

This is a postprint version of the following published document:

Ndjiongue, A. R., Ngatched, T. M. N., Dobre, O. A. & Armada, A. G. (2020). VLC-Based Networking: Feasibility and Challenges. *IEEE Network*, 34(4), pp. 158–165.

DOI: [10.1109/mnet.001.1900428](https://doi.org/10.1109/mnet.001.1900428)

© 2020, IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

VLC-Based Networking: Feasibility and Challenges

Alain R. Ndjiongue[†], Telex M. N. Ngatched[‡], Octavia A. Dobre[‡] and Ana G. Armada[⊖]

Abstract—Visible-light communication (VLC) has emerged as a prominent technology to address the radio spectrum shortage. It is characterized by the unlicensed and unexploited high bandwidth, and provides the system with cost-effective advantages because of the dual-use of light bulbs for illumination and communication and the low complexity design. It is considered to be utilized in various telecommunication systems, including 5G, and represents the key technology for light-fidelity. To this end, VLC has to be integrated into the existing telecommunication networks. Therefore, its analysis as a network technology is momentous. In this article, we consider the feasibility of using VLC as a network technology and discuss the challenges related to the implementation of a VLC-based network, as well as the integration of VLC into existing conventional networks and its inclusion in standards.

INTRODUCTION

Visible light communication (VLC) is a data transmission technology which exploits the light beam as a communication medium. It is a variant of optical wireless communications, which uses light-emitting diodes (LEDs) as antennas and is characterized by short transmission range. In the indoor environment, VLC provides both data transmission and illumination [1]. Its main applications include light-fidelity (Li-Fi), indoor positioning, as well as vehicle-to-vehicle and infrastructure-to-vehicle communications. It has recently been demonstrated that using laser diodes (LDs), VLC can also be utilized in access networks [2]. The efficient utilization of VLC for such applications requires its analysis as a network technology, which is the focus of this article.

The interest in the VLC technology can be evidenced by the growing number of research works in the literature [1], [3]–[6] (and references therein), the prototypes and field trials proposed by researchers and industry, and by the standardization activities. Following these efforts, the effective deployment is seen as the next key step. Several challenges are to be overcome when practically deploying communication systems using VLC in both simplex and duplex configurations. Among these challenges, we underline the fact that the return path in a VLC-based communication system may use a different technology, such as radio frequency (RF), power line communication, fiber optics, and free space optical. If using VLC, the return path can be based on a different wavelength. Another important challenge is the illumination coverage. The VLC transmission range is limited, as it is imposed by the lighting coverage of the source, which is short by nature [7]. LEDs and LDs are the two main types of light sources considered in VLC. Compared to LEDs, whose lighting range is only a couple of hundred meters, LDs provide an illumination

coverage in the order of a couple of kilometers. On the other hand, since only positive and real signals can be successfully transmitted in VLC systems, the modulation schemes that can be employed should produce a non-complex and asymmetric signal.

The fact that light cannot go through opaque objects confers a security aspect to VLC. However, it compels the indoor VLC-based network to be confined in a room. Consequently, VLC can be used in optical wireless personal area network (OWPAN) and several OWPANs may be linked using VLC to form a wide OWPAN (W-OWPAN). In OWPANs with multiple access points (APs) and mobile user devices (UDs), handover is one of the most challenging problems [8].

While there are many proposals for VLC transmitter and receiver, the success of the technology depends on the ability to create networks with them and facilitate the deployment. This article discusses the use of VLC as a network technology and its integration into existing networks. It describes VLC-based networking and presents topologies and network structures. It also examines the main types of VLC-based W-OWPAN and introduces connectivity configurations. The article proposes an architecture for VLC-based networks, highlights challenges related to VLC-based network design and implementation, and underlines the recommendations of IEEE on VLC networking. Finally, the future of networking using VLC is discussed.

VLC-BASED NETWORKING

This section introduces VLC-related networks, highlights link configurations and types of networks, and provides an overview of the communication protocols for VLC-based networks.

VLC Connectivity Configurations

Two main topologies, defined by the shape of the light beam, govern the transmission in VLC-based networks [9]: point-to-point (P2P) and point-to-multipoint (P2MP) topologies. In the P2P topology, the light source, which has a narrow beam with a small divergence angle, is only exploited for communication and cannot be used for illumination. In the P2MP topology, also defined as AP-based VLC network, the beam has a diffuse or a quasi-diffuse shape. In this case, the light source serves as communication antenna and illumination device simultaneously. These topologies, together with the connectivity mode, critically characterize the design of a VLC-based network. In these topologies, six connectivity scenarios can be defined based on the link between the light source and the photodetector (PD), as depicted in Fig. 1. Scenarios (1), (2), and (3) represent line-of-sight cases, whereas Scenarios (4), (5), and (6) utilize non-line-of-sight links; the latter respectively correspond to the former when an obstacle constrains the message signal to reach the UD through reflected rays.

[†] Alain Richard Ndjiongue is with the Faculty of Engineering and the Built Environment, University of Johannesburg.

[‡] Telex M. N. Ngatched and Octavia A. Dobre are with the Faculty of Engineering and Applied Science, Memorial University.

[⊖] Ana G. Armada is with the Signal Theory and Communications Department, Universidad Carlos III de Madrid.

