Integration of Downlink Scheme VLC Access Techniques for Low-cost Implementation Indoor Communication System: A Survey

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Abstract: Integration of Visible Light Communication (VLC) system to Power Line Communication (PLC) or Ethernet (PoE) in terms of channel gain are introduced. The paper proposes the efficient system after comparison in terms of cost installation as a substitute for the use of optical fiber as a transmission media for this hybrid system to adopt early in the in-building coverage as a potential candidate to replace the radio-based traditional indoor system (DAS system) for low-to-medium transmission as commonly refer as small-cell. The downlink scenario has been chosen to apply with each different advantages and disadvantages of these hybrid technologies. In this paper, we provide a survey of each hybrid channel gain model with the introduction of input-dependent and input-independent noise to the input signal with data rates as the output with the error measurement of bit error rate (BER) using common optical single or multi-carrier modulation. After comparison, we can conclude that hybrid VLC with PLC as the network backhauling has the advantage in terms of already-existed facility and easy-installment for an external adapter and this hybrid system tends to applied lower LED power consumption even though achieved lower data rates making this hybrid system has full potential to be applied in the near future.

1 INTRODUCTION

Indoor wireless coverage has become an important key in telecommunication operator solutions which consume a lot of data traffic. According to Ericsson Mobility Report 2021, total global mobile data traffic in Q1 2021 exceeded 66 exabytes per month in which dominated by smartphones that account 95% of total mobile traffic and is projected to grow by a factor of close to 5 to reach 237 exabytes per month in 2026 (Ericsson, 2021). Cell densification such as small-cell to femto-cell arises when traffic capacity in-buildings increases dramatically which is beyond the ability of the macro-cell to carry the traffic, as a result, the operator will lose a significant revenue (5gamericas, 2018). The use of high frequency transmission signals up to millimeter wave and the installation of active antennas such as multibeam to beamforming are becoming a trend in small cell solutions. As for the use of solutions such as the example above if adjusted from outdoor to cover indoor site is still not optimal due to the thickness of the building walls and inefficient power generated and the data traffic it carries. Digitalize indoor coverage (DIC) product such as Huawei's lampsite were introduced around 2014 which uses optical fiber and Ethernet for transmission media instead of RF cables which were applied by the previous system, the distributed antenna system (DAS). However, the use of indoor based on small cells also results in increased radio interference between the edges of the cell will result in a decrease in speed or even not smooth in handover which has an effect on the quality of service (QoS). One of the solutions is to explore visible light communication (VLC) that has the potential to compensate for what RF-based systems lacking

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including a spectrum deficit due to exponential growth in demand for wireless transmission capacity.

The visible light communication market has a CAGR of 101% over the forecast period (2019-2024) with expected to reach value of USD 391.62 billion by 2024 based on research and markets report (Researchandmarkets, 2019). This market development is based on the significant growth in the application of indoor LEDs which are the main signal source for VLC replacing inefficient fluorescent lamps and incandescent bulbs. LED lights are highly powered efficient, low carbon emission and long-life span making this illumination type are 75% less power consumption and lasting 25% longer compared to previous type which is incandescent lamp (Nardelli et al., 2017). With the high potential to offer more efficacy, decreasing prices and even lower power consumption, it is estimated that the global market share of LED lighting usage would increase from 46% in 2019 to 75% in 2025 (Zissis et al., 2021).

