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Performance Analysis of Peak to Average Power Ratio in Multi Carrier Modulation Schemes of Visible Light Communication

by

Arun Kumar Mehta

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“Performance analysis of Peak to Average Power Ratio in multi carrier modulation schemes of visible light communication”

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DEPARTMENTAL ACCEPTANCE

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ABSTRACT

VLC system based on the OFDM technology suffers from the high PAPR affecting the performance of the System. ACO-OFDM and DCO-OFDM are the major multi carrier modulation schemes in VLC. High PAPR not only leads to distortion and degradation of performance of VLC system but also makes system complex. SLM and PTS techniques are attractive PAPR reduction techniques in VLC system which provide significant reduction in PAPR. Combination of PTS and SLM with DCT gives better result in terms of PAPR reduction. In this research work, the partitioned sub blocks data are firstly transformed by a DCT into new modified data and the scheme utilizes the PTS and SLM technique to further reduce the PAPR of the OFDM signal. The PAPR performance is evaluated using a simulation and the results show that the new scheme yields improved PAPR performance in comparison to PTS, SLM, DCT, PTS+SLM scheme and original OFDM.

Keywords: ACO-OFDM, DCO-OFDM, DCT, PAPR, PTS, SLM

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LIST OF ABBREVIATIONS

ACO-OFDM	Asymmetrically Clipped Optical OFDM
AWGN	Additive White Gaussian Noise
CP	Cyclic Prefix
DCO-OFDM	DC biased Optical OFDM
FFT	Fast Fourier Transform
FOV	Field of view
FSO	Free Space Optical communication
HACO-OFDM	Hybrid ACO-OFDM
IFFT	Inverse Fast Fourier Transform
IM/DD	Intensity Modulation and Direct Detection
IS	Integrating-Sphere
ISI	Inter Symbol Interferences
LACO-OFDM	Layered ACO-OFDM
LED	Light Emitting Diode
Li-Fi	Light Fidelity
LOS	Line-of-Sight
MATLAB	Matrix Laboratory
OFDM	Orthogonal Frequency Division Multiplexing
O-OFDM	Optical OFDM
OOK	On-Off Keying
OWC	Optical Wireless Communication
PAPR	Peak-to-Average Power Ratio
RF	Radio Frequency
RMS	Root Mean Square
SE	Spectral Efficiency
U-OFDM	Unipolar OFDM
VLC	Visible Light Communication
VPPM	Variable Pulse Position Modulation

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Growing requirement of mobile application encourages the development of wireless communication. Wireless communication is typically achieved by radio frequency (RF) signal transmission. There are usually four protocols used for short-range wireless communication. [1] However, the RF spectra of the four protocols are licensed and may be congested. For additional applications and economical consideration, it may be preferable to develop new techniques for wireless communication.

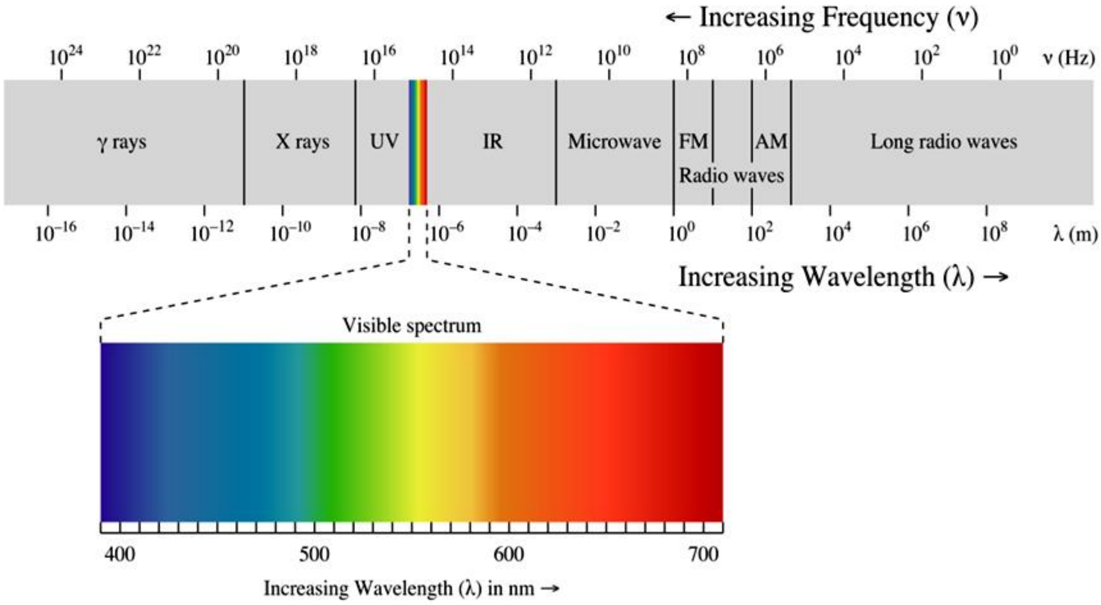

Figure 1: Electromagnetic Spectrum

(Source: Hayat and Buck et al., 2008)

Prosperous development of Light-emitting diode (LED) technology has made LED a promising luminance source. Compared to traditional fluorescent lamp, LED is advantageous of being brighter and lower power consumed. These characteristics guarantee more efficient power usage. For environmentally friendly and green concern, this is especially a significant advantage. LED also has higher modulation bandwidth than fluorescent lamp. Visible Light Communication (VLC) enjoys several appealing advantages such as the abundance of unlicensed spectrum, low electromagnetic interference, and high security. Meanwhile, due to the integration of communication and lighting, VLC is anticipated to be a promising technique for future wireless connections VLC uses LED lamps which allow a faster and more flexible data transmission method compared to current Wi-Fi technologies. Since light is everywhere and does not cross walls, it can provide illumination and wireless indoor communication simultaneously at significantly higher security levels than RF technologies. VLC provides a number of unique advantages over its Radio Frequency (RF) counterpart, such as secure connectivity, absence of electromagnetic unregulated bandwidth for high data rate, a high degree of spatial reuse, lesser interference and the potential combination with existing lighting.

Table 1: Comparison between VLC and RF Communication

Property	VLC	RF
Bandwidth	Unlicensed	Limited
Electromagnetic interference	No	Yes
Power consumption	Low	Medium
Mobility	Limited	High mobility
Standards	802.15.7	Several
Coverage	Less	Wide
Risk on health	Blue Light Hazard	Several
Cost of Implementation	Low	Medium

Due to the widely employment of LEDs, The emerging VLC has attracted much attention for indoor wireless communications. The first VLC using LED was demonstrated in 1999, where an audio signal was transmitted using visible light. After more than a decade evolution of the VLC, in 2011, VLC protocols and PHY layer were proposed in the IEEE standard 802.15.7, [2]. where the data communication and lighting application were merged. This standard defines a physical layer (PHY) and medium access control (MAC) layer for VLC and promises data rates sufficient to support audio and video multimedia services. It supports three PHY types, namely, PHY I, PHY II and PHY III. PHY I is designed for outdoor usage with low data rates in the order of tens to hundreds of kb/s. PHY II is intended for indoor usage with moderate data rates in the order of tens of Mb/s. PHY III is designed for VLC systems with multiple light sources and detectors. OFDM signals are combined with the bit- and power-loading techniques, and CAP signals of various modulation are pre-emphasized to modulate one of the RGB chips The maximum 2.93 Gb/s aggregate data rates of OFDM is achieved after optimizing RGB chips. [3].