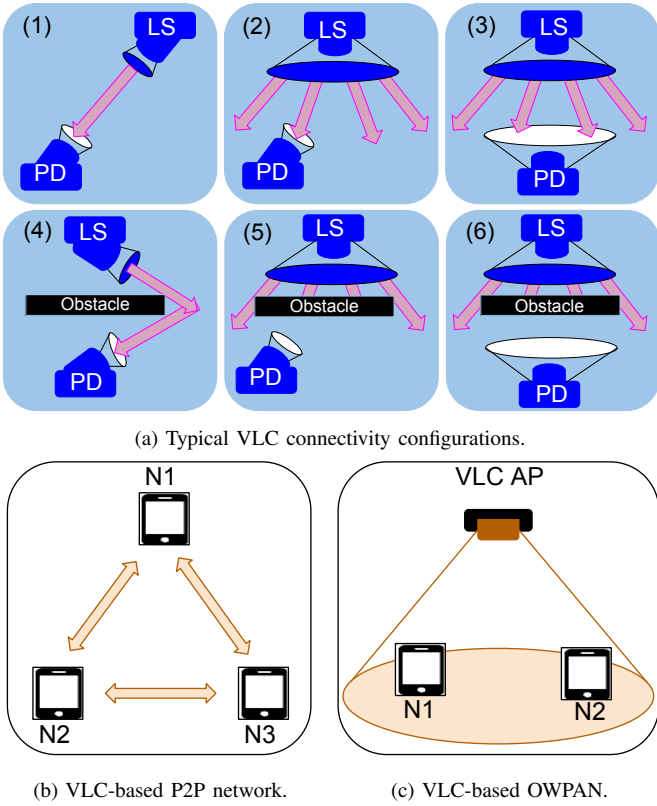


Fig. 1: Illustration of VLC-based PANs. LS: light source.

The light source and the UD may be connected based on the P2P configuration (Fig. 1b), where the VLC receiver is made up of a narrow field-of-view [Fig. 1a, Scenario (1)]. Using the P2MP configuration (Fig. 1c), the receiver may have a narrow field-of-view [Fig. 1a, Scenario (2)], or a wide field-of-view [Fig. 1a, Scenario (3)].

VLC-based networks utilizing APs, i.e., OWPAN, may have two variants: (i) the conventional distributed architecture, where each light source contains both the electrical front-end and the optical front-end, and thus, performs both baseband processing and power allocation. Each VLC AP serves as a unique optical transceiver. It receives the message to be re-transmitted from the backbone network and proceeds with the re-transmission; (ii) the centralized light access network architecture, in which all VLC APs computational resources are grouped into a unique centrally managed pool [10]. Here, the AP contains only an optical front-end, and thus, is only in charge of connecting the light source to both the communication and electrical signals. The centralized light access network architecture decreases the associated cost and complexity of each VLC light source for an efficient implementation, and also reduces interference from neighboring cells.

VLC-based Communication Protocol

VLC-based networks use a communication protocol which is adapted from the generic Open Systems Interconnection protocol model and utilizes the layered-architecture of the Transmission Control Protocol/Internet Protocol (TCP/IP) model. When compared to protocols developed for RF-based networks, the communication protocol for VLC-based networks

mainly differs on the two bottom layers. This difference is crucial in the design of VLC-based networks because the antenna used in the VLC technology (LED/LD) may also be exploited for illumination. Consequently, the design of a VLC-based network card, which includes an LED/LD or a PD, is different from that of the conventional network card. The physical (PHY) layer, on the transmitter side, decides on the bit representation across the networking medium and on the illumination level, while on the receiver side, it is in charge of detecting the message-signal. An example of a protocol for VLC-based networks, referred to as decoupled TCP, is proposed in [11]. While this protocol utilizes the layered-architecture of the TCP/IP model, it considers a unidirectional link between VLC APs and UDs in an aggregate VLC-based network.

Classification of VLC-based Networks

VLC-based networks are defined by five main characteristics: (i) the transmission distance, which determines if the system is relayed or non-relayed; (ii) the need of a return path, which makes the network duplex or simplex; (iii) the technology used in the return path, which defines whether the network is standalone or aggregate; (iv) the category of UDs and protocols, which specifies whether the network is homogeneous or heterogeneous; (v) the use of single or multiple channels to transmit data. These network types are presented in Fig. 2 and discussed in the following.

Relayed vs. Non-relayed VLC-based Networks: To create a network with VLC, the data to be transmitted may be generated locally or remotely, depending on the transmitter-receiver distance. Hence, networks with VLC can be classified as relayed or non-relayed networks. For the latter, the transmission distance is within the lighting range of the light source. Here, a relay is not needed because the receiver is situated at the correct distance under the transmitter's light beam.

On the contrary, if the transmission distance is outside the illumination coverage of the light source, or if the light is severely attenuated at the receiver, as illustrated in Fig. 2a, then the transmitted message is first sent to a relay, which then forwards it to the recipient [12]. In this case, the transmission may be based on IEEE 802.15.7 (VLC), IEEE 802.3 (Ethernet), IEEE 802.11 [wireless fidelity (Wi-Fi)], IEEE 1901 (power line communications), etc. An example of a relayed VLC-based network is the Li-Fi, in which the original message is transmitted to the VLC AP via RF, fiber optics or any other data communication technology.

Note that cooperative communication techniques which have been widely used in RF systems to improve reliability, can also be employed in relayed VLC-based networks [12]. Traditional cooperative techniques, such as amplify-and-forward and decode-and-forward can be adopted. More spectral-efficient relaying techniques, such as incremental decode-and-forward and incremental selective decode-and-forward, can also be used.

Simplex vs. Duplex VLC-based Networks: In numerous VLC applications such as infrastructure-to-vehicle communications, the return path is not required. The message is transmitted from one node to another and not vice-versa. This type of links, also known as simplex links, present the advantage of low-complexity and ease of implementation.

