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LED Based Indoor Visible Light Communications: State of the Art

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Abstract

Visible Light Communication (VLC) is an emerging field in Optical Wireless Communication (OWC) which utilizes the superior modulation bandwidth of Light Emitting Diodes (LEDs) to transmit data. In modern day communication systems, the most popular frequency band is Radio Frequency (RF) mainly due to little interference and good coverage. However, the rapidly dwindling RF spectrum along with increasing wireless network traffic has substantiated the need for greater bandwidth and spectral relief. By combining illumination and communication, VLC provides ubiquitous communication while addressing the shortfalls and limitations of RF communication. This paper provides a comprehensive survey on VLC with an emphasis on challenges faced in indoor applications over the period 1979-2014. VLC is compared with Infrared (IR) and RF systems and the necessity for using this beneficial technology in communication systems is justified. The advantages of LEDs compared to traditional lighting technologies are discussed and comparison is done between different types of LEDs currently available. Modulation schemes and dimming techniques for indoor VLC are discussed in detail. Methods needed to improve VLC system performance such as filtering, equalization, compensation and beamforming are also presented. The recent progress made by various research groups in this field is discussed along with the possible applications of this technology. Finally, the limitations of VLC as well as the probable future directions are presented.

1 Introduction

Wireless communication has gone through several paradigm shifts starting from the discovery of Electromagnetic (EM) waves, wireless telegraphy, and the invention of the radio. Figure 1 depicts the EM spectrum along with the wavelength band of various waves which include radio wave, microwave, infrared, ultra violet, X-ray and gamma ray. Along the EM spectrum, as the wavelength decreases, the frequency as well as the energy of the waves increases. The visible light band occupies the frequency range from 400 THz to 800 THz and the radio wave occupies the band from 3 kHz to 300 GHz. Radio Frequency (RF) has been the most widely used portion of the EM spectrum for communication purposes, mainly due to little interference in the frequency band and wide area coverage. However, several factors including the rapidly decreasing RF spectrum is driving the needs for an alternative technology. Visible Light

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Communication (VLC) is emerging as a solution to overcome the crowded radio spectrum for wireless communication systems. In VLC, information is transmitted by modulating the intensity of an optical source operating in visible range of the EM spectrum at a rate much faster than the response time of the human eye, which is effectively perceived as a steady glow.

LEDs due to their unique characteristic of high switching rate had predominantly become the most suitable light source for VLC. With the recent thrive for energy efficient light sources for residential, retailing and commercial units, LEDs are rapidly replacing traditional lighting fixtures, which make the case of using them for VLC much more stronger.

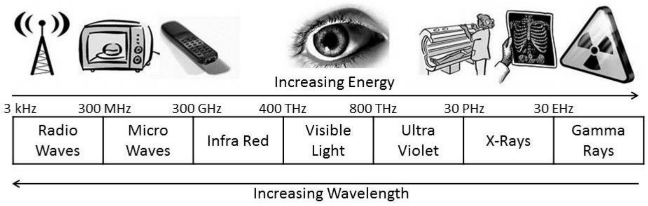

Figure 1: The Electromagnetic Spectrum

In VLC, the possibilities of usage are numerous; users could download information from signage by merely pointing a mobile phone or a PDA towards the fixture, with a visibly defined 'hot-spot'. Data could be transferred from one mobile device to another, by pointing a beam of light, making alignment simple with the visible beam. Other uses include indoor broadband access, power line communication, indoor localization, vehicle to traffic light and vehicle to vehicle communication, underwater communication, distributed lighting remote monitoring and control etc.

The earliest known use of visible light wireless communication comes from Alexander Graham Bell, who in 1880 developed a photophone [1] which transmitted voice data over 200 m using beams of sunlight. Several other demonstrations featuring fluorescent lights for communication with low data rates were investigated [2]. The concept of using fast switching LEDs as well as modulating visible light for communication was presented for the first time by Pang *et al.* in 1999 [3]. In 2001, RONJA (Reasonable Optical Near Joint Access) used visible light beams to transmit data at 10 Mb/s over 1.4 km [4]. Utilizing White-LED (WLED) for illumination and communication began to take shape in the early 2000s in Japan, pioneered by Tanaka *et al.* [5] at Keio University. In 2003, the Visible Light Communication Consortium (VLCC) was founded to promote and standardize VLC technology [6]. Recently, the hOME Gigabit Access project (OMEGA) in Europe, aimed at delivering gigabit data rates for home users, has been developing Optical Wireless (OW) as a viable technology to supplement existing wireless RF technologies [7, 8]. The initiative includes industrial partners such as Siemens and France Telecom. Notable other research groups include Center for Ubiquitous Communication by light (UC-Light) [9], Center on Optical Wireless Applications (COWA) [10], Smart Lighting Engineering Research Centre (Boston University) [11], University of Edinburgh [12] and Oxford University [13]. In 2011, the first IEEE standard for 802.15.7 VLC was published by the IEEE 902.15 working group for Wireless Personal Area Networks (WPANs) [14, 15].

There are a few survey papers regarding this field which had been published previously. A recent survey by Wu *et al.* covers the literature for the benefits of using VLC as a potential

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Table 1: Comparison of this study with available surveys

Approach	Key concept	Wu *et al.* [16]	Khaligi *et al.* [17]	Sevincer *et al.* [18]	Tsonev *et al.* [19]	Ma *et al.* [20]	Demers *et al.* [21]	Kumar *et al.* [22]	This survey
LED	Illumination theory			✓				✓	✓
	Classification of types								✓
VLC	Link structure	✓	✓	✓		✓		✓	✓
	MIMO systems	✓	✓	✓					✓
	Hybrid schemes			✓			✓		✓
PLC				✓		✓			✓
Modulation	Basic theory	✓	✓	✓	✓			✓	✓
	Comparison		✓						✓
Dimming schemes	Basic concept	✓		✓				✓	✓
	Comparison								✓
Driver circuitry				✓				✓	✓
Multiple access					✓				✓
Networking perspective				✓	✓		✓		
Receiver	Front end analysis							✓	✓
	Classification								✓
Market analysis									✓
Limitations					✓			✓	✓
Performance enhancement	Filtering								✓
	Equalization								✓
	Optical beamforming		✓				✓		✓
Recent progress	Latest literature	✓							✓
	Research groups								✓
Applications			✓	✓				✓	✓

5G wireless access system [16]. Khaligi *et al.* covered the aspects of Free Space Optics (FSO) for outdoor long range links mainly focusing towards IR in [17]. Sevincer *et al.* [18] gave a well detailed report on the various aspects of FSO communications which included propagation model, directionality, stationary and mobile scenarios. Drivers and thermal management for Solid State Lighting (SSL), VLC channel model, noise, modulation, dimming and multiplexing techniques were also discussed briefly. Tsonev *et al.* reviewed the development of Li-Fi systems in cellular networks utilizing OFDM, as well as potential uplink schemes in [19]. Ma *et al.* comprehensively stated the prospects of integrating VLC with Power Line Communication (PLC) in [20]. Basic theory and system components of VLC were discussed as well as relaying and Multiple-Input Multiple-Output (MIMO) techniques for PLC-VLC integrated system. Demers *et al.* presented a survey which focused mainly on Free Space Optics (FSO) in a networking point of view [21]. The survey brings forward methodologies by which FSO can be implemented in cellular networks to increase the capacity of the system. Kumar *et al.* also did a survey which covered VLC system architecture, Bit Error Rate (BER), required power, detailed theory on LEDs, progress in luminous efficacy of LEDs and various indoor and outdoor applications of VLC [22]. A brief comparison of this survey with the other published work, related to some of the key fields in OWC is presented in Table 1.

This paper focuses mainly on the development of VLC for indoor broadband communication systems. The rest of this paper is organized as follows. Section 2 discloses the drawbacks of RF technology and the features and factors which make VLC more viable for indoor wireless communication. Section 3 presents background information and theory about OWC. LED illumination theory and comparison of various types of LED is also presented in this section. Section 4 focuses on the basic structure of a VLC link, MIMO techniques, hybrid schemes, modulation schemes and dimming methods used in VLC. The driver circuitry used in VLC as well as various VLC performance challenges such as interference, non-linearity etc. are also discussed. Section 5 reviews the recent development and the contributions by research groups involved in the field of VLC. Section 6 discusses about different indoor and outdoor applications of this technology which include intelligent lighting, intelligent transport system, PLC etc. Shortcomings and drawbacks of VLC at its current stage are presented in Section 7. Finally, Section 8 presents important conclusions that are drawn from this survey as well as the future prospects of this technology.

2 Motivation

Communication by visible light has been gaining popularity as a supplement and substitute for RF communication in recent times. The change is driven by several factors:

- *Dwindling RF Spectrum:* The RF spectrum is a natural resource of the state, and its usage is regulated to remove signal interference and pollution, as well as for efficient spectral usage [23]. It is cheaper for mobile operators to acquire spectrum, rather than building more base stations to enhance capacity [24]. Furthermore, it reduces the chance for potential future competitors from entering the market. As the demand for wireless data transmission is constantly increasing, the radio frequency spectrum is becoming increasingly congested [25]. Thus the remaining spectrum is dwindling and spectral management is fast becoming a concern [26]. There have been developments to use up the Terahertz frequency range which lies between the RF and microwave spectrum [27, 28], but it would mean creating an entirely new class of infrastructure compatible with the wavelength band. On the other hand visible light has 10,000 times greater spectrum than radio waves (Radio waves correspond to a frequency band of ~ 3 kHz to ~ 300 GHz, while the visible light correspond to a frequency band of ~ 400 THz to ~ 780 THz) [29]. With 12 billion light bulbs in operation around the world with unlicensed, reusable bandwidth, there can be 12 billion potential VLC transmitters.

- *The Capacity Crunch:* Mobile data will grow 6.3 times between 2013 and 2018 and the growth will be strongest outside Europe and North America [30]. Due to explosions in data usage, there is a major concern for mobile operators to focus on public Wireless Fidelity (Wi-Fi) and other alternative technologies. Level one mobile network operators expect 22% of their capacity they add in 2013 to come from public Wi-Fi and by 2018, 75% of their small cells will have integrated Wi-Fi [31]. These statistics reflect the growth in wireless network usage. The global appetite for wireless broadband data access is increasing by the day, with forecasts of a 18 fold increase in mobile traffic in 2016 compared to 2011, fueled by the smartphone, laptop and tablet popularity. Broadband service providers are introducing usage caps due to high demand and diminishing bandwidth. On the other hand the potential communication bandwidth of visible light (~ 400 THz) is incomparably wider than the conventional RF bandwidth [32]. As a re-

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sult in contrast to limited spectra of traditional radio frequency, VLC systems have huge available unregulated bandwidth resource to compliment short-range wireless transmission [33, 34].

- *Interference:* VLC is intrinsically safe and does not cause any interference with RF signals [35]. Thus this technology is perfectly suitable for communication in hospital, industrial and aerospace applications [20].

- *Security:* RF waves pass through walls, and are susceptible to snooping. Since light is confined to an area surrounded by opaque boundaries, there can be well defined coverage zones with enhanced security for VLC.

- *Spatial reuse:* Since VLC is facilitated by emission of highly directional and confined visible light, there can be coexistence of many non-interfering links in close proximity which allows greater data density [36] and spatial reuse of modulation bandwidth in adjacent communication cells [37, 38].

- *Safety:* In illumination conditions, there are no health hazards of visible light. Unlike IR, visible light satisfies the eye-and-skin safety regulations [38] making it safe for usage in any scenario with far larger emitted optical power [20] giving VLC communication an edge in terms of transmission distance over IR. Furthermore, fluorescent lamps are known to have mercury emissions from broken lamps during their disposal, which can have adverse environmental and health concerns [39, 40]. However, there is recently a lot of attention on the effect of pulsed light on human responses, a study carried out by Katsuura *et al.* revealed pupillary response under a 100 μs pulsed blue light to be significantly higher than under normal conditions [41].

- *Energy efficiency:* LEDs are energy efficient and highly controllable light sources, allowing them to be part of a *Green technology* [42]. Thus VLC had emerged as an eco-friendly green communication technology [43, 44]. LEDs roughly use one twentieth the amount of energy of a conventional light source. If all conventional light sources are replaced by LEDs, the global electricity consumption would reduce by as much as 50 percent [42], the CO_2 emissions will reduce by over 10 gigatons and crude oil consumption by 962 million barrels, amounting to financial savings in excess of one trillion dollars, and energy savings of 1.9 x 10^{20} joules over a decade [45]. According to a recent U.S Department of Energy report, by the year 2025, SSL technology has the possibility of providing energy savings of up to 217 terawatt-hours (TWh) [46].

- *Moving towards a smart power grid:* There is inherent benefit to leveraging existing power line infrastructure to provide connectivity while exploiting energy-efficient LED illumination systems for wireless downlink. The ubiquity of LED lighting together with power line networks leads us to conclude that VLC will be a strong complementary wireless technology to indoor PLC much in the way that Wi-Fi currently supports broadband Ethernet connections [20].

- *Easy implementation into existing infrastructure:* VLC can easily be implemented into existing lighting infrastructure with the addition of a few relatively simple and cheap front end components operating in baseband [47]. The VLC transmitters are widely deployed due to their symbiotic relationship with indoor energy efficient lighting [20].

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Thus there can be inherent benefits of leveraging on existing lighting infrastructure intended for illumination which has led to significant interest in short range indoor VLC [48].

- *Low cost:* Another advantage of VLC devices is their comparative low cost. Some popular RF links operating over approximately 10 m provide data rates of up to 1 Mb/s in the 2.4 GHz band for a cost of near US $5 per module. While, VLC links can transmit at 4 Mb/s over short distances using optoelectronic devices which cost approximately US $1 per module [49]. The implementation cost of VLC is less since only a few upgrades of existing lighting infrastructure is required rather than the initial set up cost of an entire communication system. Besides LED infrastructure is also expected to decrease in price and according to the US Department of Energy, by 2017 the dollars per kilolumen ($/klm) pricing of LEDs is expected to decrease roughly by 55% relative to current pricing [50].

The inherent benefits of replacing traditional lighting technology with LED lighting combined with the unique features and vast unregulated bandwidth of visible light promotes the concept of combining illumination with communication to implement VLC. The unique features of VLC which had been discussed earlier will make way for it to be one of the most significant technological breakthrough in communication systems.

3 Background

3.1 Optical Wireless Communication

The optical domain in the EM spectrum includes IR, visible and ultra violet light. Wireless IR is used extensively in remote controls. Optical fiber cables which utilize optical wavelengths to transmit data over fiber are the fastest and most reliable transmission method. Even though high speeds are achievable in fiber based optical communication, in optical wireless, the performance is mainly limited by interference from other light sources and transmitter bandwidth. This makes visible light spectrum specifically more suitable for indoor short range access as shown in Table 2. For long haul transmission, RF is widely used since the interference in the wavelength band is far lower than OW, and wide area transmission is not severely impaired by obstacles. RF waves which are reflected off surfaces and arrive at different times at the receiver create multipath dispersion, degrading system performance. Photo-Diode (PD) used in OW have detection surface diameters several hundred times the wavelength of light, where the integrating effect in the PD averages out any spatial multipath interference [51]. The devices used are considerably cheaper than the RF counterparts [5] and utilize baseband digital technology [51] making transmission and reception simpler than in RF communication (RFC), where coherent methods such as heterodyne reception causes higher system complexity. However, OW receivers built for incoherent reception show lower sensitivity than RF antennae due to the photo-electric conversion mechanism.

OW spectrum is unregulated, and at indoor short distance links, the SNR value of OW is higher, with Line Of Sight (LOS) point to point links having higher bandwidth and little interference. The spectrum in each room can be reused as the generated signal will be confined within the room, which cannot be implied when RF is being used. With the recent development of efficient white LEDs [52], offices and homes can combine indoor illumination with VLC.

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Table 2: Comparison of visible light communication to radio frequency and infrared communication

Index	Radio frequency communication (RFC)	Infrared Communication (IRC)	VLC
Available Spectrum	$\sim$ 300 GHz (licenced)	$\sim$ 400 THz (unlicenced)	$\sim$ 400 THz (unlicenced)
Safety	Intensity Regulated	Intensity Regulated	Unregulated
Noise/Interference	Little	High	High
Security	Limited	High	High
Coverage	Wide	Limited	Limited
Multipath	High	Low	Low
System Complexity	High	Low	Low
Electromagnetic Interference (EMI)	Yes	No	No
Infrastructure	Access point	Access point	Illumination
Power Consumption for short range links	Medium	Low	Low (Combined with LED illumination)

3.2 LED illumination

Illumination has come a long way from fires and candles through to the LED. Progressively at each step improvements were made, culminating with current LEDs. Incandescent lamps is still a widely used lighting technology, however due to high amount of useful energy being lost in the form of heat, the trend shifted towards the use of fluorescent lamps. As seen in Figure 2, the lifetime and luminous efficacy[1] of LED lamps are significantly higher compared to all the traditional lighting technology.

LED is a solid state semiconductor device which has the capability of changing electrical energy directly into light energy. The key structure in an LED is a semiconductor chip which creates a p-n junction. It contains semiconducting material doped with impurities to create a p-n junction. Charge carriers, mainly electrons and holes flow into the junction from electrodes with different voltages. On applying voltage, an electron meets a hole, and falls into a lower energy level, releasing energy in the form of photons which is seen as emitted visible light. This effect is called *electroluminescence* [53].

LEDs have a wide range of advantages compared to traditional lighting technologies:

- LEDs are energy efficient and generate less heat [54]. They can reduce energy consumption by 80% in general and domestic lighting applications [55].
- LEDs have longer service lifetime and can operate for 25,000 to 50,000 hours before their output drops to 70% compared to standard incandescent bulbs having a lifetime of 6000 to 15000 hours only [56, 57].
- They have higher luminous efficacy than traditional lighting sources. The development of efficient InGaN based alloys for blue and green LEDs opened the doors for efficient WLEDs [52], which over the last 2 decades have surpassed the luminous efficacy of incandescent light bulbs (14 lm/W) and recently fluorescent lamps (75 lm/W), with Cree Inc. producing a 254 lm/W WLED in 2012 [58].

[1] Luminous efficacy, measured in lumens per Watt of electrical power, is a metric defining the power conversion efficiency of input electrical energy to light, weighted by the human eye response [52].

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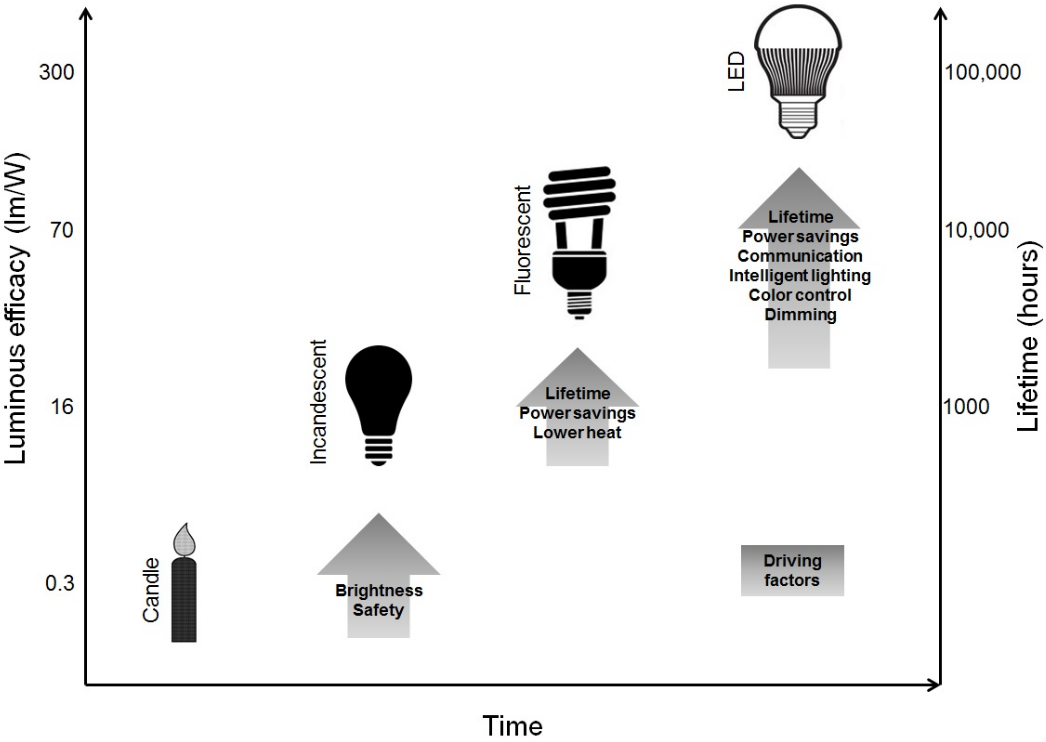

Figure 2: Development of illumination technology

- They are free from hazardous substances like mercury [59].
- The inherent modulation bandwidth of LEDs (up to 100's of MHz) [20] can be exploited to provide a dual role as a communication device besides illumination.
- LEDs have unprecedented versatility in controlling radiation spectrum, thus being able to generate lights with a high diversity of color and intensity [22].
- They have the ability to work under unforgiving environments and ambient lighting conditions [60].

These exciting complementary communication aspects to LED lighting have generated considerable research and industrial interest in using LEDs for VLC. With High Brightness LEDs (HB-LEDs) gaining popularity in indoor illumination, traffic lighting, outdoor displays, utilizing the existing lighting infrastructure for VLC will be an exciting technological breakthrough.

3.3 LED types

This section summarizes the different categories of LEDs along with their key features. The comparison between these various types of LEDs is presented in Table 3. As it can be seen, each type has its own special characteristics allowing them to be specifically chosen for different types of applications with specific requirements.

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Table 3: Comparison of different types of LEDs

Parameter	pc-LED	RGB LED	μ-LED	OLED
Bandwidth	3-5 MHz	10-20 MHz	$\geq$300 MHz	$\leq$1 MHz
Efficacy	130 lm/W	65 lm/W	N/A	45 lm/w
Cost	Low	High	High	Lowest
Complexity	Low	Moderate	Highest	High
Application	Illumination		Bio-sensors	Display

PC-LEDs: White light by LEDs is produced primarily using two methods. The first method, using a Phosphor Converted LED (pc-LED) employs a single blue Indium Gallium Nitride (InGaN) LED chip to pump a Yttrium Aluminum Garnet (YAG) phosphor coating. The phosphor converts part of the blue light to green, yellow and red portion of the spectrum while the other part of the blue light is leaked out, the mixture of which produces white [61]. Depending on the amount of phosphor, white light produced by pc-LEDs can be categorized as warm-white, neutral-white or cool-white, and characterized by Correlated Color Temperature[2] (CCT).

Multi-chip LEDs: The 'multi-chip' approach utilizes 3 or more LED chips emitting different colors, typically Red, Green and Blue (RGB), to produce white light. Depending on the light intensities of the different chips, color control can be achieved. Multi-chip WLEDs have lower Color Rendering Index[3] (CRI) than pc-LEDs. Pc-LEDs are cheaper and less complex compared to these multi-chip LEDs, however they have a bandwidth limitation due to the low phosphor conversion efficiency.