Table 2: VLC IEEE 802.15.7 physical layer standard

Standard	**Modulation**	**Speed**	**Multi-Optical Sources**
PHY I	OOK, VPPM	11.67 to 266.6 kb/s	No
PHY II	OOK, VPPM	1.25 to 96 Mb/s	No
PHY III	CSK	12 to 96 Mb/s	Yes

VLC is one of the latest wireless technologies for optical communication technique LED technology. The improvements of power efficiency and cost reduction enable the use of LEDs for dual-purposes of both providing illumination as well as for communication, making VLC an economical and multi-purpose data transmission solution. [4] From the other side, orthogonal frequency division multiplexing (OFDM) is considered a good candidate for VLC systems due to its high spectral efficiency and capacity to combat inter-symbol interferences (ISI). However, OFDM signals need to be modified to work with VLC systems that used intensity modulation and direct detection (IM/DD), due to the fact that only real and positive signals are required to drive the LEDs. Several optical forms of OFDM such as asymmetrically clipped optical OFDM (ACO-OFDM), DC biased optical OFDM (DCO-OFDM), and unipolar OFDM (U-OFDM) have been proposed to generate real and positive OFDM signals compatible with the LED characteristics and IM/DD system [5]. However, all these forms obtain a real valued time domain signal by constraining the input data vector of the inverse fast

Fourier transform (IFFT) to have Hermitian symmetry by adding the conjugate of the complex signal before the IFFT. This reduces the spectral efficiency, doubles the required bandwidth and the system complexity. Moreover, the constraint imposed by the dynamic range of the LED is also limiting the signal. For example, in the DCO-OFDM case, by adding DC-bias to the signal, the generated bipolar signal is converted to unipolar. However, even with a large bias, some negative peaks of the signal will be clipped and the resulting distortion causes bit-error-rate (BER) performance degradations due to the large peak-to-average power ratio (PAPR) of OFDM. In ACO-OFDM, clipping of all negative values at zero and modulating only odd subcarriers will result in the unipolar signal. However, ACO-OFDM sacrifices a large portion of bandwidth to achieve the asymmetrical property.

1.2 Problem statement

The performance for single carrier modulation schemes is restricted by the number of parameters. For the high data rate transmission single-carrier modulation may not be feasible due to too much complexity of the equalizer in the receiver. To overcome the frequency selectivity of the wideband channel experienced by single-carrier transmission, multiple carriers can be used for high data rate techniques such as OFDM. Multi-carrier phenomena is considered to be one of the major development in VLC system and among them OFDM is becoming the important standard. However, high PAPR is the major drawback of OFDM, which results in lower power efficiency hence impedes in implementing OFDM. To overcome the low power efficiency requires not only large back off and large dynamic range DAC but also highly efficient HPA and linear converters. These demands result in costly hardware and complex systems. Therefore to lessen the difficulty of complex hardware design it has become imperative to employ efficient PAPR reduction techniques. OFDM is based on the generation of a multicarrier signal, whereas each sub-carrier is independently modulated (M-QAM) to create several parallel communications channels. Considering illumination is a unipolar signal, the traditional RF bipolar OFDM has to be adjusted. Although by many techniques Optical OFDM can be achieved. Two of them are most frequently used; by adding a dc-bias signal, known DCO-OFDM or by removing all the negative values at the original bipolar modulating signal, known as ACO-OFDM. OFDM is an attractive technique to realize high data rate communication in LED based VLC system. Because of, high PAPR of OFDM makes VLC-OFDM system very sensitive to nonlinearity of

LEDs .Performance of VLC system depends on different parameters. The PAPR performance and BER performance are two major performance parameters for designing efficient VLC system. Due to the available signal power of VLC systems, the tradeoff between the data rate and Signal to Noise Ratio (SNR) can be used.

1.3 Objectives

- To minimize and compare the PAPR incurred in DCO-OFDM and ACO-OFDM of VLC.
- To analyze the performance parameter (BER, SNR) of DCO-OFDM and ACO-OFDM.

1.4 Organization of the thesis

The rest of the thesis is organized as follows. A survey of related work on PAPR minimization and performance analysis of DCO-OFDM and ACO-OFDM is presented in Chapter 2. In Chapter 3, theory related to the proposed method of PAPR minimization is discussed. The proposed methods for minimizing the PAPR incurred are explained in Chapter 4. In Chapter 5, the quantitative results obtained for the proposed method are compared and analyzed. Conclusion and possible future recommendation for the proposed method are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

VLC makes the most of the fast switching times of LEDs to transmit information. High transmission rates have been achieved with different modulation schemes as OFDM. However, the main asset of LED lamps, which is energy efficiency, has been overlooked. This paper analyzes how the modulation schemes affect the energy efficiency of LED lamps. We compare the effect of switched waveform (OOK, VPPM) and continuous waveform (OFDM) modulation schemes. [6]

One of the best techniques to increase data rate and improve spectral efficiency for indoor VLC is by employing OFDM. To efficiently exploit the optical bandwidth, OFDM based approach is proposed for VLC that increases the bandwidth efficiency. [7]

An integrated single mode fiber (SMF) and VLC system based on Hadamard transform combined with OFDM reduces the LED nonlinearity through reducing the high PAPR of the system and the BER of system has been improved. [8]

OFDM has been widely studied and adopted in VLC systems because of its high spectral efficiency and low-complexity implementation. However, OFDM-based VLC systems suffer from a PAPR, along with the nonlinear transfer characteristics of LEDs. All OFDM signal subcarriers are divided into groups, and each group is transmitted by an individual LED chip while the same receiver structure is maintained. The PAPR is reduced significantly because only some of the subcarriers are located on each LED chip. Hence, the achievable input power can be increased, leading to a higher SNR and a BER. [9]

Optical OFDM is an appealing modulation scheme in VLC systems. Recently, a number of O-OFDM schemes have been proposed. Among them, DCO-OFDM is a widely used scheme for its high spectral efficiency and low complexity. Since VLC involves a combination of illumination and communication, different optical power is often required to achieve a certain illumination level. However, clipping noise will dominate a severe performance degradation of DCO-OFDM when a relatively high or low illumination level is imposed, and it restricts applications of DCO-OFDM in future VLC systems. [10]

Half of the time-domain transmitted signals carry meaningful information while the other half are set at zeros after asymmetric clipping in optical OFDM systems, such as pulse amplitude modulated discrete multi-tone (PAM-DMT) and ACO-OFDM. By specifically exploiting the asymmetric structure of O-OFDM like PAM-DMT and ACO-OFDM, a new framework for implementing O-OFDM with enhanced performance in terms of both BER and PAPR is presented. Asymmetric signal reconstruction, instead of direct clipping, in time domain before transmission is introduced. Asymmetric reconstruction refines the time-domain statistics of the O-OFDM signals by constructively exploiting zero-padded signal positions in conventional O-OFDMs. In this way, the PAPR of the reconstructed O-OFDM signals is effectively reduced. [11]

