LED BASED VISIBLE LIGHT COMMUNICATION: TECHNOLOGY, APPLICATIONS AND CHALLENGES – A SURVEY

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ABSTRACT
Visible Light Communication (VLC) using light emitting diodes (LEDs) is a technology that provides an opportunity for high-speed low-cost wireless communication, being an alternative for effective and efficient communication that can cope with the actual high-speed wireless services demand. In this paper, we give an overview of LED-based VLC and provide a comprehensive survey on advances and research activities in this technology, focusing on several aspects such as main elements of VLC systems, potential applications and challenges for practical implementation, integration and commercialization. In addition, VLC is compared with radio frequency (RF) systems and future directions in the field of high-speed LED-based VLC systems are considered.

KEYWORDS: *Visible Light Communication, Optical Wireless Communication, Light Emitting Diode, Smart Lighting*

I. INTRODUCTION

Visible Light Communication (VLC) using Light Emitting Diodes (LEDs) comprises optical wireless communication (OWC) links using visible light spectrum, in which LEDs are applied with two functions, illumination and communication, simultaneously [1-2]. In VLC, communication takes place by modulating the intensity of the LED light in such a way that it is undetectable to the human eyes, having no negative effect on the illumination functionality. VLC is a category of OWC, which also includes Infrared (IR) and Ultra Violet (UV) communications, yet VLC is particularly of interest because the same visible light used for lighting is also used for communication.
The use of visible light as a wireless communication medium is nothing new. In old times humans communicated across great distances using beacon fires, mirror reflections, and light houses. But the first known electronic wireless communication using visible light comes from Alexander Graham Bell, who in 1880 developed a photophone [3] which transmitted modulated voice data over 200 m using beams of sunlight. After that, several incremental improvements on Bell design were done using tungsten lamps with IR filters, and high-pressure vapor and mercury arc lamps [4]. Later, there were other demonstrations featuring fluorescent lights for communication with low data rates [5]. Then, the idea of using visible light as an effective fast communication medium has been retaken with the development of LED lighting systems with lower power consumption and longer life-time compared to other types of lamp systems, in addition to other advantages such as high lighting efficiency, specific spectrum and environmental friendliness. Nowadays, LEDs are becoming the lighting source for almost all illumination applications [2, 6], and such lighting systems provide an infrastructure for VLC with the use of LEDs not only for illumination but for high speed data transmission.
The concept of VLC using fast switching LEDs was conceived in Japan in 1999 by Pang et al. [7], who described a VLC system implemented on LED traffic lights to provide open space, wireless broadcasting of audio messages. In 2001, Kulhavy of Twibright Labs developed RONJA (Reasonable Optical Near Joint Access) [8], a free technology project for reliable free-space optical data links using visible light with a range of 1.4 km and communication speed of 10 Mbps full duplex. The use

of white-LED for both lighting and communication was driven by Tanaka et al. in the early 2000s [9-10], reporting a 400 Mbps data transmission based on numerical analyses and computer simulations. Over the past few years research groups have been able to demonstrate that high data rates up to the gigabit per second range are possible with LED based VLC using the right choice of modulation and line coding schemes, and use of equalizers at transmitter and receiver [11-14]. On the other hand, there are many initiatives to promote and standardize VLC technology. For instance, the Visible Light Communication Consortium (VLCC) [15], which includes major companies in Japan, was established in November 2003 to publicize and standardize the VLC technology; the OMEGA (HOME Gigabit Access) project in Europe, run by researchers from companies, universities and research institutions to develop a home/office access network capable of delivering high-bandwidth services and content at a transmission speed of 1-Gbps using a combination of power cables, radio signals and light [16]; the IEEE 802.15.7 Visible Light Communication Task Group [17], initiated in 2009, which has completed a PHY and MAC standard for VLC, and the Li-Fi Consortium [18], founded in 2011 and conformed by technology companies and research institutions in optical communication technology, with the aim of introducing optical wireless technology, developing the concept and roadmap to establish the new technology in the market. Other important research centers and institutes that are also undertaking R&D activities to develop and commercialize VLC technology include University of Oxford (U.K.), Smart Lighting Engineering Research Centre (Boston University), UC-Light Center (University of California, U.S.), Keio University (Japan), and University of Edinburgh.