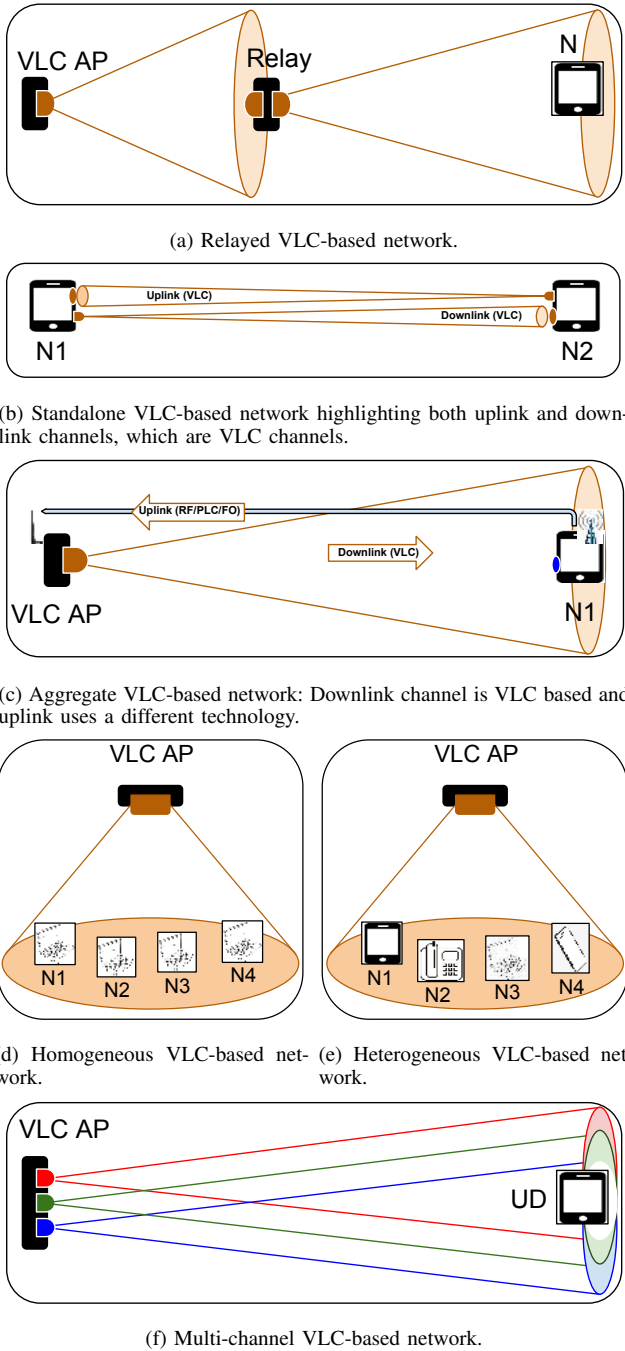


Fig. 2: Relayed, standalone, aggregate, homogeneous, heterogeneous, and multi-channel VLC-based networks.

However, if the application requires a return path, Li-Fi for example, then the link is said to be duplex. Duplex links use both downlink and uplink traffic and have higher design complexity. Technologies for return path (uplink traffic) can be any other data communication technology, such as those listed for relayed VLC-based networks. Simplex and duplex VLC links can be combined with relayed and non-relayed networks.

Standalone vs. Aggregate VLC-based Networks: Standalone and aggregate VLC-based networks are based on a duplex link, but differ on whether or not the same technology is used in both downlink and uplink connections.

In the former, both downlink and uplink use the VLC technology [2]. As shown in Fig. 2b, the duplex connection between two nodes using VLC will be more efficient if the two (downlink and uplink) light beams do not interfere, and correspond to two P2P links. If the light sources are also used for illumination, then numerous interference signals and significant path loss are expected. This would occur even if the links use different wavelengths.

For the latter, VLC is used for downlink and a different technology is employed in uplink. This configuration is illustrated in Fig. 2c, where the light source is employed to guide the downlink traffic, and serves as an illumination device as well. This configuration has been investigated in the literature in the deployment of Li-Fi [5] and the practical implementation of 5G [13], in both its enhanced mobile broadband and massive machine type communications slices. The former uses Wi-Fi, whereas the latter uses cellular to complement the VLC. A variance of aggregate VLC-based networks can be obtained by connecting the UD to the router using a duplex VLC in parallel with another technology, resulting in two independent connections between the router and the UD. As an example, VLC and RF can be combined such that the UD is connected to the router via both VLC AP and RF AP in both downlink and uplink [13]. This helps to manage the traffic on the RF channel and release its spectrum during congestion time.

Homogeneous vs. Heterogeneous VLC-based Networks: The concept of homogeneity/heterogeneity is related to the similarity between UDs and their connectivity protocols, and is generally associated with AP-based networks. In a homogeneous VLC-based network, several similar UDs are connected to the VLC AP using analogous connectivity protocols, whereas in a heterogeneous VLC-based network, different types of UDs with different connectivity protocols are linked to the VLC AP. These two types of VLC-based networks are illustrated in Figs. 2d and 2e. Note that the concept of VLC heterogeneous networks is to be contrasted from aggregate VLC-based networks, which are also seen and defined by some researchers as heterogeneous networks due to the use of different technologies.

Multi-channel VLC-based Networks: A multi-channel VLC-based network can be implemented using a class of light-sources that exploits multiple wavelengths to generate light [14]. In contrast to single channel VLC-based networks, the beam in multi-channel VLC-based networks is formed by several single light beams, as illustrated in Fig. 2f for a single user. Typically, such networks use the color-shift-keying scheme [14] or may exploit the multiple-input multiple-output technique [15] to transmit data. In both cases, considering a single user, the data rate is improved when compared with single channel systems. In the case where multiple users are connected to the AP, a multi-channel VLC-based network also helps to multiplex the users.