A dimmable scheme for VLC system based on multi-layer ACO-OFDM, which is able to support a wide dimming range for different illumination requirements. Multiple layers of ACO-OFDM occupying different subcarriers are combined so that almost all the subcarriers can be used for data transmission. The polarities of different layers of ACO-OFDM are varied to obtain flexible time-domain waveform, which can fully exploit the dynamic range of LEDs and achieve better performance. The scaling factor and modulation order for each layer as well as the DC bias are optimized for different dimming requirements to achieve improved spectral efficiency. [12]

An improved hybrid optical OFDM and PWM scheme for visible light communications. A bipolar optical OFDM signal is converted into a PWM format where the leading and trailing edges convey the frame synchronization and modulated information, respectively. It is insensitive to the nonlinearity of the LED as LEDs are switched ‘on’ and ‘off’ between two points. Therefore, the tight requirement on the PAPR in optical OFDM is no longer a major issue. It demonstrates that it offers an improved bit error rate performance compared to ACO-OFDM. [13]

Dual-mode index modulation aided orthogonal frequency multiplexing (DM-OFDM) is recently proposed, where the spectral efficiency is enhanced compared with conventional OFDM schemes. Two different optical DM-OFDM schemes for visible light communications, dual mode index modulation aided DC-biased optical OFDM

(DM-DCO-OFDM) and dual-mode index modulation aided unipolar OFDM (DM-U-OFDM). In the optical DM-OFDM schemes, subcarriers are partitioned into OFDM sub blocks, divided into two groups within each sun block, and modulated by two different modes of constellations. Additional information bits can be transmitted implicitly by the indices of subcarriers modulated by the same constellation alphabet. In order to generate non-negative signals, the real-valued time-domain signals are DC biased in DM-DCO-OFDM, whilst positive and negative signals are transmitted separately in DM-U-OFDM. [14]

The performance of indoor VLC systems using a (DCO-OFDM scheme is investigated and impact of nonlinearity of LED and its beam angle on the VLC system performance is studied and analyzed the effect of modulation order, number of subcarriers, signal scaling and biasing operation on the PAPR) which is a major issue in OFDM based VLC system. It shows that the BER decreases as the degree of nonlinearity increases and a better BER can be achieved as the LED behavior approaches linear model. In addition, it is shown that reducing the QAM order or increasing the number of subcarriers may reduce the effect of the LED nonlinearity, thus improving the BER performance of the VLC system. [15]

CHAPTER 3

THEORETICAL BACKGROUND

Visible light communications (VLC) is a branch of optical wireless communication that involves electromagnetic waves in the visible spectrum. Many VLC communication applications that are described are valid for OWC systems and vice versa. VLC is a subset of OWC that uses visible light spectrum to communicate. Currently the interest for visible light communication is increasing and being researched on to find technologies that make visible light communication possible.

With respect to OWC, VLC applications consider only the visible spectrum and not the infrared or ultraviolet spectrum. One of the primary technological developments in visible light communication is the availability of cheap and high-powered light-emitting diodes (LEDs). Visible light communication uses commercial LEDs to communicate which are readily available and cheap, and capable of switching at high frequencies. LEDs have a wide white wavelength emission spectrum that involves all the visible. This may seem as a very restrictive simplification but in practice it is not, because, thanks to the receiver photodiode and lenses filter, one can consider the transmitter light as a sum of many single monochromatic waves.

The transmitter for VLC should be a device that can manipulate the visible light to generate a signal that could be interpreted from a receiver device. In general as light transmitter the OWC technologies use two devices: light emitting diode (LED) and laser diode (LD). For VLC LEDs seems to be the best choice, respect to LDs. The LEDs devices are cheapness and are not harmful for eyes.

To decode the transmitted signal one should be able to detect and discern its properties. In general this is possible with two methods: direct detection and coherent detection. For both techniques in VLC the transmitted signal is light wave. The device dedicated to detection of photon is called photo detector. Photo-detectors are transducers that transform the received light (photons) into an electrical signal. Photo detector is a square-law detector because the current generated from it is proportional to the square of instantaneous optical field on its surface. A particular type of photo detector that is used in VLC (and OWC) for its simplicity, dimension and for the low cost is the photodiode. Direct detection is the detection of the transmitted envelope of optical power. Unlike common radio techniques this tech doesn’t need a local oscillator and it’s simple and economic.

To simulate VLC systems one of the most important features is the channel block. The channel represents how the transmitter light ray moves through space to arrive at the receiver. The two main components to analyze VLC channel are the line of sight transmission (LOS) and the not line of sight transmission (NLOS). The NLOS transmission generally is given by rays which are reflected on obstacles and, after some bounces, hit the detector. As mentioned before to model the channel a starting approach is to consider the VLC wave as monochromatic.

All transmission systems use waves to communicate. In particular radio and optical communication use electromagnetic waves to transport information. The electromagnetic spectrum is very broad and is categorized by wavelength or by frequency. These quantities are closely linked by the formula:

$$\lambda = c/f \tag{3.1}$$

Where c is the speed of light, is the wavelength an f is the frequency. The VLC electromagnetic spectrum is in general divided in wavelength intervals that match approximately to colors perceived by the human eye.

3.1 Light Emitting Diodes

A Light Emitting Diode (LED) is a semiconductor device of P-N junction. The LED emits light as a result of electronic excitation by applying a forward voltage bias across the p-n junction of the LED. The application of voltage causes the electrons in the led to reach an unstable excited state, and when these electrons return to the stable state after some time it leads to the release of energy (photons) emitting light. This transfer of electrons from valence band to conduction band and reverse is the reason for the working of LEDs. The selection of LED for the system depends on factors such as its luminous efficiency, power efficiency, etc.

3.2 Photo Detectors

Photo detectors are light sensitive devices used to determine the optical signals generated by the LEDs. Photo detectors are also known as photo sensors. They convert optical light signals into electrical signals. The electrical signal generated by the photo detector is directly proportional to the amount of light falling on the sensor's surface. A good photo detector needs to have large response of the incident optical signal, sufficient instantaneous bandwidth to capture the incoming signal and higher noise immunity. It should be more immune to temperature fluctuations. The factors that affect the selection of photo detector are dark current and noise-equivalent power.

3.3 Flickering

Flickering is the rapid variation of the intensity of the source. This phenomenon is always present in VLC light sources because the transmission method uses intensity variations to transmit the signal. However flickering denotes a light flashing that is perceivable from human eyes and causes distress. The flickering is perceptible from humans when the light source does not meet certain conditions. Flickering is characterized by controllable factors like the light bulb blink frequency or the illumination intensity variation and uncontrollable factors like the people degree of light/dark adaptation, the age and fatigue.