Organic Light Emitting Diodes (OLED): OLEDs generate light using an organic layer sandwiched between positive and negative carriers, and are used mainly in flat panel displays. The typical frequency response for OLEDs are in the order of 100's of kHz, far lower than inorganic LEDs which makes OLEDs less suitable for high speed applications. The lifetime of typical white OLEDs is $\sim$50,000 hours, less than the typical inorganic LED lifetime. But since its a more flexible light source than inorganic LEDs, research has been ongoing to improve the frequency response by equalization [62–65]. Luminous efficacy of 45 lm/W is delivered by OLED panel recently developed by Konica Minolta, however this efficacy was achieved at the cost of a reduced lifetime (LT50[4]) of around 8000 hours [66].

Micro LEDs (μ-LED): AlGaN based micro-light emitting diode arrays have been in development for VLC and Polymer Optical Fiber (POF) recently [67]. μ-LEDs have the potential to be used as display panels incorporating high density parallel communication. These arrays typically emit light in 370-520 nm wavelength range, with the possibility of using wavelength conversion to produce white light. Each individual pixel ranges from 14-84 μm, the 3-dB band-

[2] A measure of the appearance of color in an lamp, in reference to a heated source. Measured in Kelvin (K). Typically, cool white LEDs have a CCT of $\sim$ 6000K, neutral $\sim$ 4000K and warm $\sim$ 3000K

[3] A measure of how accurately a light source renders color, in comparison to natural light as seen from the human eye. Generally, a CRI >90 is acceptable for illumination purposes [52]

[4] A measurement of LED lifetime which denotes the time taken by an LED operating under constant current to reach to 50% of its initial luminance level

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width reaches 450 MHz allowing speeds of up to 1.5 Gb/s [67–70]. The high bandwidth is possible due the very low capacitance in the LEDs. Recently, University of Strathclyde, along with researchers from University of Oxford, Edinburgh, Cambridge, and St.Andrews have begun researching into GaN based LEDs for ultra-parallel high density communication [71]. μLED arrays based on III-nitride semiconductors having emission wavelength from visible to ultraviolet range emerged as ideal light sources for optogenetic neuromodulation and microarray biosensors [72]. Jeon *et al.* in [73] demonstrated the fabrication of a matrix-addressable μ-LED based on InGaN, a planarization scheme incorporating SiO_2 deposition and chemical-mechanical polishing was used. The device showed superior current handling capabilities, light output densities and heat sinking properties compared to conventional broad-area LEDs.

Resonant Cavity LEDs (rc-LED): The extraction efficiency of conventional LEDs is poor due to the large difference in refractive index between the narrow gap semiconductor and the surrounding medium which is typically air. To improve light extraction near IR wavelength range, resonant cavity enhancement was first demonstrated by Schubert *et al.* in 1992 [74]. Developing high brightness resonant cavity LEDs (rc-LEDs) would benefit VLC for color displays. rc-LEDs typically emit light at $\sim$ 650 nm with a narrow line width, and can be modulated in excess of 100 MHz [75, 76]. Recently, the enhancement of photoluminescence spectra at room temperature of an ALInSb rc-LED was demonstrated with a free spectral range of around 6 THz [77].

Even though HB-LEDs are more expensive than current fluorescent and incandescent lights, the market is poised to grow, and prices are expected to drop in the near future. The LED market has skyrocketed to make comparable to NAND and DRAM markets in the near future [43]. It is expected that packaged LED market will experience tremendous growth between 2012 and 2018 [78] and by 2018 majority of the new energy efficient lighting installations are expected to be LED based, thus LED prices will continue to fall in the coming years. The installed base of LEDs in the U.S. has increased in all LED applications to about 105 million units, which is double the amount in 2012 [46]. The Original Equipment Manufacturer (OEM) prices for LED lamps and packages in 2020 is expected to be one tenth of the 2010 price, and the value based market share of LEDs is expected to reach 60% by 2020 [79]. Figure 3 shows a recent example from Navigant Research for commercial lighting sector which includes lighting for office, retail, education, healthcare etc. As seen in the figure, a dramatic increase in revenue from global commercial LED sales is expected until the year 2019. There will be a slight decrease in LED revenue from 2019 to 2021 and a significant decrease in sale of linear fluorescent lamps (T5, T8 and T12), Compact Fluorescent Lamps (CFL) and High-Intensity Discharge (HID) lamps [46].

In summary, visible light is the more suitable for indoor OWC compared to the popular IR band which is preferable for long haul communication. The high switching capability of LEDs along with other important features such as energy efficiency and longer lifetime make them the most favorable light source that can be incorporated into VLC. At present, a range of various types of LED is available, each having its own characteristics and unique properties. Based on the features, they can be used in different types of lighting applications. The potential market growth of LED lighting technology is foreseen to be very strong in the coming years, which create a strong case for this lighting technology to be integrated into VLC.

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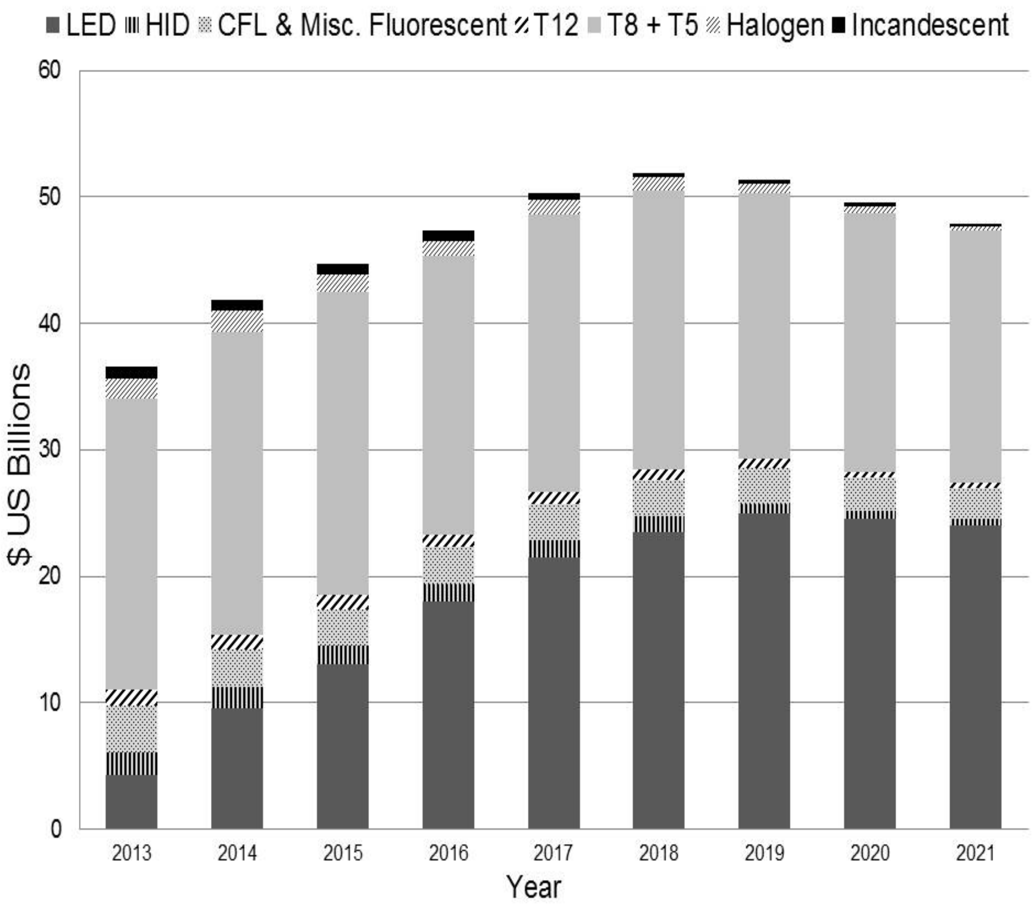

Figure 3: Global commercial lighting revenue forecast, 2013-2020 [46]

4 Visible Light Communication (VLC) System

4.1 Basic Structure

Typical VLC links use LOS configuration, due to its illumination purpose. Furthermore, lower path loss and dispersion over short distances gives way to higher bandwidth. LEDs emit incoherent[5] light, hence Intensity Modulation (IM) is done where the transmitted signal is modulated into the instantaneous optical power of the LED. The radiant intensity is controlled by the forward current through the LED, and must be in the operating region within the linear portion of the LEDs V-I curve. Figure 4 shows the ideal current-output modulation behavior under constant bias. Ideally, an input current I_{LED} with constant DC bias current I_{DC} and current swing I_{SP} can be expressed as

$$I_{LED} = I_{DC} + I_{SP}. \tag{1}$$

This would produce an output optical power of

$$P_O = P_{DC} + P_{SP}. \tag{2}$$

[5]Photons have different wavelength and phase, unlike coherent light sources such as lasers.

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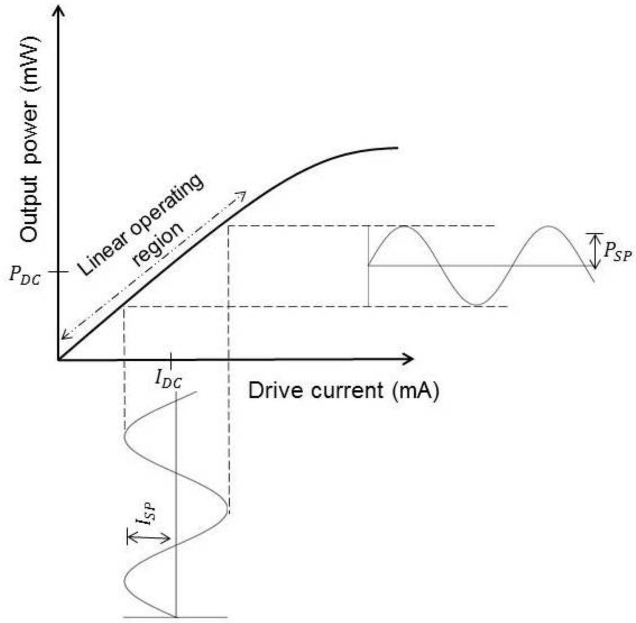

Figure 4: Current-output power behavior, with input current swing I_{SP}

Since IM changes instantaneous power of the LED, Direct Detection (DD) is the only feasible down conversion method. DD uses a photodiode to convert the incident optical signal power into a proportional current. The setup is far simpler than coherent detection used in RF, where a local oscillator is used to extract the baseband signal from the carrier. Modulation frequencies are kept high enough to avoid flicker, as it can have adverse health effects [80, 81]. Typical office lighting standards[6] require illumination levels of 400-1000 lux [82].

Figure 5 shows a general VLC link structure for an IM/DD based VLC system. The optically modulated signal waveform, $I_{t,sig}$ and average DC level, I_{DC} are superimposed using a bias tee[7] as shown in equation 1. The driving signal, I_{LED} is used to drive the LEDs which converts the electrical signal into intensity modulated optical signal. The light with optical power, P_O travels across the optical channel and is passed through an optical filter (used to improve system performance which is discussed in greater details in Section 4.9) and is focused onto the PD by a focusing lens if necessary. At this stage, the PD converts the optical signal back to the electrical signal. Noise adds up to the system at this level which are comprised of thermal and shot noise. Thermal noise is the electronic noise generated due to thermal agitation of charge carriers inside a conductor, photon-generated shot noise is induced by ambient light. The received photo-current, I_{rec} is then amplified which is followed by signal processing and demodulation to retrieve the transmitted data.

Cool white LEDs have the least phosphor, hence most efficient and have a higher portion of its optical power in the blue peak [83] enabling better reception with blue filtering, which suppresses the slower phosphorescence in the emitted white light. The influence of the type of LED on system performance may be marginal, with a study on the type of LED suitable for VLC yet to be done.

[6]European lighting standards EN12464-1 requires a minimum of 500 lux

[7]A diplexer which is used to set a DC bias point as well as combining switching signals with the DC component by using a capacitor and driven in the LED's linear operating region

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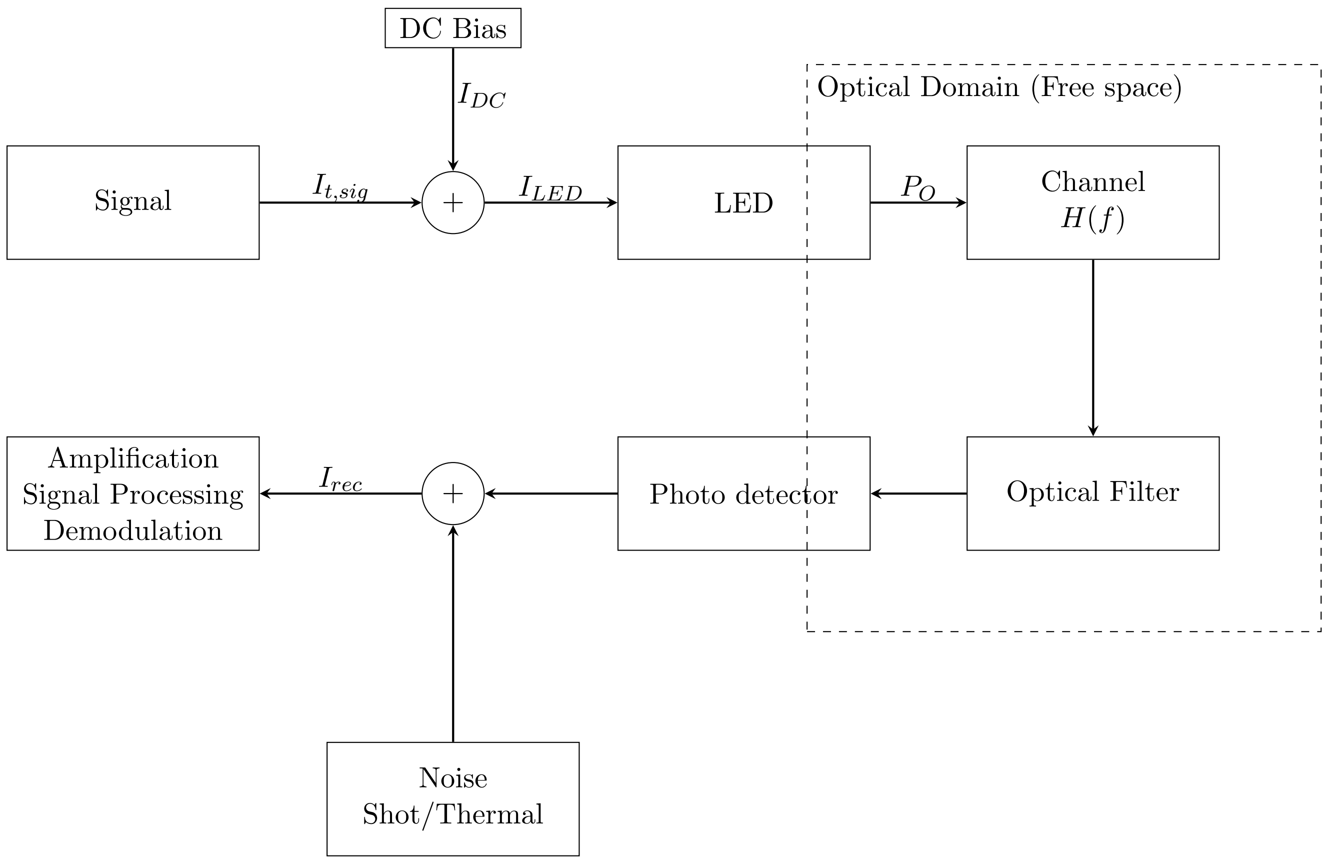

Figure 5: General VLC link structure

Multi-path effect leading to dispersion and attenuation is virtually nonexistent in OW links. Indoor reflections are well modelled as Lambertian emitters [84, 85], which scatters incident light omni-directionally with the same power, creating a diffuse environment. Efforts are being made to characterize the channel characteristics for VLC, because infra-red [86] models may not necessarily be accurate enough.

4.2 Receivers in VLC systems

In VLC, constructive and destructive interference patterns occurs on a micron scale and averaged by the receiver, which is thousand times greater in size. Therefore, VLC exhibits no Doppler shift, as a result sophisticated receiver tracking algorithm are not needed [47] which allows a photo detector to be simply used as the receiver. There are generally two types of photo detectors used in VLC systems. The PIN[8] PD and Avalanche PD (APD), the latter having a higher gain. The downside of using an APD is the excess shot noise generated by the higher photocurrent [87]. PIN PDs have been the predominant PD used in VLC due to high temperature tolerance, lower cost and are ideal in scenarios where the receiver gets flooded with relatively high intensity light. APDs are more useful with weak incident light intensity, demonstrations using APDs can be found in [88–91]. Typical silicon PDs used in

[8]A wide intrinsic ('i') semiconductor region is sandwiched between 'p' type and 'n' type semiconductor regions, hence P-I-N

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VLC have reponsivity curves peaking at 800 nm, with higher sensitivity to red light than green or blue [92]. Vucic *et al.* demonstrating VLC using RGB LEDs have shown data rates and performance for the three colors being different, and the red channel always having a higher frequency response and higher data rate than the others [88, 93].

There are generally three types of receiver configuration that can be used in VLC which are single element receiver, selective combining receiver and image diversity receivers. Single element photo detectors is the most popular amongst these options and had been widely used and experimented in VLC. Selective combining receivers, or diversity combining receivers for VLC have been proposed by Lee *et al.* [94] for outdoor intelligent traffic light systems and by Armstrong *et al.* [83] utilizing OFDM for indoor use. The system in [83] is of more relevance to this article. It combines the advantage of blue filtering and the higher received optical power of the blue + phosphor light. Of the two input streams, the selective combiner selects the sub-carrier OFDM channel with a higher SNR. The performance of the system is however only marginally better than blue filtering approach, together with the fact that it significantly increases receiver complexity; as a result, adoption may not be viable. Image diversity receivers [95, 96] utilize an array of photo detectors and a lens to separate signals coming from different sources. This is particularly useful in MIMO applications for VLC, and has been successfully demonstrated in [89, 97]. Imaging receivers are adaptable to different source positions than non-imaging receivers. Recent demonstration by Azhar *et al.* using an imaging receiver has produced a total 1.1 Gb/s with 4 transmitters and 9 receivers [98]. Another receiver configuration, called angle diversity receivers have a wide Field of View (FOV) [95], but are bulky and expensive and built for collecting light from only diffuse links. With so many preferences, the receiver configuration in a VLC system is mainly designed based on the performance milestones the system needs to achieve.

Aspheric lenses have been used predominantly to increase the receiver FOV and to concentrate more light into the photo detector surface area [98]. Hemispherical lenses are widely used in commercial IR systems, due to its wide FOV and omnidirectional gain [51], suited for non-directed diffuse links. In [99], a hemispherical lens in an upside down orientation is said to achieve high spatial diversity for use in MIMO VLC systems.

An optical receiver's front end usually consists of a pre-amplifier which amplify the weak current induced in the PD. The amplifiers used in VLC can be classified mainly into three categories: low impedance amplifier, high impedance amplifier and Trans-Impedance Amplfier (TIA). The choice and design of the front end is usually a trade-off between speed and sensitivity [100]. If a high impedance amplifier is used, the thermal noise is significantly reduced; thereby improving receiver sensitivity. However the main disadvantage of high impedance front end is the low bandwidth. This can be countered by using an equalizer which will be discussed in Section 4.9. Thermal noise prevails in the receiver connected to a low impedance front end making this class of amplifiers to be impractical for use in VLC systems. TIA on the other hand provides an equal balance of high sensitivity along with large bandwidth. As a reason, this class of amplifier had become increasingly popular and had been used in various VLC systems. Photo Parametric Amplifier (PPA) is another class of amplifier which was observed to perform well at zero bias for the PD [101]. PPA can offer potential advantages over conventional receiver with respect to tunability [102] and noise performance.

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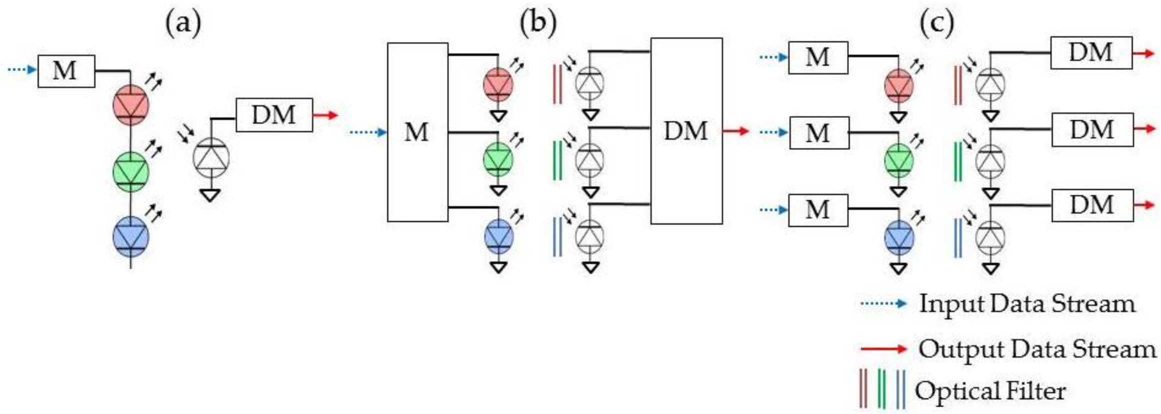

Figure 6: Configurations for utilizing multiple light sources in VLC

4.3 Multi-chip VLC

The properties and specifications of multi-chip LEDs have already been described in Section 3.3. When using multi-chip LEDs in VLC, there are three ways to utilize the chips:

- Connecting the pins in series to modulate all sources at the same time (Figure 6(a)).
- Independently modulate each chip for a single communication channel (Figure 6(b)).
- Independently modulate each chip enabling parallel communication channels (Figure 6(c)).

These methods are depicted in Figure 6, in the figure 'M' denotes modulation and 'DM' denotes demodulation. In the first method, we see a considerable bandwidth enhancement compared to pc-LEDs, since there is no slow phosphor component in the generated light. Optical filtering is used in pc-LED systems to suppress the slow phosphor decay and extract the much faster blue response, but this comes at the cost of losing a considerable portion of the received signal power. However, in multi-colored sources, almost the entire optical power of the emitted spectrum for each channel can be harnessed by optical filtering. This is because no phosphor wavelength converters are present.

The second method is utilized in the newly introduced Color Shift Keying (CSK) modulation by IEEE. The intensity of each color channel generates a specific color point in the CIE 1931 color coordinates. This can be utilized as constellation points for modulation purposes. Optical filters are required at the receiver to extract the intensities of each color channel to generate the color coordinate. This method is discussed elaborately in Section 4.6.

In the third method, each color can be modulated independently, provided white color balancing is maintained [92]. At the receiver, optical filtering is used to extract data from each color channel. This system has the potential for Wavelength Division Multiplexing (WDM) [88].

In RF based MIMO, there are two types of gains: multiplexing gain and diversity gain. multiplexing or in other words antenna gain arises from the increase in SNR when the signal received by multiple antennas spaced apart is combined. On the other hand, diversity gain arises due to the reduction of the required SNR for a given BER induced by the use of

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Table 4: Difference between MIMO and SISO

Parameter		SISO	MIMO
Number of Transmitter		Single	Multiple
Number of Receiver		Single	Multiple
Number of Channel		Single	Multiple
BER (at 5dB SNR) [104]	AWGN channel	0.45	0
	Rayleigh channel	0.5	0.25
Aggregate Data Rate		Low	High
Optical Crosstalk		Null	High
Application		Mobile wimax-16e, WLAN 11n,11ac, 11ad, 3GPP LTE	Radio, satellite, GSM and CDMA

multiple antennas. Multi-chip VLC mechanisms differ from MIMO system's diversity gain and multiplexing gain modes as they are independent channels with no correlation. Each transmission channel has its own optical spectrum, hence can be filtered out by using a corresponding optical filter.

