



Fibre optic-VLC versus laser-VLC: a review study

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Abstract

The exponential increase in the demand for a fast and reliable wireless mobile network motivates the need for researchers to engage more actively in visible light communication (VLC) technology. This increase happens in parallel with the augmentation of the population to be accommodated. As a result, the radio frequency spectrum is overcrowded. VLCs, which are part of optical wireless communications, are unregulated ultra-wideband spectrums that offer an alternative to solve RF bandwidth exhaustion. The OWC has demonstrated, among others, a throughput of 100 Gbps and is capable of offloading large data traffic from RF networks. One of the VLC main backdrops is the distance for which light signals can be transmitted, which is generally short in nature. However, this is overcome by its combination with other technologies, such as fibre optics (FO) and laser technologies, to mention only a few, which form a cascaded system with VLC. The data offloaded is fed to the cascaded system of FO-VLC and laser-VLC. In this paper, we provide a comparative review of cascaded FO-VLC and laser-VLC systems. We survey the technology that can provide optimized communication and high bandwidth. The choice of cascaded system to be used or considered is dependent on the area of application. A comparison is conducted from the simulated results of both cascaded systems considering parameters such as the gain and throughput. The FO-VLC cascaded system shows that system gain always decreases as distance increases for a range of reflection coefficient, ρ , and slightly decreases with attenuation coefficient, α . The gain of the laser-VLC cascaded system decreases with an increase in transmission distance for a given range of floor and ceiling reflection coefficient and decreases slightly with attenuation intensity, γ . From our investigation, it is clear that FO-VLC and laser-VLC are outstanding optical cascaded systems, which can be exploited in applications with a harsh environment. This research also highlights standardization efforts, advanced modulation schemes and coding techniques so far for VLC, FO and laser system and their promising applications.

Keywords Visible light communication · Fibre optics · Laser · FO-VLC cascaded channel · Laser-VLC cascaded channel · Channel model.

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1 Introduction

Radio frequency (RF) is a technology which uses electromagnetic signals to transfer data. RF is made up of waves of electromagnetic radiation with frequencies ranging from 3 kHz to 300 GHz. It usually occurs at the speed of light and propagates through air and many other materials; it has been widely used in many industries such as televisions, broadcasting systems, radars, computers and most mobile platform networks, just to mention a few. Communication using RF is affected by the limited channel capacity and transmission rate. To achieve a high data rate beyond 10 Gbps, it is hard using the band-limited RF spectrum. This is because of the exponential increase in the demand for fast and reliable mobile network that happens in parallel with the augmentation of the population to be accommodated.

The request for data rate has increased exponentially with the augmentation of the number of users. To contain this deficiency of RF spectrum extinction [1], there are series of techniques adopted which include multiple-input and multiple-output (MIMO), cell splitting with the handover and advanced modulation technique [2]. From the statistics provided by Corps Information Systems Control Officer (CISCO) mobile, the rate at which data traffic will be affected is estimated to 27 times increase within this half decade (2016 to 2021) [3]. However, in the 1990 s, optical wireless communication (OWC) technologies were not yet massively exploited. They came into play later when transmitting and receiving devices were readily available at very low-cost [4]. Then, it was important to adopt ultra-fast OWC such as visible light communication (VLC) [5–7].

For the past three decades, research has been done on OWC systems, which are capable of supporting data traffic at a higher rate when compared to its counterpart RF systems [5, 8].

VLC is an OWC, which is intensively investigated nowadays. As an antenna, it uses light emitting diodes (LEDs) [9] and laser diodes (LDs) [10], which are also main sources of light. Comparatively, LDs illuminate with higher lighting range than LEDs.

First, a well-implemented VLC system is capable of delivering a sufficient data rate that can support audio and video multimedia services. However, VLC technology is utilized in networks that requires a transmission of small distance between the LEDs/LDs, transmitter and photo-diode (PD), receiver in indoor environments. The VLC applications in such environment are based on standardized local network known as optical wireless personal area network (OWPAN) [11, 12]. Second, the frequency range of a laser light goes from far infra-red to ultra-violet on the electromagnetic spectrum. When comparing LEDs and LDs with regard to their priorities in OWC, LDs are more enhanced and may be used for a medium range data transmission [13]. Their illumination coverage is in kilometres, which by far exceeds that of the LEDs, which ranges within hundreds of metres. Laser light communication provides a medium range access system with the help of LDs when combined with VLC. Some recent work done on a hybrid communication system of VLC over the past years which are presented by authors of the following publications [14–18].

In telecommunications, Gallium Arsenide Phosphide (GaAsP) laser is mostly used. Recently, research has shown that LD can light up to a range of more than 2000 m at 180 lumen, while their LEDs counterpart can barely reach 200 m at 100 lumens [19]. For this reason, LDs are preferably exploited in front light bulbs of vehicles. For the same reason, LDs are utilized in access network using VLC technology [20]. Third, fibre optics (FO) is exploited in numerous applications. Recently, there has been an exponential

increase in the need for information traffic due to data utilization in technologies such as internet of things (IoT), multimedia services, voice over internet, data, and video communication. It is important to make available a huge data bandwidth medium which will be capable of handling this huge amount of information. FO, which is capable of simultaneously transmitting a large amount of data, is a saviour for such bandwidth predicament and deficiency. Communication with FO occurs at optical frequencies using a light source which is modulated and transmitted in a dielectric wave-guide at a very high speed. As in the case of VLC, both LEDs and LDs are used in fibre optics and the communication can extend to thousands of kilometres as in the case of long-haul transmission to access networks and equally directed to the users (fibre to the home).

It will be interesting to assess what have been done in this exciting field when fibre and laser technologies are combined with VLC for efficient data transmission. In most applications, VLC-based OWPAN may be fed by a light beam or FO systems using amplify-and-forward (AF), decode-and-forward (DF), and selective DF (SDF), to mention only a few [11]. Due to the short range transmission of light, some cooperative communication techniques, which have been widely used in RF systems, are also applicable in VLC. Most common relays scenarios are DF and AF. While DF relay decodes the information, re-modulates and retransmits it to the receiver, AF amplifies and retransmits the received signal with no processing. In RF systems, the signal over the channel is symmetrical (positive and negative), while in optical the signal is strictly positive. As such, traditional relays such AF are accepted in VLC as it improves reliability. Also, modern spectral relay techniques could be adopted, usually in coded systems such as incremental DF and incremental selective DF [11]. Decisively, considering cost effectiveness and reliability, we confidently consider using AF over other relays scenarios in our uncoded cascaded VLC systems due to the fact that it has no signal processing between sub-channels.

The remainder of the paper is arranged as follows: Section II presents the literature review with diagrammatic and explanatory system models, modulation schemes and coding techniques exploited in these systems. Section III presents the cascaded system comprising of FO-VLC and laser-VLC. Section IV is based on comparison of some simulated results. Section V depicts the standardization efforts so far in VLC, fibre and laser and VI gives critics and concluding remarks on the different cascaded systems. This study provides a comparative review of FO-VLC and laser-VLC. We analyse parameters like the gain, power, bit error rate (BER) and cost-effectiveness, just to mention only a few of both systems.

2 Quick review

2.1 Background knowledge

The FO system is becoming very crucial and increasingly important because it is capable of offloading a large data rate to the immediate network. A couple of combination has been proposed such as FO-VLC [21], power line communication-VLC [22–24], laser-VLC [20], free-space optics (FSO)-VLC [25, 26], and RF-VLC [27–29].

The VLC system is an emerging and promising technology to solve the RF spectrum shortage. Based upon LEDs and LDs, VLC can be a prominent and available solution to accommodate the upcoming high data traffic of wireless and wired networks. VLC is an emerging communication technology which involves a light-source that is being modulated at high frequency to transmit data. As shown on the electromagnetic spectrum, it is depicted that visible light wavelength ranges from 350 to 800 nm, which corresponds to frequencies between 4.3×10^{14} Hz and 7.5×10^{14} Hz. In [30], Qi Tang et al. proposed a similar contribution which demonstrated in a hybrid fibre-visible laser light communication (fibre-VLLC) system. They used an adaptive modulation scheme and discrete Fourier transform-spread was used to reduce the peak-to-average power ratio and the impact of imbalanced SNR distribution VLC with its great features such as greater bandwidth, limited health threats, limited power consumption, with a non-licensed bandwidth. It has attracted a lot of research that has led to the realization of numerous practical applications of VLC, including those listed in 2.1.1. Note that FO and laser technologies have also attracted a lots of researchers. Some of their applications are given in 2.1.2 and 2.1.3, respectively.