3.4 Intensity modulation – Direct Detection

IM-DD and coherent transmission/detection: in general two methods of VLC transmission/detection are possible. The coherent transmission/detection is usually associated with laser diodes. The IM-DD instead is associated with LEDs. This method is used because the LED, unless one uses complex and expensive systems, cannot generate coherent waves. IM-DD is a transmission scheme in which the intensity of the optical source is modulated by the signal, and the demodulation is achieved through direct detection of the optical carrier and conversion using a photo-detector. This work treats the IM-DD and does not consider the coherent transmission/detection. The IM-DD VLC systems are cheaper and easiest to implement and the lasers on the other side are dangerous for human eyes. This is the reason which leads to consider LED IM-DD for commercial everyday applications.

3.5 Orthogonal Frequency Division Multiplexing

The necessity for high speed communication has become a top priority. Different multicarrier modulation techniques have developed to meet these demands with one of the prominent among them being OFDM.

The main principle of OFDM is to divide streams of high data rate into a number of streams of lower data rate. These data streams are transmitted using the concept of orthogonal subcarriers and transmitted in parallel. Because of transmitting these data in parallel, the duration of the symbol increases. It decreases the prorated amount of dispersion in time as a result of multipath delay spread. At the receiver a set of filter banks separate the wideband signal into subcarriers narrowband signal for demodulation. Each subchannel experiences flat fading reducing the equalization complexity in the receiver dramatically. The signal is less susceptible to the effects of channel like inter symbol interference (ISI) introduced by multipath propagation.

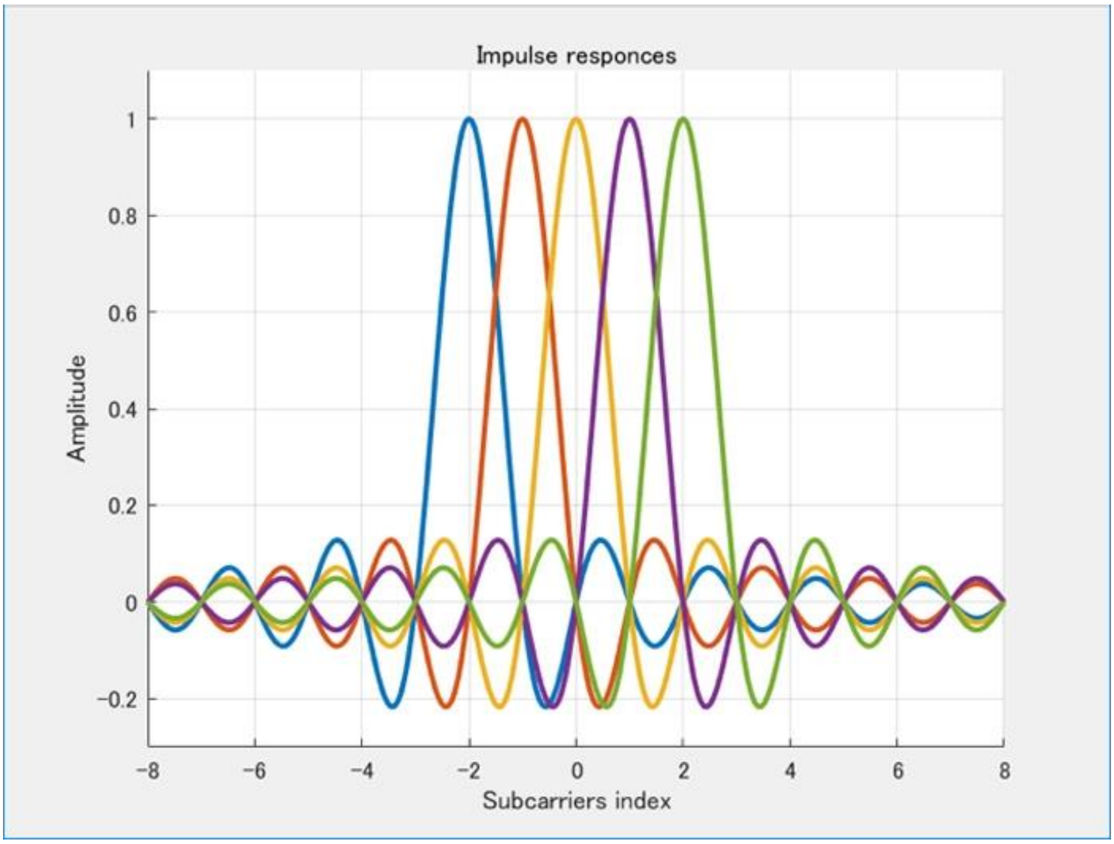

Figure 2: OFDM Signal

(Source: https://www.mathworks.com/discovery/ofdm.html)

For a VLC system, OFDM baseband signal must be real and non-negative as it modulates optical intensity rather than amplitude or phase. The modulation signals need to be both real and unipolar. Hermitian Symmetry has to be imposed on IFFT to get a real valued OFDM version of the signal while generating the optical OFDM because conventional OFDM is both complex and bipolar in nature. By imposing the Hermitian

Symmetry, we get a real valued signal. To get a unipolar OFDM, one of the methods is to add a dc-bias current to the signal to make it positive and the signal which results by this process is known as DCO-OFDM. For a constant addition of dc-bias current higher power requirement is required. For non-variance level of room illumination a constant dc-bias current is needed. Therefore, it can be concluded that power constraint is not very significant for indoor VLC systems especially which are designed for lighting applications.