4.4 MIMO and Multiple access systems

Parallel transmission offers a linear capacity gain with the number of channels in an ideal crosstalk-free configuration. Thus higher data rates can be realized by using MIMO systems. Multiple element transmitters and receivers as mentioned in Section 4.2 are used to create parallel communication channels to enhance the total system capacity. An optical MIMO system could greatly enhance the system data transmission capacity compared with a Single-Input Single-Output system (SISO), and thus has drawn much attention recently [103]. MIMO processing can relax the requirement of terminal mobility and precise mechanical alignment [98]. The differences and advantages/disadvantages of MIMO and SISO system are presented in Table 4. From the table, it is clear that MIMO outperforms SISO when considering overall communication aspects of a link.

Optical MIMO channels are not as decorrelated as RF MIMO channels. The size of receiver arrays has to be large enough to ensure that the channel matrix[9] is full-rank. By utilizing a large receiver array, it is assured that the images of the sources strike the array with no significant overlap between the detectors. This is prevalent mostly in non-imaging based MIMO systems [103]. In imaging MIMO systems, this could still occur due to the position of the receiver relative to the transmitter, which can be minimized by increasing the number of receivers. According to Zeng *et al.*, a deficient matrix should still be in considered for practical implementations [105]. In such a case, the number of sources could be adjusted so that a full rank matrix is achieved [105]. Simulations on LED array sizes utilizing imaging receivers showed that with increasing size of transmitter array, the required detector size and lens diameter also increases. A 6×6 MIMO transmitter requires a detector array as large as $5.91 \times 5.91\ cm^2$, which is quite large for mobile devices but feasible for fixed stations. Furthermore, receiver tilt affects the BER in such a way that the area must be increased by a factor of $\sqrt{2}$ to maintain the performance at 45 degrees [105]. The distance between the

[9] A matrix formed by the DC channel gains of receivers and transmitters in a MIMO system

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lens and the detector array plays a crucial role in generating a clear image at the detector. By using a larger array, a more accurate channel matrix can be constructed, and more inputs can be accommodated but at the cost of higher receiver complexity and cost. In experimental demonstrations, speed of 1 Gb/s was achieved using 9 receivers [98].

As the channel matrix becomes less well conditioned, the BER also increases due to the difference in the coefficients being of the same order as the variation in noise [106]. Thus, Multiple-Input Single-Output (MISO) technique emerged as a imperative technique for practical indoor VLC scenarios. A Multi-User MISO (MU-MISO) broadcasting system for VLC was studied in [107]. Other types of MIMO systems include a combined localization and transmission MIMO system developed by Biagi *et. al.* [108]. This system optimizes performance of a multi user MIMO system by localizing each user.

MIMO systems with spatial diversity have been studied for FSO channels in [109, 110]. In addition, the usage of the diffuse optical channel for an indoor environment was presented in [111], while [112] introduced pixelated MIMO wireless optical communication systems and presented an evaluation of their capacity.

An example of a MIMO system with three transmitters (Tx1, Tx2, Tx3) using an imaging optics is shown in Figure 7. The imaging optics projects an image of the transmitter on the detector array having 12 detectors, the signals from the transmitters Tx1, Tx2 and Tx3 are received by Rx2, Rx9 and Rx10 respectively. Hence, the detectors having an image of the transmitter can detect the signal.

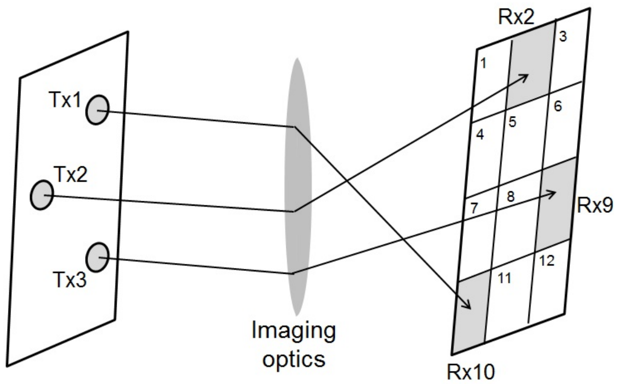

Figure 7: MIMO system using imaging optics

Optical Code Division Multiple Access (OCDMA) has been demonstrated for VLC systems [113, 114]. CDMA systems are more secure than WDMA. In synchronous CDMA, a set of orthogonal codes is used at the receiver to decode and separate each user. This method, however is open to synchronization issues and is affected by multipath reflections [113, 115]. Asynchronous CDMA systems utilize a Pseudo Noise (PN) code to differentiate between users. The PN code is however, not perfectly orthogonal between codes. Asynchronous CDMA resolves the synchronization problem to a certain extent, but with higher user number creates greater Multiple Access Interference (MAI) [113].

Cui *et al.* in [116] has theoretically analyzed a Wavelength Division CDMA (WD-CDMA) by utilizing RGB based white LEDs. A single channel from each RGB channels is active in each fixture, or femtocell. Other channels ensure whiteness. Neighboring cells use a different

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WDM channel to reduce interference from neighboring cells. The cell structure has influence of Space Division Multiple Access (SDMA), since they are analogous to directional antennae.

4.5 Hybrid VLC Schemes

VLC can be associated with existing OWC technologies such as RF and IR communication systems to enable the establishment of hybrid schemes which can utilize the diverse advantages of different systems. RF and VLC hybrid scheme proposed in [117] utilizes both WiFi and VLC. An analysis done on such a hybrid scheme showed that a hybrid system outperforms single standalone VLC system in terms of user connectivity and energy consumption [118]. The system consists of mobile terminals equipped with VLC receivers and RF transceivers, LED luminaires for VLC hotspot and a router acting as a WiFi access point. The downlink utilizes visible light and the uplink utilizes RF. Handover assessment was carried out for different scenarios where based on the capacity of WiFi channel, users were offloaded to a VLC channel. Based on analytical and simulation results, it was shown that the proposed system provides additional capacity in terms of buffer utilization and throughput. This work was recently extended for practical implementation in a software defined VLC platform where experimental investigation revealed that the hybrid system outperforms conventional WiFi for crowded multiuser environments in terms of throughput [119].

In [120], a hybrid VLC-OFDMA network model is proposed consisting of VLC hotspots (downlink) and one OFDMA access point (uplink). A protocol was proposed which combined access, horizontal and vertical handover mechanisms for mobile terminals taking the mobility of the terminal between different hotspots into account. By utilizing a new networking scheme, a unique ID was allocated for every VLC hotspot which helped in triggering appropriate handover mechanism. Simulation results show large improvements in capacity performance compared to OFDMA systems.

However RF/VLC hybrid systems are not feasible for EMI sensitive applications and increase the overall system cost since they require an entire different set of transceivers and receivers. For low cost, low speed communication, hybrid system combining VLC and IR can be used. A wireless mesh backbone utilizing such a scheme had been proposed in [8]. An experimental system designed for in-flight VLC utilizing an IR uplink achieved a speed of 512 kb/s [121].

4.6 Modulation

In VLC, the modulating signals can be used to switch LEDs at desired frequencies which contains information to be transmitted. Single carrier modulations include OOK, PPM, PAM etc. which have been widely used in IR communications [51]. These modulation methods incorporate Run Length Limited (RLL) sequences to avoid long strings of the 1s or 0s which could potentially cause flicker, and to aid clock and data recovery. Forward Error Correction (FEC) methods such as Reed Solomon (RS) [122, 123] may be used for error correction. This section gives a brief overview of various features and properties of different modulation schemes that had been used in VLC. A summarized comparison of a few of the selected schemes is presented in Table 5.

On-Off Keying (OOK): OOK is one of the simplest modulation techniques used to switch a LED between a high (bit 1) and low (bit 0) to modulate data. RLL codes such as Manchester

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coding may be used for DC balance [124]. In OOK-NRZ, *0s* and *1s* are represented by positive and negative voltages. This technique had been widely used in VLC [54, 90, 125–130] and can carry more information since there is no rest state. Fujimoto *et al.* demonstrated the simplest NRZ-OOK system with a single RGB LED (only red to transmit) achieving a bit rate of 477 Mb/s [78] and also employed duobinary technique with bandwidth enhancement (using transmitter and receiver equalization) to achieve 614 Mb/s [131]. OOK scheme for VLC system using OLED was demonstrated in [132] where a data rate of 2.2 Mb/s was achieved. A bit rate of 375 Mb/s per pixel was achieved giving an aggregate parallel data transmission rate of 1.5 Gb/s using OOK modulation for a Complimentary Metal-Oxide-Semiconductor (CMOS) controlled GaN based LED array [70]. Recently, Li *et al.* demonstrated a high bandwidth VLC system based on a post equalization circuit using OOK-NRZ modulation which achieved a data rate of 340 Mb/s [133].

Pulse Position Modulation (PPM): In L-PPM, a pulse corresponding to a certain bit is transmitted in one of L time slots within a symbol period. The average power requirement for PPM is lower than OOK [134] since it avoids the DC and lower frequency component of the spectrum [135], but it is less bandwidth efficient [51, 136]. System complexity is increased on PPM compared with OOK, as it requires stricter bit and symbol synchronization at the receiver [137, 138]. 4B6B[10] RLL scheme has been introduced for PPM in [14]. There are various modifications of PPM scheme which are applied into VLC system for achieving various performance parameters.

Expurgated PPM (EPPM) can provide a wide range of Peak-to-Average Power Ratios (PAPR[11]) needed for dimming. Interleaved EPPM can counter ISI and overlapped EPPM can counter LED bandwidth limitations [139]. Differential PPM (DPPM) can be used to achieve a transmission capacity larger than that of PPM because all the unused time slots are eliminated from within each symbol [136]. Overlapping PPM (OPPM) allows overlap between pulse positions and thus can yield higher data rates [140]. Variable PPM (VPPM) and Multiple PPM (MPPM) are the schemes amongst PPM generally used for dimming control as well as transmitting data [35, 141–144].

Pulse-Position-Pulse-Width Modulation (PPMPWM): PPMPWM is a new hybrid modulation scheme discussed in [145] which combines L-level PPM and L-level Pulse Width Modulation (PWM). The hybrid scheme overcomes PPM's pulse width aspects and low bandwidth efficiency by making use of the broadened pulses of PWM enhancing the power efficiency. This hybrid scheme has a lower BER than PPM and has strong spectral lines in the power spectrum.

Pulse Amplitude Modulation (PAM): PAM is a very basic modulation scheme which is bandwidth efficient. Data is modulated into the amplitude of the signal pulse. Modulation schemes employing multiple intensity levels such as PAM may undergo nonlinearity in LEDs luminous efficacy. Due to the dependence of the color of LED emission on input current and temperature, multiple symbol levels of PAM are subject to shifts in color temperature due to variation in drive current [146].

[10] 4-bit/6-bit scheme where one byte is encoded into 12 bits and 1 bit error is detected out of 6 bits

[11] The peak divided by the root mean square of the waveform. A high PAPR can cause an LED to operate in a non linear region leading to signal distortion

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Pulse Dual Slope Modulation (PDSM): In PDSM the binary bit *0* is represented by the rising edge of the pulse within the pulse duration (keeping the falling edge fixed) and the binary bit *1* is represented by the falling edge (keeping the rising edge fixed). During idle period, both rising and falling edges change by equal amount. Since pulse representing binary input *0* or *1* are mirror images of each other, there is no brightness discrepancy during data transmission as well as the idle pattern is chosen to maintain the average brightness constant, thus intra and inter frame flicker are avoided [25].

Generalised Space Shift Keying (GSSK): GSSK is a subset of spatial modulation [147, 148], where spatial domain is exploited to modulate information [149]. This scheme has a higher spectral efficiency than conventional OOK and PPM techniques [150]. For similar spectral efficiency, it is said to have a simpler system compared to PAM. However, one of the main limitations of this scheme is that its error performance depends strongly on having different channel gain values, which makes it only suitable for applications with fixed configuration with limited receiver mobility [151].

Color Shift Keying (CSK): Using multi-chip LEDs for VLC has been introduced in the new IEEE 802.15.7 standards published in 2011 [152]. The scheme does not modulate the colored chips independently for WDM. The transmitted bit corresponds to a specific color in the CIE 1931 coordinates. There are seven possible wavelength bands from which the RGB sources can be picked from, and the picked wavelength bands determine the vertices of a triangle inside which the constellation points (corresponding to CIE coordinates) of the CSK symbols lie. Only valid color band combinations generate a triangle. The color point for each symbol is generated by modulating the intensity of RGB chips. However CSK cannot be used in a VLC system where the source is a pc-LED (which is one of the most common sources of light in an illumination system) and implementation of CSK requires a complex circuit structure. An optional feedback loop from the receiver can be implemented for color calibration and avoiding interference from other light sources [14].

Table 5: Qualitative comparison of popular modulation schemes

Modulation	Spectral Efficiency	Power Efficiency	System Complexity	Comment
OOK	High	Low	Low	Prone to flickering
PPM	Low	High	Moderate	Complex transceiver structure
PAM	Moderate	Low	Low	Non-linearity in LED's luminosity
CAP	High	High	Moderate	Lower cost than OFDM
GSSK	High	Low	Low	Requires limited receiver mobility
OFDM	High	Moderate	High	Non-linearity for high PAPR
CSK	Moderate	Low	High	Requires feedback mechanism

Generalized Color Modulation (GCM): GCM is a color-independent modulation scheme which can be used for communication under varying target color conditions [153]. Furthermore, GCM can provide flicker-free operation, dimming control, and the ability to function

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irrespective of the number of LEDs at the transmitter or PDs at the receiver [154].

Color Intensity Modulation (CIM): CIM satisfies lighting constrains and maximizes the capacity of VLC by first setting a specific region in signal space as the target subspace and then mapping from a region in color space [155]. CIM is a superset over an inverse source coded WDM. It does not suffer from inter-channel interference, even when the channels are non-orthogonal. CIM yields a higher data rate than WDM without ISC and yields a higher rate than WDM with ISC in the non-orthogonal channels.

OFDM[12] : High data rates are realized by utilizing multiple orthogonal sub-carriers to transmit parallel data streams simultaneously, reducing Inter Symbol Interference (ISI) and the need for complex equalizers [156]. OFDM is spectrally efficient, and is robust against channel dispersion. OFDM is used extensively in RF applications such as Wi-Fi and terrestrial Digital Video Broadcasting (DVB-T). Orthogonal sub-carrier frequencies, a set of equidistant discrete carriers, are selected by an Inverse Fast Fourier Transform (IFFT), which succeeds a serial modulation scheme such as *M-ary* Quadrature Amplitude Modulation (M-QAM) or Phase Shift Keying (M-PSK). IFFT converts the frequency domain input signals into time domain output signals. A cyclic prefix (CP) is added to further limit the effect of ISI.

Since VLC uses IM, a real and unipolar valued signal needs to be produced. Therefore, the conventional OFDM scheme used in RF communications should be modified. To achieve a real valued output signal, Hermitian symmetry is used on the parallel data streams into the IFFT input [157]. This comes at the cost of losing half the available bandwidth. The DC bias added before transmission makes the signal unipolar. This method is known as DC Offset OFDM (DCO-OFDM). Depending on the channel response, each sub-carrier performance can be optimized by utilizing bit and power loading [158]. This is discussed in detail in Section 4.9. Since the IFFT block independently sums modulated subcarriers, these components in a DCO-OFDM signal could add up constructively, increasing signal amplitude and the chance of signal distortion, causing overheating at the high peaks due to non-linear operation of the LED chip [157, 159, 160]. The lower peaks could reach below the Turn on Voltage (TOV) limit of the LED. This random variation results in a high PAPR which is an inherent problem with OFDM [157]. Several methods have been proposed to mitigate the effect; such as using a linear amplifier or power back off. But the simplest method to overcome it is to clip the signal at peak levels [161]. Asymmetrically Clipped Optical OFDM (ACO-OFDM) [162] clips the OFDM signal at the zero level, while data is carried in only odd subcarriers. The method reduces the amplitude of the transmitted OFDM signal and is far more power efficient than DC biased OFDM for a given bandwidth, although coming at the cost of losing half the available bandwidth [163].

Unipolar OFDM (U-OFDM), proposed by Tsonev *et al.* [164], rearranges the OFDM samples and sends them in separate positive and negative blocks. It has the same spectral efficiency as ACO-OFDM, but at higher power efficiency. The highest data rates achieved in VLC have utilized OFDM/DMT to achieve speeds of up to 3.4 Gb/s [88, 89, 91, 93, 98, 122, 156, 165–170].

The system model of a VLC OFDM system is presented in Figure 8. The serial data bits are modulated in the 'mod' block and converted from Serial-to-Parallel (S/P). The par-

[12] Variation of OFDM is Discrete Multi-Tone (DMT), a digital baseband version of OFDM which adapts to noisy channels by varying bit and power loading in individual sub-carriers to enhance performance.

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allel modulated data bits are then inputted into the IFFT block. Their complex conjugates achieved by the convolution block denoted by '*' are used to generate real valued baseband signals by inputting them to the negative frequency whose absolute value is equal to the positive frequency. The use of Hermetian symmetry makes the IFFT output signals real. The IFFT output is Parallel-to-Serial (P/S) converted and fed to the LED by means of a bias tee. The modulated light then travels through an optical wireless channel and received by the PD. Fast Fourier Transform (FFT) is applied to the received data symbol and the demodulated data symbol are coherently combined with the complex conjugates by Maximum Ratio Combining (MRC) to obtain original data symbols.

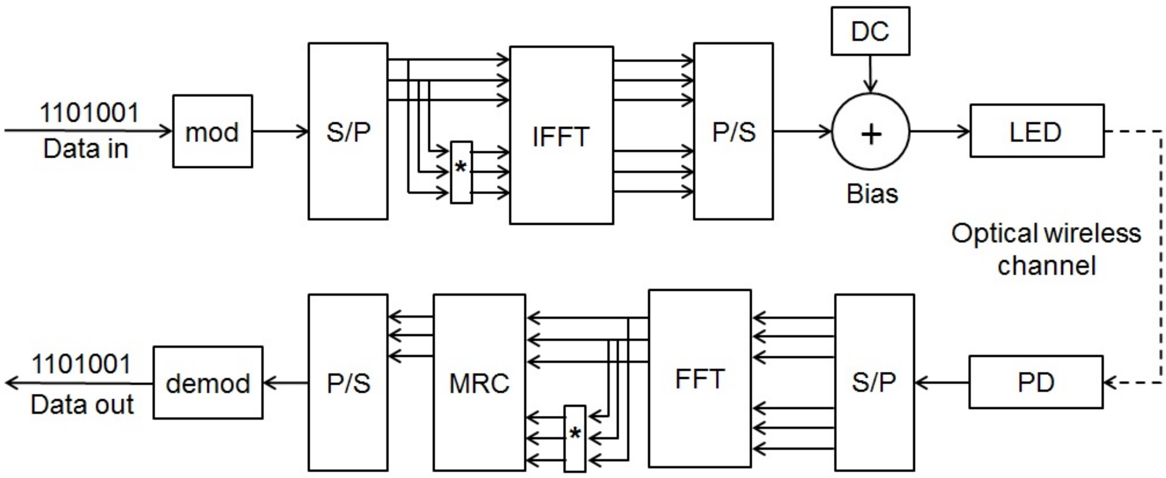

Figure 8: OFDM system block diagram

Carrier-less amplitude and phase modulation (CAP): CAP modulation is the vibrational scheme of QAM for Single Carrier (SC) systems. It is composed of two orthogonal signals similar to the in-phase and quadrature signals in QAM scheme, but does not require overhead and carrier [171]. It has high spectral efficiency and is used to increase the VLC link capacity under limited bandwidth. Figure 9 depicts CAP modulation block diagram. An encoder maps an input data stream into two independent multi-level symbol streams whose order is set depending on the channel. Each stream is then passed through In-phase and quadrature filter, whose impulse response forms a Hilbert transform pair. This makes both symbol streams orthogonal to each other [172]. These orthogonal signals are then added and passed to a DAC. Similar to OFDM, a DC bias is then added to make the signal unipolar. At the receiver, the inverse Hilbert filters, followed by a Decision Feedback Equalizer (DFE) is utilized to extract the symbol streams.

At the very basic level, CAP modulation is much simpler than OFDM, and has much lower PAPR. The two orthogonal signals allow for simpler implementation without FFT and IFFT blocks [173]. However, the complexity of the equalizer is susceptible to channel characteristics which has a significant impact on system performance. Furthermore, OFDM can 'exploit' the channel characteristics more efficiently by mapping modulation orders to fit the channel, making CAP less flexible than OFDM [174, 175].

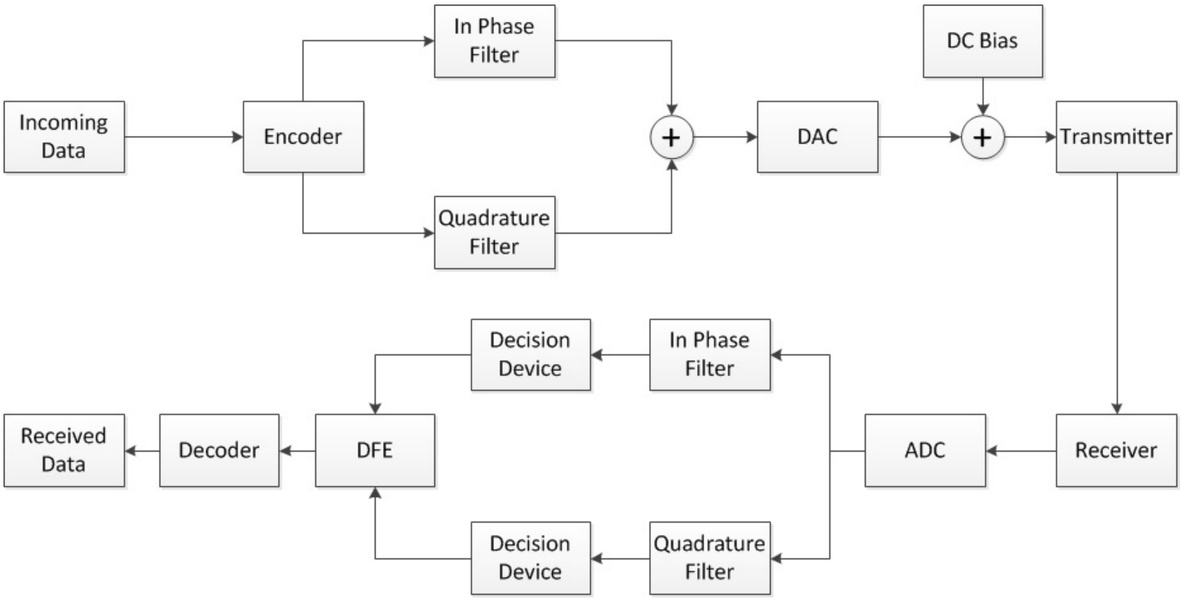

Figure 9: CAP modulation block diagram

4.7 Dimming

Integrating dimming into VLC enhances system value, saves energy and facilitates intelligent lighting solutions. It is desirable to maintain communication while a user arbitrarily dims the light source in VLC for saving power [124]. LEDs are in theory fully dimmable but not compatible with all dimmer controls designed for traditional lighting technologies. There are two general approaches in dimming LEDs:

- *Analog dimming:* The amount of light produced by a LED is directly proportional to the forward current driving the LED. Thus the brightness of an LED can be adjusted by controlling the amplitude of the forward current. The output of the LED driver is varied in proportion to a control voltage. This method is also well known as Continuous Current Reduction (CCR). It introduces no new frequencies as potential sources of EMI. However Switched Mode Power Supplies (SMPS) may have harmonics which can affect the communication link. Analog/intensity based dimming is simpler to implement and acts as a cost effective dimming scheme in VLC. Experiments performed in [176,177] show that luminous efficacy is always higher for CCR dimming scheme. For monochromatic LEDs, the dominant wavelength of photons emitted changes with direct current [177] causing chromaticity shifts [178,179], thereby causing a slight change in the CCT. CSK dimming introduced in IEEE 802.15.7 employs analog dimming by changing the drive current through the colored light sources [14, 124]. Dimming in OPPM scheme described earlier is also achieved by changing the light intensity of the LED over the pulse interval so that on average the required dimming level is maintained [140]. In [180], CCR dimming of an ACO-OFDM based VLC system was achieved by analog dimming.