In the following sections, we provide a quick view of VLC, FO and laser applications.

2.1.1 Visible light communication

A few concepts, technologies and applications proposed in VLC, with the most prominent listed below:

- Light fidelity H. Haas in 2011 first coin the word light fidelity (Li-Fi). This technology is a high data traffic network with bi-directional functionality and a well-connected VLC systems. Li-Fi is similar to wireless fidelity, that utilizes RF for data communication. Li-Fi is a leading technology in highly sensitive electromagnetic radiation areas such as aircraft and operation theatre. A Li-Fi also lends support in IoTs.
- Vehicle-to-vehicle communications VLC may be applicable in communication between vehicles because of

the ability to use already existing vehicle light and traffic infrastructure. Most important application indicated by vehicle safety communication project such as cooperate forward collision warning prior to accidents, pre-crash sensing emergency which triggers an electronic brake, lane changing warning, left and right turn assistant, and curve speed warning [31]. With the high speed of VLC, this low latency communication is applicable.

- Aqua communication VLC is suitable for such communication as RF is not able to travel perfectly under water. Therefore, VLC may be an ideal technology to be used in aqua communication networks [32].
- Hospitals Most hospitals are sensitive to electromagnetic waves and measures should be taken to move from RF with electromagnetic radiation interference to VLC as it does not interfere with radio waves and the hospital equipment [33].
- Billboard Information displayed on billboards usually comprises of an array of LEDs which are modulated to display or convey a message in train and park stations, airports, high ways and other locations where such information is vital.
- Visible light identification systems Visible light is exploited in identification system such as building and subways. For instance, by simply identify the room numbers in a building.
- A sound communication system LEDs is used for transmission of music signals. As such, sound-activated lights are design to change its LEDs' colour and orientation based on sounds picked up by an internal microphone. The result is a light that reacts to the sounds around it.
- Indoor positioning system Recently, there has been an impediment in positioning and tracking as global positioning system suffer effects of attenuation. Indoor positioning VLC has become a promising and attractive technique for indoor positioning. Indoor positioning VLC uses location information with respect to a set of positions of reference of LED for a given space to give accurate information of that location.

2.1.2 Fibre Optics

Most prominent applications of FO are listed as follows

- Medical In medical applications, FO is used as light guides, imaging tools. Also, FO is very important in carrying out some surgical operations.
- Data Storage FO is exploited as hydrophones for seismic waves and sound navigation and ranging; it light nature makes it very important in wiring aircraft, submarines and other vehicles.

- Telecommunications In general, fibre laid provides a communication medium for transmitting and receiving information.
- Industrial/Commercial In industrial and commercial fields, FO is used for imaging in areas where electromagnetic interference poses a challenge, FO is also used for sensory devices to make temperature, pressure and other measurements.
- Broadcast/community access television Companies use FO for broadcasting and also for wiring community access television, high definition television, internet services, video services and other applications.

2.1.3 Laser technology

We list below some applications of laser technology.

- Laser is use in computer devices like laser mouse, laser presentation, and other accessories;
- Lasers are also used by astronauts and other communication networks;
- Lasers serve a great tool in medical field, such as surgery and health;
- Most sophisticated weapons are made using laser such as war machines, guns and tanks;
- Lasers are used in cutting heavy matters in metallurgy companies and other related industries;
- Most industries use laser in devising modern robotics, especially in image processing.

3 Modulation schemes and coding techniques in WOC

We present an overview of the modulation and coding techniques that will be used in the next generation of high-speed wireless optical communications to deliver multi-terabit bandwidth. We provide modulation and coding techniques for VLC, FO, and laser systems. When such an approach is correctly implemented, we will have a maximum throughput at the cascaded system's access point.

3.1 Modulation schemes

Modulation techniques can be classified into single-carrier, and multiple-carrier. Schemes exploited in VLC technology include orthogonal frequency division multiplexing (OFDM), colour shift keying (CSK), on-off keying (OOK), variable on-off keying (VOOK), pulse width modulation (PWM), pulse position modulation (PPM), variable pulse position modulation (VPPM), MIMO and M -ary pulse position modulation. In [34], two types of modulation schemes were chosen for comparison. These schemes

were OOK and frequency shift keying (FSK), and it was found that OOK was cost-effective with a considerable BER. Rana Shaaban et al. proposed a CSK-code division multiple access (CDMA) VLC system where CDMA data1 and data2 added up to form the CSK signals and sent by an array of red-green-blue RGB-LEDs, to two users, with two distinct mobile-phone cameras [35]. Each user is capable of decoding its own data with specific CDMA spreading code. The simulation results in [35] show that the CSK-CDMA VLC network is capable of providing many users with simultaneous communication using many orthogonal spreading codes when compared with its counterpart OOK, while maintaining interference avoidance. Yuxian Gong et al. in their research [36] proposed a space shift keying (SSK) modulation scheme for VLC combined with MIMO. Their research was based on several transmitters exploited but only one is active at any given time in a one-to-one mapping. The authors prove that performance of the system is enhanced when the element spacing between the LEDs is increased in the single indoor deployment with a better BER in a low channel path correlation [36]. In [37], sparse-activated sub-carrier OFDM index modulation and interpolated sparse-activated sub-carrier OFDM index modulation are presented to increase the spectrum efficiency. Simulations show both schemes presented an improved spectral efficiency and BER when compared to other conventional index OFDM modulation with a gain of 5 dB. The authors in [38] provide a comprehensive review on different kind of modulation techniques, such as OOK, presenting it in an analytical and simulation to get the BER and signal-to-noise ratio (SNR) for PWM, OFDM, CSK, generalized SSK, optical asymmetric modulation with their respective advantages and disadvantages. Authors in [39] implemented a VLC system by using an alternating current—direct current power factor as a correction converter by using a dimmable property changing from 10% to 90% for OOK- M -FSK, also the system is proven to be robust with VLC systems and its applications, a data rate of 1.11 Mb/s is obtained over a transmission distance ranging up to 20 m, with the help of other external light sources. Also, in [40], the authors established VLC system for indoor application for non-return-to-zero (NRZ)-OOK, with data rate of 10 kbps at a distance ranging up to 10 m. Again, [41] presents a VLC system capable of transmitting data at a speed ranging up to 115.2 kbps for a transmission distance of 1 m utilizing OOK modulation and MATLAB as simulator. The need of choosing the right modulation technique is crucial and the basic key of building a system which is flexible and having a greater optic fibre network capacity.

There are a couple of reviews on FO communication offering some critical features, which includes efficiency and resistance to electromagnetic interference. Sheng Li has done a review on emerging technologies with FO data

Table 1 Modulation and coding techniques for VLC, FO, and Laser

Communication channel	Modulation	Coding schemes
VLC	VPPM, OFDM, CSK, OOK, C-OOK, Offset-VPPM, PWM, VOOK, MIMO, MPPM, FSK, CM-FSK, RS-FSK, CDMA, Twinkle VPPM, Multiple pulse position modulation (MPPM), HS-PSK and UFSSOOK	STBC, RC, inverse source coding (ISC), Punctured Convolutional Codes
FO	ASK, FSK, QAM, PAM, PSK, Duobinary, Return-to-Zero (RZ), Non-Return-to-Zero (NRZ)	Manchester Transmitter, CM, FEC, ECC
Laser	ASK, FSK, M-ary ASK, M-ary PSK, BPSK, PDSK, QPSK, Non-Return-to-Zero (NRZ) PPM, WDM, MIMO	Space-time trellis code (STTC), Polar codes, Turbo codes

communication bandwidth for the next-generation broadband networks [42]. Liaw and Shin [43] in their attempt to investigate which fibre laser technology is suitable and resistant for transmission, made an overview of a linear cavity tunable fibre lasers. With a laser source, different wavelength could be chosen by scanning over a wavelength range to achieve wavelength tunable. Each of the designs could achieve 0.1 nm tunable resolution.