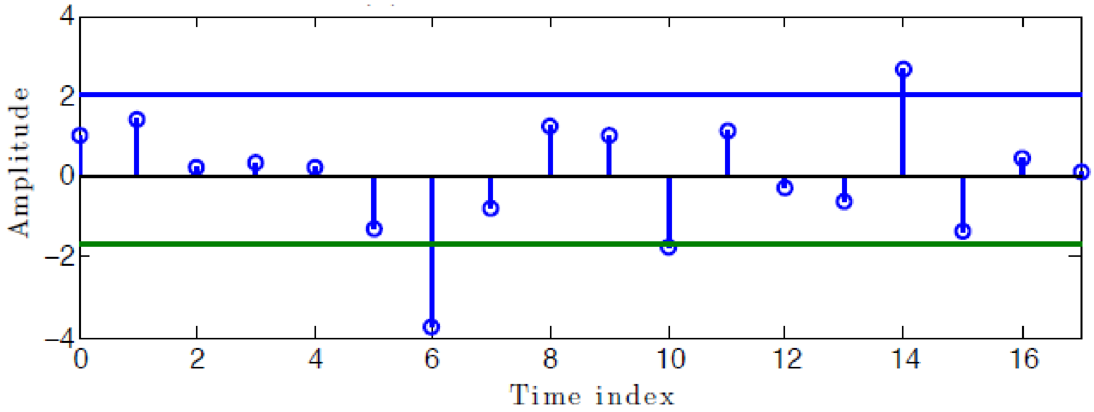

Figure 3: Time domain optical OFDM signal

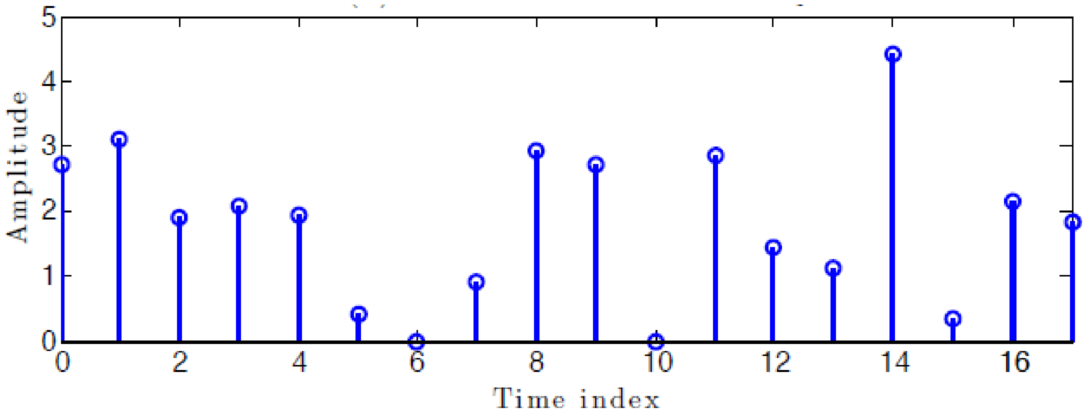

Figure 4: Time domain DCO-OFDM signal

An alternative modulation approach is required when energy efficiency is required. Unipolar OFDM modulation schemes were mainly introduced to provide energy efficient optical OFDM alternatives to DCO-OFDM such as ACO-OFDM. Unipolar OFDM modulation scheme exploit the OFDM input/output frame structure to produce a unipolar time domain waveform output. Another way of achieving unipolar signal is by clipping the signal at zero and only positive real parts are allowed to send for the transmission. OFDM signal is generated in such a way that the positive part is anti-symmetrical copy of the negative part. The resulting signal is called ACO-OFDM.

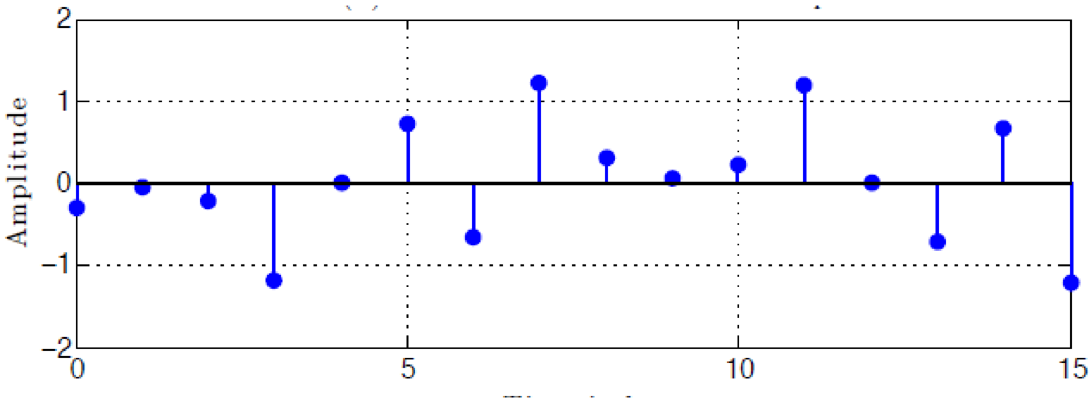

Figure 5: Time domain optical OFDM signal

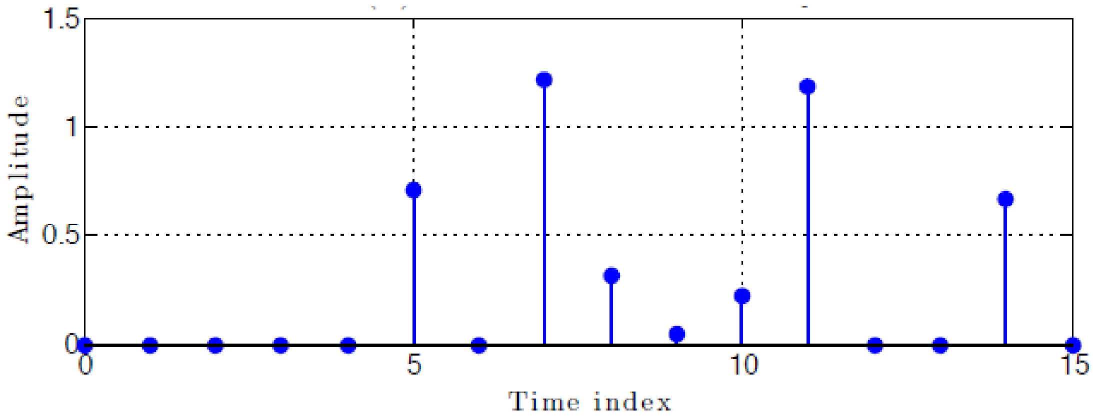

Figure 6: Time domain ACO-OFDM signal

3.6 Bit Error Rate

BER or perhaps more appropriately the bit error ratio, is the number of bits received in error divided by the total number of bits transferred. We can estimate the BER by calculating the probability that a bit will be incorrectly received due to noise. Simply, BER is defined as

$$BER = Errors/Total\ Number\ of\ Bits \tag{3.2}$$

A strong signal and an unperturbed signal path, this number as small as to be insignificant. It becomes significant at the time when we need to maintain a sufficient signal-to-noise ratio in the presence of imperfect transmission through electronic circuitry (amplifiers, filters, mixers, and digital/analog converters) and the propagation medium (e.g. the radio path or optical fiber). BER is a measure of the quality of the transmitting device, the receiver, the transmission path and its environment as it takes into consideration factors such as noise, attenuation, fading, and any error detection and correction schemes used in the interface standard. BER is usually expressed as 10 to a negative power. For example, if a transmission has a BER of 10 to the minus 4, this means that of 10,000 bits transmitted, 1 had an error. A high BER value indicates a noisy line, which can cause poor network performance.

BER can also be defined in terms of the probability of error (POE),

$$\mathrm{POE} = \frac{1}{2}(1 - \mathrm{erf}\,)\,\sqrt{E_b/\mathrm{N}_o} \qquad (3.3)$$

where, *erf* is the error function, E_b is the energy in one bit and N_o is the noise power spectral density (noise power in a 1 Hz bandwidth). The error function is different for the each of the various modulation methods. What is more important to note is that POE is proportional to E_b/N_o, which is a form of signal-to-noise ratio. The energy per bit, E_b, can be determined by dividing the carrier power by the bit rate. As an energy measure, E_b has the unit of joules. N_o is in power (joules per second) per Hz (seconds), so E_b/N_o is a dimensionless term or a numerical ratio.

3.7 Signal to Noise Ratio

SNR is the ratio between the signal power and the noise power. This dimensionless quantity is a very important parameter for all communication systems. This is a sort of quality factor for the communication system. If the SNR is low the system will not transmit correctly, it is desirable to achieve the highest possible SNR but this implies the increase of the system cost, because raising the signal power means more power consumption and lowering the noise power means increased system complexity. The best choice is in general a middle way, the SNR must be high as possible to transmit correctly but must be low enough to keep the cost of the system low.