- *Digital dimming:* A digitally modulated pulse train drives the LED at a constant current level. In digital dimming, the average duty cycle or signal density represents the

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equivalent analog dimming level. It is commonly used because of some advantages such as easy implementation and increased driver efficiency. Any modulation scheme that maintains an average duty cycle or signal density in a specified time period can be used to control and dim LEDs. For achieving precise accuracy over controlling LED lights and reduce chromatic shifts, digital dimming technique is more preferable than analog dimming [181].

4.7.1 Modulation Schemes for VLC Digital Dimming

The following subsection describes the popular modulation schemes used in VLC to execute digital dimming. A summarized comparison of some of these schemes is presented in Table 6.

Variable PPM (VPPM): VPPM is a mixture of PPM and PWM, with only 1 bit of information carried per symbol period. When the duty cycle is 50%, VPPM becomes the same as 2-PPM, and at full brightness no information can be transmitted [182]. At low dimming levels though, the data rate and performance is severely hampered due to the low bit energy. Modulation depth was varied to achieve brightness control for Single Carrier PPM (SC-PPM) VLC system in [183]

Variable OOK (VOOK): VOOK is achieved by changing the data duty cycle and filling up the non-data portion of the symbol with filler bits to achieve dimming [124, 182]. 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 as described earlier.

Pulse Width Modulation with Discrete Multi-Tone (PWM-DMT): For DMT schemes, the output DMT signal from the DAC is multiplied by the PWM signal to achieve dimming. When the PWM frequencies are too low, aliasing is said to cause large sub-carrier interference, hence the PWM needs to be sampled at a rate which is at least twice the highest sub-carrier frequency. Furthermore, if the PWM frequency is too high as to exceed the 3 dB bandwidth of the LED, the performance of the system will degrade [184]. In this case, enhancing the system bandwidth using blue filtering to extract the higher bandwidth blue component will not be possible, as the entire white light spectrum is taken into account for dimming. This would limit PWM bandwidth to ~2.5 MHz for most pc-LEDs, thus limiting the modulation bandwidth to ~1.25 MHz to limit sub-carrier interference. However, the system does not degrade in communication performance when dimming is applied given that the PWM frequency is chosen properly [184].

RPO-OFDM: Reverse Polarity OFDM (RPO-OFDM) is a novel signal format which combines the fast optical OFDM (O-OFDM) communication with the relatively slow PWM dimming signal, where both signals contribute to the effective LED brightness. Elgala *et al.* proposed this scheme based on numerical simulations in [185]. It was proposed to combine the PWM signal current $i_{LED}(t)$ with the O-OFDM time domain signal current $i_{OFDM}(t)$ in the following way:

$$i_{LED}(t) = \begin{cases} i_{PWM}(t) - m \times i_{OFDM}(t), & 0 \leq t \leq T \\ i_{PWM}(t) + m \times i_{OFDM}(t), & T < t \leq T_{PWM} \end{cases} \tag{3}$$

Table 6: Comparison of modulation based dimming schemes in VLC

	Dimming transition	Chromatic shifts	Spectral Efficiency	Disadvantage
VOOK	Smooth	No	Moderate	Data rate suffers when dimming level is too high or low
VPPM	Smooth	No	Low	No information can be transmitted at full brightness
MPPM	Intermittent	No	Moderate	Transmission time of data changes with brightness
OPPM	Non-linear	Yes	High	Higher average power requirement
PDSM	Smooth	No	Low	Higher complexity at receiver circuit
PWM-DMT	Smooth	No	High	Limited system bandwidth
RPO-OFDM	Smooth	No	High	Prone to clipping distortion at high signal power

where, m is a real valued scaling factor of the O-OFDM modulating signal. The RPO-OFDM dimming/communication signals combination algorithm can achieve both dimming and high data rate across a wide range of intensity settings while preserving compliance with industry standard dimming techniques. High dimming precision can be achieved through signal power and duty cycle variation. Thus high data rate can be maintained while offering a wide dimming range to serve illumination and/or energy saving goals.

4.7.2 Other Dimming Techniques in VLC

Inverse Source Coding (ISC): Kwon *et al.* have proposed inverse source coding based dimming for VLC, citing greater communication efficiency than the existing VOOK [186]. The method utilizes the ratio of *1*s and *0*s as on and off states for the required dimming ratio. For example, if the dimming ratio is 70%, then 70% of the output bits must be *1*s. The encoding scheme increases the number of transmitted data bits to achieve the dimming ratio. Huffman coding is generally used as the encoding scheme, where only an approximation to the required dimming ratio is achieved. The author in [186] states that this can be improved with more elaborate coding schemes. Furthermore, as the dimming ratio is moved further away from 50%, the encoding scheme adds more and more filler bits to reach the required bit balance, which in turn decreases the data rate.

Idle pattern dimming: An idle pattern is inserted between the data frames for light dimming. The duty cycle of the idle pattern can be varied to provide brightness variation. The idle pattern can either be in-band or out-of-band. In-band does not require any change in the clock and can be seen by the receiver, whereas out-of-band is typically sent at a much lower optical clock and is not seen by the receiver [25]. A compensation time ('on' or 'off' time of a light source) is inserted into either the idle pattern or into the data frame to reduce or increase the average brightness of a light source [187]. Visibility patterns are in-band idle patterns that are used in the payload of a Color Visibility Dimming (CVD) frame. The CVD frame is a frame used for color, visibility and dimming support. The CVD frame provides information such as communication status and channel quality to the user via various colors. During the CVD frame transmission, the device is still emitting light while not communicating, and it is thus able to fulfill its lighting function.

Probability based dimming: Probability of individual symbols can be changed according to dimming criterion. In [188], OOK modulation was extended to PAM and a probability based dimming scheme was proposed. This scheme can be combined with analog dimming forming a hybrid scheme. The effects of combining analog and probability based dimming on system performance was analyzed in [189]. The hybrid scheme performs dimming control by jointly optimizing the probability and intensity of PAM constellation points. The symbol intensity is at first shifted a certain percentage, the remaining shift towards the dimming target is performed by changing the symbol probability. It was concluded that optimal dimming control could be achieved by varying the probability only and intensity shift was not necessary.

4.8 Driver circuitry

Despite the apparent ease of operating LEDs with direct current, they are highly sensitive to the forward current and slight voltage changes due to their small dynamic resistance which makes the process of controlling and dimming them far more challenging. They operate under DC voltage and most of the general power supplies are AC sources. This AC-DC conversion is done by LED drivers. The driver also uses DC-DC converters to step down the line voltage based on the operating voltage of the LEDs. Considering LED characteristics, the stepped down DC voltage must be precisely maintained which can be done by adding a feedback controller to the driver circuit topology. The combination of illumination with communication places stringent requirements on LED driver design. Low power CMOS technology enables realization of system-on-chip driver circuits integrating multiple functions on a single die to control LED device performance, luminance and data modulation for smart visible light networking [190]. Unlike conventional LED drivers, the drivers for VLC have to accommodate VLC features without compromising illumination controls such as dimming. Besides these constraints, generally all driver circuits must use low power, have a long lifetime and should be able to use pulse current to drive the LEDs.

In order to develop an efficient driver circuit it is necessary to integrate all the key components of the circuitry keeping the design and requirements as the priority. Converters has different topologies (buck, boost, buck-boost etc.) and must be selected according to the voltage requirement of the LEDs. The DC input/output voltage relationship for the LED driver is based on the duty ratio of the switching signal. DC-DC converters usually have a resonant frequency and the power supply switching frequency must be lower than the resonant frequency for feedback loop stability [190]. The key characteristic of bias tee which must be considered is the cut on frequency f_{co} which is mainly determined by the capacitor used in it. If the capacitance value is high, f_{co} is reduced (which is desirable), but the power dissipation increases which means the modulation depth also increases. A very low capacitance which reduces f_{co} might lead to Baseline Wander (BLW) phenomenon causing attenuation of DC and low frequency components [191]. The BLW effect can be prevented by using high impedance to isolate the AC data source.

However, there are some general issues in driver circuit which limits the performance of VLC and lighting applications. As discussed earlier, the resonant frequency of the DC-DC converter limits the overall bandwidth of the feedback loop which is typically in the kHz range due to large capacitance and inductance values. This low bandwidth limits the data transmission rate of the VLC transmitters. Losses originating from AC power-light conversion which includes AC-DC-DC conversion, blue LED pump, phosphor packaging etc. decreases the efficiency of commercial LED bulb by 14% [192].

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There is a lot of recent work and research being conducted on LED driver circuit improvement. The driver bandwidth limitation is overcome in [190] by providing independent control of LED power supply voltage and the data/dimming block. Highest data rate of 477 Mb/s for simple OOK-NRZ was achieved in [78] by using a pre-emphasis circuit with Current Mode Logic (CML) and an emitter-follower rectifier circuit. A dimmable LED driver based on the burst mode LLC[13] resonant dc-dc converter topology was proposed in [35] to integrate VLC on a high power 80 W industrial smart lighting module. LLC resonant converter is a modified LC series resonant converter implemented by placing a shunt inductor across the transformer primary winding in the converter [193]. Both illumination control and data transfer using VPPM scheme was achieved by using average current mode controlled buck converter [141].

4.9 VLC performance challenges

Despite having inherent advantages compared to traditional communication systems, VLC still faces numerous challenges which need to be addressed. Limited bandwidth and slow modulation response of LEDs are the key challenges which limit the achievable data rate in VLC. The transmission distance is also limited due to the sharp decrease in illumination with distance. Ambient light also act as a significant source of noise in the system. This section mainly addresses the key challenges faced by VLC system and methods of countering them to enhance system performance.

Bandwidth enhancement: Commercial high brightness pc-LEDs have very low modulation bandwidth [150]. In case of pc-LEDs, the blue LED chip have a 3 dB bandwidth of around 20 Mb/s [7] and the phosphor coating used to convert the blue light to white further lowers the bandwidth to $\approx$ 2 Mb/s [36]. There are a lot of methods which can be adapted to counter the bandwidth limitation of the LEDs and the VLC system:

- *Blue Filtering:* This method enhances the 3 dB bandwidth of the LED. If the entire white spectrum is used at detection, the modulation bandwidth is limited to $\sim$2.5 MHz [125]. At higher frequencies, due to its low time constant, the yellow phosphor will not respond to the modulated signal in the LED drive current, hence generating a steady light which could saturate the receiver and increase shot noise[14], degrading system performance. Blue filtering enhances the modulation bandwidth up to $\sim$20 MHz [125, 194]. In the case of VLC, the system bandwidth is usually limited by the LED. The highest data rate achieved without blue filtering in pc-LEDs is 40 Mb/s [126], although transmitter equalization was done, enabling a 25 MHz operation.

- *Modulation beyond nominal 3 dB bandwidth:* Modulating beyond the 3 dB bandwidth has been implemented in [91, 93, 169, 170, 195], where LED drivers enabled $\sim$180 MHz bandwidth. Early methods of increasing the frequency response of LEDs include current shaping, or in other words pulse shaping. This method was initially used in optical fiber communication which reduces the rise and fall time of rc-LEDs. In its simplest case, a resistor in parallel with a capacitor is placed in series with the LED. When switching on, excess current flowing through the capacitor helps the LED reach its steady state faster. When switching off, the capacitor helps sweep out the carriers by reverse biasing

[13] A converter topology which consists of two inductors which is denoted by 'L' and one capacitor denoted by 'C', the load is connected in parallel to one of the inductors

[14] Noise generated due to the discrete nature of energy and charge of the PD [87]

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the diode [53,196]. The values for the RC circuit components is dependent on the diode series resistance, which in turn depends on the voltage across the LED. Details can be found in [53,196]. Current shaping can be viewed as a basic form of transmitter equalization, enhancing the response time of the LED, thereby increasing the 3 dB bandwidth.

- *Transmitter Equalization:* Simple pre-equalization at the transmitter to increase the usable bandwidth of a single LED has been demonstrated in [125]. The modulated data is equalized by three parallel drivers for low, medium and high frequencies before entering the bias tee. The equalized system is said to increase the bandwidth up to 45 MHz, while an increase in data rate from 40 to 80 Mb/s. Multiple-resonant equalization of multiple LEDs uses the fact that multiple LEDs can be equalized individually to enhance the bandwidth of an array of LEDs. The resonant driving circuit 'tunes the overall response of the array so that it has a higher bandwidth than an individual source [126]. The system demonstrated by Hoa Le *et al.* [126] uses an array of 16 LEDs to enhance the bandwidth from 3 MHz per individual LED to 25 MHz for the entire array without blue filtering.

- *Receiver equalization:* Demonstrations on post-equalization at the receiver [55,127] using a simple first order equalizer after PD signal amplification, has yielded a bandwidth of 50 MHz and data rate of 100 Mb/s. Combining pre-equalization at the transmitter with post-equalization at the receiver has been reported in [129] with the method described in [197]. Simulations suggest an increase in bandwidth of up to 65 MHz.

- *Adaptive Equalization:* Komine *et al.* developed an adaptive DFE technique using Least Mean Squares (LMS) algorithm [75]. The idea behind the system is that when a decision is made on the information carried on a certain symbol, that data is used to estimate the amount of ISI induced on future symbols. Simulations show a significant improvement in data rates, as well as better BER distribution when DFE is employed. If the mobile terminal is moving at higher data rates, the training sequences required to update the weights of the filters need to be sent more often, which could possibly degrade system performance.

- *Sub-carrier Equalization:* For multi carrier systems in DMT/OFDM, the achievable data rate can be maximized by optimizing the performance of each sub-carrier based on the Electrical-Optical-Electrical (EOE) channel characteristics. The idea is to scale individual sub-carriers to maintain similar transmission quality over all sub carriers. It is better to pre-equalize the signal at the transmitter rather than at the receiver, as amplifying the signal at the receiver would amplify the noise as well. These channel characteristics can be estimated by training sequences, typically sent at the beginning of each transmission block. A loading algorithm can determine the power of individual sub-carriers as well as the order of M-QAM/M-PSK constellation utilized. This is known as power loading and bit loading respectively. The algorithm used must comply with the maximum acceptable BER per sub-carrier, as well as the total power of the OFDM signal. In [89], Vucic *et al.* have used a loading algorithm by B.S.Krongold *et al.* [198], as it is known to be optimal and fast converging. Other systems utilizing sub-carrier equalization can be found in [91,122].

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Interference and Noise removal: Other light sources such as fluorescent, incandescent as well as sunlight creates background noise and interference as it shares the same wavelength band as the transmission. It is imperative that this in-band interference is removed to improve signal quality at the receiver. In [199], Manchester encoded signals were utilized to mitigate ambient optical noise. The received Manchester encoded symbol and a half bit delayed version of the same symbol are subtracted from each other and the decision is taken at the correct interval to demodulate the received bit. The system is robust against comparatively lower frequency fluorescent lighting, which have ballasts and its harmonics operating over several hundred kHz. But at higher frequency interference (possibly from other LED lamps), the performance degrades. Manchester coding was used to mitigate optical background noise generated in AC-LEDs operating at low frequency < 500 kHz as well as background fluorescent light in [199]. It had significant effect on signal quality improvement and performed better than conventional NRZ coded signals. A filter based system designed for WDM schemes has been proposed by Chang *et al.* [200]. Simulations suggested a filter based array system which can 'tune' an optical filter containing multiple element filters of differing bandpass characteristics to achieve high Signal to Interference Noise Ratio (SINR).

Non-linearity compensation and signal clipping: LED non-linearity needs to be taken into account when modulating as amplitude distortion occurs at TOV and at the saturation current in the high peaks due to the I-V characteristics of LEDs. As discussed in Section 4.6, it has a higher impact on OFDM and causes increase in BER and Inter-Carrier Interference (ICI). It is important to choose an LED with large dynamic range, low voltage-current slope characteristic and find the optimum operating point [201], while employing signal clipping or other power reduction methods [137, 202, 203]. Predistortion and postdistortion has been employed in OFDM to counteract the effect of the nonlinearities in [204–206].

Signal clipping is the simplest method of combating the high PAPR in OFDM. Making the entire LED input signal amplitude fall within the dynamic range of the LED would cause the signal power to be very low. Furthermore, the probability of a high peak occurring is statistically low [157]. The proper clipping ratio is achieved in stages by decreasing the clipping threshold of the signal and increasing the signal power, to find a point of acceptable BER and high data rate. Therefore, clipping can be used to fully utilize the LED's dynamic range. Symmetrical clipping of both high and low peaks has been employed successfully in [89, 91].

Optical beamforming: Optical beamforming is a technology of focusing LED light on a desired target. A Spatial Light Modulator (SLM) [207] is used to focus the LED light. SLM can modulate optical phase or amplitude on each pixel, it can also modulate light spatially in amplitude and phase. In [32], a location detecting algorithm is discussed to detect the exact position of the receiver. Packets are exchanged between transmitter and receiver and direction code is used when packets are exchanged to find out the exact location. SNR of the VLC system was reported to be improved by 13.4 dB.

In summary, most VLC system is IM/DD based since LEDs emit incoherent light. MIMO techniques are used to increase aggregate data rate. Dimming shcemes can be used in VLC system to save energy and allow the users to be in full control of the brightness. There are various single carrier and multiple carrier modulation schemes which are used in VLC for communication. The modulating waveform containing information is superimposed with the DC supply current and used to drive the LEDs producing intensity modulated light which is

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later received in the receiver circuit for post amplification and signal processing. The receiver front end circuit mainly consists of amplifiers which are available in different types. The choice of receiver as well as amplifiers depends on a trade off between sensitivity and speed. There are scopes of enhancing the bandwidth and performance in VLC systems at different stages since degradation occurs due to interference and noise.

5 Recent Progress

Table 7 details the recent efforts by various groups in attaining greater speeds using VLC. The table is arranged in terms of data rates achieved on a yearly basis in descending order. Type of transmitters and receivers used in each case are also stated for ease of comparison. The highest data rate had been achieved recently by using RGB LEDs [171], over a transmission distance of 0.25 m. Using WDM techniques on RGB LEDs yield higher data rates than pc-LEDs. OLEDs have lower data rates, but they are cheap to manufacture and by grouping them together a higher aggregate data rate can be achieved. It can be seen that PIN photodiode is mostly used as the receiver. The trend towards OFDM has yielded greater data rates, and with MIMO systems gaining popularity, it will continue to rise. Real time links have been demonstrated in [122, 123, 208]. In 2010, the first commercial deployment was implemented in St. Cloud, Minnesota [209]. This section apprises the recent efforts carried out by different research groups associated with VLC and the standardization of this technology.

5.1 Research groups

Listed below are some of the research groups that have been active in this area in the recent past.

- *OMEGA project:* The european hOME Gigabit Access (OMEGA) project, aimed at providing gigabit wireless connectivity to home users has been working on optical wireless communication, including developing visible light communication. Their goal is to develop heterogeneous communication through PLC, RFC and OWC to build a 'home with no wires'. For optical wireless, they intend to reach 1 Gb/s and 100 Mb/s through IR and visible light respectively. The project is funded by the European Commission and has 19 partner institutions which includes Siemens AG, Fraunhofer Henrich-Hertz Institute, France Telecom, Infineon, University of Oxford etc. Initially, they achieved 125 Mb/s using OOK-NRZ, but later moved on to DMT modulation, whilst supressing the slow phosphor component by filtering. Using symmetrical clipping, bit and power loading they achieved 513 Mb/s using a single pc-LED and an APD type receiver. In 2011, a RGB type LED was used to demonstrate WDM aggregating a rate of 803 Mb/s for 3 channels, using DMT. A year later, they achieved 806 Mb/s in a single channel of an RGB LED using a PIN type receiver instead [8, 88–90, 93].

- *Oxford University:* The approach taken by researchers in the Oxford group has been on improving data rates by using equalization and MIMO techniques. Having started with Multiple-Resonant equalization, the group demonstrated pre and post equalizer of the transmitter and receiver to enhance the 3 dB bandwidth. More recently, using MIMO, they achieved 1.1 Gb/s using pc-LEDs [98].

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Table 7: Recent performances

Year	Data rate	Distance (m)	Transmitter	Receiver	Modulation	Comment	Ref
2014	3 Gb/s	0.05	GaN μ-LED	PIN	OFDM	Pre and post equalization	[210]
2014	340 Mb/s	0.43	pc-LED	PIN	OOK-NRZ	Post equalization	[133]
2013	3.22 Gb/s	0.25	RGB	PIN	CAP (WDM)		[171]
2013	1.5 Gb/s	N/A	μ-LED	PIN	OOK	μ-LED pixel with CMOS electronics	[70]
2013	1.1 Gb/s	1	pc-LED	N/A	OFDM (WDM)	4 X 9 MIMO system	[98]
2013	575 Mb/s	0.66	RGB	PIN	QAM (WDM)	Bidirectional link	[38]
2013	500 Mb/s	5	off-the-shelf	PIN	DMT	Data rate adaptation with FEC	[211]
2013	477 Mb/s	0.40	RGB	PIN	OOK-NRZ		[78]
2013	150 Mb/s	0.5	pc-LED	PIN	OOK-NRZ	Neural network based receiver	[212]
2013	300 Mb/s	11	rc-LED	PIN	OOK-NRZ	Current shaping circuit	[130]
2013	10 Mb/s	1	pc-LED	PIN	PAM	NRZI code to mitigate interference	[213]
2013	3.4 Mb/s	0.80	pc-LED	APD	SSB-OFDM	CA-VLC system	[214]
2013	2 Mb/s	0.4	white-LED	PIN	OOK-NRZ	Duplex communication between anroid mobiles	[215]
2013	2.7 Mb/s	0.10	OLED	PIN	PPM		[132]
2013	1.4 Mb/s	N/A	OLED	PIN	OFDM		[216]
2012	3.4 Gb/s	0.3	RGB	APD	OFDM (WDM)		[195]
2012	2.1 Gb/s	0.1	RGB	APD	OFDM (WDM)	Optimum bit power loading allocation	[170]
2012	1.25 Gb/s	0.1	RGB	APD	OFDM (WDM)		[169]
2012	1.1 Gb/s	0.23	pc-LED	PIN	CAP		[217]
2012	1 Gb/s	0.1	pc-LED	APD	OFDM	Highest data rate for a single pc-lED	[91]
2012	780 Mb/s	2.5	RGB	APD	OFDM	Long distance high speed link	[168]
2012	806 Mb/s	0.08	RGB	PIN	OFDM		[93]
2012	614 Mb/s	0.40	RGB	PIN	OOK	Duobinary technique was used	[131]
2012	80 Mb/s	0.1	pc-LED	PIN	OOK	Pre-equalization	[125]
2011	803 Mb/s	0.12	RGB	APD	OFDM (WDM)	First demonstration of WDM capability	[88]
2011	410 Mb/s	0.9	RGB	APD	OFDM (WDM)	Localization aided OWC	[218]
2010	1 Gb/s	N/A	μ-LED	PIN	OOK-NRZ	LED fabricated from epitaxial wafers	[68]
2010	513 Mb/s	0.3	pc-LED	APD	OFDM (QAM)		[89]
2010	230 Mb/s	0.27	pc-LED	APD	OOK		[128]
2010	220 Mb/s	1	pc-LED	PIN	OFDM (MIMO)	2 X 9 MIMO sytem	[97]
2010	84 Mb/s	1.4	pc-LED	PIN	OFDM	Real time link	[122]
2009	231 Mb/s	0.7	pc-LED	PIN	OFDM		[166]
2009	125 Mb/s	5	pc-LED	PIN	OOK		[90]
2008	40 Mb/s	2	pc-LED	PIN	OOK	Multiple resonant equalization	[126]

- *Keio University:* Most of the early stages of the current trend in VLC was developed by Komine *et al.* from Keio University, Yokohama. This includes system modeling [84], modulation using OFDM and OOK [219], dimming as well as integrating PLC with VLC [219]. Recently, their focus has moved to VLC for intelligent transport systems utilizing existing traffic lights.