There are several interesting survey papers regarding VLC which had been published previously. For instance, Karunatilaka et al. [19] provides a comprehensive survey on VLC with an emphasis on challenges faced in indoor applications. Authors compared VLC with IR and RF systems, present the advantages of LEDs compared to traditional lighting technologies, discussed in detail modulation schemes and dimming techniques for indoor VLC and consider some methods to improve VLC system performance. The survey also discussed possible applications of this technology, and presents some limitations of VLC as well as the probable future directions in this subject. In [20], a brief survey is conducted on the most recent advances and research activities in OWC including VLC. In [21], authors introduce the concept of VLC and provide an overview of applications and design challenges for VLC, presenting also some modulations techniques used. A survey by Wu et al. [22] covers the literature work on VLC networking as part of 5G wireless communication systems, highlighting strengths and weaknesses of VLC compared to RF-based communications. Bhalero et al. [23] provide a broad overview of VLC applications and design challenges, and discussed the communication architecture presenting the structure of the physical and data link layers of the protocol stack for VLC. Sevincer et al. [2] gave a well detailed tutorial and survey on various aspects of free-space-optical (FSO) communications and smart lighting, which includes aspects of both technologies: propagation model, stationary and mobile scenarios for FSO, and drivers and thermal management for Solid State Lighting (SSL). In addition, authors discussed several topics on VLC: channel model, noise, modulation, dimming and multiplexing techniques. In [24], the authors present recent achievements and trends in high-speed indoor VLC research, addressing potential applications of this technology. In [25], Tsonev et al. reviewed the development of Li-Fi systems which are related to VLC, and discuss all key component technologies required to realize an optical cellular communication system using OFDM, as well as potential uplink schemes. A survey on several aspects of broadband power line communication (PLC), VLC and new prospects for their integration is given by Ma et al. in [26]. Kumar et al. also present a survey [27] which covered several aspects of LEDs and their use for communication purposes in VLC systems, describe the basic architecture of a VLC transceiver, consider the optical wireless channel and the performance of VLC systems, as well as various indoor and outdoor applications of VLC.

In this work we focus on three main aspects of VLC: components of VLC systems, potential applications and challenges for practical implementation, integration and commercialization. In addition, we provide a brief comparison of VLC with RF systems, and discussed the research outlook in the field of LED-based VLC systems.

The rest of the survey is organized as follows: Section II compares VLC with RF communication; Section III explores several aspects of VLC systems such as basic structure of transmitter and receiver, LED characteristics, modulation techniques, and parallel transmission, and in Section IV current and potential applications of VLC are described. Next, in Section V, the main challenges for implementation of VLC are considered and Section VI deals with the challenges for commercialization. Section VII discusses possible future directions in VLC, and finally Section VIII summarizes the survey and gives important conclusions.

II. ADVANTAGES OF VLC OVER RF

Within the electromagnetic (EM) spectrum, the Radio Frequency (RF) band (from 3 kHz to 300 GHz) has been the most widely used band for wireless communications purposes. Nevertheless, the exponential growth of wireless traffic demand is resulting in a congested, scarce and expensive RF-spectrum, limiting the achievable capacity of the networks. Conventional methods for capacity improvement, enhanced spatial reuse and inter-cell interference coordination, will not be able to overcome this limitation. Therefore, a new communications medium and an alternative technology are required to ever increase the capacity. In this sense, VLC using the visible light band (from 400 THz to 800 THz) is emerging as an option to traditional RF communication methods and may be used to complement current RF systems, particularly in indoor environments where, according to recent studies, more than 70% of the wireless traffic originates [28]. In this sense, VLC has unique advantages compared to RF to provide secure, low-cost and high-speed communications [2, 19, 20, 23, 29]: *i*) the visible light spectrum is not regulated, is license-free and is ten thousand times wider than the RF-spectrum, allowing immediate use for high-speed data transmission; *ii*) most indoor environments are LED illuminated so VLC can easily be implemented into existing lighting infrastructure using relatively simple and cheap off-the-shelf illumination components and photodetectors – resulting inexpensive systems compared to RF; *iii*) VLC is highly energy efficient in indoor environments since it uses the existing LED lighting system and thus the extra energy necessary for data communication is minimal; in addition LEDs are energy efficient and highly controllable light sources providing an eco-friendly technology; *iv*) visible light cannot penetrate solid objects and can easily be directed through optics eliminating the interference with other devices and allowing the coexistence of many non-interfering links in close proximity, which allows greater data density and spatial reuse of resources, increasing network capacity; *v*) due to the nature of the visible light, information may be contained within the confined space of the specific premises where a VLC system is deploy, eliminating the possibility of casual eavesdropping, and interference between spatially isolated communication systems, providing a secure data communication; *vi*) light waves do not create electromagnetic interference (EMI) to sensitive electronic systems, making VLC suitable for a variety of places and applications where EMI is potentially dangerous and RF is not allowed, such as airplanes and hospitals; *vii*) RF transmission power cannot be increased over certain levels because of serious health risks for humans, while there are no known concerns of safety or health for visible light in illumination conditions.