In addition to using optical fiber, Ethernet is chosen through the LAN architecture for indoor communication backbone network due to its adaptability to new technologies especially for IT infrastructure (IEEE 802.11) with high reliability, high throughput and low cost (Burton et al., 2014). Apart from optical fibre for backhauling that concern about penetration rate for housing installment and tend to cost higher, currently, the major candidates for the VLC backhaul are usually either PLC or Ethernet. However, one of the drawbacks of using PLC as data delivery access is considered a harsh environment which are noisy, unsecure and prone to electromagnetic interference (EMI). The twisted pair cable used for Ethernet (IEEE 802.3) offers a better noise immunity environment and improved security over PLC. Ethernet has compatibility with existing LAN networks and has range data rates from 10 Mbps to 10 Gbps, and has established as media access control (MAC) and physical layer (PHY) protocol for local area network (LAN) (Mark, 2014). However, PLC has the advantage of having the readily installed electrical power lines in every residence and unreachable-optical-fibre area for broadband access (IEEE, 2010). PLC has been successfully used to transmit radio programs, home automation and networking, internet access and automated meter reading (Ferreira et al., 2011). Broadband PLC solutions commonly operate in the frequency band starting at about 2 MHz and ranging up to about 30 MHz or optionally beyond. In 2009 and 2010, PLC specifications have been consolidated into two standards developing organizations, namely IEEE 1901 and ITU-T G.9960/61 (Ma et al., 2013).

Spectral and energy efficiency are some of the crucial parameters when designing a low-cost and efficient hybrid network system. According to (Wu et al., 2020), the spectral efficiency and energy efficiency of the hybrid networks are greater and considerably more energy efficient than standalone networks, respectively. Hybrid VLC-Ethernet has been reported in (Haigh et al., 2012), a narrow beam point-to-point VLC-LAN link using a single white phosphor LED and a blue filter at the receiver. In (Burton et al., 2014), the system offers data communications using the 10BASE-T Ethernet protocol with the link availability as good as a short-range CAT 5 cabling system that applies white phosphor LED with the use of a simple RC compensator at the receiver to avoids the need of higher cost blue filter is reported. Initial research of VLC systems combined with Ethernet (PoE) backhauls is explored in (Elgala et al., 2011). The first VLC and PLC integration prototype was proposed by a Japanese research group in 2003 (Komine and Nakagawa, 2003), using a single carrier binary phase shift keying (SC-BPSK) modulation. In (Komine et al., 2006), the first OFDM modulation deployment has been applied to this hybrid system to combat the multipath and to achieve higher spectral efficiency in the year 2006. In (Gheth et al., 2018), the additional relay gain turns out has a positive effect on the performance of VLC-PLC. The rest of the development focusing on these systems will be reported and highlighted more in section 4. Since then, many research findings are provided in hybrid VLC-PLC systems. Besides these two hybrid systems, a lot of VLC research combined with RF systems which are not discussed in this paper. This paper only focuses on the downlink scheme survey without an uplink scenario.

The rest of this paper is organized as follows. Section 2 reviews the system description for propose hybrid systems in terms of downlink scheme with the noise involved to the transmitter as well its channel gain for both VLC-PLC and VLC-Ethernet. Section 3 describes the common optical modulation techniques in VLC to apply in these hybrid systems from single-carrier modulation to multi-carrier modulation. The comparison of the experiment in both VLC-PLC and VLC-Ethernet based on LED power consumption and data rates are discussed in section 4. Finally, section 5 gives some concluding remarks regarding this survey as well as the next challenge of the hybrid VLC communication systems.

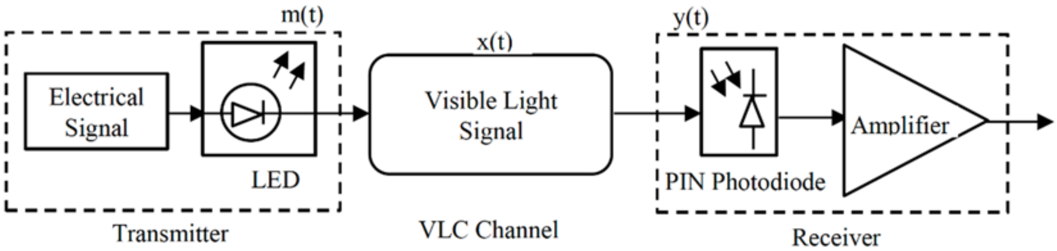

Figure 1: Point-to-point VLC system (Wang et al., 2017).