- *University of Edinburgh:* The D-Light project in University of Edinburgh aims to develop VLC for commercial usage. Their focus has been on utilizing OFDM for high speed data communication [12].

- *Boston University:* The Smart Lighting Engineering Research Center in Boston University was setup in 2008, focusing on VLC as well as nanophotonics and biosensing. New ideas which include 'Lights off' VLC [220], as well as RF/VLC hybrid methods have been proposed by Rahaim *et al* [117].

- *Sant'Anna School of Advanced Studies:* The integrated research center for photonic networks and technologies at Saint'Anna school of advanced studies has been researching in OWC as a viable replacement for RFC. Recently, they reached the highest data rate ever recorded in a VLC link which was 3.4 Gb/s [195]. Related research include VLC for plastic optical fiber communication and localization [218, 221].

- *Yeungnam University:* The effort of this research group was mainly towards dimming functionality in VLC systems [146]. They proposed coding based dimming schemes which utilized concepts implemented in information technology into VLC [15, 186, 188, 222–224].

- *KAIST University:* Kaist University's research work had also been mainly aimed towards dimming control in VLC using modulation schemes [144, 182, 225].

- *Choshun University:* The research group along with the affiliation with Northumbria University had mainly focused on PWM based dimming of VLC systems [134, 226–228].

- *Monash University:* Early works at Monash University, Melbourne were focused towards optical wireless OFDM systems. However, in the recent past works specific to VLC systems have emerged, with a focus on indoor localization and MIMO systems [229–233].

5.2 Standardization efforts

Initial standardization efforts were undertaken in Japan, by Japan Electronics and Information Technology Industries Association (JEITA) in JEITA standards CP-1221, CP-1222. Later on VLCC, together with Infrared Data Association (IrDA) published IrDA like standards for VLC in 2009 [165]. IEEE approved a comprehensive 802.15.7 VLC standard in 2011 [152]. It is a task group within the 802.15 working group for Wireless Personal Area Networks (WPAN). It is open to all optical wavelengths from 190 nm (UV) to 10 m (IR). It is open for various applications including outdoor traffic lighting systems, mobile devices, signboards and other display mechanisms as well as indoor lighting. At the moment, the standard utilizes only single carrier modulation schemes (OOK, VPPM) at a maximum achievable rate of 96 Mb/s, deemed by one of three operating modes (PHYI, PHYII, PHYIII). The standard also introduces CSK modulation for multi colored sources.

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PHYI: For high current, low bandwidth outdoor devices such as traffic lights. It uses OOK and VPPM with data rates up to 266 Kb/s.

PHY II: For indoor use for mobile devices and displays with high bandwidth, low power transmitters as well as lighting systems. It also uses OOK and VPPM with data rates up to 96 Mb/s.

PHYIII: CSK modulation utilizing multi-chip LEDs can provide data rates up to 96 Mb/s. A source capable of modulating CSK will have to comply to wavelength band plan where the peak emission wavelength lies.

Furthermore, the system utilizes flicker mitigation mechanisms and three types of dimming schemes, Cellular structure with handover mechanism to support user mobility, as well as three multi-access topologies (Point to point, Star, Broadcast).

Recently, some developments in using American National Standards Institute (ANSI) E1.11 entertainment lighting standards to provide low data rate VLC data to luminaries has emerged [234, 235]. This standard is generally referred to as DMX512, and is used mainly in theatre lighting systems control. The application scenarios include guiding viewers to seats in theatres, lighting control troubleshooting, as well as supermarket navigation. The draft mechanism packs IEEE 802 data frames into an ANSI E1.11 link using a proposed E1.45 packet format [234]. Simultaneous lighting control and unidirectional VLC communication would be possible with this methodology.

6 Related fields and applications

VLC applications based on LED lighting are more attractive in environments where the lights are always switched on. Deployment is rather easy as data can be provided from a local aggregation point to the luminaires via existing infrastructure like power cables. Other than combining with indoor illumination, VLC can be used in other scenarios, and combined with other technologies. This section lists out some of these scenarios along with the progress made and their practical implementations.

Intelligent Transport Systems (ITS): VLC is favorably considered in intelligent transportation systems where LEDs are used as road side unit [236]. It could be used for traffic light to vehicle, Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communications to send location or safe driving information [237]. Initial studies were done in Japan [238], even though patents had been filed beforehand. The main reason that V2V technology has not yet seen its adoption is that there is very low incentive for early adopters to purchase a new vehicle with the technology. Many envisioned applications that use multi-hop communications require a minimum market penetration rate of 10% or more [239]. The difficulty in VLC in ITS is that the receiver must be able to track the transmitter while in motion. Furthermore, increased link distances and intense background noise play a major role as well. Most proposed ITS applications utilize high speed cameras for reception [240, 241], while image sensors have also been proposed [242]. Cameras are favored as it facilitates tracking. Information is carried on the pixels of the LED array in the transmitter. In these systems, the system bandwidth is limited by the high speed camera frame rate. The frame rates need to be at least twice the modulation frequency of the LEDs, and typical frames rates are around 1000 fps, which limits the modulation frequency to ~ 500 Hz. Implementation may not be feasible currently as high speed cameras are expensive, and complex image processing may be

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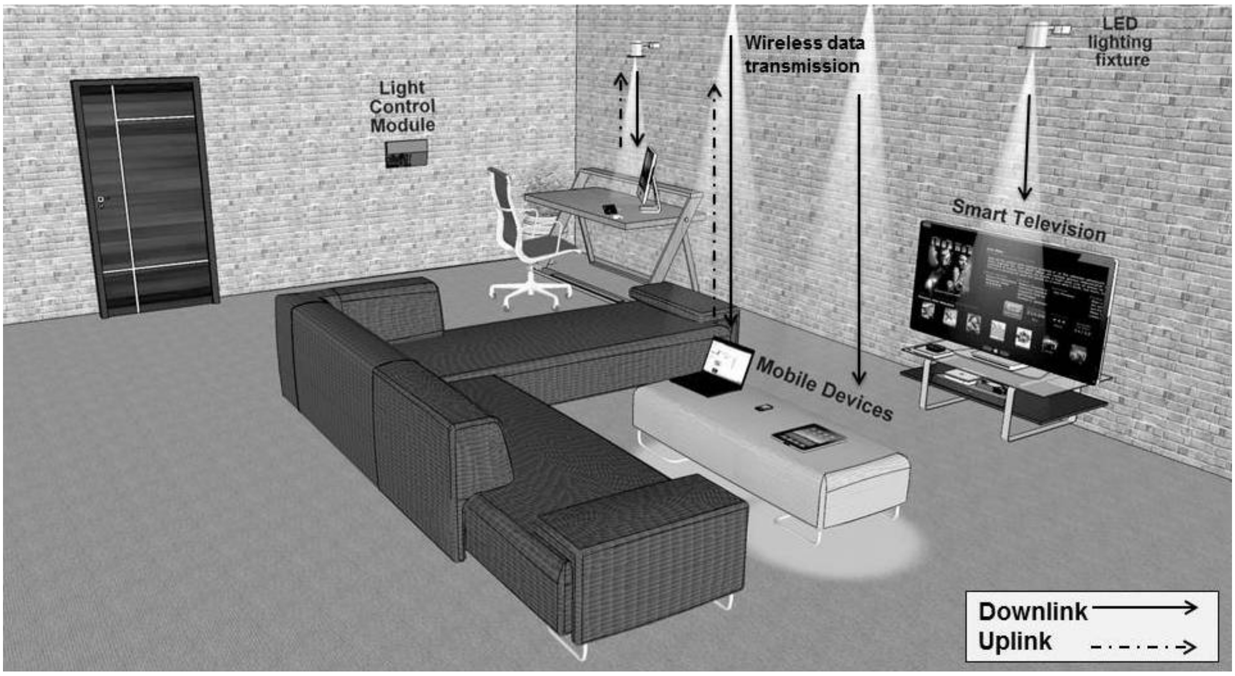

Figure 10: Indoor illumination integrated with VLC for next generation smart home lighting

required for transmitter tracking and demodulation. By integrating VLC into traffic system many useful applications can be achieved such as collision warning and avoidance, lane change assistance/warning and cooperative adaptive cruise control [243].

Intelligent Lighting: These systems cooperate and control lighting in a space to cater to user needs, while saving power. Intelligent lighting systems effectively form a Wireless Sensor Network (WSN), to monitor factors such as light intensity, color and control illumination by dimming. LEDs have offered higher flexibility for intelligent lighting solutions, due to low energy consumption, color control from multi-chip LEDs, dimming and VLC. Several systems have been proposed for combining VLC and intelligent lighting [244, 245]. Examples include turning on lights at a certain area only when required, low light for watching movies, bright light for reading and video conferencing [246]. Recently, Philips made 'Hue', an intelligent lighting fixture which can be color controlled and dimmed using an iPhone [247]. The device uses Wi-Fi to link with the user; the system is still under development, with plans of using GPS to automatically turn on lights as the user approaches home [248]. Figure 10 depicts the concept of a VLC integrated smart home where LED luminaries are used for illumination and communication simultaneously. Devices such as laptop, cellphone, smart television etc. can be greatly utilized by this technology. There is a light control module at the corner of the room which will allow users to control the light intensity according to mood and preference through their mobile device.

Indoor Localization: Just like the inventors of Global Positioning Systems (GPS) could never predict the enormous range of applications currently in use, the case might be same for Visible Light Positioning (VLP) [232]. Accurate indoor positioning is in demand in several markets where LED lighting is currently being adopted, such as the retail store and enterprise

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markets. Retailers, shopping malls and supermarkets are interested in positioning technology because it has the potential to vastly increase the revenue of all parties involved in the store's product supply chain [47]. In various indoor environment, GPS signals are not present and radio fails due to rich multipath propagation, whereas artificial lighting is omnipresent [211]. With WLEDs illuminating indoors, the infrastructure, together with VLC can be used for localization [218, 249, 250]. The market for mobile indoor positioning in the retail sector is expected to reach $5 billion by 2018 [47]. In 2013, a major supermarket in Korea had a special event in which customers could experience sale navigation and lighting coupon test service using VLC technology. This test service was planned to help shoppers easily find the discounted items for which lighting coupons are available, so it was named sale navigation [234]. This location service is similar to proposed VLC applications in theaters, where VLC data might help guide audience members to their seats, or in museums, where VLC data might trigger a particular audio guide script to explain a display. Carrier Allocation VLC (CA-VLC) has been studied for next generation inbuilt networks that provide Location Based Service (LBS) and positioning with lighting functions [214].

Plastic Optical Fiber (POF) Communication: Cheaper, flexible PMMA (polymethacrylate) type silicon POFs have been gaining popularity in recent times, as a substitute to glass optical fibers for short range links. POFs have its lowest attenuation window within 520-780 nm (green-red) visible wavelength range, but have higher attenuation (∼150 dB/km) as opposed to Glass Optical Fibers (GOF) (0.2-3 dB/km) [251]. Furthermore, POFs withstand vibrations better, have a smaller bend radius than GOFs and has no EMI, which could be useful in intra-vehicular communications. Gigabit transmission rates have been demonstrated over several meters [252]. Cossu *et al.* demonstrated a combined VLC and POF communication concept for home and office use, where POF (50 m) is used to distribute, while VLC link (2.5 m) is used for final transmission to the receiver. The system achieved a transmission rate of 200 Mb/s [221].

Power Line Communication (PLC): PLC, also known as Broadband over Power Line (BoPL) uses ubiquitous power lines to transmit data, where electrical power sockets can be used to power up devices as well as receive data. The technology has been around for a while, but has not really taken off around the world, with a handful of European and Asian countries using BoPL [253]. The technology needs to compete with the price and quality of current Digital Subscriber Lines (DSL), but the advantage is that power lines can reach remote areas not covered by DSL [254]. The main issues in PLC include high interference from appliances connected to the network [255], impedance and channel variations, non-white noise in nature and phase changes [256] . PLC fits in very well with VLC, as the data in the power line can be used to modulate LEDs directly [219, 257]. It was suggests that speed of 600 Mb/s is possible over power lines [258]. Besides MIMO and relaying techniques were proposed in [20] for integrating PLC with VLC.

Underwater communication: High speed underwater communication has been in development in recent years for WSN deployment, Remotely Operated Vehicles (ROV) [259] and for diver communication [260]. The 2.4 GHz ISM RF band has limited wavelength and speed due to extremely high attenuation in seawater with other wavelengths. Acoustic (sonar) communication devices are expensive and also have limited data rate (∼ 10 kb/s) due to the slow speed of acoustic waves in water [261]. Hence OW, including VLC is being looked at as an alternative method of high speed communication under water. In clear water, absorption of visible light is higher towards the red part of the spectrum, with minimal absorption at around 450nm; however, this could change depending on the constituents and impurities in the water, such as plankton or algae [262]. Therefore, the operational wavelength may well be determined by the application and environment. A system using visible LEDs for underwater transmission can be found in [262]. Penguin ASI developed an underwater communications device for ROVs using visible LEDs with data rates of up to 20 Mb/s [263, 264]. VLC integrated in underwater communication can also be used to provide real time feedback to swimmers [265, 266].

EMI-sensitive applications: Since VLC causes no electromagnetic interference (EMI) and has only a slight influence on electronic devices [267]; it can be used in EMI-sensitive environments such as aircraft cabins, hospital and spaceship. It can also be used in hazardous environments such as petrochemical plants, where RF is prohibited. A reading lamp based VLC system for in-flight entertainment was discussed in [142] where a visible light link was used as the downlink and infrared link as the uplink channel.

In summary, VLC complimented by the growing LED lighting infrastructure is expected to play a vital role in the future 4G wireless access networks. This unique technology which combines illumination with communication, can give rise to various indoor and outdoor applications such as intelligent lighting, indoor localization, PLC, ITS etc. At present, there are loads of research work being conducted on each of these applications in order to enhance their performance and facilitate their practical application in a broader commercial aspect.

7 Limitations

For eventual adoption, several basic system level issues can be identified which require attention:

Uplink: Providing an efficient uplink scheme for VLC has been a problem, as VLC with illumination has a broadcast characteristic with distributed sources [137, 268, 269]. A visible light uplink would be inefficient for portable devices which run on low power, and may also be considered inconvenient and unpleasant. Proposed schemes include RF, infrared, near UV and retro-reflective transceivers. Using RF could prove costly and power inefficient to integrate an entirely different set of transceivers together with the optical domain transceivers. Furthermore, RF may not be acceptable in certain scenarios where VLC is utilized to minimize EMI such as in hospitals. Retro reflective transceiver modulates the incident light and reflects it back as the uplink [270], but the modulation speed is low resulting in lower data rates. UV portion of the spectrum has little interference, with little sunlight in the UV band reaching Earths surface, due to ozone layer absorption in the atmosphere. Most links designed for UV are NLOS long distance links utilizing atmospheric scattering [271]. For these reasons IR seems to be a viable solution for the uplink. A ceiling mounted IR PD could be deployed. An experimental system designed for in-flight VLC utilizing an IR uplink of 512 kb/s has been demonstrated in [121]. Experiments conducted by Cui *et al.* in [272] measured the path loss for three optical band which are IR, near UV and visible light. The results are presented in Table 8. The experimental setup had the transmitter for the uplink placed about 1.8 m below the ceiling and was pointed straight up. According to the results, for LOS path, near UV had the least restrictive safety requirement and least background interference compared

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to the other two options. For NLOS configuration, the best performance was shown by IR.

Table 8: Path loss for different uplink options [272]

Uplink type	Distance (m)	LOS path loss (dB)	NLOS path loss (dB)
IR (850 nm)	1.8	32	38.5
Near UV (375 nm)	1.7	30.4	49
Visible (470 nm)	1.8	34.1	47.2

Interference: Other artificial and natural light sources create interference and effectively act as unmodulated sources at the receiver, increasing shot noise and if high enough can saturate the receiver. Factors such as Multi-Path Dispersion (MPD) and Fluorescent Light Interference (FLI) must also be considered. When VLC is combined with illumination exclusively in an indoor lighting scenario, the effect of incandescent and fluorescent lighting may be ignored. But unavoidable situations may arise when LED lighting used for VLC has to be combined in conjunction with other artificial lighting systems. The shot noise from sunlight is stationary, varying little over time and produces a steady but strong noise current. Artificial light could vary rapidly in time due to harmonics of the mains frequency, which itself varies the optical power incident on the photo detector [85, 273], thereby varying the amount of shot noise induced in the PD. A significant portion of the shot noise can be removed by filtering [85, 274], such as the blue filtering approach for pc-LED VLC systems.

Shadowing: Indoor VLC is built for LOS links. Therefore receivers are expected to have a clear LOS to the lighting system at most times. The effect can be minimized by distributing lighting sources so that high SNR is maintained throughout. Analyses of shadowing effect and solutions by Komine *et al.* can be found in [75, 275].

Lights off mode: Since indoor VLC aims to combine illumination with communication, it begs an important question of transmitting data when the lights are off. In the case where VLC is used as a supplement to RF and IR in a hybrid scheme, the transmission could just switch to radio waves or IR. But in an exclusive VLC setup, transmitting data with lights off become very difficult. Some data transmission can be achieved by making the light emitted to be low enough for humans to be perceptibly off [220]. Simulations by Borogovac*et al.* suggest satisfactory minimum speeds are possible when the light intensity (perceptibly off) can be controlled depending on the amount of ambient light in the room [220].

Effect of LED junction temperature and long term stability: Thermal management is an important issue in the design of high power LEDs. High junction temperature affects dominant wavelength [276], internal efficiency and spectral width [277]. Variation in the drive current, ambient temperature and self-heating causes changes in junction temperature. In case of emerging HB-LEDs for illumination and VLC which run at high drive currents, high junction temperatures could cause signal power degradation over time, reducing SNR [278]. The effect could be higher in illumination fixtures where arrays of hundreds of LEDs are connected close together. Long term light output and lifetime of an LED [279] drastically reduce when they are subject to excessive heat, as a result one of the significant advantages of OW systems compared to RF gets undermined. For VLC to be implemented effectively,

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LED junction temperature must be kept to a minimum.

Challenges in commercialization: There are certain business challenges which are preventing the widespread adoption of VLC in consumer market. For integrating downlink VLC, two different industries need to work together. One is the lighting OEMs which need to make certain modifications to their lamp and fixture designs. On the other hand the mobile device manufacturers need to install high speed photodiode receivers in their devices [47]. From the lighting manufacturers' perspective, the extremely high lifetime of LEDs may initially cause a high revenue in LED sales but later might lead to 'socket saturation'. In case of the mobile device manufacturers, integrating a new hardware into their existing devices may lead to unnecessary increase in cost and change in robustness of design.

In MIMO systems, even though in recent times progress has been made [97, 98, 103, 105], several system issues are yet to be resolved:

- *Channel Cross-talk:* Ideally light from one transmitter would impinge on a single receiver, which would require a static, precise alignment [98]. In real life, this is not possible as the image of a single source would be detected on multiple receivers. Some sort of overlap would be inevitable, especially for a relatively large number of transmitters. Cross-talk occurs when other communication channels create interference in the received signal channel of interest. Tran *et. al.* mentions cross-talk as the main limiting factor in optical MIMO systems [280].

- *Terminal Mobility:* If the receiver or transmitter is mobile, the image impinged on the detector array will change; intelligent control is required to extract data even when the light detection is handed over from one photo detector to another. The channel matrix will have to update over time using an intelligent learning algorithm [97]. In such cases, a dynamic solution would require rate adaptive techniques as the channel conditions vary due to a deficient channel matrix which requires a reduction in number of transmitters to make the matrix full rank.

- *Transmitter signal separation:* In certain cases, the light from several sources could fall on a single detector, rendering the channel matrix to not have a full rank, making signal extraction from all channels impossible. This could be the result of improper alignment at specific locations in a room.

- *Coverage:* For optimal operation, the receiver must be able to detect signals from most light sources anywhere in a room, which would require a wide beam angle for the transmitter and a wide field of view for the receiver. Doing this would relatively reduce the detected signal intensity, while opening the doors for higher ambient light interference upon reception. If the detector FOV is increased, lambertian reflections off walls could create secondary images of sources on the detector array which could cause cross talk and interference. Furthermore, a reduction in bandwidth, and achievable data rate will also occur.

At initial stages of research, it is advised to the readers to gain an understanding regarding IR optical wireless. The IR channel model is similar to VLC channel model. Since this band had been used for communications for a longer period of time, there is availability of papers covering theoretical aspects to a deeper extent. This also helps in finding research gaps by identifying work done in IR communication which had not been implemented in VLC. However it must be noted that due to the difference in wavelength, there is a difference in reflectivity of the surfaces which have significant impact on channel characteristics. When practical implementation of VLC systems is considered, factors such as junction temperature and variation in illumination level tend to become much more prominent which is not well modeled in simulation based analysis. TIA should be used in the down conversion sector initially since it gives an optimal balance between speed and responsivity and later the receiver front end can be chosen based on preference of the application the receiver would be used in. It is more sensible to begin work with single carrier modulation schemes, which is simpler to implement and once enough understanding is gained about various constraints which affect VLC systems in a practical framework, complex modulation schemes can be used for improving the data rate.

8 Conclusion

The spectral and bandwidth drawbacks of RF communication motivates the use of visible band for communication purposes. LEDs have emerged as one of the most energy efficient and promising lighting infrastructure; with the unit prices expected to decrease, the market adoption and domination of LED light sources is inevitable. The fast switching capability of LEDs allow them to be used as an optical source in VLC. In this paper, VLC link structure as well modulation schemes and dimming methods were discussed elaborately. Different modulation and dimming schemes have different characteristics and are expected to be chosen based on the functional requirements of the application they are used in. Recent progress amongst various research groups associated with VLC, enabled communication speeds of above 1 Gb/s. There are various system level issues VLC is currently facing such as interference, noise, shadowing etc. which is preventing its rapid growth. By the efforts initiated by the related research communities, these issues are foreseen to be countered, making way for VLC to be a promising communication technology for indoor applications.