The unique features and clear benefits of VLC by combining LED lighting with communication make it one of the most important technological innovations in communication systems. VLC is not expected to replace RF, but rather complement it in the context of heterogeneous networks where the best of both worlds (visible light and radio frequency) are used. For example, VLC can be integrated, as complementary wireless technology, to indoor power line communication (PLC) systems [26] in the way that Wi-Fi currently supports broadband Ethernet connections.

III. VISIBLE LIGHT COMMUNICATION SYSTEMS

Since VLC technology provides communication and lighting, typical LED based VLC systems are implemented using an intensity modulation and direct detection (IM/DD) scheme with a line-of-sight (LOS) configuration due to its illumination purpose. This has several advantages such as the possibility to implement the system using the current state of off-the-shelf illumination components and photo detectors, and a higher bandwidth due to lower path loss and dispersion over short distances [19]. In the transmitter, IM is implemented through the modulation of the transmitted signal into the instantaneous optical power of the LED by controlling the radiant intensity with the forward current through the LED. High modulation frequencies are used to avoid flicker, which can have adverse health effects. In the receiver, the transmitted signal is recovered using direct detection (DD). In this simple method, a photodiode is used to convert the incident optical signal power into a proportional current. Due to the changes in instantaneous power, DD is the only possible signal recovery process of the signal. Figure 1 shows a general VLC link structure for an IM/DD based VLC system.

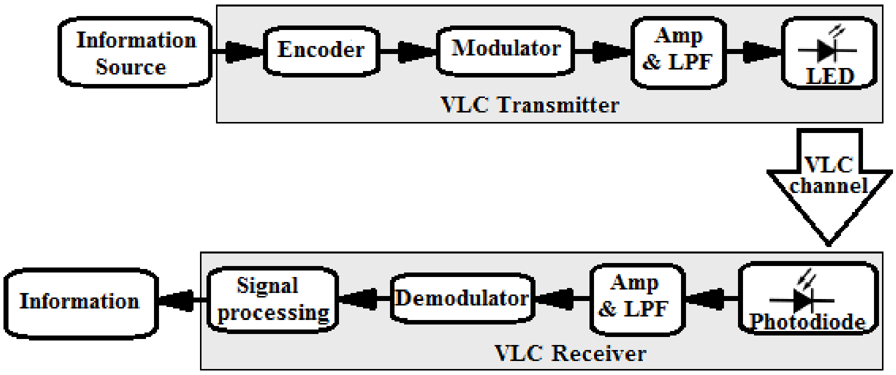

Figure 1. General VLC link using IM/DD.

3.1 LED Types

There are different types of LEDs, each with its own special characteristics which make them suitable for different types of applications with specific requirements. Valuable information about different categories of LEDs including key features and a comparison between them can be found in [19]. Here, we summarize some of the most important types of LEDs that can be used for VLC.

pc-LEDs. The Phosphor Converted LED is a blue LED with a phosphor layer coated on top of it in order to convert part of the blue light to green, yellow and red while the other part of the blue light is leaked out, resulting a mixture which produces white light. These LEDs are low cost but have a bandwidth limitation (the direct modulation frequency is limited to a few MHz) due to the slow response of the phosphor.

Multi-chip LEDs. These LEDs consist of three or more LED chips which emit different colors, typically Red, Green and Blue (RGB), to produce white light. They have the advantage that color control can be achieved depending on the light intensities of the different chips, and three individual color channels can be implemented, each providing approximately 15 MHz bandwidth.

Micro LEDs (μ-LEDs). These diode arrays have been in development for VLC recently and have the potential to be used as display panels incorporating high density parallel communication allowing speeds of up to 1.5 Gbps.

Resonant Cavity LEDs (rc-LED). These LEDs use the resonant cavity method to improve the light extraction efficiency as well as other properties as directionality, intensity and purity. rc-LEDs are particularly suited for optical communication applications, more specifically data communication via Plastic Optical Fiber (POF) and IR wireless communication, but high brightness rc-LEDs would benefit VLC for color displays. They can be modulated in excess of 100 MHz.

3.2 Channel characteristics for indoor VLC

Indoor VLC channel is usually characterized by the optical wireless (OW) channel, which was initially used for IR communication but has been applied to the visible spectrum. Nevertheless, efforts are being made to characterize the channel for VLC, because IR models may not necessarily be accurate enough [30]. In [31], authors examine and compare various channel models for both indoor and outdoor OWC systems.