Shashi Jawla et al. propose a study on the performance of different modulation format which include amplitude shift keying (ASK), FSK, phase shift keying (PSK) and polarization phase shift keying (PPSK) [44]. Proposed that if the optic fibre communication channel uses a multilevel signaling, one or more bit per symbol will be transmitted using M -ary ASK modulation scheme and when using multiple phases obviously more than one bit per symbol is transmitted when making use of M -ary PSK modulation format. In [45], the authors proposed an overview on experiment for a 10.7 Gb/s polymethyl-methacrylate polymer optical fibre with large-core of 1 mm. The authors proposed that in an optic fibre communication channel, a low latency, low power consumption with low complexity, simple NRZ is the primary choice. They also proposed an overall performance of pulse amplitude modulation added to feed-forward equalization or decision-forward equalization at a better complexity in addition with an added advantage of a small speed and inexpensive components, this makes such modulation schemes a powerful and promising solution for next-generation network of 10 Gb/s power over fibre systems [45].

For any laser that is connected to the current source may be modulated depending on whether it is an analogue or digital application. The modulation is in response to the changes within the cavity of the laser. The output usually produces an amplitude modulation, optical frequency or frequency modulation and pulse modulation. A couple of some advanced modulation techniques are used in laser technology. To obtain a 50 GHz bandwidth, a more energy efficient internal modulated laser sources known as direct modulation laser (DML) is used. During this modulation, there is a 3 dB power loss and some other propagation losses. This always

becomes a problem when it requires to transmit higher bit rate. Recently, this modulation has been able to approach that of externally high-speed modulated laser [46].

3.2 Coding techniques

Indoor VLC system is characterized by transmission using LEDs in small distances, which are free from atmospheric degradation. The performance of a VLC system is affected by interference due to multipath propagation. The overall system can be enhanced with increased capacity performance without an increase in the transmission power, if a careful signal processing is done and advanced coding techniques are exploited. Researchers have in the past, proposed techniques with multiple LEDs, MIMO [47] techniques for VLC systems, exploited space-time-block coding (STBC) [48, 49] and repetitive coding (RC) techniques [47, 50, 51]. In [52], a comprehensive line-of-sight (LoS) and non-light-of-sight (NLoS) numerical performance analysis conducted with a STBC and RC to investigate the coding technique that is suitable for VLC system. Abdulmalik Alwarafy et al. in their work pointed out that RC outperforms STBC in a single photo-detector reception scenario with a maximum likelihood detection. However, when a MIMO technique was exploited, STBC performs better than RC having an extra complexity at the receiver for a LoS scenario. The authors in [50] proposed a binary system using Alamouti STBC having one carrier communication receiver with an outdoor image-sensor-based VLC network. The work in [51] demonstrated a multiple-input single-output (MISO) VLC network using RC technique by adding the pilot bit which permits reliability in blind approximations of channel coefficients. The authors in [47] presented linear space codes used in an indoor VLC MIMO having two transmitters and multiple receivers. In [53], the authors proposed an RC and spatial modulation (SM) coding scheme by optimizing the way LEDs are placed and the power of the LEDs for a 4x4 MIMO configuration while obtaining a unified SNR with respect to the BER and bits per symbol. The data rate in

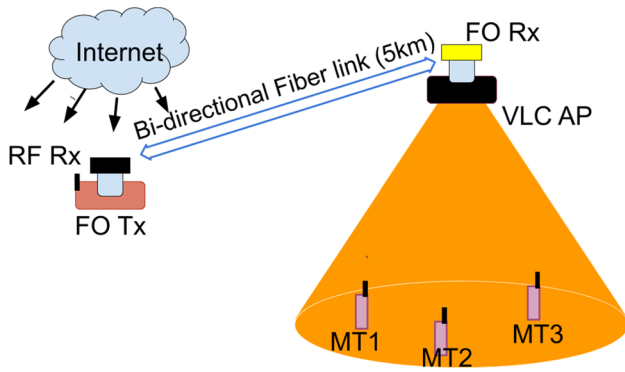


Fig. 1 Cascaded network of fibre optic (FO) and visible light communications (VLC) technology

each polarization per symbol period for FO communication channel can be improved by a joint design of modern coding techniques coupled with a modern modulation, for instance, coded modulation and forward error correction [54]. All of them are already a crucial factor in FO communication network standards. Table 1 shows some very crucial modulations and coding techniques offered in the field of VLC, FO, and laser technology.

Error correction coding is an essential signal processing technique to improve the channel bandwidth of optical communication systems. The ITU-T G975 recommended Reed Solomon (RS) (255, 239) code, which are mostly applicable in long distance or long-haul fibre optical communication networks. The proposed code offered a net gain of about 4.3 dB with an output BER of 10^{-8} after the coding correction. Monte-Carlo also proposed an analysis for RS (255, 239) code with 6.7% redundancy simulation and theoretical performance over a white Gaussian noise (AWGN) communication channel having a hard decision decoding and BPSK signalling. Mohammed Abdul Alwahab et al. in [55] performed a comparison between the candidate of RS codes in terms of coding gain. The RS (255, 235) code performs almost twice with the redundancy compared to the RS (255, 247) code which offers about 1 dB coding gain. RS (255, 223) offers a 2 dB coding gain with 4.5 times more redundancy in coding than RS (255, 247) code (Fig. 1).

4 The architecture of VLC systems

There are two major integral parts of a VLC system, we have the transmitter and the receiver. These parts are made of three common layers: the physical, MAC and the application layer. For the purpose of this paper, only two integral parts will be discussed for simplicity.

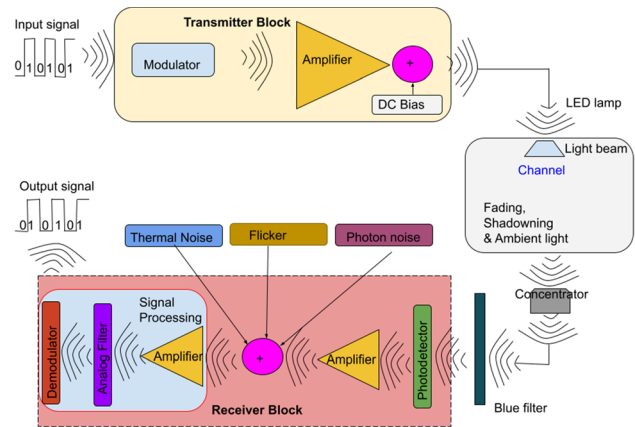


Fig. 2 Communication system of visible light communications (VLC) technology

The transmitter part of the VLC is usually the source of light. The development of LED lighting makes the technology much more interesting using solid-state lighting. The efficiency of LEDs, as well as the white light they emit and wavelength, make LEDs the best choice for a VLC light source. There are many spectra for which light is produced by LED light. The commonly used ones for producing white light is the trichromatic commonly known as RGB [14, 56].

The receiver of VLC systems usually consists of optical filter, optical concentrators and amplification circuits. The light generator from the transmitter is usually weak due to beam divergence. The signals are then picked up by the optical concentrator and amplifies the signal. The signal is then picked up by the photo-diode and converts it to current value. This model is depicted in Figs. 2, 3, 4.

4.1 Cascaded systems with VLC

As mentioned earlier, several technologies can be combined with VLC to form a cascaded system: Power line communication (PLC)-VLC, FO-VLC, RF-VLC, for example. The reason of this combination is multiple. The most significant reasons are related to the fact that VLC stands alone only for short-distance transmissions. However, reasons related to security are also accounted. In this section, we focus only on FO-VLC and laser-VLC, which are the main targets of this paper. The mathematical modelling will be derived from Fig. 5.

4.2 FO-VLC system model

In [21], authors proposed a system that is composed of two main subsystems, Fig. 1, with each having its transmitter and receiver. The initial sub-system, FO, comprising

of FO-Tx and FO-Rx has access to data traffic from the "cloud", while the second subsystem VLC, comprising of FO-transmitter (FO-Tx), FO-receiver (FO-Rx), VLC-transmitter (VLC-Tx), VLC-receiver (VLC-Rx). VLC-Tx is made of one or several LEDs, which produce light rays. The latter are detected by the mobile terminals (MTs), which constitute the VLC-Rx. As shown in Fig. 1, data collected from RF by FO-Rx are re-transmitted through a 5 km distance to a VLC access point (AP) down to the indoors MTs. Considering the fact that, the link between FO (outdoor) and VLC (indoor) has no data processing, this system is said to be based on an AF strategy. The amplification gain (Fig. 3) reduces the attenuation that is experienced in the optical fibre link.

The channel is hybrid with the transfer function of the bridge considered as unity [21]. Communication in the FO sub-channel is governed by

$$Y_{FO} = H_{FO}X_{FO} + N_{FO}, \tag{1}$$

where X_{FO} is the alphabet at the FO-Tx, Y_{FO} is the detected alphabet, H_{FO} is the FO channel transfer function and N_{FO} is the noise introduced at the bridge.