PROPOSED ARCHITECTURE FOR VLC-BASED NETWORKS

In Fig. 3a, we propose an architecture for VLC-based W-OWPAN. It highlights the duplex link required between UDs and APs (indoor), and between APs (outdoor). The system links two VLC-based OWPANs (OWPAN A and OWPAN B) in which nodes (A_1 and A_2 ; B_1 and B_2) are respectively connected to APs (VLC AP₁ and VLC AP₂) in an aggregate

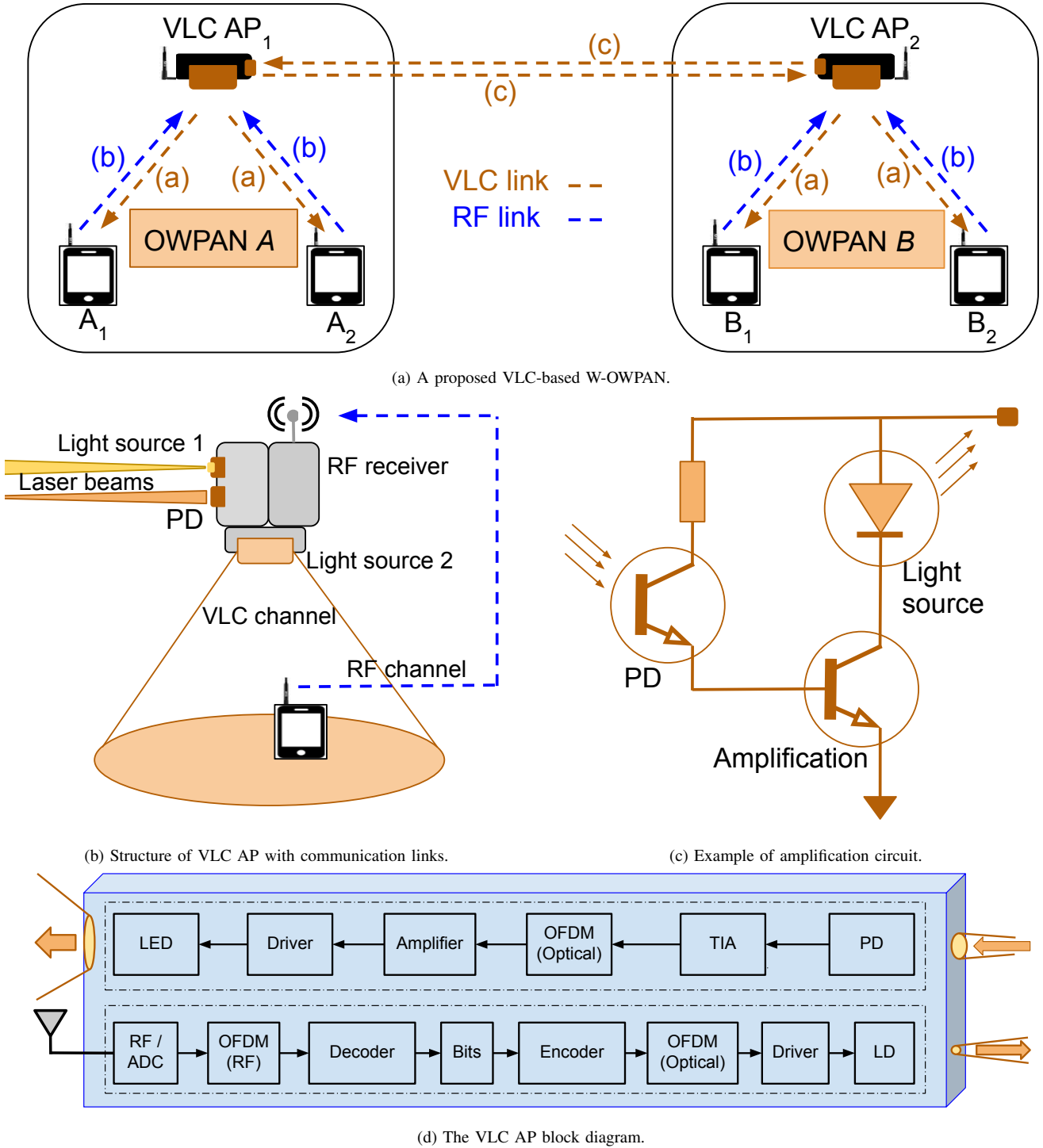


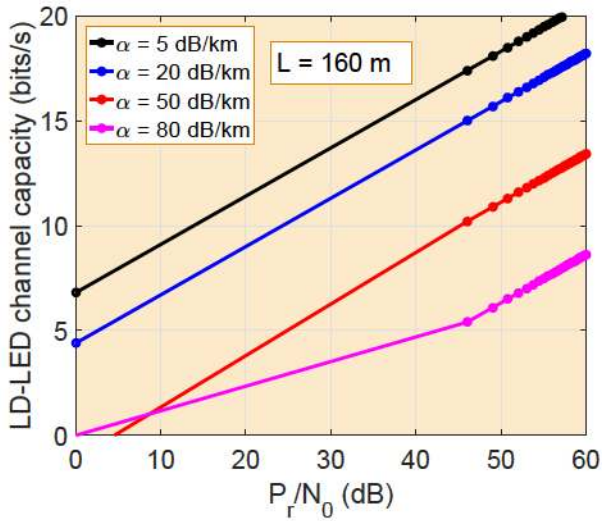
Fig. 3: Proposed VLC-based W-OWPAN, with the structure of the VLC AP, its block diagram, and the amplification circuit.

VLC-based network. The VLC AP₁-to-VLC AP₂ link is a laser beam connection, whereas the VLC AP-to-UD link has LED-based downlink traffic and is also used for illumination, and the uplink UD-to-AP is based on RF.

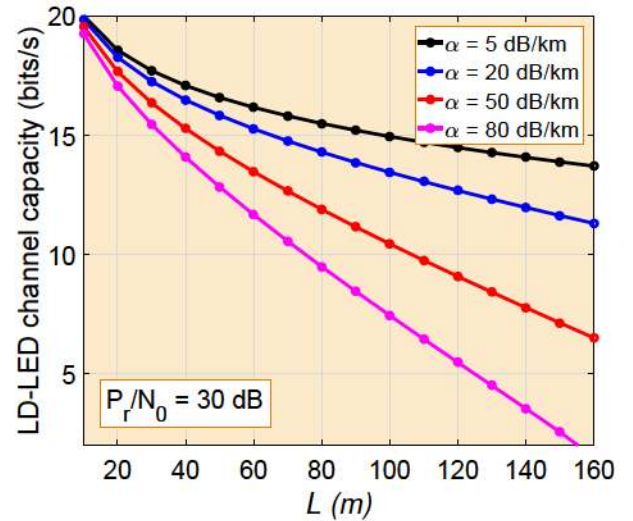
Network and VLC AP Structures

The VLC AP, whose structure is shown in Fig. 3b, performs four main operations: one VLC detection, one RF detection and two VLC transmissions. Thus, each AP consists of a