In general, in OW links the multipath effect leading to dispersion and attenuation is virtually non-existent, and in indoor environments, the received optical signal experiences time dispersion due to reflections from walls and other objects. Most reflections are typically diffuse in nature, and most are well-modelled as Lambertian emitters [32, 33], which scatters incident light omni-directionally with the same power, creating a diffuse environment.

3.3 Transmitter

A typical LED based VLC transmitter contains a signal generator (information source), mechanisms for run length limited (RLL) line coding and channel coding for forward error correction (FEC), and a modulator, followed by the LED driver and the LEDs. RLL lines codes are used to avoid long runs of

1s and 0s that could potentially cause flicker and clock and data recovery detection problems. Several FEC schemes are used and support both long and short data frames for high-data-rate indoor and low-data-rate outdoor applications. For indoor applications Reed-Solomon (RS) codes are better suited for high-data-rate implementation and interface well in conjunction with the RLL line codes. For outdoor applications, stronger codes using concatenated RS and convolutional codes are used to overcome the path loss due to longer distance and potential interference introduced by optical noise sources. Then, the modulator adapts the signal to the channel for transmission. The modulation methods available for VLC, particularly for indoor applications, must support dimming and provide flicker mitigation. Integrating dimming into VLC enhances system value, saves energy and facilitates intelligent lighting solutions, which requires efficient dimming techniques that allow a balance between the two basic functions of VLC: illumination and communication. An interesting overview of dimming mechanisms for VLC to save energy and provide precise illumination control is given in [34]. The modulating signals are used to switch LEDs at desired frequencies using LED drivers. These drivers rely on transconductance amplifiers to convert voltage signals to corresponding current signals to excite the light sources (LEDs) for both communication and illumination purposes.

3.4 Modulation

This section gives a brief overview of various features and properties of different modulation schemes for VLC, mainly, on-off keying (OOK), variable pulse-position modulation (VPPM), color shift keying (CSK) and orthogonal frequency division multiplexing (OFDM). The first three methods are offered in the physical (PHY) types of the IEEE 802.15.7 standard. PHY I and PHY II are defined for a single light source, and support OOK and VPPM, while PHY III uses multiple optical sources with several frequencies (colors) and uses CSK. All three schemes can coexist with each other, provide flicker mitigation and support dimming, allowing trade-off between data rates and diming ranges [35].

OOK is the most commonly used IM/DD modulation scheme in VLC due to its simple implementation. In this method basically the LED intensity is changed between two distinguishable levels corresponding to the data bits (1 or 0). This method combined with other techniques such as NRZ line coding, doubinary pre-coding and equalization, enables high data rates [36]. A modified OOK, called Variable OOK (VOOK) can provide dimming. It is achieved by changing the data duty cycle and filling up the non-data portion of the symbol with filler bits [35]. No data can be transmitted at full brightness. It is possible to provide OOK dimming by changing the average intensity level of the transmitted light, but it would risk chromatic shift.

VPPM is a mixture of pulse-position modulation (PPM) (used for communication), and pulse-width modulation (PWM) (used for dimming control), with only 1 bit of information carried per symbol period. When the duty cycle is 50%, VPPM becomes the same as binary PPM, and at full brightness no information can be transmitted. At low dimming levels though, the data rate and performance is severely hampered due to the low bit energy. A valuable modelling and analysis of VPPM for VLC is given in [37]. Compared to OOK, the required average power for PPM is lower, but it is less bandwidth efficient, and system complexity is higher, as it requires stricter bit and symbol synchronization at the receiver. There are several modifications of the PPM scheme which are applied into VLC system for achieving certain performance parameters. For instance, Multiple PPM [38] which is also used for dimming control as well as data transmission; expurgated PPM (EPPM), interleaved EPPM to counter ISI, and overlapped EPPM to counter LED bandwidth limitations [39]; differential PPM (DPPM) to achieve a transmission capacity larger than that of PPM because all the unused time slots are eliminated from within each symbol [40]; and overlapping PPM (OPPM) which allows overlap between pulse positions and thus can yield higher data rates [41].

CSK is an intensity modulation scheme that transmits data imperceptibly through the variation of the color emitted by red, green, and blue (RGB) multi-chip light emitting diodes. In CSK, the M-ary color coding scheme groups consecutive $k = \log_2 M$ incoming bits into M-ary CSK symbols mapped onto a two-dimension color constellation point in the form of a *xy* color coordinate set. The color coordinates are generated by the intensity of the three light sources; hence, these *xy* color coordinates are converted to a three-element optical intensity vector before transmission, which represent the power of the light sources [42, 43]. CSK cannot be used in a VLC system where the source is a pc-LED and implementation of CSK requires a complex circuit structure. An advantage of CSK is that the power envelope of the transmitted signal is fixed; therefore, CSK reduces the potential for human health complications related to fluctuations in light intensity.