The gain of a FO channel is given by [21]

$$H_{FO} = He^{-\alpha z/2} e^{-jknz} e^{-jD\omega^3 z/(4\pi)}, \tag{2}$$

where k is known as the propagation constant, $\omega = 2\pi f$ is called the angular frequency, n is the refractive index, α is the absorption coefficient of the fibre, and D is known as the dispersion coefficient. H_{FO} is as a function of the transmission distance L , depicted in Fig. 6, for different values of attenuation.

Communication in the VLC sub-channel is governed by

$$Y_{VLC} = H_{VLC}X_{VLC} + N_{VLC}, \tag{3}$$

where Y_{VLC} is the detected alphabet at MT, X_{VLC} is the alphabet at the VLC AP, H_{VLC} is the VLC channel transfer function, and N_{VLC} is the noise received by MT. In the VLC sub-channel, the transfer function is made up of (i) the LoS and (ii) and the NLoS (diffuse link) parts [21].

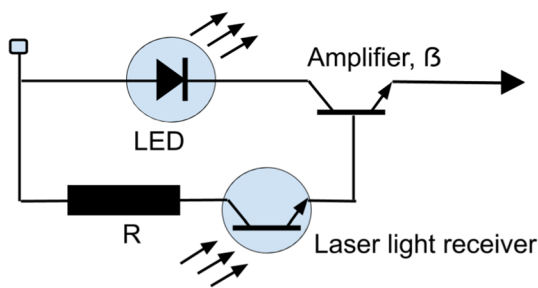


Fig. 3 Example of circuit used in the AF bridge

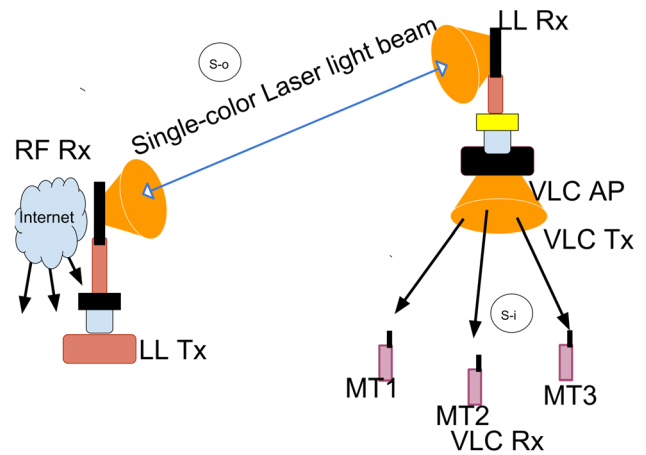


Fig. 4 Cascaded single-channel VLC access network based on LD (outdoor)-LED (indoor)

The equations describing LoS and NLoS are well elaborated in Eq. 4 and Eq. 5.

$$H_{LoS(VLC)} = \frac{A_r(\eta + 1) \cos^n \phi \cos \varphi}{2\pi d^2} e^{-j2\pi f t_{LoS}}, \tag{4}$$

$$H_{Diff(VLC)} = \frac{A_r \rho e^{-j2\pi f t_{Diff}}}{A_{room}(1 - \rho)(1 + \frac{jf}{f_o})}, \tag{5}$$

, respectively, where A_r and A_{room} are the effective PD area and the area of the room, respectively, ϕ is the irradiance angle, ρ is the average walls reflectivity, η is the Lambertian order given by $\eta = -\log_2(2)/\log_2(\theta/2)$ and φ the incidence angle. Note that f_o is the 3 dB cut-off frequency of a pure diffuse channel. H_{VLC} is the VLC channel frequency response shown in Fig. 7, for different values of ρ , of the indoor walls, floor and ceiling reflection. The transfer function of the VLC subsystem is the summation of the LoS and NLoS links, given by

$$H_{VLC} = \frac{A_r(\eta + 1) \cos^n \phi \cos \varphi}{2\pi d^2} e^{-j2\pi f t_{LoS}} + \frac{A_r \rho e^{-j2\pi f t_{NLoS}}}{A_{room}(1 - \rho)(1 + \frac{jf}{f_o})}, \tag{6}$$

The overall communication channel is governed by

$$Y = HX + N. \tag{7}$$

By combining Eqs. 1, 3, and Eq. 7 is given by

$$Y_{VLC} = H_{VLC}H_{FO}X_{FO} + H_{VLC}N_{FO} + N_{VLC}. \tag{8}$$

Comparing Eq. 7 and Eq. 8, we can deduce that

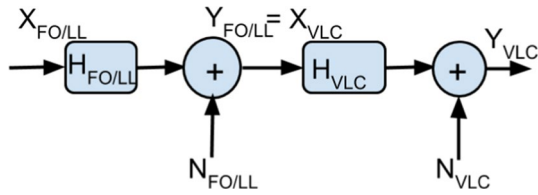


Fig. 5 Simplified channel model depicting an access system based on a cascaded (FO, VLL)-VLC

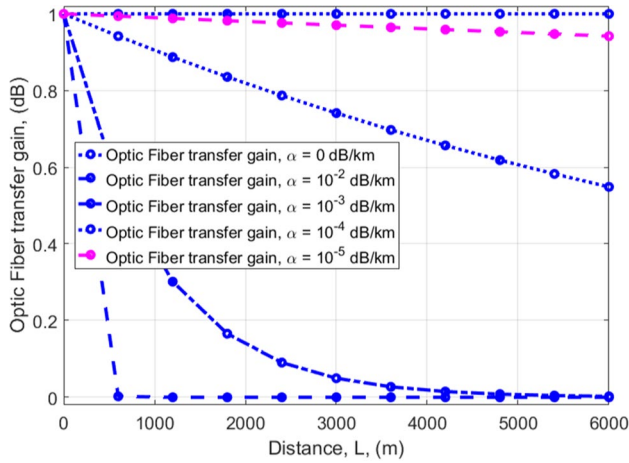


Fig. 6 Variation of fibre optic channel gain with a selected transmission distance for chosen attenuation coefficient, α

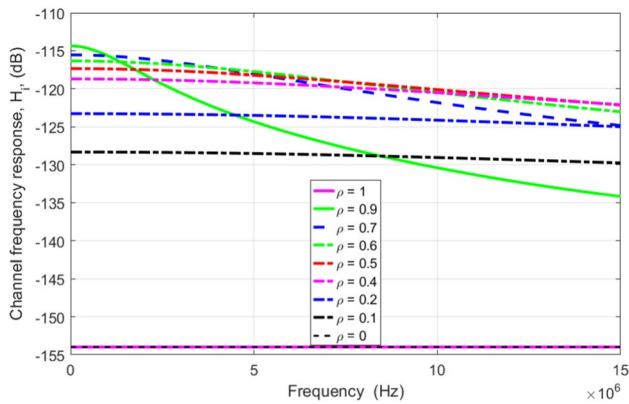


Fig. 7 Variation of the indoor VLC frequency channel response versus frequency with different coefficient of ρ of the indoor walls, floor and ceiling reflection

$$\begin{cases} Y = Y_{VLC}, \\ H = H_{VLC}H_{FO}, \\ X = X_{FO}, \\ N = H_{VLC}N_{FO} + N_{VLC}. \end{cases} \quad (9)$$

Finally, the overall transfer function for the FO-VLC cascaded system can be deduced and is given by

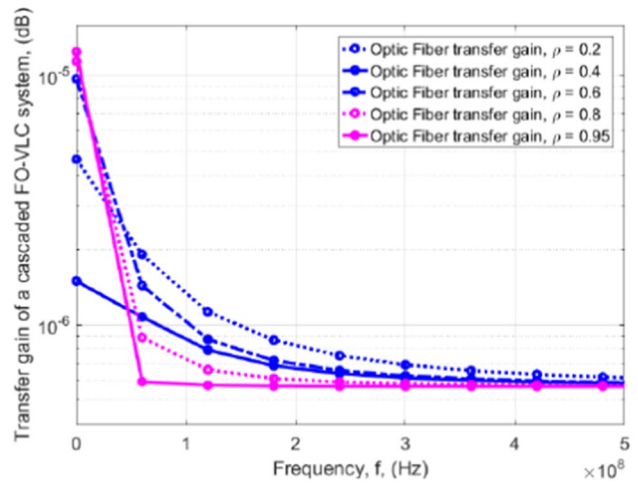


Fig. 8 Variation for the overall FO-VLC transfer gain with the wall, ceiling and floor reflection coefficient, ρ , in indoor VLC, for frequencies up to 1 GHz, over $L = 5000$ m distance of the FO cable [21]

$$H_{FO-VLC} = \left[\frac{A_r(\eta + 1) \cos^n \phi \cos \varphi}{2\pi d^2} e^{-j2\pi f t_{LoS}} + \frac{A_r \rho e^{-j2\pi f t_{NLoS}}}{A_{room}(1 - \rho)(1 + \frac{jf}{f_0})} \right] \times H_O e^{-\alpha z/2} e^{-jknz} e^{-jD\omega^3 z/(4\pi)}, \quad (10)$$

In Fig. 8, the gain of the cascaded system of FO-VLC is such for a reflection coefficient, ρ , ranging from 0.2 to 0.95, the transfer gain decrease slightly with frequency up to 1 GHz over a distance (L) of 5 Km.