The future prospects of VLC look bright, primarily with the ever increasing popularity of LEDs. With LEDs anticipated to rapidly replace traditional lighting technology, VLC is foreseen to be readily implemented into general lighting infrastructures which will give rise to several beneficial applications. By turning on a switch, broadband internet can be accessed by the same fixture which is providing illumination. VLC together with PLC can be part of a ‘Smart grid’, capable of controlling and keeping track of any device connected to the grid. The user could communicate with the ‘home network’ through VLC, managing and monitoring all activities. With potential for VLC in intelligent transport networks and indoor localization, the smart grid concept can be expanded even further allowing end users to simultaneously utilize VLC for information systems, traffic update, location estimation and most importantly wireless communication.

Nomenclature

μ-LED Micro Light Emitting Diode

ACO-OFDM Asymmetrically Clipped Optical OFDM

APD Avalanche Photo-Diode

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AWGN Additive White Gaussian Noise

BER Bit Error Rate

BLW Base-Line Wander

BoPL Broadband over Power Line

CA-VLC Carrier Allocation VLC

CAP Carrier-less Amplitude and Phase modulation

CCR Continuous Current Reduction

CCT Correlated Color Temperature

CFL Compact Fluorescent Lamps

CIM Color Intensity Modulation

CML Current Mode Logic

CMOS Complimentary Metal Oxide Semiconductor

COWA Center on Optical Wireless Applications

CP Cyclic Prefix

CRI Color Rendering Index

CSK Color Shift Keying

CVD Color Visibility Dimming

DCO-OFDM DC Offset OFDM

DD Direct Detection

DFE Decision Feedback Equalization

DMT Discrete Multi-Tone

DPPM Differential PPM

DSL Digital Subscriber Line

EM Electro-Magnetic

EMI Electro-Magnetic Interference

EOE Electrical-Optical-Electrical

EPPM Expurgated PPM

FEC Forward Error Correction

FFT Fast Fourier Transform

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FLI Fluorescent Light Interference

FOV Field Of View

FSO Free Space Optical

GCM Generalized Color Modulation

GOF Glass Optical Fibers

GPS Global Positioning Systems

GSSK Generalised Space Shift Keying

HB-LED High Brightness Light Emitting Diode

HID High Intensity Discharge

ICI Inter-Carrier Interference

IFFT Inverse Fast Fourier Transform

IM Intensity Modulation

InGaN Indium Gallium Nitride

IR Infra-Red

IRC Infra-Red Communication

IrDA Infrared Data Association

ISC Inverse Source Coding

ISI Inter Symbol Interference

ITS Intelligent Transport Systems

JEITA Japan Electronics and Information Technology Industries Association

LED Light Emitting Diode

LMS Least Mean Squares

LOS Line Of Sight

MIMO Multiple-Input Multiple-Output

MISO Multiple-Input Single-Output

MPD Multi-Path Dispersion

MPPM Multiple PPM

MRC Maximum Ratio Combining

MU Multi-User

OCDMA Optical Code Division Multiple Access

OEM Original Equipment Manufacturer

OFDM Orthogonal Frequency Division Multiplexing

OLED Organic Light Emitting Diode

OMEGA hOME Gigabit Access

OOK On-Off Keying

OPPM Overlapping PPM

OW Optical Wireless

OWC Optical Wireless Communication

PAM Pulse Amplitude Modulation

PAPR Peak-to-Average Power Ratio

pc-LED Phosphor-Converted Light Emitting Diode

PD Photo-Diode

PDSM Pulse Dual Slope Modulation

PLC Power Line Communication

POF Polymer Optical Fiber

PPA Photo Parametric Amplifier

PPM Pulse Position Modulation

PPMPWM Pulse-Position-Pulse-Width Modulation

PSK Phase Shift Keying

PWM Pulse Width Modulation

QAM Quadrature Amplitude Modulation

rc-LED Resonant Cavity Light Emitting Diode

RF Radio-Frequency

RFC Radio Frequency Communication

RGB Red, Green, Blue

RLL Run Length Limited

RONJA Reasonable Optical Near Joint Access

ROV Remotely Operated Vehicles

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RPO-OFDM Reverse Polarity OFDM

RS Reed Solomon

RSU Road Side Unit

SC Single Carrier

SINR Signal to Interference Noise Ratio

SISO Single-Input Single-Output

SLM Spatial Light Modulator

SMPS Switched Mode Power Supplies

SSL Solid State Lighting

TIA Trans-Impedance Amplifier

U-OFDM Unipolar OFDM

VLC Visible Light Communication

VLCC Visible Light Communication Consortium

VLP Visible Light Positioning

VOOK Variable OOK

VPPM Variable PPM

WDM Wavelength Division Multiplexing

Wi-Fi Wireless Fidelity

WLED White Light Emitting Diode

WPAN Wireless Personal Area Network

WSN Wireless Sensor Network

YAG Yttrium Aluminum Garnet

References

[1] A. G. Bell, W. G. Adams, Tyndall, and W. H. Preece, "Discussion on the photophone and the conversion of radiant energy into sound," *Journal of the Society of Telegraph Engineers*, vol. 9, no. 34, pp. 375–383, 1880.

[2] D. Jackson, T. Buffaloe, and S. Leeb, "Fiat lux: a fluorescent lamp digital transceiver," *IEEE Transactions on Industry Applications*, vol. 34, no. 3, pp. 625–630, 1998.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2015.2417576, IEEE Communications Surveys & Tutorials

[3] G. Pang, T. Kwan, C.-H. Chan, and H. Liu, “Led traffic light as a communications device,” in *IEEE/IEEJ/JSAI International Conference on Intelligent Transportation Systems*, Tokyo, Japan, 1999, pp. 788–793.

[4] K. Kulhavy, “Home:ronja,” RONJA, 2012. [Online]. Available: http://ronja.twibright.com/

[5] Y. Tanaka, S. Haruyama, and M. Nakagawa, “Wireless optical transmissions with white colored led for wireless home links,” in *11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2000)*, vol. 2, London, UK, 2000, pp. 1325–1329.

[6] VLCC, “Visible light communications consortium,” 2007. [Online]. Available: http://www.vlcc.net/modules/xpage1/

[7] J. Grubor, S. Randel, K. D. Langer, and J. W. Walewski, “Broadband information broadcasting using led-based interior lighting,” *Journal of Lightwave Technology*, vol. 26, no. 24, pp. 3883–3892, 2008.

[8] “Home gigabit access project,” 2012. [Online]. Available: http://www.ict-omega.eu/

[9] Bourns College of Engineering, “Center for ubiquitous communication by light,” 2012. [Online]. Available: http://www.uclight.ucr.edu/

[10] The Pennsylvania State University, “Center on optical wireless applications,” 2012. [Online]. Available: http://cowa.psu.edu/

[11] Smart Lighting Engineering Research Center, “Synthesizing light for the benefit of humanity,” 2008. [Online]. Available: http://www.bu.edu/smartlighting/

[12] G. Povey, “D-light project hits target,” 2011. [Online]. Available: http://visiblelightcomm.com/d-light-project-hits-target/

[13] University of Oxford, “Visible light communications,” 2012. [Online]. Available: http://www.eng.ox.ac.uk/communications/research/optical-communications/current-projects-1/visible-light-communications

[14] *Short-Range Wireless Optical Communication Using Visible Light*, IEEE Standard for Local and Metropolitan Area Networks–Part 15.7 Std., 2011.

[15] Y. Suh, C.-H. Ahn, and J. K. Kwon, “Dual-codeword allocation scheme for dimmable visible light communications,” *IEEE Photonics Technology Letters*, vol. 25, no. 13, pp. 1274–1277, 2013.

[16] S. Wu, H. Wang, and C.-H. Youn, “Visible light communications for 5g wireless networking systems: from fixed to mobile communications,” *IEEE Network*, vol. 28, no. 6, pp. 41–45, 2014.

[17] M. Khalighi and M. Uysal, “Survey on free space optical communication: A communication theory perspective,” *IEEE Communications Surveys Tutorials*, vol. PP, no. 99, pp. 1–1, 2014.

[18] A. Sevincer, A. Bhattarai, M. Bilgi, M. Yuksel, and N. Pala, "Lightnets: Smart lighting and mobile optical wireless networks: A survey," *IEEE Communications Surveys Tutorials*, vol. 15, no. 4, pp. 1620–1641, 2013.

[19] D. Tsonev, S. Videv, and H. Haas, "Light fidelity (li-fi): towards all-optical networking," *Proc. SPIE*, vol. 9007, pp. 900 702–900 702–10, 2013.

[20] H. Ma, L. Lampe, and S. Hranilovic, "Integration of indoor visible light and power line communication systems," in *17th IEEE International Symposium on Power Line Communications and its Applications (ISPLC)*, Johannesburg, South Africa, 2013, pp. 291–296.

[21] F. Demers, H. Yanikomeroglu, and M. St-Hilaire, "A survey of opportunities for free space optics in next generation cellular networks," in *Ninth Annual Communication Networks and Services Research Conference (CNSR)*, Ontario, Canada, May 2011, pp. 210–216.

[22] N. Kumar and N. Lourenco, "Led based visible light communication: A brief survey and investigation," *Journal of Engineering and Applied Sciences*, vol. 5, pp. 296–307, 2010.

[23] P. Ryan, "Application of the public-trust doctrine and principles of natural resource management to electromagnetic spectrum," *Michigan Telecommunications and Technology Law Review*, vol. 10, no. 2, p. 285, 2004.

[24] H. Baldwin, "Wireless bandwidth: Are we running out of room?" 2012. [Online]. Available: http://www.computerworld.com/s/article/9223670/Wireless-bandwidth-Are-we-running-out-of-room-

[25] M. Oh, "A flicker mitigation modulation scheme for visible light communications," in *15th International Conference on Advanced Communication Technology (ICACT)*, PyeongChang, Korea, 2013, pp. 933–936.

[26] B. Love, D. Love, and J. Krogmeier, "Like deck chairs on the titanic: Why spectrum reallocation wont avert the coming data crunch but technology might keep the wireless industry afloat," *Washington University Law Review*, vol. 89, p. 705, 2012.

[27] C. Jastrow, K. Munter, R. Piesiewicz, T. Kurner, M. Koch, and T. Kleine-Ostmann, "300 ghz transmission system," *Electronics Letters*, vol. 44, no. 3, pp. 213–214, 2008.

[28] I. Hosako, N. Sekine, M. Patrashin, S. Saito, K. Fukunaga, Y. Kasai, P. Baron, T. Seta, J. Mendrok, and S. Ochiai, "At the dawn of a new era in terahertz technology," *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1611–1623, 2007.

[29] H. Parikh, J. Chokshi, N. Gala, and T. Biradar, "Wirelessly transmitting a grayscale image using visible light," in *International Conference on Advances in Technology and Engineering (ICATE)*, Mumbai, India, 2013, pp. 1–6.

[30] R. Wood, "Wireless network traffic worldwide: forecasts and analysis 2013-2018," Analysys Mason Limited, Tech. Rep., 2013. [Online]. Available: http://www.analysysmason.com/Research/Content/Reports/Wireless-traffic-forecasts-Oct2013-RDTN0/

[31] C. Gabriel, "Wireless broadband alliance industry report 2013: Global trends in public wi-fi," Marvedis Rethink - Wireless Broadband Alliance, Tech. Rep., 2013. [Online]. Available: http://www.wballiance.com/wba/wp-content/uploads/downloads/2013/11/WBA-Industry-Report-2013.pdf

[32] S. M. Kim and S. M. Kim, "Performance improvement of visible light communications using optical beamforming," in *Fifth International Conference on Ubiquitous and Future Networks (ICUFN)*, Da Nang, Vietnam, 2013, pp. 362–365.

[33] D. Borah, A. Boucouvalas, C. Davis, S. Hranilovic, and K. Yiannopoulos, "A review of communication-oriented optical wireless systems," *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, no. 1, pp. 91–119, 2012.

[34] G. Dede, T. Kamalakis, and D. Varoutas, "Evaluation of optical wireless technologies in home networking: An analytical hierarchy process approach," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 3, no. 11, pp. 850–859, 2011.

[35] S. Zhao, J. Xu, and O. Trescases, "A dimmable led driver for visible light communication (vlc) based on llc resonant dc-dc converter operating in burst mode," in *28th Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, California, USA, 2013, pp. 2144–2150.

[36] M. Biagi, T. Borogovac, and T. Little, "Adaptive receiver for indoor visible light communications," *Journal of Lightwave Technology*, vol. 31, no. 23, pp. 3676–3686, 2013.

[37] C. Chow, C. Yeh, Y. Liu, P. Huang, and Y. Liu, "Adaptive scheme for maintaining the performance of the in-home white-led visible light wireless communications using ofdm," *Optics Communications*, vol. 292, no. 1, pp. 49 – 52, 2013.

[38] Y. Wang, Y. Wang, N. Chi, J. Yu, and H. Shang, "Demonstration of 575-mb/s downlink and 225-mb/s uplink bi-directional scm-wdm visible light communication using rgb led and phosphor-based led," *Optics Express*, vol. 21, no. 1, pp. 1203–1208, 2013.

[39] M. J. Eckelman, P. T. Anastas, and J. B. Zimmerman, "Spatial assessment of net mercury emissions from the use of fluorescent bulbs," *Environmental science & technology*, vol. 42, no. 22, pp. 8564–8570, 2008.

[40] S. Bose-O'Reilly, K. M. McCarty, N. Steckling, and B. Lettmeier, "Mercury exposure and children's health," *Current problems in pediatric and adolescent health cares*, vol. 40, no. 8, pp. 186–215, 2010.

[41] T. Katsuura, Y. Ochiai, T. Senoo2, S. Lee, Y. Takahashi, and Y. Shimomura1, "Effects of blue pulsed light on human physiological functions and subjective evaluation," *Journal of Physiological Anthropology*, vol. 31, no. 1, pp. 1–5, 2012.

[42] M. Kavehrad, "Sustainable energy-efficient wireless applications using light," *IEEE Communications Magazine*, vol. 48, no. 12, pp. 66–73, 2010.

[43] K. Pujapanda, "Lifi integrated to power-lines for smart illumination cum communication," in *International Conference on Communication Systems and Network Technologies (CSNT)*, Gwalior, India, 2013, pp. 875–878.

[44] M. Uddin, M. Chowdhury, and Y. M. Jang, "Priority-based resource allocation scheme for visible light communication," in *Second International Conference on Ubiquitous and Future Networks (ICUFN)*, Jeju Island, Korea, 2010, pp. 247–250.

[45] J. Kim and E. Schubert, "Transcending the replacement paradigm of solid-state lighting," *Optics Express*, vol. 16, no. 26, pp. 21 835–21 842, 2008.

[46] N. Bardsley, S. Bland, L. Pattison, M. Pattison, K. Stober, F. Welsh, and M. Yamada, "Solid-state lighting research and development: multi-year program plan," U.S. Department of Energy, Tech. Rep., 2014. [Online]. Available: http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html

[47] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 26–32, 2013.

[48] D. O'brien, "Visible light communications: Challenges and potential," in *IEEE Photonics Conference (IPC)*, Arlington, Virginia, USA, 2011, pp. 365–366.

[49] "Infrared data association," 2012. [Online]. Available: http://www.irda.org/

[50] J. Tuenge, "Ssl pricing and efficacy trend analysis for utility program planning," U.S. department of energy, Tech. Rep., 2013. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_trend-analysis_2013.pdf

[51] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265–298, 1997.

[52] M. H. Crawford, "Leds for solid-state lighting: Performance challenges and recent advances," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 15, no. 4, pp. 1028–1040, 2009.

[53] E. Schubert, *Light-Emitting Diodes.* Cambridge University Press, 2006.

[54] M. Zhang and Z. Zhang, "Fractionally spaced equalization in visible light communication," in *IEEE Wireless Communications and Networking Conference (WCNC)*, Shanghai, China, 2013, pp. 4282–4287.

[55] C. W. Chow, C. H. Yeh, Y. F. Liu, and Y. Liu, "Improved modulation speed of led visible light communication system integrated to main electricity network," *Electronics Letters*, vol. 47, no. 15, pp. 867–868, 2011.

[56] X. He, Z. Xiao, and S. He, "A design of led adaptive dimming lighting system based on incremental pid controller," in *Proc. SPIE 7852, LED and Display Technologies*, Beijing, China, 2010, pp. 78 520W–78 520W–7.

[57] J. Hecht, "Changing the lights: Are leds ready to become the market standard?" *Optics and Photonics News*, vol. 23, no. 3, pp. 44–50, 2012.

[58] Cree Inc., "Cree sets new r&d performance record with 254 lumen-per-watt power led," 2012. [Online]. Available: http://www.cree.com/news-and-events/cree-news/press-releases/2012/april/120412-254-lumen-per-watt

[59] S. P. Ying, C.-W. Tang, and B.-J. Huang, “Charaterizing leds for mixture of colored led light sources,” in *International Conference on Electronic Materials and Packaging (EMAP)*, Kowloon, China, 2006, pp. 1–5.

[60] L. Svilainis, “Comparison of the emi performance of led pwm dimming techniques for led video display application,” *Journal of Display Technology*, vol. 8, no. 3, pp. 162–165, 2012.

[61] D. Steigerwald, J. Bhat, D. Collins, R. Fletcher, M. Holcomb, M. Ludowise, P. Martin, and S. Rudaz, “Illumination with solid state lighting technology,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 8, no. 2, pp. 310–320, 2002.

[62] H. Le Minh, Z. Ghassemlooy, A. Burton, and P. A. Haigh, “Equalization for organic light emitting diodes in visible light communications,” in *IEEE GLOBECOM Workshops (GC Wkshps)*, Houston, Texas, USA, 2011, pp. 828–832.

[63] Z. Ghassemlooy, “Oled-based visible light communications,” in *IEEE Photonics Society Summer Topical Meeting Series*, Seattle, Washington, USA, 2012, pp. 102–104.

[64] P. A. Haigh, Z. Ghassemlooy, M. Hoa Le, S. Rajbhandari, F. Arca, S. F. Tedde, O. Hayden, and I. Papakonstantinou, “Exploiting equalization techniques for improving data rates in organic optoelectronic devices for visible light communications,” *Journal of Lightwave Technology*, vol. 30, no. 19, pp. 3081–3088, 2012.

[65] H. Chun, C.-J. Chiang, and D. C. O’Brien, “Visible light communication using oleds: Illumination and channel modeling,” in *International Workshop on Optical Wireless Communications (IWOW)*, Pisa, Italy, 2012, pp. 1–3.

[66] Konica Minolta, “Oled lighting,” Konica Minolta, 2014. [Online]. Available: http://www.konicaminolta.com/oled/products/index.html

[67] A. Kelly, J. McKendry, S. Zhang, D. Massoubre, B. Rae, R. Green, R. Henderson, and M. Dawson, “High-speed gan micro-led arrays for data communications,” in *14th International Conference on Transparent Optical Networks (ICTON)*, Coventry, UK, 2012, pp. 1–5.

[68] J. J. D. McKendry, R. P. Green, A. E. Kelly, G. Zheng, B. Guilhabert, D. Massoubre, E. Gu, and M. D. Dawson, “High speed visible light communications using individual pixels in a micro light emitting diode array,” *IEEE Photonics Technology Letters*, vol. 22, no. 18, pp. 1346–1348, 2010.

[69] J. J. D. McKendry, D. Massoubre, S. Zhang, B. R. Rae, R. P. Green, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, “Visible-light communications using a cmos-controlled micro-light- emitting-diode array,” *Journal of Lightwave Technology*, vol. 30, no. 1, pp. 61–67, 2012.

[70] S. Zhang, S. Watson, J. J. McKendry, D. Massoubre, A. Cogman, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, “1.5 gbit/s multi-channel visible light communications using cmos-controlled gan-based leds,” *Journal of Lightwave Technology*, vol. 31, no. 8, pp. 1211–1216, 2013.

[71] M. Dawson, "Ultra parallel visible light communications (up-vlc)," 2012. [Online]. Available: http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/K00042X/1

[72] H. Jiang and J. Y. Lin, "Nitride micro-leds and beyond - a decade progress review," *Opt. Express*, vol. 21, no. S3, pp. A475–A484, 2013.

[73] C. Jeon, H. W. Choi, and M. Dawson, "Fabrication of matrix-addressable ingan-based microdisplays of high array density," *IEEE Photonics Technology Letters*, vol. 15, no. 11, pp. 1516–1518, 2003.

[74] E. Schubert, Y.-H. Wang, A. Cho, L.-W. Tu, and G. Zydzik, "Resonant cavity light emitting diode," *Applied Physics Letters*, vol. 60, no. 8, pp. 921–923, 1992.

[75] T. Komine, L. Jun Hwan, S. Haruyama, and M. Nakagawa, "Adaptive equalization system for visible light wireless communication utilizing multiple white led lighting equipment," *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 2892–2900, 2009.

[76] H. Oh, J. Joo, J. Lee, J. Baek, J. Seo, and J. Kwak, "Structural optimization of high-power algainp resonant cavity light-emitting diodes for visible light communications," *Japanese Journal of Applied Physics*, vol. 47, pp. 6214–6216, 2008.

[77] L. Meriggi, M. Steer, M. Sorel, C. Ironside, I. Thayne, and C. MacGregor, "Mid-wave infrared (3-5 μm) alinsb resonant-cavity leds," in *International Quantum Electronics Conference Lasers and Electro-Optics Europe (CLEO EUROPE/IQEC)*, 2013, pp. 1–1.

[78] N. Fujimoto and H. Mochizuki, "477 mbit/s visible light transmission based on ook-nrz modulation using a single commercially available visible led and a practical led driver with a pre-emphasis circuit," in *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, Anaheim, California, USA, 2013, pp. 1–3.

[79] T. Baumgartner, F. Wunderlich, A. Jaunich, T. Sato, and G. Bundy, "Lighting the way: Perspectives on the global lighting market," McKinsey & Company, Tech. Rep., 2012. [Online]. Available: http://www.ledsmagazine.com/articles/2011/08/mckinsey-releases-lighting-market-report.html

[80] R. Kuller and T. Laike, "The impact of flicker from fluorescent lighting on well-being, performance and physiological arousal," *Ergonomics*, vol. 41, no. 4, pp. 433–447, 1998.

[81] S. Berman, D. Greenhouse, I. Bailey, R. Clear, and T. Raasch, "Human electroretinogram responses to video displays, fluorescent lighting, and other high frequency sources," *Optometry & Vision Science*, vol. 68, no. 8, pp. 645–662, 1991.

[82] S. Fotios, "Lighting in offices: lamp spectrum and brightness," *Coloration Technology*, vol. 127, no. 2, pp. 114–120, 2011.

[83] J. Armstrong, R. J. Green, and M. D. Higgins, "Comparison of three receiver designs for optical wireless communications using white leds," *IEEE Communications Letters*, vol. 16, no. 5, pp. 748–751, 2012.

[84] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using led lights," *IEEE Transactions on Consumer Electronics*, vol. 50, no. 1, pp. 100–107, 2004.

[85] F. R. Gfeller and U. Bapst, "Wireless in-house data communication via diffuse infrared radiation," *Proceedings of the IEEE*, vol. 67, no. 11, pp. 1474–1486, 1979.

[86] L. Kwonhyung, P. Hyuncheol, and J. R. Barry, "Indoor channel characteristics for visible light communications," *IEEE Communications Letters*, vol. 15, no. 2, pp. 217–219, 2011.

[87] S. Hranilovic, *Wireless optical communication systems.* Springer, 2004.