2 SYSTEM MODEL

The method of the visible light communication system is to implement intensity modulation with direct detection (IM/DD) for low complexity as illustrated in Figure 1. The data are not sent in the underlying phase or amplitude of the optical carrier but rather by varying the instantaneous intensity of its power. Consequently, only positive signals can be detected at the receiver (Ma et al., 2013). In this section we discussed the characteristics of VLC and hybrid VLC channel model of the transmission systems with the introduction of noise that is independent or dependent on the input signal.

2.1 VLC Noise

The noise is generally assumed to be independent of the signal. This assumption is reasonable if the receiver suffers from intensive thermal noise. However, in practical VLC systems, due to the random nature of photon emission in the light-emitting diode (LED), the strength of noise depends on the signal itself. The main noise sources include thermal noise, shot noise and amplifier noise. The thermal noise and the amplifier noise are independent of the signal since both of the noises emerged when the surroundings of the system affected with sudden changing temperature and with the effect of amplifying received signal from VLC channel to convert into electrical signal inside receiver system, respectively, and each of the two noise sources can be modeled by Gaussian distribution. Meanwhile, the strength of the shot noise depends on the signal itself due to rapid changing when strong ambient light is occurred making this noise easy to corrupt the conversion rate of the hole and pair particle inside a photodiode. The further discussion about this mutual information analysis the input-dependent as the result of the bit error rate (BER) is well reported in (Wang et al., 2017) (Lin et al., 2018).

2.2 Ethernet Noise

The Ethernet signal originating from a computer or router could be either biphase or triple level. 100BASE-Tx (Fast Ethernet) is one of the Ethernet standards adopt MLT-3 line code or triple level as the information signal in which use Non-Return-Zero (NRZ) modulated input signal over three voltage {-1V,0V,+1V}, if we take this modulated signal transmitted over CAT5 UTP cable ethernet type, the distortions that are modeled include : {1} transmitter jitter, {2} waveform overshoot, {3} baseline wander, {4} cable attenuation, {5} flat loss, and {6} return loss (Mark, 2014). Transmitter jitter refers to a phase delay in input signal modulation that modeled as uniform probability with zero mean and a define peak-to-peak value. Waveform overshoot is overshooting characteristic to the final voltage value that this effect modeled as a second-order low pass filter. Baseline wander defines a dropped signal from an average baseline that has a tendency to affected low-frequency components more as a result of the unbalanced input signal that contains spectral energy in which this effect modeled as a second-order high pass filter. Cable attenuation referred to as propagation loss as a result of a signal traveling in an imperfect conductor modeled as a transmission line with constant attenuation and phase depending on resistance, inductance, conductance and capacitance. Flat loss contributes to the insertion loss of the transmit magnetics, receive magnetics and RJ-45 connectors, this effect modeled as three define individual terms. Return loss refers to the amount of power loss due to signal reflections inside the cable from impedance mismatches that represented as the ration of incident power to reflected electrical power.

2.3 PLC Noise

The noise in PLC systems consists of colored background noise, narrowband disturbance, and impulsive noise (Zimmermann and Dostert, 2000). Narrow-band interference results from the frequency sharing between PLC technology and radio amateurs. Background noise groups the rest of the noise generated over PLC channel apart from narrow-band interference and impulsive noise. Impulsive noise, categorized as periodic and aperiodic, is mainly generated by both human activities and electric appliances connected to the lines (Nlom et al., 2018). According to (Meng et al., 2005) (Nassar et al., 2011) (Mathur et al., 2015), impulsive noise is the most destructive noise source. One of the solutions is to apply inherent clipping or nulling mechanism that basically applied before optical modulation to combat impulsive noise as reported in (Kubjana et al., 2018) with the noise modeled as middleton class A and additive white gaussian noise (AWGN).

2.4 VLC Channel Model

In Figure 1, the drive current of an optical source is directly modulated by modulating signal m(t), which in turn varies the intensity of the optical source x(t). The receiver employs a photodetector, with a response which is the integration of tens of thousands of very short wavelengths of the incident optical signal, that generates a photocurrent y(t). The receive photocurrent is proportional to the square of received electrical field. VLC channel has transfer function is modeled by line-of-sight (LOS) as illustrate in Figure 2 below and non-LOS (NLOS) or sometime called diffuse link. VLC channel model is referred as Lambertian model and both LOS and NLOS channel are well describe in (Ghassemlooy et al., 2013).