OFDM allows high data rates transmission by using multiple orthogonal sub-carriers to transmit parallel data streams simultaneously. Since LEDs are non-coherent sources, maintaining the orthogonality is achieved in the encoding level, by introducing guard intervals with cyclic prefix as described in [44]. The inherent robustness of OFDM against multipath effects, the possibility to combine it with any multiple-access scheme such as TDMA, FDMA, CDMA and WDMA, and the possibility to use high order modulation schemes makes it an excellent choice for VLC. Moreover, the issue of high peak-to-average power ratio in OFDM can be exploited constructively for VLC [20]. The one thing should be consider is that in optical systems with IM/DD, only real-value unipolar signals are used, therefore in OFDM the subcarriers should have Hermitian symmetry (to produce real value signals), and the conventional OFDM used in RF communication should be modified. To achieve this type of output signals for VLC, there are two common schemes, namely, DC-biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) [45].

There are several other modulations schemes that can be used for VLC, including [19][35]: Pulse-Position-Pulse-Width Modulations (PPM-PWM), Pulse Amplitude Modulation (PAM), Pulse Dual Slope Modulation (PDSM), Generalized Space Shift Keying (GSSK), Generalized Color Modulation (GCM), Color Intensity Modulation (CIM), Carrier-less amplitude and phase modulation (CAP), PWM with Discrete Multi-Tone (PWM-DMT), Reverse Polarity OFDM, and Dimming-DMT.

3.5 Receiver

A typical optical receiver's front end consists of a photo detector (PD) followed by an amplifier and a limiting amplifier (LA). The rest of a basic software-defined-radio (SDR) receiver includes an analogue-to-digital converter and a digital signal processing unit. A simple PD can be used as a receiver since VLC exhibits no Doppler shift, and therefore it is not necessary a sophisticated receiver tracking algorithm [46]. The two types of PD used in VLC systems are PIN PD and Avalanche PD. The latter has a higher gain and is more useful with weak incident light intensity, but it has a high shot noise generated by the higher photocurrent. Usually the amplifier is a Trans-Impedance amplifier, and the LA is designed to be heavily non-linear. The choice and design of the front end is usually a trade-off between speed and sensitivity. The SDR system is simplified since it does not require oscillators and down-conversion mixers because in IM/DD carrier frequencies are located in the baseband.

Among many possible receiver configurations in VLC, the most common are [19]: *i*) single element receivers which are the most widely used and experimented in VLC; *ii*) selective combining receivers that have been proposed for outdoor intelligent traffic light systems and indoor applications using OFDM, and *iii*) image diversity receivers which have been proposed for multiple-input/multiple-output (MIMO) implementations in VLC.

3.6 Hybrid VLC Schemes

VLC can be combined with other existing communication technologies such as RF and IR to enable hybrid schemes which can take advantage of the best characteristics of different systems and provide better performance in terms of connectivity, energy consumption, throughput or data rate than conventional stand-alone VLC, WiFi or IR systems. There are several examples of such hybrid schemes, for instance, an indoor system that integrates WiFi and VLC luminaries [47] which utilizes broadcast VLC channels to supplement RF communications and a handover mechanism between WiFi and VLC to dynamically distribute resources and optimize system throughput; a hybrid VLC/RF system [48] proposed in an intelligent transportation system for position-based services, and a hybrid VLC/OFDMA network model giving in [49] which consists of VLC hotspots for the downlink and one OFDMA access point for the uplink.

IV. Current and Potential VLC Applications

LED based VLC has unique advantages to provide safe, secure, low-cost, and high-bandwidth communications. Many distributed applications from indoor to outdoor can benefit from VLC, including broadband access, power line communication, indoor localization, vehicle communication, distributed lighting remote monitoring and control etc. In this section, several current and potential applications [19, 20, 23] in a number of areas are briefly described.

Home and Office: VLC is a strong alternative for wireless access in RF saturation and forbidden situations. Any lighting lamp can be used to provide VLC hotspots and the same communications and sensor infrastructure can be used to monitor and control lighting and data. For example, a secure and very high data rate LAN can be deployed where computers, printers, mobile phones, and other mobile devices are interconnected using VLC. It can also be used to deal with high demand indoor wireless access to Internet and real-time bandwidth-intensive applications such as Voice over IP (VoIP), video conference, real-time video frequency monitoring, and network attached storage (NAS) [50]. Figure 2 illustrates several potential applications at home using VLC.