[88] J. Vucic, C. Kottke, K. Habel, and K. D. Langer, "803 mbit/s visible light wdm link based on dmt modulation of a single rgb led luminary," in *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, Los Angeles, USA, 2011, pp. 1–3.

[89] J. Vucic, C. Kottke, S. Nerreter, K. Langer, and J. W. Walewski, "513 mbit/s visible light communications link based on dmt-modulation of a white led," *Journal of Lightwave Technology*, vol. 28, no. 24, pp. 3512–3518, 2010.

[90] J. Vucic, C. Kottke, S. Nerreter, K. Habel, A. Buttner, K. D. Langer, and J. W. Walewski, "125 mbit/s over 5 m wireless distance by use of ook-modulated phosphorescent white leds," in *35th European Conference on Optical Communication (ECOC)*, Vienna, Austria, 2009, pp. 1–2.

[91] A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, "1-gb/s transmission over a phosphorescent white led by using rate-adaptive discrete multitone modulation," *IEEE Photonics Journal*, vol. 4, no. 5, pp. 1465–1473, 2012.

[92] Y. Tanaka, T. Komine, S. Haruyama, and M. Nakagawa, "Indoor visible light data transmission system utilizing white led lights," *IEICE transactions on communications*, vol. 86, no. 8, pp. 2440–2454, 2003.

[93] C. Kottke, K. Habel, L. Grobe, J. Hilt, L. F. del Rosal, A. Paraskevopoulos, and K. Langer, "Single-channel wireless transmission at 806 mbit/s using a white-light led and a pin-based receiver," in *14th International Conference on Transparent Optical Networks (ICTON)*, Coventry, UK, 2012, pp. 1–4.

[94] I. E. Lee, M. L. Sim, and F. W. L. Kung, "Performance enhancement of outdoor visible-light communication system using selective combining receiver," *Optoelectronics, IET*, vol. 3, no. 1, pp. 30–39, 2009.

[95] J. M. Kahn, R. You, P. Djahani, A. G. Weisbin, T. Beh Kian, and A. Tang, "Imaging diversity receivers for high-speed infrared wireless communication," *IEEE Communications Magazine*, vol. 36, no. 12, pp. 88–94, 1998.

[96] G. Yun and M. Kavehrad, "Spot-diffusing and fly-eye receivers for indoor infrared wireless communications," in *IEEE International Conference on Selected Topics in Wireless Communications.* Vancouver, Canada: IEEE, 1992, pp. 262–265.

[97] A. H. Azhar, T. Tuan-Anh, and D. O'Brien, "Demonstration of high-speed data transmission using mimo-ofdm visible light communications," in *IEEE GLOBECOM Workshops (GC Wkshps)*, Miami, Florida, USA, 2010, pp. 1052–1056.

[98] A. Azhar, T. Tran, and D. O'Brien, "A gigabit/s indoor wireless transmission using mimo-ofdm visible-light communications," *IEEE Photonics Technology Letters*, vol. 25, no. 2, pp. 171–174, 2013.

[99] T. Q. Wang, A. Sekercioglu, and J. Armstrong, "Hemispherical lens based imaging receiver for mimo optical wireless communication," in *IEEE Globecom Workshops (GC Wkshps)*, Anaheim, California, USA, 2012, pp. 1239–1243.

[100] R. R. Inguez, S. M. Idrus, and Z. Sun, *Optical Wireless Communications*. Auerbach Publications, 2008.

[101] H. Alhagagi and R. Green, "Load analysis with gain enhancement for the photo parametric amplifier (ppa)," in *14th International Conference on Transparent Optical Networks (ICTON)*, Coventry, UK, 2012, pp. 1–4.

[102] A. Khanifar, M. Milovanovic, and R. Green, "Degenerate mode of operation in photoparametric amplifying devices," in *25th European Microwave Conference*, vol. 2, Bologna, Italy, 1995, pp. 870–874.

[103] K. D. Dambul, D. C. O'Brien, and G. Faulkner, "Indoor optical wireless mimo system with an imaging receiver," *IEEE Photonics Technology Letters*, vol. 23, no. 2, pp. 97–99, 2011.

[104] S. Moghe and R. Upadhyay, "Comparison of siso and mimo techniques in 802.11n wireless local area network," in *International Conference on Emerging Trends in Electronic and Photonic Devices Systems (ELECTRO)*, Varanasi, India, 2009, pp. 245–246.

[105] L. Zeng, D. O'brien, H. Minh, G. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, "High data rate multiple input multiple output (mimo) optical wireless communications using white led lighting," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 9, pp. 1654–1662, 2009.

[106] ——, "High data rate multiple input multiple output (mimo) optical wireless communications using white led lighting," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 9, pp. 1654–1662, 2009.

[107] Z. Yu, R. Baxley, and G. Zhou, "Multi-user miso broadcasting for indoor visible light communication," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Vancouver, Canada, 2013, pp. 4849–4853.

[108] M. Biagi, A. M. Vegni, and T. D. Little, "Lat indoor mimo-vlc; localize, access and transmit," in *International Workshop on Optical Wireless Communications (IWOW)*, Pisa, Italy, 2012, pp. 1 –3.

[109] S. Wilson, M. Brandt-Pearce, Q. Cao, and I. Leveque, J.H., "Free-space optical mimo transmission with q -ary ppm," *IEEE Transactions on Communications*, vol. 53, no. 8, pp. 1402–1412, 2005.

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[110] T. Tsiftsis, H. Sandalidis, G. Karagiannidis, and M. Uysal, "Optical wireless links with spatial diversity over strong atmospheric turbulence channels," *IEEE Transactions on Wireless Communications*, vol. 8, no. 2, pp. 951–957, 2009.

[111] Y. Alqudah and M. Kavehrad, "Mimo characterization of indoor wireless optical link using a diffuse-transmission configuration," *IEEE Transactions on Communications*, vol. 51, no. 9, pp. 1554–1560, 2003.

[112] S. Hranilovic and F. Kschischang, "A pixelated mimo wireless optical communication system," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, no. 4, pp. 859–874, 2006.

[113] T. C. Schenk, L. Feri, H. Yang, and J.-P. Linnartz, "Optical wireless cdma employing solid state lighting leds," in *IEEE/LEOS Summer Topical Meeting (LEOSST)*, Newport Beach, California, USA, 2009, pp. 23–24.

[114] M. F. Guerra-Medina, O. Gonzalez, B. Rojas-Guillama, J. Martin-Gonzalez, F. Delgado, and J. Rabadan, "Ethernet-ocdma system for multi-user visible light communications," *Electronics Letters*, vol. 48, no. 4, pp. 227–228, 2012.

[115] J. Liu, Z. Pan, W. Noonpakdee, and S. Shimamoto, "Impact of light reflection on indoor wireless optical cdma systems," *J. Opt. Commun. Netw.*, vol. 4, no. 12, pp. 989–996, 2012.

[116] K. Cui, "Physical layer characteristics and techniques for visible light communications," Ph.D. dissertation, University of California Riverside, 20112.

[117] M. B. Rahaim, A. M. Vegni, and T. D. C. Little, "A hybrid radio frequency and broadcast visible light communication system," in *IEEE GLOBECOM Workshops (GC Wkshps)*, Houston, Texas, USA, 2011, pp. 792–796.

[118] H. Chowdhury, I. Ashraf, and M. Katz, "Energy-efficient connectivity in hybrid radio-optical wireless systems," in *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on*, Berlin, Germany, 2013, pp. 1–5.

[119] S. Shao, A. Khreishah, M. B. Rahaim, H. Elgala, M. Ayyash, T. D. Little, and J. Wu, "An indoor hybrid wifi-vlc internet access system," in *IEEE 11th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*, Pennsylvania, USA, 2014, pp. 569–574.

[120] X. Bao, X. Zhu, T. Song, and Y. Ou, "Protocol design and capacity analysis in hybrid network of visible light communication and ofdma system," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 4, pp. 1770–1778, 2014.

[121] R. Perez-Jimenez, J. Rufo, C. Quintana, J. Rabadan, and F. J. Lopez-Hernandez, "Visible light communication systems for passenger in-flight data networking," in *IEEE International Conference on Consumer Electronics (ICCE)*, Berlin, Germany, 2011, pp. 445–446.

[122] K. D. Langer, L. F. del Rosal, C. Kottke, J. W. Walewski, S. Nerreter, K. Habel, and J. Vucic, "Implementation of a 84 mbit/s visible-light link based on discrete-multitone

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2015.2417576, IEEE Communications Surveys & Tutorials

modulation and led room lighting," in *7th International Symposium on Communication Systems Networks and Digital Signal Processing (CSNDSP)*, Newcastle, UK, 2010, pp. 528–531.

[123] O. Bouchet, P. Porcon, M. Wolf, L. Grobe, J. W. Walewski, S. Nerreter, K. Langer, Ferna, x, L. ndez, J. Vucic, T. Kamalakis, G. Ntogari, and E. Gueutier, "Visible-light communication system enabling 73 mb/s data streaming," in *IEEE GLOBECOM Workshops (GC Wkshps)*, Miami, Florida, USA, 2010, pp. 1042–1046.

[124] S. Rajagopal, R. D. Roberts, and L. Sang-Kyu, "Ieee 802.15.7 visible light communication: modulation schemes and dimming support," *IEEE Communications Magazine*, vol. 50, no. 3, pp. 72–82, 2012.

[125] M. Hoa Le, D. O'Brien, G. Faulkner, L. Zeng, L. Kyungwoo, J. Daekwang, and O. YunJe, "80 mbit/s visible light communications using pre-equalized white led," in *34th European Conference on Optical Communication (ECOC)*, Brussels, Belgium, 2008, pp. 1–2.

[126] M. Hoa Le, D. O'Brien, G. Faulkner, Z. Lubin, L. Kyungwoo, J. Daekwang, and O. YunJe, "High-speed visible light communications using multiple-resonant equalization," *IEEE Photonics Technology Letters*, vol. 20, no. 14, pp. 1243–1245, 2008.

[127] M. Hoa Le, D. O'Brien, G. Faulkner, Z. Lubin, L. Kyungwoo, J. Daekwang, O. YunJe, and W. Eun Tae, "100-mb/s nrz visible light communications using a postequalized white led," *IEEE Photonics Technology Letters*, vol. 21, no. 15, pp. 1063–1065, 2009.

[128] J. Vucic, C. Kottke, S. Nerreter, K. Habel, A. Buttner, K. D. Langer, and J. W. Walewski, "230 mbit/s via a wireless visible-light link based on ook modulation of phosphorescent white leds," in *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, San Diego, California, USA, 2010, pp. 1–3.

[129] Z. Lubin, M. Hoa Le, D. O'Brien, G. Faulkner, L. Kyungwoo, J. Daekwang, and O. YunJe, "Equalisation for high-speed visible light communications using white-leds," in *6th International Symposium on Communication Systems, Networks and Digital Signal Processing (CNSDSP)*, Graz, Austria, 2008, pp. 170–173.

[130] P. Binh, V. Trong, D. Hung, P. Renucci, A. Balocchi, and X. Marie, "Demonstration of 300 mbit/s free space optical link with commercial visible led," in *11th IEEE International New Circuits and Systems Conference (NEWCAS)*, Paris, France, 2013, pp. 1–3.

[131] N. Fujimoto and H. Mochizuki, "614 mbit/s ook-based transmission by the duobinary technique using a single commercially available visible led for high-speed visible light communications," in *European Conference and Exhibition on Optical Communication (ECEOC)*. Amsterdam Netherlands: Optical Society of America, 2012.

[132] P. Haigh, Z. Ghassemlooy, S. Rajbhandari, and I. Papakonstantinou, "Visible light communications using organic light emitting diodes," *IEEE Communications Magazine*, vol. 51, no. 8, pp. 148–154, 2013.

[133] H. Li, X. Chen, B. Huang, D. Tang, and H. Chen, "High bandwidth visible light communications based on a post-equalization circuit," *IEEE Photonics Technology Letters*, vol. 26, no. 2, pp. 119–122, 2014.

[134] H.-J. Jang, J.-H. Choi, Z. Ghassemlooy, and C. G. Lee, "Pwm-based ppm format for dimming control in visible light communication system," in *8th International Symposium on Communication Systems, Networks Digital Signal Processing (CSNDSP)*, Poznan, Poland, 2012, pp. 1–5.

[135] J. Rufo, C. Quintana, F. Delgado, J. Rabadan, and R. Perez-Jimenez, "Considerations on modulations and protocols suitable for visible light communications (vlc) channels: Low and medium baud rate indoor visible ligth communications links," in *IEEE Consumer Communications and Networking Conference (CCNC)*, Las Vegas, Nevada, USA, 2011, pp. 362–364.

[136] S. He, G. Ren, Z. Zhong, and Y. Zhao, "M-ary variable period modulation for indoor visible light communication system," *IEEE Communications Letters*, vol. 17, no. 7, pp. 1325–1328, 2013.

[137] H. Elgala, R. Mesleh, and H. Haas, "Indoor optical wireless communication: potential and state-of-the-art," *IEEE Communications Magazine*, vol. 49, no. 9, pp. 56–62, 2011.

[138] S. Arnon, "The effect of clock jitter in visible light communication applications," *Journal of Lightwave Technology*, vol. 30, no. 21, pp. 3434–3439, 2012.

[139] M. Noshad and M. Brandt-Pearce, "Application of expurgated ppm to indoor visible light communications part i: Single-user systems," *Journal of Lightwave Technology*, vol. 32, no. 5, pp. 875–882, 2014.

[140] B. Bo, X. Zhengyuan, and F. Yangyu, "Joint led dimming and high capacity visible light communication by overlapping ppm," in *19th Annual Wireless and Optical Communications Conference (WOCC)*, Shanghai, China, 2010, pp. 1–5.

[141] K. Modepalli and L. Parsa, "Dual purpose hb-led driver for illumination and visible light communication," in *Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2013, pp. 875–880.

[142] C. Quintana, V. Guerra, J. Rufo, J. Rabadan, and R. Perez-Jimenez, "Reading lamp-based visible light communication system for in-flight entertainment," *IEEE Transactions on Consumer Electronics*, vol. 59, no. 1, pp. 31–37, 2013.

[143] J. Gancarz, H. Elgala, and T. Little, "Impact of lighting requirements on vlc systems," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 34–41, 2013.

[144] J. Kim, K. Lee, and H. Park, "Power efficient visible light communication systems under dimming constraint," in *IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Sydney, Australia, 2012, pp. 1968–1973.

[145] Y. Fan, B. Bai, and R. Green, "Ppmpwm: A new modulation format for wireless optical communications," in *7th International Symposium on Communication Systems Networks and Digital Signal Processing (CSNDSP)*, Newcastle, UK, 2010, pp. 604–609.

[146] S. H. Lee, K.-I. Ahn, and J. K. Kwon, "Multilevel transmission in dimmable visible light communication systems," *Journal of Lightwave Technology*, vol. 31, no. 20, pp. 3267–3276, 2013.

[147] R. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 4, pp. 2228–2241, 2008.

[148] M. Di Renzo, H. Haas, and P. M. Grant, "Spatial modulation for multiple-antenna wireless systems: a survey," *IEEE Communications Magazine*, vol. 49, no. 12, pp. 182–191, 2011.

[149] W. Popoola, E. Poves, and H. Haas, "Generalised space shift keying for visible light communications," in *8th International Symposium on Communication Systems, Networks Digital Signal Processing (CSNDSP)*, Poznan, Poland, 2012, pp. 1–4.

[150] ——, "Error performance of generalised space shift keying for indoor visible light communications," *IEEE Transactions on Communications*, vol. 61, no. 5, pp. 1968–1976, 2013.

[151] W. Popoola and H. Haas, "Demonstration of the merit and limitation of generalised space shift keying for indoor visible light communications," *Journal of Lightwave Technology*, vol. 32, no. 10, pp. 1960–1965, 2014.

[152] "Ieee 802.15 wpan taskgroup 7 (tg7) visible light communication," 2014. [Online]. Available: http://www.ieee802.org/15/pub/TG7.html

[153] P. Das, Y. Park, and K.-D. Kim, "Color-independent ofdm-based visible light communication," in *Fifth International Conference on Ubiquitous and Future Networks (ICUFN)*, Da Nang, Vietnam, 2013, pp. 672–673.

[154] P. Das, B.-Y. Kim, Y. Park, and K.-D. Kim, "Color-independent vlc based on a color space without sending target color information," *Optics Communications*, vol. 286, no. 0, pp. 69–73, 2013.

[155] K.-I. Ahn and J. Kwon, "Color intensity modulation for multicolored visible light communications," *IEEE Photonics Technology Letters*, vol. 24, no. 24, pp. 2254–2257, 2012.

[156] H. Elgala, R. Mesleh, H. Haas, and B. Pricope, "Ofdm visible light wireless communication based on white leds," in *IEEE 65th Vehicular Technology Conference (VTC)*, Dublin, Ireland, 2007, pp. 2185–2189.

[157] J. Armstrong, "Ofdm for optical communications," *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 189–204, 2009.

[158] K.-D. Langer, J. Vucic, C. Kottke, L. Fernandez, K. Habe, A. Paraskevopoulos, M. Wendl, and V. Markov, "Exploring the potentials of optical-wireless communication using white leds," in *13th International Conference on Transparent Optical Networks (ICTON)*, Stockholm, Sweden, 2011, pp. 1–5.

[159] H. Elgala, R. Mesleh, and H. Haas, "A study of led nonlinearity effects on optical wireless transmission using ofdm," in *6th IEEE and IFIP International Conference on Wireless and Optical Communications Networks (WOCN)*, Cairo, Egypt, 2009, pp. 1–5.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2015.2417576, IEEE Communications Surveys & Tutorials

[160] ——, "Indoor broadcasting via white leds and ofdm," *IEEE Transactions on Consumer Electronics*, vol. 55, no. 3, pp. 1127–1134, 2009.

[161] L. Xiaodong and J. Cimini, L. J., "Effects of clipping and filtering on the performance of ofdm," *IEEE Communications Letters*, vol. 2, no. 5, pp. 131–133, 1998.

[162] J. Armstrong and A. J. Lowery, "Power efficient optical ofdm," *Electronics Letters*, vol. 42, no. 6, pp. 370–372, 2006.

[163] J. Armstrong and B. J. C. Schmidt, "Comparison of asymmetrically clipped optical ofdm and dc-biased optical ofdm in awgn," *IEEE Communications Letters*, vol. 12, no. 5, pp. 343–345, 2008.

[164] D. Tsonev, S. Sinanovic, and H. Haas, "Novel unipolar orthogonal frequency division multiplexing (u-ofdm) for optical wireless," in *IEEE 75th Vehicular Technology Conference (VTC)*, Yokohama, Japan, 2012, pp. 1–5.

[165] K. D. Langer, J. Vucic, C. Kottke, L. F. del Rosal, S. Nerreter, and J. Walewski, "Advances and prospects in high-speed information broadcast using phosphorescent white-light leds," in *11th International Conference on Transparent Optical Networks (ICTON)*, Azores, Portugal, 2009, pp. 1–6.

[166] J. Vucic, C. Kottke, S. Nerreter, A. Buttner, K. D. Langer, and J. W. Walewski, "White light wireless transmission at 200+ mb/s net data rate by use of discrete-multitone modulation," *IEEE Photonics Technology Letters*, vol. 21, no. 20, pp. 1511–1513, 2009.

[167] M. Z. Afgani, H. Haas, H. Elgala, and D. Knipp, "Visible light communication using ofdm," in *2nd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM)*, Barcelona, Spain, 2006, pp. 6–13.

[168] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "Long distance indoor high speed visible light communication system based on rgb leds," in *Asia Communications and Photonics Conference (ACP)*, Guangzhou China, 2012, pp. 1–3.

[169] C. Kottke, J. Hilt, K. Habel, J. Vučić, and K.-D. Langer, "1.25 gbit/s visible light wdm link based on dmt modulation of a single rgb led luminary," in *38th European Conference and Exhibition on Optical Communication (ECOC)*, Amsterdam, Netherlands, 2012, pp. 1–3.

[170] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "2.1 gbit/s visible optical wireless transmission," in *European Conference and Exhibition on Optical Communication (ECOC)*, Amsterdam, Netherlands, 2012, pp. 4.16–4.18.

[171] F.-M. Wu, C.-T. Lin, C.-C. Wei, C.-W. Chen, Z.-Y. Chen, and H.-T. Huang, "3.22-gb/s wdm visible light communication of a single rgb led employing carrier-less amplitude and phase modulation," in *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, Anaheim, California, USA, 2013, pp. 1–3.

[172] "xdsl modulation techniques," Nextep Broadband and NEC Australia Pty Ltd, Tech. Rep., 2001. [Online]. Available: http://www.tech2u.com.au/products/dsl/pdf/DSL_Modulation_Techniques.pdf

[173] F. Wu, C. Lin, C. Wei, C. Chen, Z. Chen, H. Huang, and S. Chi, "Performance comparison of ofdm signal and cap signal over high capacity rgb-led-based wdm visible light communication," *IEEE Photonics Journal*, vol. 5, no. 4, pp. 7 901 507–7 901 507, 2013.

[174] R. Rodes, M. Wieckowski, T. T. Pham, J. B. Jensen, J. Turkiewicz, J. Siuzdak, and I. T. Monroy, "Carrierless amplitude phase modulation of vcsel with 4 bit/s/hz spectral efficiency for use in wdm-pon," *Opt. Express*, vol. 19, no. 27, pp. 26 551–26 556, 2011.

[175] F. Sjoberg, "A vdsl tutorial," Lulea Tekniska University, Tech. Rep., 2000. [Online]. Available: http://epubl.ltu.se/1402-1528/2000/02/LTU-FR-0002-SE.pdf

[176] Y. Gu, N. Narendran, T. Dong, and H. Wu, "Spectral and luminous efficacy change of high-power leds under different dimming methods," in *Sixth International Conference on Solid State Lighting*, vol. 6337, San Diego, California, USA, 2006, pp. 63 370J–63 370J–7.

[177] M. Dyble, N. Narendran, A. Bierman, and T. Klein, "Impact of dimming white leds: chromaticity shifts due to different dimming methods," in *Proc. of SPIE 5941, 5th International Conference on Solid State Lighting*, Bellingham, Washington, USA, 2005, pp. 291–299.

[178] K. Lee and H. Park, "Modulations for visible light communications with dimming control," *IEEE Photonics Technology Letters*, vol. 23, no. 16, pp. 1136–1138, 2011.

[179] H.-S. Kim, D.-R. Kim, S.-H. Yang, Y.-H. Son, and S.-K. Han, "Transmission performance variation by dimming control in carrier allocation based visible light communication," in *17th Opto-Electronics and Communications Conference (OECC)*, Busan, Korea, 2012, pp. 743–744.

[180] I. Stefan, H. Elgala, and H. Haas, "Study of dimming and led nonlinearity for aco-ofdm based vlc systems," in *IEEE Wireless Communications and Networking Conference (WCNC)*, Paris, France, 2012, pp. 990–994.

[181] S. Sarhan and C. Richardson, "A matter of light, part 4 - pwm dimming," 2012. [Online]. Available: http://www.eetimes.com/design/power-management-design/4012236/A-matter-of-lightPart-4---PWM-dimming

[182] L. Kwonhyung and P. Hyuncheol, "Modulations for visible light communications with dimming control," *IEEE Photonics Technology Letters*, vol. 23, no. 16, pp. 1136–1138, 2011.

