alignment and shadowing, intercell interference, uplink and RF augmentation, and mobility and coverage issues. The good news is that the research community is increasingly interested in this technology, and, as new ideas come to light, we can expect the wireless world to shine increasingly brighter.

ABOUT THE AUTHORS

Monica Figueiredo (monica.figueiredo@ipleiria.pt) earned her B.Sc. degree in electrical engineering from the University of Coimbra, Portugal, in 1999; her M.Sc. degree in electronics and telecommunications engineering from the University of Aveiro, Portugal, in 2003; and her Ph.D. degree in electrical engineering from the University of Aveiro, Portugal, in 2012. She began her research activities in 2001 at the Instituto de Telecomunicações, Aveiro, Portugal, becoming a member of the Integrated Circuits group in 2012. She joined the Department of Electronics of the Polytechnic Institute of Leiria, Portugal, in 1999, where she is currently an assistant professor. She teaches different courses in digital electronic and communication systems. Her research interests include timing circuits and high-speed integrated electronics, digital systems' implementation in field-programmable gate arrays, and visible light communication systems.

Luís Nero Alves (nero@ua.pt) earned his M.Sc. degree in electronics and telecommunication engineering and his Ph.D. degree in electrical engineering from the University of Aveiro, Portugal, in 2000 and 2008, respectively. His expertise is on integrated circuit design for optical wireless applications. Since 2008, he has been the lead researcher in the Integrated Circuits group at the Instituto de Telecomunicações, Aveiro, Portugal. His current research interest is in the design and performance analysis of optical wireless communication systems, with a special focus on visible light communications and materials and devices for IoT sensing devices. He has served as a member of the COST action IC1101 on optical wireless communications, and he has authored and coauthored several research articles in these fields. He has also served in the technical program committee of several international conferences on the field of optical wireless communications. He has also served as reviewer for several journals in optical communications. He is a Member of the IEEE.

Carlos Ribeiro (cribeiro@av.it.pt) (carlos.ribeiro@ipleiria.pt) earned his B.Sc. degree in electrical engineering and his M.Sc. degree in electrical and computer engineering from the University of Coimbra, Portugal, in 1996 and 2003, respectively. In 2010, he earned his Ph.D degree in electrical engineering from the University of Aveiro, Portugal. He is a signal processing for communications researcher in the Wireless Communications group of Instituto de Telecomunicações, Portugal. He joined the Department of Electronics at the Polytechnic Institute of Leiria, Portugal, in 1997, where he is currently an assistant professor. His main research topics are Phy algorithms for radio frequency and visible light communication systems and their implementation. He has published tens of papers in international journals and conferences and has participated in several national and European projects.

REFERENCES

[1] Cree Inc. (2016, May 24). Cree extends groundbreaking OSQ Series to deliver 58 percent efficacy increase and new higher output luminaire. [Online]. Available: http://www.cree.com/News-and-Events/Cree-News/Press-Releases/2016/May/Cree-Extends-Groundbreaking-OSQ-Series-to-Deliver-58-Percent-Efficacy-Increase

[2] U.S. Department of Energy. (2014, Aug.). Energy savings forecast of solid-state lighting in general illumination applications. [Online]. Available: https://www.energy.gov/sites/prod/files/2015/05/f22/energysavingsforecast14.pdf

[3] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Wireless Optical Communication Using Visible Light*, IEEE Standard 802.15.7, 2011.

[4] H. Chen, C. Wu, H. Li, X. Chen, Z. Gao, S. Cui, and Q. Wang. (2016). Advances and prospects in visible light communications. *J. Semiconductors.* [Online]. *37(1).* Available: http://iopscience.iop.org/article/10.1088/1674-4926/37/1/011001/pdf

[5] International Energy Agency. (2014, Sept. 24). Energy efficient end-use equipment (4E) – Solid State Lighting Annex: Potential health issues of SSL," Technical Report, SSL Annex Task 1. [Online]. Available: http://ssl.iea-4e.org/files/otherfiles/0000/0072/IEA_4E_SSL_Annex_Health_Aspects_Study_final.pdf

[6] W. O. Popoola, "Impact of VLC on light emission quality of white LEDs," *J. Lightwave Technol.*, vol. 34, no. 10, pp. 2526–2532, May 2016.

[7] J. Gancarz, H. Elgala, and T. D. C. Little, "Impact of lighting requirements on VLC systems," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 34–41, Dec. 2013.

[8] S. Y. Jung, S. Hann, and C. S. Park, "TDOA-based optical wireless indoor localization using LED ceiling lamps," *IEEE Trans. Consum. Electron.*, vol. 57, no. 4, pp. 1592–1597, Nov. 2011.

[9] J. Rufo, J. Rabadan, F. Delgado, C. Quintana, and R. Perez-Jimenez, "Experimental evaluation of video transmission through LED illumination devices," *IEEE Trans. Consum. Electron.*, vol. 56, no. 3, pp. 1411–1416, Aug. 2010.

[10] Z. Zhang, X. Yu, L. Wu, J. Dang and V. O. K. Li, "Performance analysis of full-duplex visible light communication networks," in *Proc. IEEE Int. Conf. Communications (ICC)*, London, 2015, pp. 3933–3938.

[11] M. Ayyash, H. Elgala, A. Khreishah, V. Jungnickel, and T. Little, "Coexistence of WiFi and LiFi toward 5G: Concepts, opportunities, and challenges," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 64–67, Feb. 2016.