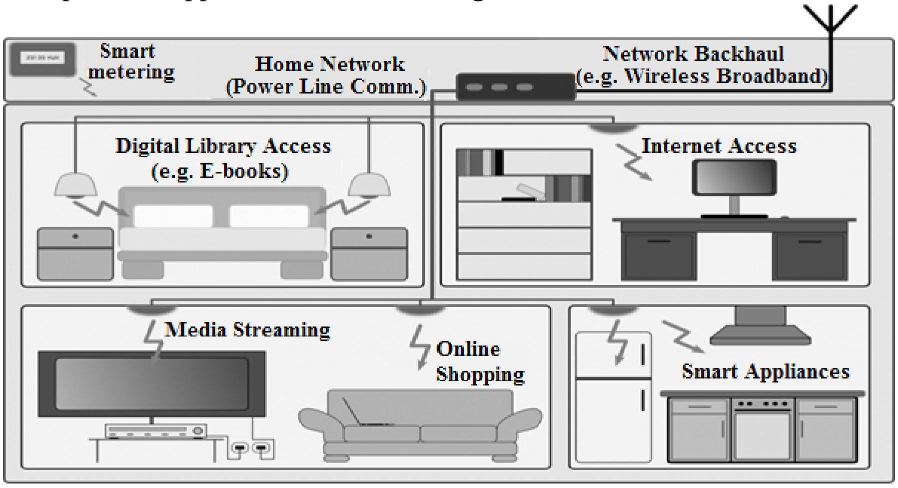

Figure 2. VLC applications at home [51].

Transport systems: Nowadays, LEDs are used in head/tail-lights for vehicles, street lamps, signage and traffic signals. This allows the deployment of smart traffic systems based on VLC where vehicles can communicate with each other about speed, routes and destinations of themselves to avoid traffic accidents and share traffic information which is unknown in advance for traffic management; and some infrastructures could share valuable information with passing vehicles to help drivers and ensure road safety [52]. Other examples include traffic lights and street lamps that can display and transmit modulated information to vehicles, and aircraft navigation lights with identification transmission. Other promising VLC application is the use of the traveller lighting in aircrafts to transmit music and video, and exchange data with wired base stations in the aircraft cabin [53].

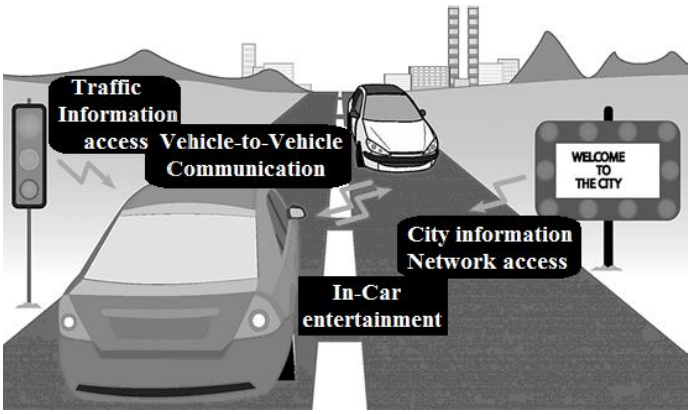

Figure 3. VLC for transport information systems [51].

Hospitals, industry and dangerous environments: VLC systems have a lot of advantages in environments susceptible to EMI such as hospitals, mines and petrochemical plants [54-56]. Most medical equipment requires isolation from EMI and RFI; therefore, VLC is suitable to provide equipment and staff communications. Other example is the industrial lighting with inbuilt communications and localization that can provide intrinsically safe communications in areas with flammable materials.

Underwater communications: VLC is an excellent alternative for high speed underwater communication compared to RF transmission, which is still extremely difficult, and acoustic communication which results expensive and have limited data rate. Several systems have been proposed for wireless sensor networks, remotely operated vehicles and diver communication applications [57, 58].

Public areas: Theatres, museums, malls and other public areas can be equipped with accurate positioning, localization and navigation systems based on VLC. A mobile indoor positioning system might help, for example, guide audience members to their seats in theatres, trigger a particular audio or video guide script in a museum, or help shoppers to find discounted items in a store [59]. In addition it will be possible to provide information and communication in case of civil contingencies.

Defence and Security: VLC technology can be activated and deployed in the visible spectrum providing natural advantages like secure and covert communication, not affected by RF interference and with no omnidirectional emissions. In addition to very high data rate communication, positioning and range information can be provided replacing GPS based systems in many places. These characteristics also make VLC systems suitable in a disaster recovery situation.