4.3 Laser-VLC system model

Here, the end-to-end system is also made up of two main subsystems, composing of a transmitter and receiver. Again, the first subsystem serves as a backbone network to the second subsystem. The laser subsystem uses LDs, and the VLC subsystem uses LEDs. The backbone is exploited in a peer-to-peer (P2P) topography. A couple of possibilities are exploited which include (i) single colour LD-LED system, (ii) multiple colour LD-LED system, and (iii) hybrid combination. By considering a single colour LD-LED system, the original data from the RF cloud is then transmitted using the laser light beam which uses a single colour light source. The light is detected by the laser light detector (LLD) included in the Laser-Tx. The detected light is then amplified and re-transmitted over LED light beam and finally detected by the PD. Various modulation techniques such as OOK [57, 58], VPPM [57, 58] and OFDM may be exploited [57–59].

In this system, Fig. 4, we have two transfer functions, H_{LL} and H_{VLC} , which all correspond to the outdoor and

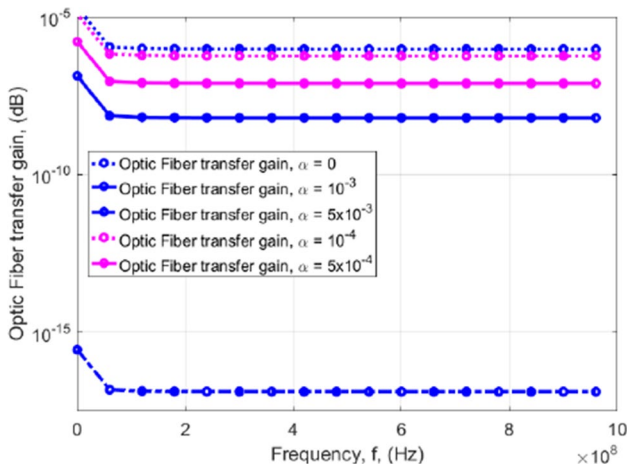


Fig. 9 Variation of the overall optic fibre channel gain with the FO attenuation coefficient, α , for frequencies up to 1 GHz, over $L = 5000$ m distance of the FO cable [21]

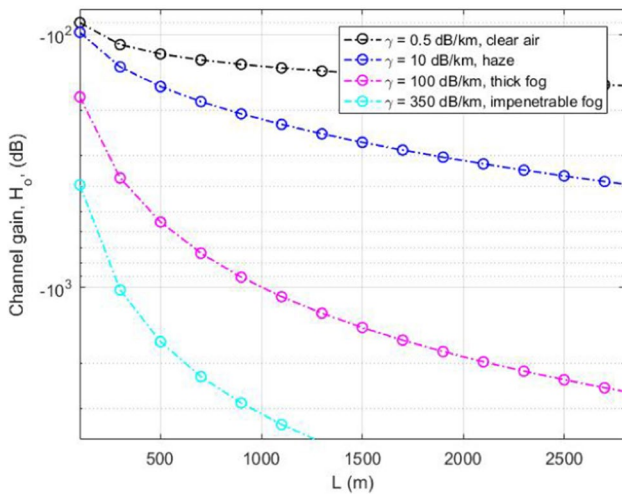


Fig. 10 Variation for line-of-sight of a 2 km of the laser outdoor channel gain with the coefficient γ of the attenuation intensity

indoor channels, respectively. It is assumed that there is no processing between the sub-channels, the transfer function of the bridge is unity. The outdoor sub-channel is governed by

$$Y_{LL} = H_{LL}X_{LL} + N_{LL}, \tag{11}$$

where X_{LL} is the message from the source, Y_{LL} is the message at the laser side, and N_{LL} the AWGN.

The outdoor part is made up of a single mode Gaussian beam stochastic channel governed by [60]

$$H_{LoS(LL)} = \frac{2A_l e^{-\gamma L}}{\pi \theta^2 L^2}, \tag{12}$$

where A_l is the effective area of laser receiver, θ is the small angle beam divergence, L is the range of transmission of the fibre and γ is the intensity of the attenuation coefficient (Fig. 9).

The laser channel gain of the outdoor environment, as shown in Fig. 10, decreases with an increase in transmission distance. The parameters used in the analysis were as follow: $0 \leq L \leq 5$ km, $A_l = 4.8 \mu m^2$, $\theta = 3./1000$, $\gamma = 0.5./1000$.

For the outdoor–indoor channel transition the message–signal gotten by the LLD is then convoluted by channel frequency response of the system. Therefore, the message received by the LED follows Eq. 11.

For the indoor channel, the signal and noise that comes from the outdoor environment of the system are convoluted by the indoor impulse response. The transition in the overall system is the same as that of FO, governed by Eq. 8, where $H = H_{VLC}H_{LL}$ and $N = H_{LL}N_{LL} + N_{VLC}$. Assuming that no attenuation is observed at the bridge, the transfer function of the bridge is unity. It is seen that both LD and the LED light transmit data in a similar model, as they both obey the optical propagating principle. As such they have a common transfer function. Again, for the outdoor laser P2P model, the transmitter and receiver are both fixed and there exists no path loss. Thus, eliminating the diffuse part of the channel. Then, the outdoor of the P2P transfer function is governed by

$$H_{LL} = H_{LoS(LL)}. \tag{13}$$

Contrary to outdoor P2P model, the indoor LED channel takes into account LoS and diffuse (NLoS) links parts. Hence, the indoor channel model is governed by

$$H_{VLC} = H_{LoS(VLC)} + H_{Diff(VLC)}. \tag{14}$$

Here, LoS and Diff represent the LoS and NLoS links, respectively. The overall cascaded LL-LED model is gotten by doing a convolution of the outdoor channel with its indoor counterpart. Hence, the transfer function H is governed by

$$H = [H_{LoS(VLC)} + H_{Diff(VLC)}]H_{LoS(LL)}. \tag{15}$$

Finally, the overall transfer function of the LL-VLC cascaded system is given by

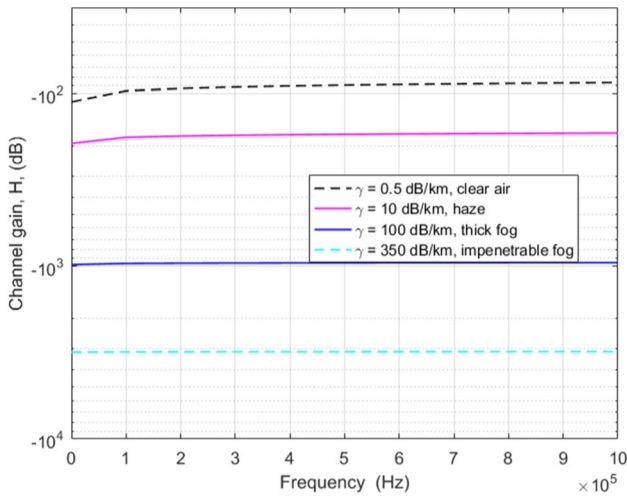


Fig. 11 Overall cascaded laser-VLC (H_{LL-VLC}), (outdoor-indoor) channel gain for multiple values of the attenuation coefficient, γ , over 2 km

$$H_{LL-VLC} = \left[\frac{A_r(\eta + 1) \cos^n \phi \cos \varphi}{2\pi d^2} e^{-j2\pi f t_{LoS}} + \frac{A_r \rho e^{-j2\pi f t_{NLoS}}}{A_{room}(1 - \rho)(1 + \frac{jf}{f_0})} \right] \times \frac{2A_l e^{-\gamma L}}{\pi \theta^2 L^2}, \tag{16}$$

5 Comparison

Generally, the gain of FO-VLC is such that the cascaded system always decreases as the distance of the signal being transmitted increases for a range of reflection coefficient, ρ , and slightly decreases with attenuation coefficient, α , up to gigahertz, for some values of α , as shown in Fig. 6, with the gain of the channel being 10^{-5} dB for a 5 km of the FO transmission length. Similarly, the gain of the LL-VLC cascaded system decreases with an increase in transmission distance for a given range of floor and ceiling reflection coefficient, ρ . The gain also decreases slightly with attenuation intensity, γ , for frequency up to Giga Hertz. For some values of ρ , in the range $0 < \rho < 1$, as shown in Fig. 9. The gain of the channel is -304 dB for a 2 km of the transmission range (Fig. 11). Comparing FO-VLC and laser-VLC cascaded models, both systems present a clear and concise features (Table 2).