VLC receiver, an RF receiver, and two VLC transmitters. The VLC transmitters include two light sources. The first light source, which is used for both lighting and communication [the downlink (a) in Fig. 3a] is made up of LEDs, and utilizes the P2MP topology. It represents the message source for the optical connection between VLC AP and UDs. The second light source is an LD, which produces a light with a narrow beam due to its small divergence angle [link (c) in Fig. 3a]. This light source connects the two VLC APs (P2P) and is not



(a) Capacity of a simplex downlink of a W-OWPAN versus P_r/N_0 , for different values of the attenuation factor, α .



(b) Capacity of a simplex downlink of a W-OWPAN versus L , for different values of the attenuation factor, α .

Fig. 4: Channel capacity of VLC-based W-OWPAN.

Table I: Parameters used in the analysis.

Parameter	Symbol	Value	Unit
Attenuation coefficient	α	5, 20, 50, 80	dB/km
Distance between OWPANs	L	160	m
Laser detector effective area	A_c	100	mm ²
Small angle divergence	θ	8.38×10	rads
Room area	A_r	25	m ²
Photodetector area	A_a	26	mm ²
Average walls' reflectivity	ρ	0.7	N/A
Angle of incidence	ϕ	1.2217	rads
Half-intensity beam angle	$\phi_{1/2}$	0.5236	rads
Distance between LED and PD	d	2.5	m
Angle of irradiance	Φ	1.7453	rads
Frequency	f	10	MHz
Cutoff frequency at 3 dB	f_0	1.7111	MHz
Delay of the line-of-sight link	t_1	0.01	ns
Delay of non line-of-sight link	t_2	0.03	ns
Responsivity of the laser detector	λ_1	0.8	N/A
Responsivity of the PD	λ_1	0.8	N/A
Received power/noise power	P_r/N_0	30	dB
Amplification coefficient	g_0	100	N/A
Beam natural waist	ω_0	0.588	mm
Wavelength	λ	1550	nm

used for illumination. The PD included in each VLC AP is used to detect the light produced by the opposite counterpart. The UDs are equipped with a PD, which is in charge of detecting the optical signal from link (a) and converting it into an electric current, and an RF transmitter which connects UDs to the VLC AP through link (b). Here, the RF receiver included in the VLC AP detects the uplink signal.

For a complete connection between the two sub-networks, OWPAN *A* and OWPAN *B*, the overall connection is RF (b)-LD (c)-LED (a), in both directions. The first relaying scenario, which is RF (b)-LD (c) (uplink traffic), is based on decode-and-forward strategy, because the signals over both channels are symmetric (positive and negative) for RF and strictly positive for VLC. In this case, a direct signal conversion using the amplify-and-forward strategy, would result in an important loss of data. The second relaying scenario, which is LD (c)-LED (a) (downlink traffic), is built on the amplify-and-forward strategy, as it provides the system with cost-effective advantages. Here, the relay uses the circuit diagram shown in Fig. 3c. The related amplification gain (see Figs. 3b and 3c), helps to mitigate the attenuation experienced by the optical signal over link (c).

The VLC AP, whose block diagram is shown in Fig. 3d, is made up of two parallel equipment to achieve full signal re-transmission. Data to be sent from any UD of OWPAN *A* is firstly treated using the orthogonal frequency division multiplexing (OFDM) principle, for example. Afterwards, the obtained signal is transmitted using the RF channel (uplink). The resulting signal is collected from the RF channel by the RF antenna (in VLC AP₁) and digitized. The obtained digital signal is treated and the resulting bits are decoded. These bits are re-encoded, and the packets are converted into optical OFDM signals. Through an LD-driver, the latter is forwarded to an LD for re-transmission. At VLC AP₂, a PD equipped with a lens to concentrate the beam on the receiving area and a transconductance amplifier converts the laser light into an electrical signal. The latter is then amplified and forwarded to

a conventional high-power LED via an analog LED-driver, for simultaneous lighting and communication within OWPAN *B*. The LED broadcasts a light containing optical OFDM signals, which are collected by the PDs of the UDs. Finally, this received signal is demodulated, decoded and the resulting bits are sent to the recipient.

W-OWPAN Channel Capacity

The link evaluation of the proposed W-OWPAN is fundamentally related to the overall channel behavior, which is a combination of the channels of links (a), (b) and (c), as the overall link is a cascaded combination of the three links. Thus, the performance of the system is dictated by the worst channel. Since link (b), which is RF-based, has been extensively studied in the literature, the channels analyzed are only those of links (a) and (c). Link (a) is the indoor optical part of the system, and its channel is a stochastic beam based on the diffuse topology. Its gain mainly depends on the geometrical parameters of the room and those of the beam. Link (c), the outdoor section of the system, is a narrow beam due to the small divergence angle and is based on the P2P topology. Its channel depends on: (i) the attenuation of the laser power through the atmosphere, which is deterministic and described by the exponential Beers-Lambert law; (ii) the atmospheric turbulence; and (iii) the pointing error also modeled as Beckmann misalignment. Note that atmospheric turbulence and pointing errors are random and their distributions vary. Apart from these, the signal-to-noise ratio takes into account the laser detector effective area, the attenuation coefficient, α , the input power, the distance between OWPANs, L , the beam angle, the transmission bandwidth, and the noise power. The maximum rate related to link (a) can be calculated based on its own signal-to-noise ratio, which fundamentally depends on the PD's effective area, the receiver field-of-view, the light incident angle, the Lambertian order, the transmit power, the transmission bandwidth, the amplification gain, the distance between VLC APs and UDs, and the noises over the channel. The link between OWPAN-A and OWPAN-B is established without significant turbulence effects and pointing error.