[12] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "LED based indoor visible light communications: State of the art," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1649–1678, 2015.

[13] D. Tsonev, S. Videv, and H. Haas, "Light fidelity (Li-Fi): Towards all optical networking," in *2013 Proc. SPIE Optoelectronics, Photonic Materials and Devices Conference (OPTO)*, 2013, Art ID. 900702.

[14] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, 2015.

[15] A. Tsiatmas, C. P. M. J. Baggen, F. M. J. Willems, J. P. M. G. Linnartz, and J. W. M. Bergmans, "An illumination perspective on visible light communications," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 64–71, July 2014.

[16] M. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, 2014.

[17] European Commission. (2013, June). Lighting the cities: Accelerating the deployment of innovative lighting in European cities. [Online]. Available: http://cordis.europa.eu/fp7/ict/photonics/docs/ssl-cip/lighting-the-cities_en.pdf

[18] K. Warmerdam, A. Pandharipande, D. Caicedo, and M. Zuniga, "Visible light communications for sensing and lighting control," *IEEE Sensors J.*, vol. 16, no. 17, pp. 6718–6726, Sept.1, 2016.

[19] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs). (2008, Mar. 9). Visible light communication: Tutorial. [Online]. Available: http://www.ieee802.org/802_tutorials/2008-03/15-08-0114-02-0000-VLC_Tutorial_MCO_Samsung-VLCC-Oxford_2008-03-17.pdf

[20] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.

[21] S. Rodríguez, R. Perez-Jimenez, B. R. Mendoza, F. J. Lopez-Hernandez, and A. Ayala, "Simulation of impulse response for indoor visible light communications using 3D CAD models," *EURASIP J. Wireless Commun. and Networking*, vol. 7, Jan. 2013.

[22] F. Miramirkhani and M. Uysal, "Channel modeling and characterization for visible light communications," *IEEE Photon. J.*, vol. 7, no. 6, pp. 1–16, Dec. 2015.

[23] J. Grubor, S. Randel, K.-D. Langer, and J. W. Walewski, "Broadband information broadcasting using LED-based interior lighting," *J. Lightwave Technol.*, vol. 26, no. 24, pp. 3883–3892, 2008.

[24] J. Armstrong, "Optical domain digital-to-analog converter for visible light communications using LED arrays," *Photon. Res.*, vol. 1, no. 2, pp. 92–95, Aug. 2013.

[25] K. Langer, "DMT modulation for VLC," in *Visible Light Communication*, 1st ed., S. Arnon, Ed. Cambridge, U.K.: Cambridge Univ. Press, 2015.

[26] F. M. Wu, C. T. Lin, C. C. Wei, C. W. Chen, Z. Y. Chen, H. T. Huang, and Sien Chi, "Performance comparison of OFDM signal and CAP signal over high capacity RGB-LED-based WDM visible light communication," *IEEE Photon. J.*, vol. 5, no. 4, Aug. 2013. doi: 10.1109/JPHOT.2013.2271637.

[27] L. Zeng, D. C. O'Brien, H. L. Minh, G. E. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won "High data rate multiple input multiple output (MIMO) optical wireless communications using white LED lighting," *IEEE J. Sel.. Areas Commun.*, vol. 27, no. 9, pp. 1654–1662, Dec. 2009.

[28] H. Shen, Y. Deng, W. Xu, and C. Zhao, "Rate-maximized zero-forcing beamforming for VLC multiuser MISO downlinks," *IEEE Photon. J.*, vol. 8, no. 1, pp. 1–13, Feb. 2016.

[29] S. Kim, "Adaptive FEC codes suitable for variable dimming values in visible light communication," *IEEE Photon. Technol. Lett.*, vol. 27, no. 9, pp. 967–969, May 2015.

[30] S. Kim and S.-Y. Jung, "Modified Reed–Muller coding scheme made from the bent function for dimmable visible light communications," *IEEE Photon. Technol. Lett.*, vol. 25, no. 1, pp. 11–13, Jan. 2013.

[31] J. Kim and H. Park, "A coding scheme for visible light communication with wide dimming range," *IEEE Photon. Technol. Lett.*, vol. 26, no. 5, pp. 465–468, Mar. 2014.

[32] NetWorld2020 European Technology Platform for Communications Networks and Services Expert Working Group. (2014, Sept.). 5G: Challenges, research priorities, and recommendations (joint white paper). [Online]. Available: http://www.networld2020.eu/wp-content/uploads/2015/01/Joint-Whitepaper-V12-clean-after-consultation.pdf

[33] NetWorld2020 European Technology Platform for Communications Networks and Services Expert Working Group. (2016, Jan. 7). White paper for research beyond 5G. [Online]. Available: http://www.networld2020.eu/wp-content/uploads/2016/03/B5G-Vision-for-Researchv-1.1b_final-and-approved.pdf

[34] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" *J. Lightwave Technol.*, vol. 34, no. 6, pp. 1533–1544, Mar. 2016.

[35] R. X. G. Ferreira, E. Xie, J. J. D. McKendry, S. Rajbhandari, H. Chun, G. Faulkner, S. Watson, A. E. Kelly, E. Gu, R. V. Penty, I. H. White, D. C. O'Brien, and M. D. Dawson, "High bandwidth GaN-based micro-LEDs for multi-gb/s visible light communications," *IEEE Photon. Technol. Lett.*, vol. 28, no. 19, pp. 2023–2026, Oct. 2016.