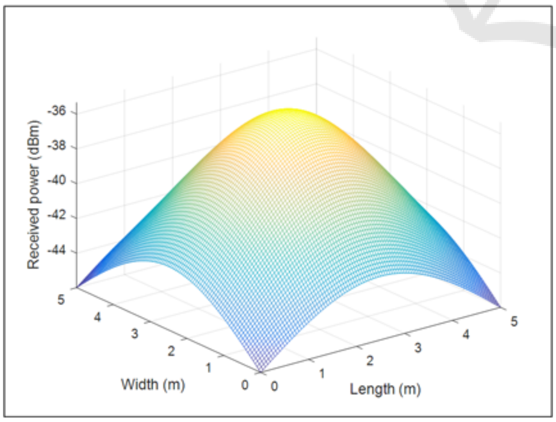

Figure 2: VLC channel for line-of-sight scheme in 5mx5mx3m room.

Typical VLC channel in LOS condition above is simulated using MATLAB program with VLC parameters : $\emptyset_{1/2}$= 70°, Ω = 1x10^{-4} m, d = 2 m, Ω_r = 5x5x3 m, and φ and α are 70° and 60°, respectively.

2.5 VLC-PLC Channel Model

Based on frequency range and data rates, power line communication is divided into narrowband and broadband. Broadband PLC (BBPLC) has a range of frequencies from 2 MHz to 300 MHz and data rate for more than 500 Mbps, making this type of PLC technology could support high-demand service. The In-home power line network is made of a high number of branches with short length. If it presents high attenuation, strong fading effects and phase non-linearity summarize this hostile communications medium (Ndjiongue et al., 2017).

The channel model in PLC can be modeled by top-down or bottom-up approaches also known as time domain and frequency domain-based, respectively (Tonello and Versolatto, 2011) (Zimmermann and Dostert, 2002). The bottom-up model transfer function of PLC channel is well describe in (Zimmermann and Dostert, 2002). Model of cascaded PLC-VLC represented in the Figure 3 that use AF relaying (Ndjiongue et al., 2017), this amplified and forwarded mechanism occurred when the signal is detected as input for VLC channel in which the signal sent over PLC channel undergo an attenuation factor. Therefore, PLC signal is amplified in order to re-transmit over the VLC channel. If we use the model according to (de Beer et al., 2013), all activities involving PLC channel distortions do not reach the VLC channel, thus the scenario presented in the Figure 3 exhibits cancellation of the PLC noise at the input of the VLC channel.

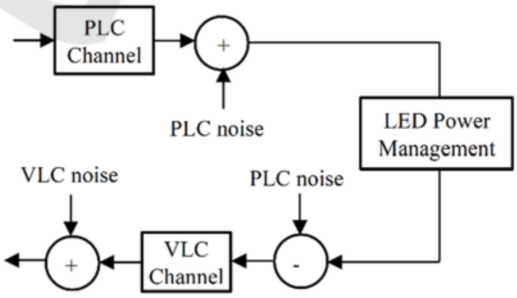

Figure 3: The model of hybrid VLC-PLC system introduce AF relaying mechanism (Ndjiongue et al., 2017).