3.8 Multipath propagation and fading

Both VLC and radio signals propagate in the medium and arrive at the receiver. The signal that arrives at the receiver is divided in two components: the direct component (line of sight, LOS) and the diffusive component (Not line of sight, NLOS). The diffusive component is due to the reflected part of the signal that is generated from the interaction with an obstacle. For example for indoor VLC a component of the signal hits the various walls and bounces to the transmitter. Multipath propagation is due to the diffusive component of the signal. A consequence of multipath propagation is fading, or the attenuation of the signal. Fading can also be due to shadowing form obstacles between the source and the receiver.

3.9 Peak to average power ratio

In an OFDM system can have high peak values in the time domain since many subcarrier components are added due to an IFFT operation and when the parallel data streams are summed up to create the OFDM signal. The peak power of the signal occurs when the subcarrier-modulated symbols are added in the same phase. A high PAPR value is an inherent disadvantage of OFDM and it causes nonlinear signal distortions and high power requirements for the transmitter amplifier Therefore, OFDM systems are known to have a high PAPR, compared with single-carrier systems. The high PAPR is one of the most detrimental aspects in the OFDM system, as it decreases the SQNR of ADC and DAC and hence the efficiency of the power amplifier in the transmitter. PAPR is the ratio between the square of the peak and variance of the wave. High PAPR of transmitted signals is one of the major issues of the OFDM system. [16] A large dynamic range of input data symbols is the main cause of getting high PAPR. An OFDM signal consists of independent data symbols modulated on N orthogonal subcarriers, and when these signals are added to the same phase, higher peak amplitude is observed. LEDs are used as transmitters in VLC and LEDs can be easily affected by high power signal. Therefore, a thorough attention must be paid to this high PAPR problem when OFDM is used in VLC. LEDs have a limited operating voltage range and the voltage-to-current relationship shows a nonlinear behavior. The nonlinear V-I characteristic of LEDs distorts the OFDM signal with high PAPR. Due to the high peak power, LED chips may be overheated. So, the high PAPR of the OFDM signal should be reduced before it is fed into transmitter LEDs.

CHAPTER 4

METHODOLOGY

4.1 System Model

Modulation is the set of transmission techniques aimed to transmit a signal called modulating signal by means of another signal called carrier signal. The modulation schemes used in VLC are in general different from the ones used in radio communication modulation, because they use power to transmit information and not directly the wave amplitude. Power is in general proportional to the square of the amplitude. Furthermore, VLC is used for low cost systems and uses the IM-DD technique that in general is not used for radio because it has only one degree of freedom and consequently low throughput may be convenient with IM-DD techniques as the light frequency band is very large and unlicensed. Furthermore, VLC is blocked by the walls and because of this in every room one can have a different VLC system without worrying about interference with other wireless networks.

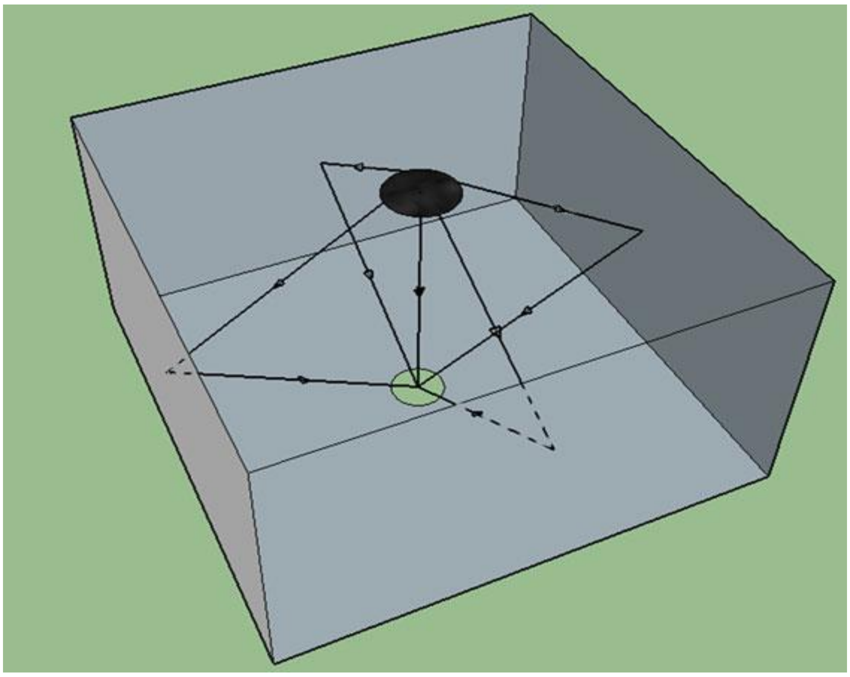

Figure 7: Indoor visible light communication environment

The IM-DD technique is the most used method to communicate with VLC for its low cost and for its simplicity. Typical VLC uses LEDs to communicate with photodiodes: the modulating signal is the current signal and the receiver is a photo detector that produces a photocurrent. For indoor VLC system in general, there is a LED device which is used as transmitter. There may be a number of receivers having an optical receiver (photodiode). A simple model of such a VLC system consisting of single optical transmitter (LED) on ceiling and optical receiver (photo diode) on floor is shown in Figure 7.

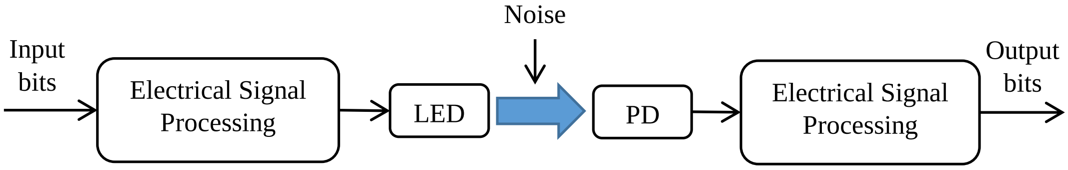

Figure 8: Generic model of standard VLC System

The generic model for standard visible light communication system is show in Figure 8. Due to the use of LED device, it is possible to transmit the different types of signal at a time in visible light communication system. For this multiple signal transmission in VLC, OFDM system was introduced for VLC. OFDM is one of the most widely used modulation technique for the transmission of high data rate, which provides high spectral efficiency, low complexity and nonlinear distortion.

The block diagram for the VLC system is shown in Figure 9. At the system transmitter, the transmitted data bits are randomly generated and converted from serial to parallel to form symbols for M-QAM. The QAM symbols are then modulated by IFFT to transform the symbols into time-domain samples.