In Fig. 12, for some values of ρ , in the range $0 < \rho < 1$, a transmission range of 0.5 km. The channel gain -150 dB shows the best scenario for $\gamma = 0.5$ dB/km and $\rho = 0.8$ with clear air.

It is known that the relationship of the optical power which is transmitted using LED and that received by the LED where the transmitted and received visible light is having a flat frequency response, denoted by a direct current (DC) gain (H_d). Thus, the relationship between optical

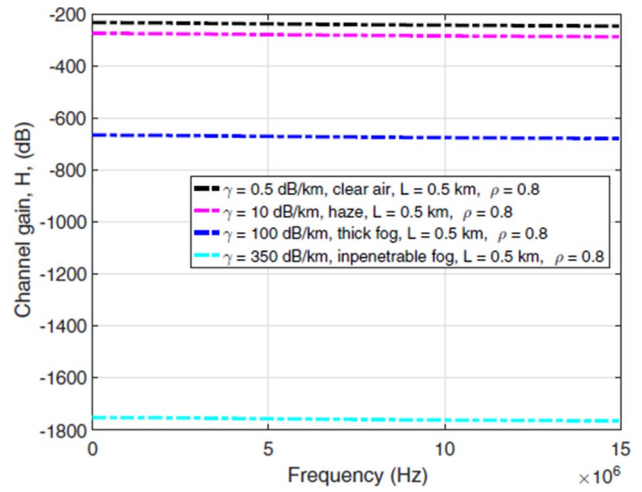


Fig. 12 Overall VLC (LD-LED, outdoor-indoor) channel frequency response for multiple values of the coefficient γ of the attenuation intensity, over 2 km; considering a reflection coefficient $\rho = 8$ [20]

received power (P_r) in watts and optical transmitted power (P_t) can be denoted as

$$P_r = H_d P_t \lambda. \tag{17}$$

where λ is responsivity of the PD. In both channels, we assume a value of 0.9, domineering power transmitted to be 10 watts and gain 10^{-5} . Therefore, for a cascaded system of FO-VLC with various light sources, we assume Eq. (17) for a system where there is no data processing between the sub-channels then, $P_{r_{FO-VLC}} = 10^{-5} \times 10 \times 0.9$, $P_{r_{FO-VLC}} = 10^{-9}$ watts. Again, for a cascaded system of LL-VLC with similar light sources, $P_{r_{FO-VLC}} = 10^{-151} \times 10 \times 0.9$ and $P_{r_{FO-VLC}} = 9^{-151}$ watts.

The most important factor of VLC is controlling dimming, since it uses lights expected for illumination, as such a good quality signal for communication. In this paper, the FO-VLC is limited in the fact that, most components and setup of a fibre link are expensive. Although, expensive in terms of implementation, Fo-VLC communication is free from electromagnetic interference. On the other hand, LL-VLC has a limited range of transmission with an increased complexity of implementation and cost effective.

6 Standardization efforts

Standards simply define the technical requirement and specifications for a particular technology or product to ensure it is in conformity or compatible with other international products to maintain a minimum level of safety. It is important to enhance the physical challenges in light communication systems in order to overcome its numerous challenges. Having

Table 2 Comparison between the FO-VLC and laser-VLC channels

Property of Model	FO-LED Cascaded channel	Laser-VLC Cascaded Channel
Gain	10^{-5} dB	-150 dB
Medium	FO + VLC	Laser + VLC
Cost	Expensive	Less Expensive
Noise Sources	Amplifiers, sunlight	sunlight
Beam directionality	Steering Single beam for both sub-channels	singled wavelength and coherent in One direction
Mode of Communications	Channels both Wired and Wireless	Both wireless channels
Modulation techniques	With best modulation technique being M -ary pulse position modulation in VLC systems and M -ary phase shift keying in quadrature phase shift keying for FO communication [34]	with best modulation technique being M -ary pulse position modulation in VLC systems [34]
Complexity	The same	The same
Applications	Stadiums, underwater-to-hospitals, offices	Stadiums, Offices, vehicle and transportation
Interference/Noise	Little for FO and High for VLC	High for both
Multi-path	Low for FO and high for VLC	Overall high for both
Coverage	Wide for overall FO-VLC	limited

in mind here that various domain of visible light communication could have a wide benefit from a well standardization structure. A comprehensive widely accepted standardization will greatly mitigate the gap between academia and the industry while improving development, and fasten up the deployment towards the market. In this standard, a number of ways are proposed to mitigate dimming and flickering in OWPAN [12]. Dimming which is defined as the method of controlling the brightness perceived by a user from a light source, according to the user specifications, dimming can be accomplished by adjusting the pulse width, pulse amplitude and by adding compensation symbols. This standard also proposed methods to mitigate flicker for intra-frame and interframes.

6.1 Standardization efforts in VLC

The initial standardization of VLC began at a very early age by the Japan Electronics and Information Industries Association and the VLC consortium in 2007. Further worked done on the CP_{1223} which is a simplified version of CP_{1222} , released in 2013. Again a IEC 62943 while approved in 2014, it is still being developed by Visible Light Communication Association. Alongside Japanese efforts in standardizing VLC, IEEE 802.15 Task Group 7 began in 2009. Later on, it published several drafts in 2010/2011 and 2018/2019. In September 2014, IEEE 802.15.7 was launched for Short-Range Wireless Optical Communication Using Visible Light. This standardization addresses mainly the issue of the link layer and the physical layer design specifications. Due to the fact that IEEE 802.15.7 provided very low data rate there was need for revising the standards by task group TG_{7r1} [35]. Nevertheless, applications for indoor and outdoor VLC face diverse challenges in terms of speed, robustness and data rates. It is important that subsequent and future

efforts should focus on providing a VLC standard for outdoor VLC applications. In this context, we can say one can not independently talk on a global accepted standardization point of view based on VLC standardization in general and outdoor VLC in particular. Since they exist the Japanese VLCA standard, and European standards, likewise different research groups are demanding different specification standardization.

6.2 Standardization efforts in laser

In 1994, the standardization of safety products by IEC 825.1 was published, for applications of lasers and its products and eventual installation. In 1993 another standard of IEC 825.1 similar to that of IEC 825.1:1994 was published specifying the various requirements for manufacturing of laser equipment. Also, IEC 825.1 points out actions that should be taken when laser hazards such as radiation to the skin and eyes are concerned. Again, machine safety-based standard type A, known as EN 12626, was published. This standard incorporates the laser processing machines and this is equivalent to ISO 11553. ISO also publish a couple of standards including beam parameter which are only applicable to the performance of the laser. EN 60204 specifies requirement for the electrical safety of laser machines. EN 60825.1 was also published based on laser equipment. Again, 481 and 482 specify issues of measurement of airborne particles and chemical agent at work place. Furthermore, EU 643 and IWG 6 setup norms and standards to obtain recommendations concerning laser safety.

In August 1997, various working groups ranging from WG 1 to WG 11 were also established. Eventually the United State standards, member of the ISO and IEC were also published

which include the ANSI Z136 series adopted safety guidelines for using laser. The standards are not mandatory but could be considered for reference by the state laws. ANSI standards also published for fibre communication system with Z136.2-1988 and lasers for medical application with Z136.3-1996. ANSI standards also include Z136.4 for outdoor use, Z136.6 for educational purposes and it is still under development. ANSI B11.21 were also published for laser machine tools.