V. LIMITATIONS AND CHALLENGES FACED BY VLC

Despite having inherent advantages compared to other communication systems, VLC still faces numerous challenges which need to be addressed. VLC is in an early development stage, and for the eventual commercial adoption several issues or limitations require attention [19, 20, 21, 23, 27]. Some of these issues are addressed in this section.

Modulation bandwidth. One of the major challenges in VLC is the low modulation bandwidth available from LEDs, which is typically several megahertz. This low bandwidth limits the achievable data rate. There are several methods to improve the bandwidth available for communications using white-light LEDs, that include: blue filtering, in which the yellow phosphor component at the receiver is blocked by using a blue filter, enhancing the modulation bandwidth up to ~20 MHz, but with a penalty by reducing the received power; pre-equalization at the transmitter, which is registered to increase the bandwidth up to ~45 MHz; post-equalization at the receiver after the PD signal amplification, which is registered to increase the bandwidth up to ~50 MHz; combining equalization at the transmitter and the receiver; adaptive equalization based on the least mean squares algorithm to estimate and compensate the Inter-symbol Interference (ISI), improving the data rates as well as the bit-error-rate; and sub-carrier equalization for multi-carrier systems using DMT/OFDM, which uses signal pre-equalization at the transmitter and channel estimation.

Interference and Noise. Other artificial and natural light sources such as fluorescent, incandescent and sunlight create background noise and interference as it shares the same wavelength band as the VLC transmission. This in-band interference must be removed to increase the signal-to-interference-noise-ratio (SINR) at the receiver. Optical filters are a simple method to eliminate the vast majority of interference from natural and artificial sources, and combined with further analogue and digital filtering after the photo-detector, it could ensure remaining interference is negligible. Manchester encoding has proofed robust against lower frequency fluorescent lighting and mitigate optical background noise generated in AC-LEDs operating at low frequency < 500 kHz.

Nonlinearity. LEDs are the main source of nonlinearity in optical systems, and it has to be taken into account when modulating as amplitude distortion occurs, having a significant impact on the performance of the optical system. The nonlinearity has a higher impact on OFDM and causes increase in BER and Inter-carrier Interference (ICI). In order to control the LED nonlinearity induced distortion, it is necessary to search for an optimum DC operating point and optimal OFDM signal power to modulate the LED intensity. Moreover, error-performance can be improved by considering an LED with large dynamic range, low voltage-current slope characteristics, while employing signal clipping or other power reduction methods. Degradation in OFDM can greatly be mitigated by using the pre-distortion and post-distortion to counteract the effect of the nonlinearities.

Up-link channels. VLC can be used for data transmission in either upward or downward direction. The fundamental task of illumination makes VLC naturally suited for broadcast applications, and providing an effective uplink to the distributed transmitter structures has been a problem [60]. The uplink and downlink can be isolated in different ways like wavelength, time and code, and also by spatial or optical isolation. Nevertheless, due to cost reasons and high bandwidth VLC may be implemented to provide a high capacity uncongested downlink while Wi-Fi or IR may provide a reliable uplink where congestion is less likely. Several up-link approaches have been proposed, including IR, near UV, RF and retro-reflective transceivers, but further study needs to be done to investigate other solutions and compare the performance of all these options [61-63].

Levels of illumination. Since VLC is based on an illumination source, there is an important task in minimizing the degradation of information transmission performance when the level of illumination changes, up to the point of being able to transmit even in those situations when lights are usually off. When locations are occupied, lights are usually on for illumination purpose and hence VLC can take place at no power cost. But during conditions when lights tend to be off, VLC could not take place. Then, it is necessary for the lights to be on but dimmed up to provide the necessary power required for VLC to transmit information without the illumination being noticed. In general, it is necessary to adjust brightness of LEDs as time changes while keeping the transmission within acceptable performance, which require techniques to control the LED power and the data transmission and dimming control functions.

Line of sight (LOS). Indoor VLC is built for LOS. Receivers are expected to have a clear LOS to the lighting system at most times which is a definite advantage because the signal will be stronger. Visible light signals can be reflected but does not penetrate most of objects which can be a coverage disadvantage and distributed lighting sources must be provided to maintain a high SNR throughout. If light levels are low and VLC receivers do not have LOS, communication is greatly limited and hence the data rate reduces. Therefore, it is also important to analyse the shadowing effect and find possible solutions to it.

Mobility. OWC systems are required to allow for user mobility. If the receiver or transmitter is mobile, the link can be lost due to movement or rotation of the terminal. Hence, it is necessary and important to have link recovery, rate adaptive techniques and handover mechanisms to maintain the communications. Such problems are challenging and need to be investigated [64].