The PLC-VLC cascaded channel is the product of the convolution of two impulse response of VLC LOS and NLOS channel with the bottom-up model of VLC-PLC channel, in which the frequency domain as

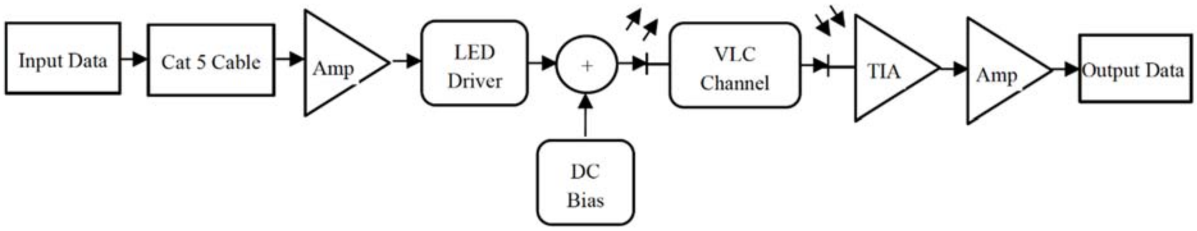

Figure 4: The model of hybrid VLC-Ethernet downlink system (Mark, 2014).

a result of the multiplication of their each transfer functions. The frequency response of the above modeled hybrid system based on the Welch method is well describe in (Ndjiongue et al., 2017).

2.6 VLC-Ethernet Channel Model

Category 5 cable model of length 1-100 meter, typical Ethernet channel using the parameters which are describes in section 2.2 modeled as transfer function according to (Mark, 2014). Given the link model in Figure 4, that the component can be considered linear and time-invariant, the channel is consist of a hybrid wired with cable type CAT 5 and a wireless VLC link. From Figure 4 downlink scheme of VLC-Ethernet system, the received signal of VLC-Ethernet using cable distortions CAT 5 transfer function of Ethernet noise parameters is given (Mark, 2014).

3 OPTICAL MODULATION

In visible light communication, light is modulated based on the changes of the light intensity; consequently, the communication link would be affected by non-linearity of the voltage-luminance characteristic. However, voltage-luminance characteristics experience memory-effect as a result of temperature increases in LED. Common LEDs that installed commercially are yellow phosphor with blue LED chip, this type of VLC light source has limited in terms of available bandwidth because of slow response time of phosphor. The limited bandwidth of VLC channel leads to inter-symbol interference (ISI) at high data rates, to overcome this limitation, pre and post equalization and better-receive system using blue filter at the receiver are the option to enhance the lack of data rates, modulation technique usage also important to expand the throughput as it can produce higher spectral efficiency which is the key elements in VLC system. VLC Consortium (VLCC) has introduced the first IEEE 802.15.7 standard in 2009 (Rehman et al., 2018). The standard proposes on-off keying (OOK), color shift keying (CSK) and variable pulse position modulation (VPPM) techniques for indoor and outdoor communication with the highest achievable data rates for indoor communication can go up to 96 Mbps. This paper highlighted the optical modulation that often used for VLC as well as hybrid systems in terms of single-carrier modulation and multi-carrier modulation.

3.1 Single-carrier Modulation

Single-carrier modulation (SCM) techniques, such as on-off keying (OOK), pulse amplitude modulation (PAM), pulse width modulation (PWM), and pulse position modulation (PPM) are categorized to implement for this VLC system (Islim and Haas, 2016). In general, single carrier modulation techniques are suitable candidates when desirable throughput is low to moderate data rates applications, even though unappropriate for high data rates. This modulation technique offers low-complexity which leads to a low-cost system, as well as this low-complexity, can support illumination control. An OOK scheme is applied for uplink modulation for full-duplex LED to LED VLC system as reported in (Niaz et al., 2017), this simple modulation technique is also chosen for VLC-Ethernet 10Base-T hybrid system that uses OOK-NRZ (Burton et al., 2014). The PPM is more power-efficient than OOK, however, it requires more bandwidth than OOK to support equivalent data rates. Differential PPM (DPPM) emerged to cope with this limitation. In (Quintana et al., 2011), DPPM is adopted for the modulation downlink VLC channel for a hybrid VLC-Ethernet system. The effect of unequal bit duration for input signal could affect the illumination performance, this to prevent any possible flickering, Variable PPM (VPPM) appeared as the standard 802.15.7 to support dimming control. One way to improve bandwidth efficiency in SCM is to apply equalization algorithms in both pre or post equalizers. According to (Lian et al., 2019), M-PAM is used to enhance the data rates as the authors use various multiple access schemes for a multi-user system.