IFFT is a fast algorithm to compute Inverse Discrete Fourier transform (IDFT), which is the reverse processes of DFT. OFDM uses IFFT to transform a set of multiplexed, overlapping subcarriers in the frequency domain to a signal of its time-domain equivalent form. A single OFDM symbol carries a set of data symbols, X in the frequency-domain. The OFDM symbol is a vector, which consists of a set of N subcarriers. The IFFT algorithm output which is the Inverse Discrete Fourier transform (IDFT) OFDM symbol vector x in the time-domain, which is given by equation 4.1

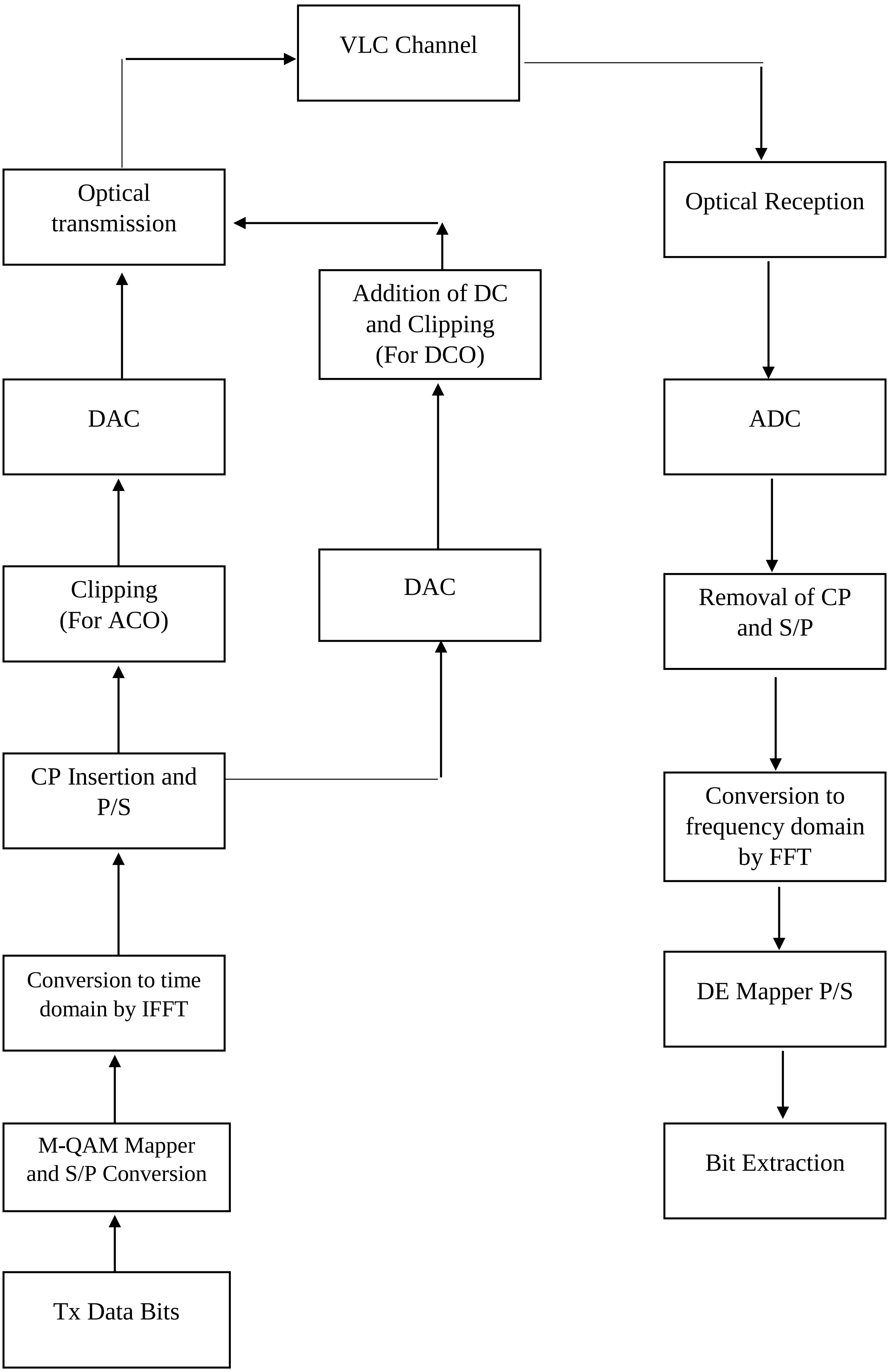

Figure 9: System Block Diagram of VLC System

$$x_m = \frac{1}{N}\sum_{K=0}^{N-1} X_k \, e^{j\frac{2\pi km}{N}} \qquad for\ 0 \le m \le N-1 \qquad (4.1)$$

Where N is the size of IFFT and X_k is the k^{th} subcarrier symbol.

The corresponding FFT conversion pair to equation 4.1 can be expressed as equation 4.2.

$$X_k = \frac{1}{N}\sum_{m=0}^{N-1} X_m \, e^{-j\frac{2\pi km}{N}} \qquad for\ 0 \le k \le N-1 \qquad (4.2)$$

The output of equation 4.2 is a complex signal and cannot be used in an intensity modulation and direct detection (IM/DD) system such as the LED based VLC. Hermitian symmetry is used to achieve a real-valued IFFT output. This is a transpose-conjugate copy of the active subcarriers, which is added to the other half of the IFFT frame; where the elements of new IFFT input vector, X_H are

$$X_H = [X_0\,, X_1\,, X_2\,, \dots\dots\dots\dots\dots\dots.\dots\dots., X_N\,, X^*_{N-1}\,, X^*_{N-2} \dots\dots\dots X^*_2\,, X^*_1] \qquad (4.3)$$

and the DC component, $X_0 = X_N = 0$. This results in a 2N-point IFFT output of the OFDM symbol. Equation (4.1) is modified to

$$x_m = \frac{1}{N}\sum_{h=0}^{2N-1} X_{H,h} \, e^{j\frac{2\pi hm}{N}} \qquad for\ 0 \le m \le 2N-1 \qquad (4.4)$$

where h is the h^{th}-subcarrier symbol of X_H. The OFDM symbol is a periodic function with a period, $T_p=1/\Delta f$, and Δf is the subcarrier spacing which is given by $\Delta f = B/(N-1)$ where B is the signal modulation bandwidth.

At the receiver, a fast Fourier transform (FFT) operation performs the conversion from the time to the frequency domain and each element of the FFT output Y_h is given by equation 4.5

$$Y_h = \sum_{m=0}^{2N-1} y_m \, e^{j\frac{2\pi hm}{N}} \qquad for\ 0 \le h \le 2N-1 \tag{4.5}$$

where y is vector consists of a set of amplitudes of the received time-domain signal of length *2N*. In an additive white Gaussian noise (AWGN) channel, the transmitted and the received signal are given by equation 4.6

$$y = x + n_{\mathrm{AWGN}} \tag{4.6}$$

where n is AWGN noise component, by substituting equation (4.6) in equation (4.5)

$$Y_h = \sum_{m=0}^{2N-1} x_m \, e^{j\frac{2\pi hm}{N}} + \sum_{m=0}^{2N-1} n_{AWGN,m} \, e^{j\frac{2\pi hm}{N}} \qquad for\ 0 \le h \le 2N-1 \tag{4.7}$$

where x_m and $n_{AWGN,m}$ are the signal and noise amplitude of the m-th point of the *2N* point time domain signal. $N_{AWGN,h}$ is a Gaussian noise component of the h-th FFT output at the receiver is given by equation 4.8

$$N_{AWGN,h} = \sum_{m=0}^{2N-1} n_{AWGN,m} \, e^{-j\frac{2\pi hm}{N}} \qquad for\ 0 \le h \le 2N-1 \tag{4.8}$$

Therefore, Equation 4.7 can be reduced to equation 4.9

$$Y_h = X_h + N_{AWGN,h} \tag{4.9}$$

An advantage of OFDM transmission is that it can overcome this ISI problem by using a cyclic prefix (CP) inserted at the beginning of the OFDM frame. The CP is a cyclical copy of an end fraction of the OFDM frame.