The analytical results shown in Fig. 4 are obtained using the parameters displayed in Table I. These values are commonly used in the literature in practical implementation of both free space optical and indoor VLC. Taking into account the ratio of received signal power to the received noise power, P_r/N_0 , it is clear that the channel capacity increases as P_r/N_0 increases regardless of the value of α (Fig. 4a). This capacity decreases as the outdoor distance, L , increases (Fig. 4b). For low values of α , this decrement is slow, while it exhibits a fast drop for higher values of α . Although some outdoor VLC impairment factors, such as turbulence, scintillation and pointing error, are not taken into account here, these results give a good indication on the harshness of the overall channel, which is mostly affected by the outdoor part of the network.

STANDARDIZATION EFFORTS

The deployment of VLC technology and efficient implementation of OWPANs require rules and regulations, which are still in the development phase. A few drafts have recently been prepared, each having specific focuses. Examples are those proposed by the Visible Light Communication Consortium

and IEEE. Among them, IEEE provides the major contribution because its proposition is broader and looks at most aspects of the VLC technology. In the sequel, we focus on the efforts of IEEE, which is led by the IEEE 802.15.7 Task Group. It proposes a layer-based architecture which follows the IEEE 802.15.4 layout based on TCP/IP. Their efforts focus on media access control (MAC) and PHY layers because the upper layers are similar to the other networking standards, such as IEEE 802.11. An overview of the IEEE 802.15.7 MAC and PHY layers is discussed next.

MAC Layer Frame

The IEEE 802.15.7 standard proposes a MAC frame which consists of three main parts, namely the MAC header, payload, and footer. It depends on the targeted PHY layer (PHY I to VI), and the network topology (P2P, P2MP, OWPAN, etc.). The standard supports three main MAC network types, which are P2P, star, and broadcast [7]. P2P uses the configuration in Scenario (1) of Fig. 1a, while star and broadcast use Scenarios (2) and (3), and are based on the P2MP topology. In each of these network categories, the nodes have a unique 64-bit address that is used for communication within the network, which in general is an OWPAN. The P2P topology may be a duplex transmission that uses the configuration illustrated in Fig. 2b based on an extra-narrow beam, while the other types use the diffuse link shown in Fig. 2c.

To achieve transmission in OWPAN using the P2MP topology, the IEEE 802.15.7 MAC layer utilizes a super-frame format. It is used to group and align channels in order to determine channel locations in the received stream, and is defined by the coordinator (VLC AP). The latter is the owner of the super-frame, and consequently, allocates guaranteed time slots and forms the contention free period.

Physical Layer

The IEEE 802.15.7 PHY layer has evolved within the original and actual version of the standard. Compared to the original version of IEEE 802.15.7, which has three categories of physical layers (PHY I, PHY II, and PHY III), the newer version, IEEE 802.15.7/D3a, divides the VLC PHY layer into six categories, i.e., PHY I to VI. Each of them is characterized by particular specifications related to the modulation scheme, forward error correction techniques, data rate, to mention only a few parameters. PHY I is dedicated to data rates between 11.67 kbps and 266.6 kbps. It is divided into two sections: 11.67 kbps to 100 kbps and 35.56 kbps to 266.6 kbps depending on the optical clock rate used. Hence, the choice of optical clock rate determines if the header is transmitted with 11.67 kbps or 35.56 kbps. 11.67 kbps is used for an optical clock rate of 200 kHz. A Manchester code is employed as line code, and Reed Solomon and convolutional codes are used for error correction. They are combined with the on-off keying, selected as the modulation scheme. 35.56 kbps is selected to transmit the header for an optical clock rate of 400 kHz. Here, variable pulse position is the modulation of choice with 4B6B line code and Reed Solomon as an outer code. A full description of the six PHY layers proposed in IEEE 802.15.7/D3a is provided in Table II.

Table II: IEEE 802.15.7/D3a: Summary of the operating modes for PHY I to VI [7].

Mod. scheme	Line Code	Clock Rate	Forward Error Correction		Data Rate	Std. Version
			Outer Code	Inner Code		
—PHY I—						
OOK	Manchester	200 kHz	RS	CC	11.67 kbps to 100 kbps	, ☒/D2a/D3/D3a
VPPM	4B6B	400 kHz	RS	--	35.56 kbps to 266.6 kbps	, ☒/D2a/D3/D3a
—PHY II—						
VPPM	4B6B	3.75 MHz/7.5 MHz		RS	1.25 Mbps to 5 Mbps	, ☒/D2a/D3/D3a
OOK	8B10B	15 MHz to 120 MHz		RS	6 Mbps to 96 Mbps	, ☒/D2a/D3/D3a
—PHY III—						
CSK	--	12 MHz/24 MHz		RS	1.25 Mbps to 5 Mbps	, ☒/D2a/D3/D3a
OOK	8B10B	15 MHz to 120 MHz		RS	12 Mbps to 96 Mbps	☒/D3/D3a
—PHY IV—						
UFSOOK	--	Multiframe rate		MIMO path dependent	10 bps	☒/D3/D3a
Twinkle	--	4x bit rate		RS	4 kbps	☒/D3/D3a
VPPM						
S2-PSK	Half-rate code	10 Hz		Temporal error correction	5 kbps	☒/D3/D3a
HS-PSK	Half-rate code	10 kHz		RS	22 kbps	☒/D3/D3a
Offset VPPM	--	25 Hz		RS	18 bps	☒/D3/D3a
—PHY V—						
RS-FSK	--	30 Hz		XOR FEC	120 bps	☒/D3/D3a
C-OOK	Manchester/4B6B	2.2 kHz/4.4 kHz		Hamming code	Optional/RS	400 bps
CM-FSK	--	10 Hz	--	Optional	60 bps	☒/D3/D3a
MPM	--	12.5 kHz		Temporal error correction	7.51 bps	☒/D3/D3a
—PHY VI—						
A-QL	--	10 Hz	RS	CC	5.54 kbps	☒/D3/D3a
HA-QL	Half-rate code	10 Hz	RS	CC	140 bps	☒/D3/D3a
VTASC	--	30 Hz		RS	512 kbps	☒/D3/D3a
SS2DC	--	30 Hz		RS	368 kbps	☒/D3/D3a
IDE-MPSK	--	30 Hz		RS	32 kbps	☒/D3/D3a
BLEND						
IDE-WM	--	30 Hz		RS	256 kbps	☒/D3/D3a