3.2 Multi-carrier Modulation

Multi-carrier modulation (MCM) schemes, such as orthogonal frequency division multiplexing (OFDM) can be used to overcome multipath fading with deploying cyclic prefix in every subcarrier that leads to high-speed transmission in VLC system. Moreover, this multi-carrier modulation can maximize the system performance by supporting adaptive power and bit loading which can adapt the channel utilization to the frequency response of the channel (Islim and Haas, 2016). OFDM is more robust to frequency selective channels than a single-carrier modulation scheme due to OFDM subcarrier can be individually modulated and controlled (Armstrong, 2009). However, one of the challenges for an optical OFDM implementation is the high peak-to-peak power ratio (PAPR) of the time-domain signal that leads to signal distortions due to the non-negativity constraint for the optical time-domain signal and a reduced energy-efficiency (Ma et al., 2017). Other optical modulations appeared to minimize this issue by applying DC-biased OFDM (DCO-OFDM) that adding a DC bias to the real bipolar signals to clipping the remaining negative samples of the lower part of bipolar signal. In (Kubjana et al., 2018) the authors use this modulation technique to combat impulsive noise, the DC bias also limits the performance of the system in which larger DC bias results in the increase of power required. High DC bias would also incur some distortions as a result of the upper clipping of the OFDM waveform. Asymmetrically clipped optical OFDM (ACO-OFDM) used to avoid zero-clipping distortion. ACO-OFDM modulates only odd frequency subcarriers and set zero value for the even frequency subcarriers to eliminate the negative part of the signal without the need for any DC biasing. In (Niaz et al., 2017), the authors have chosen ACO-OFDM scheme to modulate the signal on the downlink channel that used Red-Green-Blue (RGB) LEDs for the proposed transmitter system. However, skipping half of the subcarriers reduce the spectral efficiency to half of that in DCO-OFDM, as a result, the signal-to-noise (SNR) dropped by 3 dB. Another method for zero clipping without using DC biased is Unipolar OFDM (U-OFDM) and clipping enhanced optical OFDM (CEO-OFDM). If U-OFDM uses the second frame of subcarriers for the negative part of bipolar signal, CEO-OFDM uses another extra frame to re-transmit and recover both positive and negative after clipped and both modulation techniques produce half of spectral efficiency use in DCO-OFDM. Authors in (Lian and Brandt-Pearce, 2018), reported that CEO-OFDM can dramatically reduce the clipping distortion but still require higher modulation constellation to achieve higher data rates than other OFDM techniques. PAPR reduction also achieved by adopting pre-coding as reported (Sharifi, 2019), using Vandermonde like matrix (VLM) scheme resulting this system outperforms and reducing PAPR value on another pre-coding that usually used in both DCO-OFDM and ACO-OFDM. Spatial optical OFDM (SO-OFDM) is also considered when an array of light sources is used to transmit so that subcarrier of OFDM could send allocated equally to different LEDs resulting in low-PAPR value. In (Ma et al., 2017) SO-OFDM is used to compare between single-user and multi-user system, for multi-user in hybrid VLC-PLC purposes, OFDM scheme shown to outperforms OFDM-TDMA.

4 HYBRID SYSTEMS COMPARISON

After discussing optical modulation techniques that often implemented for VLC as well as hybrid VLC system, and we have outlined both typical channel gain in the transfer function, Table 1 and 2 below summarize the achievement of hybrid VLC-PLC and VLC-Ethernet in terms of modulation technique used and certainly the throughput data rates in the end as this parameter is crucial to be applicable in the near future. This table below only represent the downlink scheme achievement without considering uplink data rates as this scenario still open in discussion which suitable for these hybrid systems. The power consumption is define according to LED usage rather than in backhauling powerline or Ethernet. For modulation techniques indicate that apply in the VLC channel rather than inside both backbone networks. Common Ethernet and PLC cable length on both the above table is 100 m. Number 3 and 4 in Table 1, the authors experiment with two methods to achieve better BER performance even though lower data rates are produced. The authors did not mention the modulation technique is specific rather than explaining equalizer and amplifier in the transmitter and in an additional blue filter in the receiver system. Number 5, authors also did not mention in terms of power consumption for LED usage, and for BER performance they added a blue filter in the receiver system. For Table 2, numbers 1 and 2, the authors used modulation error ratio (MER) instead of BER and accounted for 23,5 dB and 24 dB on average,

Table 1: The VLC-Ethernet system for indoor Downlink scheme experiment.