The international standardization of laser in order to improve optical communication globally and permit the sharing of communication infrastructure is very essential. In [61], a consultative system for space data systems (CCSDS) back then in 1982 stated goals that will go long way to enhance governmental likewise commercial interoperability with cross-support, at the same time reducing risk and development time and cost. The CCSDS developed standards recommendation which are now ISO standards associated with space link communication and ground data networks. Also, CCSDS later formed an optical communication group which was co-chaired by NASA and European space agency in January 2014.

6.3 Standardization efforts in Fibre Optics

With the inherent need for high data communication, FO provides a promising technology capable of handling huge amount of data. Fibre Optic Technical Advisory group made some standardization efforts to integrate IEEE 802.8 into traditional IEEE 802 copper-based-network. There are three efforts of standardization, categorize into military, computer, and industrial use [62].

6.3.1 Military

The SAE AE-9C Fibre Optic Subcommittee aided the establishment of the Air Force in implementing MIL-STD-1773, considered version MIL-STD-1553 multiplex data bus. Again, the SAE AE-9C Fibre Optic Subcommittee did a review and upgrade that resulted in the implementation of MIL-STD-1760A.

6.3.2 Computer

This effort was brought forth by Project 802 under the IEEE Computer Society working on FOs networks with speeds up to 20 Mbits/s with length up to 2.5 km.

6.3.3 Industrial

In a bit to standardize industrial FO manufacturing, Manufacturing Automation Protocol came with efforts to control

the manufacture of equipment with coaxial-cable backbone. Because this needed to be in compatibility with FO. A 802.4 F/O TAG, with token-passing bus, FO implementation considered a hybrid copper-fibre media system. Later, a group of task force successfully setup under 802.4 working group combined efforts from 802.4, PROWAY-ISA and 802.8

7 Conclusion

In any communication systems, it is imminent for such system to upload it best possible data traffic in a minimum available bandwidth with cost effectiveness. This is the main goal of such communication network. This review illustrates that in both VLC cascaded systems, FO-VLC has shown without doubts that it is a promising way of providing a good communication networks to support the unprecedented increase in data traffic. There are many various ways where VLC-based networks can be used in real-time applications that is going to renovate the present and future lifestyle. In this article, a review is provided for cascaded OWC which are FO-VLC and laser-VLC. This study takes into consideration a couple of aspects for the state-of-the-art of cascaded OWC research from the point of view of communication engineering: modulation techniques, cascaded OWC channel modelling, coding technologies, quick comparisons, and standardization efforts. This survey will help readers to have a better understanding of cascaded OWC channel characteristics with their various related features that may limit the performance of such cascaded OWC networks.

Besides making available the readers with important and necessary technical theoretical information and a much clearer picture of cascaded OWC networks, we also highlighted some crucial challenges of cascaded VLC networks. Unlike free space optical communication, cascaded VLC systems are not over exploited, and the principal problem is more challenging. The proposed layouts of FO-VLC and LL-VLC improve system optimization, and the simulation results prove the system with FO-VLC provides reliable, optimal power to the MTs, and almost uniform. Moreover, FO-VLC cascaded technology with an M -ary phase shift keying modulation scheme can improve the data rate and boost the overall VLC cascaded throughput. With their numerous advantages, we strongly believe that cascaded FO-VLC and laser-VLC are good candidates for VLC backbone.

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Data availability The data that support the findings of this study are available in IEEE xplore repository, [20, 21].

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References

- Paulraj, A.J., Gore, D.A., Nabar, R.U., Bolcskei, H.: An overview of MIMO communications—a key to gigabit wireless. *Proc. IEEE* **92**(2), 198–218 (2004)
- Song, J., Ding, W., Yang, F., Yang, H., Yu, B., Zhang, H.: An indoor broadband broadcasting system based on PLC and VLC. *IEEE Trans. Broadcast.* **61**(2), 299–308 (2015)
- CiscoJ, CM.: Global mobile data traffic forecast update. Cisco visual networking index; 2016–2021 White Paper. (2017)
- Sterckx, K.L., Elmirghani, J.M.H., Cryan, R.A.: Pyramidal fly-eye detection antenna for optical wireless systems. *IEEE Colloq. Opt. Wirel. Commun.* (1999). <https://doi.org/10.1049/ic:19990696>
- Gfeller, F.R., Bapst, U.: Wireless in-house data communication via diffuse infrared radiation. *Proc. IEEE* **67**(11), 1474–1486 (1979)
- Kavehrad, M.: Sustainable energy-efficient wireless applications using light. *IEEE Commun. Mag.* **48**(12), 66–73 (2010)
- Heatley, D., Wisely, D., Neild, I., Cochrane, P.: Optical wireless: the story so far. *IEEE Commun. Mag.* **36**(72–74), 79 (1999)
- Kavehrad, M.M.: Broadband room service by light. *Sci. Am. SCI AMER* **297**, 82–87 (2007)
- Ndjiongue, A.R., Ferreira, H., Ngatched, T.: Visible light communications (VLC) technology. *Wiley Encycl. Electr. Electron. Eng.* pp. 1–15 (2015)
- Zafar, F., Bakaul, M., Parthiban, R.: Laser-diode-based visible light communication: toward gigabit class communication. *IEEE Commun. Mag.* **55**(1), 144–151 (2017)
- Ndjiongue, A.R., Ngatched, T., Dobre, O., Armada, A.: VLC-Based Networking: Feasibility and Challenges (2019)
- IEEE draft standard for local and metropolitan area networks - Part 15.7: short-range optical wireless communications. *IEEE P802.15.7/D3*, pp. 1–412 (2018)
- Chowdhury, M., Hossan, M.T., Islam, A., Jang, Y.M.: A comparative survey of optical wireless technologies: architectures and applications. *IEEE Access* (2018). <https://doi.org/10.1109/ACCESS.2018.2792419>
- Singh, A., Srivastava, A., Bohara, V.A., Rao, G.S.V.: Outage and power saving analysis for hybrid cellular-visible light communication and direct cellular downlink. In: Proceedings of the 20th IEEE International Conference on Transparent Optical Networks (ICTON)
- Teli, S.R., Chvojka, P., Vitek, S., Zvanovec, S., Perez-Jimenez, R., Ghassemlooy, Z.: A SIMO hybrid visible-light communication system for optical IoT. *IEEE Internet Things J.* **9**(5), 3548–3558 (2022)
- You, X., Chen, J., Zhong, Y., Chen, S., Yu, C.: Efficient dimming control with time domain hybrid modulation in indoor hybrid visible light/infrared communication systems. In: Proceedings of the 24th IEEE OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC), pp. 1–3 (2019)
- Kamalakis, T., Ghassemlooy, Z., Zvanovec, S., Nero, Alves L.: Analysis and simulation of a hybrid visible-light/infrared optical wireless network for IoT applications. *J. Opt. Commun. Netw.* **14**(3), 69–78 (2022)
- Yang, L., Huang, Z., Yi, X., Wang, H., Li, L., Lyu, S.: Improved proportional fairness algorithm in visible light communication/WiFi hybrid networks. In: Proceedings of the 19th IEEE International Conference on Optical Communications and Networks (ICOCN), pp. 1–3. Qufu, China (2021)
- Ndjiongue, A.R., Ferreira, H.: An overview of outdoor visible light communications. *Wiley Trans. Emerg. Telecommun. Technol.* **29** (2018)
- Ndjiongue, A.R., Ngatched, T., Ferreira, H.: Access Telecommunication Systems Using VLC Technology: Cascaded LD-LED Channel Analysis (2018)
- Fon, R.C., Ndjiongue, A.R., Ouahada, K.: Cascaded optic fibre-visible light communications: channel model and analysis. In: Proceedings of the IEEE International Conference on Advances in Big Data, Computing and Data Communication Systems (icABCD)
- Nlom, S.M., Ndjiongue, A.R., Ouahada, K.: Cascaded PLC-VLC channel: an indoor measurements campaign. *IEEE Access* **6**, 25230–25239 (2018)
- Kubjana, M.D., Shongwe, T., Ndjiongue, A.R.: Hybrid PLC-VLC based on ACO-OFDM. In: Proceedings of the IEEE International Conference on Intelligent and Innovative Computing Applications (ICONIC), pp. 1–5 (2018)
- Feng, S., Bai, T., Hanzo, L.: Joint power allocation for the multi-user NOMA-downlink in a power-line-fed VLC network. *IEEE Trans. Vehicular Technol.* **68**(5), 5185–5190 (2019)
- Gupta, A., Sharma, N., Garg, P., Alouini, M.: Cascaded FSO-VLC communication system. *IEEE Wirel. Commun. Lett.* **6**(6), 810–813 (2017)
- Pesek, P., Zvánovec, S., Chvojka, P., Ghassemlooy, Z., Haigh, P.A.: Demonstration of a hybrid FSO/VLC link for the last mile and last meter networks. *IEEE Photonics J.* **11**(1), 1–7 (2019)
- Rakia, T., Yang, H., Gebali, F., Alouini, M.: Optimal design of dual-hop VLC/RF communication system with energy harvesting. *IEEE Commun. Lett.* **20**(10), 1979–1982 (2016)
- Obeed, M., Salhab, A.M., Zummo, S.A., Alouini, M.: Joint optimization of power allocation and load balancing for hybrid VLC/RF networks. *IEEE/OSA J. Opt. Commun. Netw.* **10**(5), 553–562 (2018)
- Khreishah, A., Shao, S., Gharaibeh, A., Ayyash, M., Elgala, H., Ansari, N.: A Hybrid RF-VLC system for energy efficient wireless access. *IEEE Trans. Gr. Commun. Netw.* **2**(4), 932–944 (2018)
- Tang, Q., Li, K., Liu, X., Kong, L.: Performance analysis of spectral efficiently adaptive modulation dft-spread polar coordinate-based ofdm in hybrid fiber-visible laser light communication system. In: Proceedings of the IEEE 20th International Conference on Communication Technology (ICCT), pp. 594–598. Nanning, China (2020)
- HS, D.: Vehicle Safety Communications Project Task 3 Final Report Identify Intelligent Vehicle Safety Applications Enabled by DSRC (2005)
- Farr, N., Bowen, A., Ware, J., Pontbriand, C., Tivey, M.: An Integrated, Underwater Optical/Acoustic Communications system, pp. 1–6 (2010)
- Ng X.W., Chung WY.: VLC-based medical healthcare information system. *Biomed. Eng. Appl. Basis Commun.* **24** (2012)
- Netsianda, R.E., Ouahada, K., Ndjiongue, A.R.: A Comparative Study of Different Modulations for Visible Light Communications (2017)
- Shaaban, R., Faruque, S.: A Survey of Indoor Visible Light Communication Power Distribution and Color Shift Keying Transmission, pp. 149–153. Lincoln, Dearborn (2017)