= IEEE Std 802.15.7-2011; ☒ = IEEE P802.15.7; OOK = on-off keying; VPPM = variable pulse position modulation; CC = convolutional encoder; UFSOOK = undersampled frequency shift OOK; PSK = phase-shift-keying; S2-PSK = spatial 2-PSK; C-OOK = camera OOK; CM-FSK = camera M-ary frequency-shift-keying; VTASC = variable transparent amplitude-shape-color; SS2DC = sequential scalable 2D code; A-QL = asynchronous quick link; HS-PSK = hybrid spatial phase-shift-keying; HA-QL = hidden asynchronous quick link.
 -- no line code or no forward error correction code is proposed.

CHALLENGES RELATED TO VLC-BASED NETWORKING

In light of the above discussion, it is clear that one of the most important challenges of VLC-based networks practical deployment resides in the integration of the technology used in the uplink. It is also worth underlining the dual-use of the light source, as a telecommunication antenna and illumination device, which requires efficient algorithms to meet both lighting and communication requirements.

In case of mobile UDs, the handover mechanism represents another challenge if several VLC APs are used. It is important to note that, since the propagation of the transmitted signal in VLC technology is different compared to RF, the handover techniques exploited for RF systems cannot be directly applied to VLC-based networks [8].

In aggregate VLC-based networks involving technologies such as RF, fiber optic, power line communications, and free space optical, the message frame compatibility is a critical issue that must be addressed. VLC systems must be compatible with the existing schemes.

Relayed networks based on the amplify-and-forward strategy are cost-effective compared to other schemes such as decode-and-forward, because the signal is just amplified

and forwarded without any processing. For this reason, the amplify-and-forward scenario should be the primary choice. The modulation schemes exploited in the first link should be similar or compatible with that of the second link, for an efficient implementation of the bridge between the channels. In this case, finding the correct combination between modulation schemes to be used in different technologies represents another challenge.

Note that these challenges, related to single channel systems, increase with the number of channels in multi-channel networks.

More importantly, high capacity and throughput represent two challenges in VLC-based networking due to the bandwidth limitations of LEDs and LDs. However, solving this specific drawback is the responsibility of not only the networking designers, but also that of the LEDs/LDs manufacturers. Any solution to this design aspect should maintain compatibility between data transmission and illumination functions.

RESEARCH OPPORTUNITIES FOR VLC-BASED NETWORKS

The proof of the VLC concept has now been well established [5], [13]. A few companies such as Pure Li-Fi have

started to manufacture VLC APs and optical components for mobile devices such as laptops and mobile phones. In a near future, VLC equipment will be extended to other VLC systems including standalone and aggregate, relayed and non-relayed, simplex and duplex, homogeneous and heterogeneous, and multi-channel VLC-based systems. Several applications are targeted including indoor positioning, internet broadcasting, massive data transfer between two VLC nodes, underwater communications, intelligent transportation systems, and health-care applications.

There are considerable opportunities for the design and implementation of VLC-based networks. Research is needed to explore VLC-based networking in different VLC-based network types discussed in this article. These new efforts will be associated not only with research in telecommunication, but also with improvement happening in the lighting industry, which will lead to undeniable enhancement of both lighting and communication performances.

The heterogeneous network will require more studies and analysis before integration, as the technologies and protocols in place need to be compatible. Synchronization between frequencies in some cases needs to be handled carefully.

More experimental results and practical deployments are required to corroborate results obtained by theoretical analysis. This applies to all enumerated VLC-based network types and represents a great deal of research opportunity for standalone, aggregate, homogeneous, heterogeneous, duplex, and relayed networks using VLC technology.

Most research results in VLC technology are related to Li-Fi, intelligent transportation systems, indoor positioning and some cooperative systems. VLC can be associated with power line communications, Wi-Fi and free space optical to form cost-effective communication systems. Emerging VLC applications such as massive data transfer between two VLC nodes and those in the underwater environment need to be investigated. VLC can mimic technologies such as Bluetooth to transfer files between two nodes. This has not been investigated yet. Potential underwater applications of VLC that deserve to be explored include surveillance, climate change, and oceanic fauna monitoring. Channel modeling, network protocols, design and practical implementation issues of these applications represent potential research directions.

CONCLUSION

This article has elaborated on VLC-based networking through possible connectivity configurations, along with applicable topologies and technologies for the return path in duplex transmissions. The protocol models are highlighted and reveal that VLC-based networks use the layered protocol with differences at both MAC and PHY layers compared to conventional networks. Specifications for these two layers are provided for the IEEE 802.15.7/D3a standard in terms of modulation and forward error correction schemes. An architecture of a VLC-based network for sharing data between two OWPANs, linked using a duplex outdoor VLC backbone subsystem, is also proposed and discussed, and the related link capacity is presented. Finally, research opportunities toward the utilization of VLC technology in OWPAN and its integration into existing conventional networks is outlined.