No [Ref]	Transmitter	Receiver	Modulation	Power Consumption	BER <	Data Rates	Transceiver Distance
1. (Quintana et al., 2011)	blue LED coated with yellow phosphor	PIN Photodiode	DPPM	5 W	$1x10^{-8}$	2 Mbps	1,5 – 2 m
2. (Burton et al., 2014)	blue LED coated with yellow phosphor	PIN Photodiode	OOK-NRZ	7 W	$1x10^{-9}$	10 Mbps	2 m
3. (Zwierko et al., 2016)	blue LED coated with yellow phosphor	PIN Photodiode	N/A	N/A	$1x10^{-4}$	100 Mbps	3 m
4. (Zwierko et al., 2016)	blue LED coated with yellow phosphor	PIN Photodiode	N/A	N/A	$1x10^{-9}$	10 Mbps	30 m
5. (Shao et al., 2015)	blue LED coated with yellow phosphor	PIN Photodiode	OFDM	N/A	N/A	74 Mbps	2 m

Table 2: The VLC-PLC system for indoor Downlink scheme experiment.

No [Ref]	Transmitter	Receiver	Modulation	Power Consumption	BER <	Data Rates	Transceiver Distance	Remark
1. (Ding et al., 2015)	blue LED coated with yellow phosphor	Avalanche Photodiode	TDS-OFDM	1 W	N/A	48 Mbps	5 m	Single-user
2. (Song et al., 2015)	two LEDs of blue LED with yellow phosphor	Avalanche Photodiode	OFDM	1 W	N/A	48 Mbps	3 m	AF relaying
3. (Kashef et al., 2016)	multi LEDs serve as AP	Photodiode	OFDM	100 mW	N/A	10 Mbps	150 m	Single-user
4. (Song et al., 2016)	multi LEDs	Photodiode	OOK-NRZ	N/A	$1x10^{-5}$	5 Mbps	3 m	DF relaying
5. (Sun et al., 2017)	multi LEDs	Photodiode	OFDM	N/A	$1x10^{-5}$	5 Mbps	3 m	DF relaying

respectively. Number 3, the authors explain the system model without specifically mention BER performance and the type of VLC receiver photodiode. Number 6 of Table 1 and number 4 of Table 2, both authors showed almost the same system model only used different modulation techniques and did not mention the power usage of both systems.

5 CONCLUSION AND FUTURE WORK

After we review specifically in terms of channel gain, modulation techniques, and achievable experiment for hybrid VLC system in particular VLC with PLC backhauling and VLC with Ethernet network, it shows that both systems are under research to reach acceptable throughput in order to compete with RF-based system. Overall, the VLC-Ethernet system tends to have higher data rates compared to VLC-PLC but the gap is still approachable. With VLC-PLC demonstrates a lower power consumption on LED driver. For VLC, the integration with PLC is much easier that it can utilize the ubiquitous power line to back up the VLC by adding PLC signal and forward it to the bias current of LED and the installation can be very easy by adding some modules to the LED adapter without changes to the facilities. Both hybrid systems mentioned in this paper could be prioritized in terms of faster penetration rate and low-cost installment to the area of non-optical cable and making the optical fibre for backhauling VLC network as the second option. For future work, the energy-efficient uplink scheme for hybrid VLC-PLC and VLC-Ethernet can be investigated, where the option between Infrared, RF and WiFi are among the potential to adopt as these technologies are well researched and already-equipped in the user devices.

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