[183] H. Sugiyama, S. Haruyama, and M. Nakagawa, "Brightness control methods for illumination and visible-light communication systems," in *3rd International Conference on Wireless and Mobile Communications (ICWMC)*, Guadeloupe, France, 2007, pp. 78–83.

[184] G. Ntogari, T. Kamalakis, J. Walewski, and T. Sphicopoulos, "Combining illumination dimming based on pulse-width modulation with visible-light communications based on

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2015.2417576, IEEE Communications Surveys & Tutorials

discrete multitone," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 3, no. 1, pp. 56–65, 2011.

[185] H. Elgala and T. D. C. Little, "Reverse polarity optical-ofdm (rpo-ofdm): dimming compatible ofdm for gigabit vlc links," *Optics Express*, vol. 21, no. 20, pp. 24 288–24 299, 2013.

[186] J. K. Kwon, "Inverse source coding for dimming in visible light communications using nrz-ook on reliable links," *IEEE Photonics Technology Letters*, vol. 22, no. 19, pp. 1455 –1457, 2010.

[187] J. Kim and H. Park, "A coding scheme for visible light communication with wide dimming range," *IEEE Photonics Technology Letters*, vol. 26, no. 5, pp. 465–468, 2014.

[188] K.-I. Ahn and J. K. Kwon, "Capacity analysis of m-pam inverse source coding in visible light communications," *Journal of Lightwave Technology*, vol. 30, no. 10, pp. 1399–1404, 2012.

[189] J.-Y. Wang, J.-B. Wang, M. Chen, and X. Song, "Dimming scheme analysis for pulse amplitude modulated visible light communications," in *International Conference on Wireless Communications Signal Processing (WCSP)*, Hangzhou, China, 2013, pp. 1–6.

[190] A. Mirvakili and V. Koomson, "High efficiency led driver design for concurrent data transmission and pwm dimming control for indoor visible light communication," in *IEEE Photonics Society Summer Topical Meeting Series*, Seattle, Washington, USA, 2012, pp. 132–133.

[191] A. Azhar and D. O'Brien, "Experimental comparisons of optical ofdm approaches in visible light communications," in *IEEE Globecom Workshops (GC Wkshps)*, Atlanta, USA, 2013, pp. 1076–1080.

[192] J. Tsao, M. Coltrin, M. H. Crawford, and J. Simmons, "Solid-state lighting: An integrated human factors, technology, and economic perspective," *Proceedings of the IEEE*, vol. 98, no. 7, pp. 1162–1179, 2010.

[193] H. Choi, *AN-4151 Half-Bridge LLC Resonant Converter Design Using FSFR-Series Fairchild Power Switch (FPS)*, Fairchild Semiconductor. [Online]. Available: http://www.fairchildsemi.com/an/AN/AN-4151.pdf

[194] J. Grubor, S. Randel, K. D. Langer, and J. W. Walewski, "Bandwidth-efficient indoor optical wireless communications with white light-emitting diodes," in *6th International Symposium on Communication Systems, Networks and Digital Signal Processing (CNS-DSP)*, Graz, Austria, 2008, pp. 165–169.

[195] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "3.4 gbit/s visible optical wireless transmission based on rgb led," *Optics Express*, vol. 20, no. 26, pp. B501–B506, 2012.

[196] E. Schubert, N. Hunt, R. Malik, M. Micovic, and D. Miller, "Temperature and modulation characteristics of resonant-cavity light-emitting diodes," *Journal of Lightwave Technology*, vol. 14, no. 7, pp. 1721–1729, 1996.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2015.2417576, IEEE Communications Surveys & Tutorials

[197] Z. Lubin, D. O'Brien, H. Le-Minh, L. Kyungwoo, J. Daekwang, and O. Yunje, "Improvement of date rate by using equalization in an indoor visible light communication system," in *4th IEEE International Conference on Circuits and Systems for Communications (ICCSC)*, Shanghai, China, 2008, pp. 678–682.

[198] B. S. Krongold, K. Ramchandran, and D. L. Jones, "Computationally efficient optimal power allocation algorithms for multicarrier communication systems," *IEEE Transactions on Communications*, vol. 48, no. 1, pp. 23–27, 2000.

[199] C. Chow, C. Yeh, Y. Liu, and P. Huang, "Mitigation of optical background noise in light-emitting diode (led) optical wireless communication systems," *IEEE Photonics Journal*, vol. 5, no. 1, pp. 7 900 307–7 900 307, 2013.

[200] C.-C. Chang, Y.-J. Su, U. Kurokawa, and B. I. Choi, "Interference rejection using filter-based sensor array in vlc systems," *IEEE Sensors Journal*, vol. 12, no. 5, pp. 1025–1032, 2012.

[201] I. Stefan, H. Elgala, R. Mesleh, D. O'Brien, and H. Haas, "Optical wireless ofdm system on fpga: Study of led nonlinearity effects," in *IEEE 73rd Vehicular Technology Conference (VTC)*, Budapest, Hungary, 2011, pp. 1–5.

[202] H. Elgala, R. Mesleh, and H. Haas, "An led model for intensity-modulated optical communication systems," *IEEE Photonics Technology Letters*, vol. 22, no. 11, pp. 835–837, 2010.

[203] I. Neokosmidis, T. Kamalakis, J. W. Walewski, B. Inan, and T. Sphicopoulos, "Impact of nonlinear led transfer function on discrete multitone modulation: Analytical approach," *Journal of Lightwave Technology*, vol. 27, no. 22, pp. 4970–4978, 2009.

[204] H. Elgala, R. Mesleh, and H. Haas, "Predistortion in optical wireless transmission using ofdm," in *9th International Conference on Hybrid Intelligent Systems (HIS)*, Shenyang, LiaoNing, China, 2009, pp. 184–189.

[205] D. Lee, K. Choi, K.-D. Kim, and Y. Park, "Visible light wireless communications based on predistorted ofdm," *Optics Communications*, vol. 285, no. 7, pp. 1767–1770, 2012.

[206] H. Qian, S. Yao, S. Cai, and T. Zhou, "Adaptive postdistortion for nonlinear leds in visible light communications," *IEEE Photonics Journal*, vol. 6, no. 4, pp. 1–8, 2014.

[207] J. Remenyi, P. Varhegyi, L. Domjan, P. Koppa, and E. Lorincz, "Amplitude, phase, and hybrid ternary modulation modes of a twisted-nematic liquid-crystal display at 400 nm," *Applied Optics*, vol. 42, no. 17, pp. 3428–3434, 2003.

[208] J. Vucic, L. Fernandez, C. Kottke, K. Habel, and K. D. Langer, "Implementation of a real-time dmt-based 100 mbit/s visible-light link," in *36th European Conference and Exhibition on Optical Communication (ECOC)*, Torino, italy, 2010, pp. 1–5.

[209] Smartgrid, "St. cloud first to sign on for new technology," 2010. [Online]. Available: http://smart-grid.tmcnet.com/news/2010/11/19/5148608.htm

[210] D. Tsonev, H. Chun, S. Rajbhandari, J. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. Kelly, G. Faulkner, M. Dawson, H. Haas, and D. O'Brien, "A 3-gb/s single-led ofdm-based wireless vlc link using a gallium nitride μ led," *IEEE Photonics Technology Letters*, vol. 26, no. 7, pp. 637–640, 2014.

[211] L. Grobe, A. Paraskevopoulos, J. Hilt, D. Schulz, F. Lassak, F. Hartlieb, C. Kottke, V. Jungnickel, and K.-D. Langer, "High-speed visible light communication systems," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 60–66, December 2013.

[212] S. Rajbhandari, P. Haigh, Z. Ghassemlooy, and W. Popoola, "Wavelet-neural network vlc receiver in the presence of artificial light interference," *IEEE Photonics Technology Letters*, vol. 25, no. 15, pp. 1424–1427, 2013.

[213] Y. Liu, C. Yeh, Y. Wang, and C. Chow, "Employing nrzi code for reducing background noise in led visible light communication," in *18th OptoElectronics and Communications Conference (OECC) held jointly with 2013 International Conference on Photonics in Switching (OECC/PS)*, Kyoto, Japan, 2013, pp. 1–2.

[214] H.-S. Kim, D.-R. Kim, S.-H. Yang, Y.-H. Son, and S.-K. Han, "Single side-band orthogonal frequency division multiplexing signal transmission in rf carrier allocated visible light communication," *Optoelectronics, IET*, vol. 7, no. 6, pp. 125–130, 2013.

[215] L. Fan, L. Ding, F. Liu, and Y. Wang, "Design of wireless optical access system using led based android mobile," in *International Conference on Wireless Communications Signal Processing (WCSP)*, Hangzhou, China, 2013, pp. 1–4.

[216] P. Haigh, Z. Ghassemlooy, and I. Papakonstantinou, "1.4-mb/s white organic led transmission system using discrete multitone modulation," *IEEE Photonics Technology Letters*, vol. 25, no. 6, pp. 615–618, 2013.

[217] F.-M. Wu, C.-T. Lin, C.-C. Wei, C.-W. Chen, H.-T. Huang, and C.-H. Ho, "1.1-gb/s white-led-based visible light communication employing carrier-less amplitude and phase modulation," *IEEE Photonics Technology Letters*, vol. 24, no. 19, pp. 1730–1732, 2012.

[218] G. Cossu, M. Presi, R. Corsini, P. Choudhury, A. M. Khalid, and E. Ciaramella, "A visible light localization aided optical wireless system," in *IEEE GLOBECOM Workshops (GC Wkshps)*, Houston, Texas, USA, 2011, pp. 802–807.

[219] T. Komine, S. Haruyama, and M. Nakagawa, "Performance evaluation of narrowband ofdm on integrated system of power line communication and visible light wireless communication," in *1st International Symposium on Wireless Pervasive Computing (ISWPC)*, Phuket, Thailand, 2006, pp. 16–18.

[220] T. Borogovac, M. B. Rahaim, M. Tuganbayeva, and T. D. C. Little, "Lights-off visible light communications," in *IEEE GLOBECOM Workshops (GC Wkshps)*, Houston, Texas, USA, 2011, pp. 797–801.

[221] G. Cossu, A. Khalid, P. Choudhury, R. Corsini, M. Presi, and E. Ciaramella, "Vlc-signals distribution over gi-pof for in-home wireless networks," in *International Workshop on Optical Wireless Communications (IWOW)*, Pisa, Italy, 2012, pp. 1–3.

[222] S. H. Lee and J. K. Kwon, "Turbo code-based error correction scheme for dimmable visible light communication systems," *IEEE Photonics Technology Letters*, vol. 24, no. 17, pp. 1463–1465, 2012.

[223] S. Kim and S.-Y. Jung, "Modified reed muller coding scheme made from the bent function for dimmable visible light communications," *Photonics Technology Letters, IEEE*, vol. 25, no. 1, pp. 11–13, 2013.

[224] R. Lee, K. Yun, J.-H. Yoo, S.-Y. Jung, and J. K. Kwon, "Performance analysis of m-ary ppm in dimmable visible light communications," in *Fifth International Conference on Ubiquitous and Future Networks (ICUFN)*, Da Nang, Vietnam, 2013, pp. 380–383.

[225] K. Lee and H. Park, "Channel model and modulation schemes for visible light communications," in *IEEE 54th International Midwest Symposium on Circuits and Systems (MWSCAS)*, Seoul, Korea, 2011, pp. 1–4.

[226] H.-J. Jang, J.-H. Choi, E. B. Cho, and C. G. Lee, "Simulation of a vlc system with 1 mb/s nrzook data with dimming signal," in *International Conference on Advanced Infocom Technology (ICAIT)*, Wuhan, China, 2011, pp. 1–3.

[227] E. Cho, J.-H. Choi, C. Park, M. Kang, S. Shin, Z. Ghassemlooy, and C. G. Lee, "Nrz-ook signaling with led dimming for visible light communication link," in *16th European Conference on Networks and Optical Communications (NOC)*, 2011, pp. 32–35.

[228] J.-H. Choi, E.-B. Cho, Z. Ghassemlooy, S. Kim, , and C. G. Lee, "Visible light communications employing ppm and pwm formats for simultaneous data transmission and dimming," *Optical and Quantum Electronics*, vol. 46, no. 5, 2014.

[229] J. Yew, S. Dissanayake, and J. Armstrong, "Performance of an experimental optical dac used in a visible light communication system," in *IEEE Globecom Workshops (GC Wkshps)*, Atlanta, USA, 2013, pp. 1110–1115.

[230] T. Wang, Y. Sekercioglu, and J. Armstrong, "Analysis of an optical wireless receiver using a hemispherical lens with application in mimo visible light communications," *Journal of Lightwave Technology*, vol. 31, no. 11, pp. 1744–1754, 2013.

[231] T. Wang, Y. Sekercioglu, A. Neild, and J. Armstrong, "Position accuracy of time-of-arrival based ranging using visible light with application in indoor localization systems," *Journal of Lightwave Technology*, vol. 31, no. 20, pp. 3302–3308, 2013.

[232] J. Armstrong, Y. Sekercioglu, and A. Neild, "Visible light positioning: a roadmap for international standardization," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 68–73, 2013.

[233] M. Mondal and J. Armstrong, "Analysis of the effect of vignetting on mimo optical wireless systems using spatial ofdm," *Journal of Lightwave Technology*, vol. 32, no. 5, pp. 922–929, 2014.

[234] S.-K. Lim, K. Ruling, I. Kim, and I. S. Jang, "Entertainment lighting control network standardization to support vlc services," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 42–48, 2013.

[235] *Asynchronous Serial Digital Data Transmission Standard for Controlling Lighting Equipment and Accessories*, Plasa Standards Std.

[236] N. Kumar, N. Lourenco, D. Terra, L. Alves, and R. L. Aguiar, "Visible light communications in intelligent transportation systems," in *IEEE Intelligent Vehicles Symposium (IV)*, Madrid, Spain, 2012, pp. 748–753.

[237] S. Okada, T. Yendo, T. Yamazato, T. Fujii, M. Tanimoto, and Y. Kimura, "On-vehicle receiver for distant visible light road-to-vehicle communication," in *IEEE Intelligent Vehicles Symposium (IV)*, Xi'an, China, 2009, pp. 1033–1038.

[238] M. Akanegawa, Y. Tanaka, and M. Nakagawa, "Basic study on traffic information system using led traffic lights," *IEEE Transactions on Intelligent Transportation Systems*, vol. 2, no. 4, pp. 197–203, 2001.

[239] M. Ergen, "Critical penetration for vehicular networks," *IEEE Communications Letters*, vol. 14, no. 5, pp. 414–416, 2010.

[240] S. Iwasaki, C. Premachandra, T. Endo, T. Fujii, M. Tanimoto, and Y. Kimura, "Visible light road-to-vehicle communication using high-speed camera," in *IEEE Intelligent Vehicles Symposium*, Eindhoven, Netherlands, 2008, pp. 13–18.

[241] M. Wada, T. Yendo, T. Fujii, and M. Tanimoto, "Road-to-vehicle communication using led traffic light," in *IEEE Intelligent Vehicles Symposium (IV)*, Las Vegas, Nevada, USA, 2005, pp. 601–606.

[242] H. Binti Che Wook, T. Komine, S. Haruyama, and M. Nakagawa, "Visible light communication with led-based traffic lights using 2-dimensional image sensor," in *3rd IEEE Consumer Communications and Networking Conference (CCNC)*, Las Vegas, NV, USA, 2006, pp. 243–247.

[243] S.-H. Yu, O. Shih, H.-M. Tsai, and R. Roberts, "Smart automotive lighting for vehicle safety," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 50–59, 2013.

[244] M. Miki, E. Asayama, and T. Hiroyasu, "Intelligent lighting system using visible-light communication technology," in *IEEE Conference on Cybernetics and Intelligent Systems (CIS)*, Bangkok, Thailand, 2006, pp. 1–6.

[245] J. Feng-Lin, P. Yu-Chi, and W. Zong-Cheng, "An ac led smart lighting system with white light fso communication," in *International Symposium on Computer Communication Control and Automation (3CA)*, vol. 2, Tainan, Taiwan, 2010, pp. 488–491.

[246] S. Bhardwaj, T. Ozcelebi, and J. Lukkien, "Smart lighting using led luminaries," in *8th IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)*, Mannheim, Germany, 2010, pp. 654–659.

[247] Philips Corporation, "Philips hue," 2012. [Online]. Available: http://www.meethue.com/en-US

[248] M. Prigg, "Fancy a new colour scheme for your house? apple stores start selling ibulbs you can control with an app (but they do cost an eye-watering 49 each),"

2012. [Online]. Available: http://www.dailymail.co.uk/sciencetech/article-2224709/The-iBulb-Apple-Stores-begin-selling-multicoloured-lightbulb-control-app.html

[249] M. Yoshino, S. Haruyama, and M. Nakagawa, "High-accuracy positioning system using visible led lights and image sensor," in *IEEE Radio and Wireless Symposium*, Orlando, Florida, USA, 2008, pp. 439–442.

[250] Z. Zhou, M. Kavehrad, and P. Deng, "Indoor positioning algorithm using light-emitting diode visible light communications," *Optical Engineering*, vol. 51, no. 8, pp. 085 009–1–085 009–6, 2012.

[251] P. Polishuk, "Plastic optical fibers branch out," *IEEE Communications Magazine*, vol. 44, no. 9, pp. 140–148, 2006.

[252] S. Lee, F. Breyer, D. Cardenas, S. Randel, and A. Koonen, "Real-time gigabit dmt transmission over plastic optical fibre," *Electronics letters*, vol. 45, no. 25, pp. 1342–1343, 2009.

[253] M. Kavehrad, "Broadband room service by light," *Scientific American*, vol. 297, no. 1, pp. 82–87, 2007.

[254] N. Pavlidou, A. J. Han Vinck, J. Yazdani, and B. Honary, "Power line communications: state of the art and future trends," *IEEE Communications Magazine*, vol. 41, no. 4, pp. 34–40, 2003.

[255] W. Gibbs, "The network in every room," *Scientific American*, vol. 286, no. 2, pp. 38–43, 2002.

[256] C. Lo and N. Ansari, "The progressive smart grid system from both power and communications aspects," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 3, pp. 799–821, 2011.

[257] T. Komine and M. Nakagawa, "Integrated system of white led visible-light communication and power-line communication," *IEEE Transactions on Consumer Electronics*, vol. 49, no. 1, pp. 71–79, 2003.

[258] M. Kavehrad and F. Amirshahi, "Hybrid mv-lv power lines and white light emitting diodes for triple-play broadband access communications," *Achieving the Triple Play: Technologies and Business Models for Success*, pp. 167–178, 2005.

[259] I. Rust and H. Asada, "A dual-use visible light approach to integrated communication and localization of underwater robots with application to non-destructive nuclear reactor inspection," in *IEEE International Conference on Robotics and Automation (ICRA)*, Minnesota, USA, 2012, pp. 2445–2450.

[260] S. Arnon, "Underwater optical wireless communication network," *Optical Engineering*, vol. 49, no. 1, pp. 015 001–015 001–6, 2010.

[261] J. Giles and I. Bankman, "Underwater optical communications systems. part 2: basic design considerations," in *IEEE Military Communications Conference (MILCOM 2005)*, Atlanta City, New Jersey, USA, 2005, pp. 1700–1705.

[262] F. Schill, U. R. Zimmer, and J. Trumpf, "Visible spectrum optical communication and distance sensing for underwater applications," in *Proc. of Australasian Conference on Robotics and Automation (ACRA)*, Canberra, Australia, 2004, pp. 1–8.

[263] J. Vucic and K. Langer, "High-speed visible light communications: State-of-the-art," in *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, Los Angeles, California, USA, 2012.

[264] Penguin Automated Systems Inc. (2012) Penguin asi. [Online]. Available: http://www.penguinasi.com/

[265] R. Hagem, D. Thiel, S. O'Keefe, and T. Fickenscher, "Optical wireless communication for real time swimmers feedback: A review," in *International Symposium on Communications and Information Technologies (ISCIT)*, Gold Coast, Australia, 2012, pp. 1080–1085.

[266] R. Hagem, S. O'Keefe, T. Fickenscher, and D. Thiel, "Self contained adaptable optical wireless communications system for stroke rate during swimming," *IEEE Sensors Journal*, vol. 13, no. 8, pp. 3144–3151, 2013.

[267] Y. Nakamura and M. Saito, "Evaluation of clipping effect on ofdm signals for visible light communications," in *International Symposium on Intelligent Signal Processing and Communications Systems (ISPACS)*, Naha-shi, Japan, 2013, pp. 753–757.

[268] L. Hanzo, H. Haas, S. Imre, D. O'brien, M. Rupp, and L. Gyongyosi, "Wireless myths, realities, and futures: From 3g/4g to optical and quantum wireless," *Proceedings of the IEEE*, vol. 100, pp. 1853–1888, 2012.

[269] D. O'brien, L. Zeng, H. Le-Minh, G. Faulkner, J. Walewski, and S. Randel, "Visible light communications: Challenges and possibilities," in *IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Cannes, France, 2008, pp. 1–5.

[270] T. Komine, S. Haruyama, and M. Nakagawa, "Bi-directional visible-light communication using corner cube modulator," in *Proc. Wireless and Optical Communications (WOC)*, Banff, Canada, 2003.

[271] Z. Xu and B. Sadler, "Ultraviolet communications: potential and state-of-the-art," *IEEE Communications Magazine*, vol. 46, no. 5, pp. 67–73, 2008.

[272] K. Cui, G. Chen, Q. He, and Z. Xu, "Indoor optical wireless communication by ultraviolet and visible light," in *Proc. SPIE Free-Space Laser Communications IX*, vol. 7464, San Diego, California, USA, 2009, pp. 74 640D–74 640D–9.

[273] A. J. C. Moreira, R. Valadas, and A. de Oliveira Duarte, "Optical interference produced by artificial light," *Wireless Networks*, vol. 3, no. 2, pp. 131–140, 1997.

[274] ——, "Characterisation and modelling of artificial light interference in optical wireless communication systems," in *6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, vol. 1, Ontario, Canada, 1995, pp. 326–331.

[275] T. Komine and M. Nakagawa, "A study of shadowing on indoor visible-light wireless communication utilizing plural white led lightings," in *1st International Symposium on Wireless Communication Systems (ISWCS)*, Mauritius, 2004, pp. 36–40.

[276] R. Mesleh, H. Elgala, and T. Little, "On the performance degradation of optical wireless ofdm communication systems due to changes in the led junction temperature," in *20th International Conference on Telecommunications (ICT)*, Casablanca, Morocco, 2013, pp. 1–5.

[277] S. Chhajed, Y. Xi, Y. Li, T. Gessmann, and E. Schubert, "Influence of junction temperature on chromaticity and color-rendering properties of trichromatic white-light sources based on light-emitting diodes," *Journal of Applied Physics*, vol. 97, no. 5, pp. 054 506–0–054 506–8, 2005.

[278] C. Ma, H. Zhang, K. Cui, M. Yao, and Z. Xu, "Effects of led lighting degradation and junction temperature variation on the performance of visible light communication," in *International Conference on Systems and Informatics (ICSAI)*, Yantai, China, 2012, pp. 1596–1600.

[279] N. Narendran and Y. Gu, "Life of led-based white light sources," *Journal of Display Technology*, vol. 1, no. 1, pp. 167–171, 2005.

[280] T. A. Tran and D. C. O'Brien, "Performance metrics for multi-input multi-output (mimo) visible light communications," in *International Workshop on Optical Wireless Communications (IWOW)*, Pisa, Italy, 2012, pp. 1–3.

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