Multipath distortion. When the transceivers are equipped with wide beam, the copies of the same signal from different paths arrive at the destination with different delays, because each path has different length from source to destination. This creates multipath distortion which can cause ISI that severely degrades the performance.

VI. CHALLENGES OF VLC COMMERCIALIZATION

Even though VLC has the potential to provide safe, secure, low-cost and high-bandwidth communications and enhance wireless network performance, the widespread adoption of VLC in the consumer market face certain business challenges. One critical challenge is the fact that VLC depends on two different industries, lighting and communication, requiring a coordinated work from different manufacturers and regulatory bodies in order to bring attractive products to market and frameworks to ensure compatibility of any techniques. Some work on VLC standardization has already been done, including the IEEE 802.15.7 standard for short-range OWC using visible light, and the VLC Consortium that has developed several standards for VLC. The development of a PHY layer for VLC with the same features as cellular communications, may allow the replacement of the standard RF front-end with an optical alternative. This will remove the need to standardize the entire communication system, and VLC may be employed in a large-scale network with minimal infrastructure and coordination efforts, facilitating its commercialization.

Other challenge is to find an “impact use case” to offer a sufficient incentive for potential companies and get the market attention. This use case seems to be the high-accuracy indoor positioning since it does not require additional hardware in mobile devices and there is already great interest in it from the lighting manufacturers and their customers. Other very attractive use case is the downlink use in indoor networking applications to provide data connectivity in point-to-point scenarios, but there are still some technical issues to overcome.

Finally, it seems a challenge to find where the place is for VLC and how to make the best use of it, and in general OWC technologies, in the next generation heterogeneous wireless communications.

Market conditions

Despite VLC technology is still in the research and development phase, with some technical challenges and the need for standardization, companies are actively working on the commercialization of the technology. VLC market is projected to start taking place from 2015, supported by the LED lighting proliferation. A market research report by Market & Market [65] indicates that the VLC market size is expected to grow with a CAGR (compound annual growth rate) of 87.313% from 2014 to 2020. The report indicates that by 2016, the market will enter into almost all main application areas of VLC technology, accounting communication application for the largest percentage share, followed by automotive application; whereas in the components market, transmitter and receiver are the highest revenue earner. VLC applications covered in the report include intelligent traffic management system, indoor communication, in-flight entertainment, underwater communications and location-based services. Future applications of VLC, which are in the development stage, include M2M communications, smart city, WSN and ubiquitous computing etc. According to the report, the major companies involved in the research and development of VLC technology are LVX System (U.S.), NAKAGAWA Laboratories (Japan), Oledcomm- France LiFi (France), Outstanding Technology (Japan), and Casio Computer (Japan).

VII. FUTURE WORK

As it was discussed in previous sections, currently VLC technology is in a development stage with several limitations and challenges, both technical and commercial that must be addressed. Thus, future work in VLC will include, in addition to solutions of the previously stated issues, development of new LED materials and devices with better characteristics, not only for lighting but for communication (for transmission and reception mode); improve the transmitter design under power and thermal considerations which are issues related to the illumination-communication trade-off of VLC; improve channel models for VLC, especially for outdoor no-line-of-sight environments; upgrading of current lighting infrastructure to support communication and development of standards to support networking of light sources to provide communication; solutions to allow VLC in dark environments or really low intensity illumination; improvement of protocols of layers 2 and 3 due to challenges imposed by the directionality and spatial correlation of neighbouring optical structures; implementation of optical receivers in already commercial devices such as smartphones, laptops, watches, etc.; seamless interoperability with other networks, and other not yet known problems that could arise.

VIII. CONCLUSION

The ubiquity of emerging LED lighting in offices, homes, commercial displays, traffic signals, electronic devices, home appliances etc., arises the opportunity to provide wireless communication from every light source using the visible spectrum. Thus, LED based VLC has recently emerged as an important area of research in the field of wireless communications. Its dual purpose – communication and lighting, an already set infrastructure based on LED illumination, and limitations of RF communication, have attracted attention on VLC potential applications and scenarios where it can be deployed. VLC, and in general OWC techniques, are promising complementary technologies to RF communication systems for both indoor and outdoor applications, in next generation wireless communication systems. Being a relatively modern technology, there are, of course, many technical and commercial challenges that VLC systems are currently facing and that have to be overcome, but it is clear that its deployment and propagation have already begun.

In this survey, we have referenced valuable works that demonstrate the potential capacity and advantages of VLC as well as applications and scenarios of LED based VLC, discussed main technical and commercialization challenges, and considered open problems that need further study.

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