REFERENCES

- [1] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surv. Tutor.*, vol. 17, no. 4, pp. 2047–2077, Fourth quarter 2015.
- [2] A. R. Ndjiongue, T. M. N. Ngatched, and H. C. Ferreira, "Access telecommunication systems using VLC technology: Cascaded LD-LED channel analysis," in *Proc. IEEE GLOBECOM Conf., Abu Dhabi, UAE*, Dec. 2018, pp. 1–6.
- [3] T. Kishi, H. Tanaka, Y. Umeda, and O. Takyu, "A high-speed LED driver that sweeps out the remaining carriers for visible light communications," *IEEE/OSA J. Lightw. Technol.*, vol. 32, no. 2, pp. 239–249, Jan. 2014.
- [4] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" *IEEE/OAS J. Lightw. Technol.*, vol. 34, no. 6, pp. 1533–1544, Mar. 2016.
- [5] M. Ayyash, H. Elgala, A. Khreishah, V. Jungnickel, T. Little, S. Shao, M. Rahaim, D. Schulz, J. Hilt, and R. Freund, "Coexistence of WiFi and LiFi toward 5G: concepts, opportunities, and challenges," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 64–71, Feb. 2016.
- [6] Y. Wang, N. Chi, Y. Wang, L. Tao, and J. Shi, "Network architecture of a high-speed visible light communication local area network," *IEEE Photon. Technol. Lett.*, vol. 27, no. 2, pp. 197–200, Jan. 2015.
- [7] **IEEE Std 802.15.7-2018**, "IEEE standard for Local and metropolitan area networks—Part 15.7: Short-range optical wireless communications," *IEEE Standards Association*, pp. 1–407, 23 Apr. 2019.
- [8] Q. Dang and M. Yoo, "Handover procedure and algorithm in vehicle to infrastructure visible light communication," *IEEE Access*, vol. 5, pp. 26466–26475, Nov. 2017.
- [9] A. Ndjiongue and H. C. Ferreira, "An overview of outdoor visible light communications," *Wiley Trans. Emerg. Telecommun. Technol.*, vol. 29, no. 7, pp. 1–15, Jun. 2018.
- [10] R. C. Kizilirmak, O. Narmanlioglu, and M. Uysal, "Centralized light access network (C-LiAN): a novel paradigm for next generation indoor VLC networks," *IEEE Access*, vol. 5, pp. 19703–19710, Sep. 2017.
- [11] Y. Liu, X. Qin, T. Zhang, T. Zhu, X. Chen, and G. Wei, "Decoupled TCP extension for VLC hybrid network," *IEEE/OAS J. Opt. Commun. Netw.*, vol. 10, no. 5, pp. 563–572, May 2018.
- [12] Z. Na, Y. Wang, M. Xiong, X. Liu, and J. Xia, "Modeling and throughput analysis of an ADO-OFDM based relay-assisted VLC system for 5G networks," *IEEE Access*, vol. 6, pp. 17586–17594, Mar. 2018.
- [13] A. F. Hussein, H. Elgala, and T. D. C. Little, "Evolution of multi-tier transmission towards 5G Li-Fi networks," in *Proc. IEEE GLOBECOM Conf., Abu Dhabi, UAE*, Dec. 2018, pp. 1–7.
- [14] P. Ge, X. Liang, J. Wang, C. Zhao, X. Gao, and Z. Ding, "Optical filter designs for multi-color visible light communication," *IEEE Trans. Commun.*
- [15] F. I. K. Mousa, N. Al Maadeed, K. Busawon, A. Bouridane, and R. Binns, "Secure MIMO visible light communication system based on user's location and encryption," *IEEE/OAS J. Lightw. Technol.*, vol. 35, no. 24, pp. 5324–5334, Dec. 2017.

BIOGRAPHIES

Alain. R. Ndjiongue (S'14–M'18) received the M.Eng. and D. Ing degrees in Electrical and Electronic Engineering from the University of Johannesburg, Johannesburg, South Africa, in 2013 and 2017 respectively. He is currently senior lecturer at the same university. His research interests are in Digital Communications including power line communications, visible-light communications, optical communications and hybrid systems. Dr. Ndjiongue is actually an active reviewer for several high impact factor IEEE COMSOC conferences. He was a 2017 and 2018 exemplary reviewer for IEEE CL and OSA, and is a 2019 top 1% peer reviewer in the Essential Science Indicators (ESI) research.

Telex. M. N. Ngatched (M'05–SM'17) is an Associate Professor and Coordinator of the Engineering One program at the Grenfell Campus at Memorial University, Canada. His research interest include 5G enabling technologies, visible light and power-line communications, optical communications for OTN, and underwater communications. Dr. Ngatched is an Associate Editor of the IEEE Open Journal of the Communications Society and the Managing Editor of IEEE Communications Letters. He was the publication chair of IEEE CWIT 2015, an Associate Editor with the IEEE Communications Letters from 2015 to 2019, and Technical Program Committee (TPC) member and session chair for many prominent IEEE conferences in his area of expertise.

Octavia A. Dobre (M'05–SM'07) is a Professor and Research Chair at Memorial University, Canada. She was a Visiting Professor at Massachusetts Institute of Technology, as well as a Royal Society and a Fulbright Scholar. Her research interests include technologies for 5G and beyond, as well as optical and underwater communications. She published over 250 referred papers in these areas. Dr. Dobre serves as the Editor-in-Chief (EiC) of the IEEE Open Journal of the Communications Society. She was the EiC of the IEEE Communications Letters, a senior editor and an editor with prestigious journals, as well as General Chair and Technical Co-Chair of flagship conferences in her area of expertise. She is a Distinguished Lecturer of the IEEE Communications Society and a fellow of the Engineering Institute of Canada.

Ana Garcia Armada (S'96–A'98–M'00–SM'08) is a Professor at University Carlos III of Madrid, Spain. She has published around 150 referred papers and she holds four patents. She serves on the editorial board of IEEE Communications Letters, IEEE Trans. on Communications and IEEE Open Journal of the Communications Society. She has served on the TPC of more than 50 conferences and she has been part of many organizing committees. She has received several awards from University Carlos III of Madrid, including an excellent young researcher award and an award to best practices in teaching. She was awarded the third place Bell Labs Prize 2014 for shaping the future of information and communications technology. Her research mainly focuses on signal processing applied to wireless communications.