36. Gong, Y., Ding, L., He, Y., Zhu, H., Wang, Y.: Analysis of space shift keying modulation applied to visible light communications. In: Proceedings of the IET International Conference on Information and Communications Technologies, Beijing, China, pp. 503–507 (2013)
37. Aziz, A.F., Aly, O.A.M., Mohammed, U.S.: High efficiency modulation technique for visible light communication (VLC). In: Proceedings of the IEEE 36th National Radio Science Conference (NRSC), pp. 100–107. Port Said, Egypt (2019)
38. Aliaberi, A., Sofotasios, P.C., Muhaidat, S.: Modulation schemes for visible light communications. In: Proceedings of the IEEE International Conference on Advanced Communication Technologies and Networking (CommNet), pp. 1–10. Rabat, Morocco (2019)
39. Salmento, M.L.G., Soares, G.M., Alonso, J.M., Braga, H.A.C.: A dimmable offline LED driver with OOK-M-FSK modulation for VLC applications. *IEEE Trans. Ind. Electron.* **66**(7), 5220–5230 (2019)
40. Sindhubala, K., Vijayalakshmi, B.: Design and performance analysis of visible light communication system through simulation. In: Proceedings of the IEEE International Conference on Computing and Communications Technologies (ICCCT), pp. 215–220 (2015)
41. Das, P.K., Sengupta, J.: Design and evaluation of wireless transceiver for visible light communication. In: Proceedings of the IEEE 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT), pp. 1–4 (2018)
42. Li, C.S.: Emerging Technology for Fiber-Optic Data Communication, pp. 631–651 (2008)
43. Liaw, S., Shin, C.: An Overview for Recent Development in Tunable Fiber Lasers 07–10 May, pp. 1–2 (2014)
44. Jawla, S., Singh, R.: Different modulation formats used in optical communication system. *IOSR J. Electron. Commun. Eng.* **8**, 15–18 (2013)
45. Loquai, S., Kruglov, R., Schmauss, B., Bunge, C., Winkler, F., Ziemann, O., Hartl, E., Kupfer, T.: Comparison of modulation schemes for 10.7 Gb/s transmission over large-core 1 mm PMMA polymer optical fiber. *J. Lightwave Technol.* **31**(13), 2170–2176 (2013)
46. Matsui, Y., Schatz, R., Carey, G., Sudo, T., Roxlo, C.: Direct modulation laser technology toward 50-GHz bandwidth. In: Proceedings of the IEEE International Semiconductor Laser Conference (ISLC), pp. 1–2. Kobe, Japan (2016)
47. Gao, X., Zhang, J.K., Jin, J.: Linear space codes for indoor MIMO visible light communications with ML detection. In: Proceedings of the 10th IEEE International Conference on Communications and Networking in China (ChinaCom), pp. 142–147 (2015)
48. Masuda, K., Kamakura, K., Yamazato, T.: Spatial modulation in layered space-time coding for image-sensor-based visible light communication. In: Proceedings of the IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 1–6 (2016)
49. Amano, Y., Kamakura, K., Yamazato, T.: Alamouti-type coding for visible light communication based on direct detection using image sensor. In: Proceedings of the IEEE Global Communications Conference (GLOBECOM), pp. 2430–2435 (2013)
50. Ebihara, K., Kamakura, K., Yamazato, T.: Spatially-modulated space-time coding in visible light communications using 2×2 LED array. In: Proceedings of the IEEE Asia Pacific Conference on Circuits and Systems (APCCAS), pp. 320–323 (2014)
51. Zhu, Y., Sun, Z., Zhang, J., Zhang, Y., Zhang, J.: Training receivers for repetition-coded MISO outdoor visible light communications. *IEEE Trans. Veh. Technol.* **66**(1), 529–540 (2017)
52. Alwarafy, A., Alresheedi, M., Abas, A.F., Alsanie, A.: Performance evaluation of space time coding techniques for indoor visible light communication systems. In: Proceedings of the IEEE International Conference on Optical Network Design and Modeling (ONDM), pp. 88–93 (2018)
53. Celik, Y., Akan, A.: Performance analysis of indoor mobile MIMO visible light communications. In: Proceedings of the 26th IEEE Signal Processing and Communications Applications Conference (SIU)
54. Chang, F., Onohara, K., Mizuochi, T.: Forward error correction for 100 G transport networks. *IEEE Commun. Mag.* **48**(3), S48–S55 (2010)
55. Minshid, M.: Error correction code in optical fiber. *J. Eng. Dev.* **11**, 108–119 (2007)
56. Shahjalal, M., Islam, M.M., Hasan, M.K., Chowdhury, M.Z., Jang, Y.M.: Multiple access schemes for visible light communication. In: Proceedings of the IEEE Eleventh International Conference on Ubiquitous and Future Networks (ICUFN), pp. 115–117. Zagreb, Croatia (2019)
57. Kaushal, H., Kaddoum, G.: Optical communication in space: challenges and mitigation techniques. *IEEE Commun. Surv. Tutor. Firstquarter* **19**(1), 57–96 (2017)
58. Khalighi, M.A., Uysal, M.: Survey on free space optical communication: a communication theory perspective. *IEEE Commun. Surv. Tutor. Fourthquarter* **16**(4), 2231–2258 (2014)
59. Ahmad, F., Ramachandrapura, S., Manattayil, J., Raghunathan, V.: Path-loss optimized indoor laser-based visible light communication system for variable link length gigabit-class communication. *IEEE Photonics J.* **12**(4), 1–12 (2020)
60. Borah, D.K., Boucouvalas, A., Davis, C., Hranilovic, S., Yianopoulos, K.: A review of communication-oriented optical wireless systems. *EURASIP Journal on Wireless Communications and Networking* (2012)
61. Edwards, B.L., Israel, D.J.: Commercialization and standardization progress towards an optical communications Earth relay. In: IEEE Aerospace Conference, pp. 1–7 (2015)
62. Schumacher, W.: Standardization efforts in fiber optics. *IEEE J. Sel. Areas Commun.* **3**(6), 950–952 (1985)

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optical communication, laser communication and IoTs

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