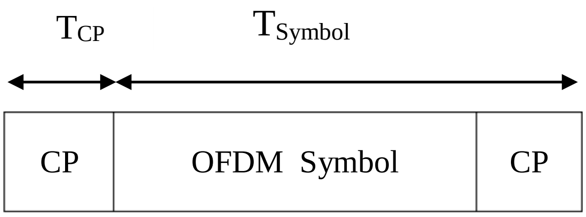

Figure 10: Cyclic Prefix adding process in OFDM Signal

In OFDM signals, the cyclic prefix is used as a guard interval. It is inserted at the beginning of each OFDM symbol as a copy of the end symbol. To mitigate the effect of ISI due to multipath propagation, guard interval is applied. To overcome the noise and distortion at the beginning of the next symbol, due to delays, one possible way is to shift the symbols further from each other. But for a continuous communication system, such existence of a blank space for is not desirable. To solve this, a copy of the last part of the symbol is inserted at the beginning of each symbol. This process is known as addition of cyclic prefix. The Cyclic prefix is added after the IFFT at the transmitter. At the receiver side, the cyclic prefix is removed and the original signal is received.

The prefix is longer than the estimated delay spread in the channel; this mitigates the detrimental effect caused by the dispersive channel by localizing it in a non-information bearing prefix of the OFDM symbol which is later removed upon reception. The time domain optical OFDM symbol waveform is real and bipolar.

To get a unipolar OFDM to meet IM-DD requirements, one of the methods is to add a dc-bias current to the signal to make it positive and the signal which results by this process is known as DC-coupled optical OFDM (DCO-OFDM). [17] For a constant addition of dc-bias current higher power requirement is required. For non-variance level of room illumination a constant dc-bias current is needed. Therefore, it can be concluded that power constraint is not very significant for indoor VLC systems especially which are designed for lighting applications.

An alternative modulation approach is required when energy efficiency is required. Unipolar OFDM modulation schemes were mainly introduced to provide energy efficient optical OFDM alternatives to DCO-OFDM such as ACO-OFDM. Unipolar

OFDM modulation scheme exploit the OFDM input/output frame structure to produce a unipolar time domain waveform output. Another way of achieving unipolar signal is by clipping the signal at zero and only positive real parts are allowed to send for the transmission. OFDM signal is generated in such a way that the positive part is anti-symmetrical copy of the negative part. The resulting signal is called ACO-OFDM.

Hermitian symmetry

DC	X_1	X_2	X_3	0	X_3^*	X_2^*	X_1^*

(a)

Hermitian symmetry

0	X_1	0	X_3	0	X_3^*	0	X_1^*

(b)

Figure 11: Subcarriers mapping of the input frames
for (a) DCO-OFDM and (b) ACO-OFDM

ACO-OFDM has a reduced spectral efficiency compared with DCO-OFDM due to the restrictions imposed on their frame structures. DC bias, $B_{DC,}$ is added to an OFDM signal to convert the bipolar OFDM signal into a unipolar signal. In practice because an OFDM signal has a Gaussian distribution, if B_{DC} is not to be excessive, the peaks of the negative going signal must first be clipped. This adds a clipping noise component, $n_c(B_{DC})$, which increases as B_{DC} decreases and affects all subcarriers.

$$x(t) = x_0(t) + B_{DC} + n_C(B_{DC}) \approx x_0(t) + B_{DC} \tag{4.10}$$

The optimum clipping level depends on the signal constellation. A very high SNR is required for large constellations such as 256 QAM for practical BERs. So clipping noise must be very low and therefore B_{DC} must be large. This also increases the optical power because, $P_{opt} = E\{x\} \approx B_{DC}$. In ACO-OFDM the same configuration is optimum for all constellations. But unlike ACO-OFDM, when DCO-OFDM is combined with adaptive modulation and different constellations are used on different subcarriers, B_{DC} cannot be optimized for all constellation sizes. Due to Hermitian constraint, DCO-

OFDM has N/2 independent complex inputs for an N point IFFT. Thus for a given constellation size the data rate of DCO-OFDM is twice that of ACO-OFDM.

A real unipolar OFDM waveform can be achieved by exploiting the Fourier transformation properties on the frequency domain input OFDM frames. The principle of ACO-OFDM is to skip the even subcarriers of an OFDM frame, by only loading the odd subcarriers with useful information. X_i represents the M-QAM symbol at the i^{th} subcarrier and P_i represents the M-PAM symbol at the i^{th} subcarrier.

The total data rate for a DCO-OFDM transmission is given by

$$R_{DC0-OFDM} = \frac{B}{N}\sum_{k=1}^{N-1} \log_2 M_k \tag{4.11}$$

where B is the modulation bandwidth and $\log_2 M$ represents the number of bits per symbol of a carrier modulation scheme, which is typically M-quadrature amplitude modulation (QAM).

The signal x_m is then converted to the analog waveform $x(t)$ using a digital-to-analog converter (DAC). In a DCO-OFDM system, the positive forward signal $r(t)$ that drives the LED must be obtained from $x(t)$ after both a linear scaling (LS) and a biasing operation as

$$r(t) = \alpha x(t) + B_{DC} \tag{4.12}$$

where α and B_{DC} are both real-valued. The forward signal $y(t)$ drives the LED which in turn converts the magnitude of the input electric signal $r(t)$ into optical intensity. The human eye cannot perceive fast changing variations of the light intensity, and only responds to the average light intensity. Also, linear scaling and biasing model are adopted to ensure the forward signal is within the dynamic range of the. The value B_{DC} is the biasing level added to $x(t)$ to ensure a unipolar OFDM signal at the LED input, and α is the parameter to scale $x(t)$ within the dynamic range of LED. After the scaling and biasing operation, the resulting signal $y(t)$ will have a mean value B_{DC} and a variance $\sigma_y^2 = \sigma^2\sigma_x^2$ where σ_x^2 is the variance of $x(t)$.

In ACO-OFDM, only the odd subcarriers carry data while the even subcarriers are set to zeros in the frequency domain. The input signal to the N-point IFFT, X, consists of only odd components and satisfies the Hermitian symmetry as $X = [0, X_1, 0, X_3, \dots X_{N/2-1}, 0, X^*_{N/2-1}, \dots . X^*_3, 0, X^*_1]$. The time-domain signal x_n has the anti-symmetric property as $x_n = -x_{n+N/2}$, $(0 \leq n < N/2)$. The ACO-OFDM signal, $x_{ACO,n}$, is ensured non-negative by clipping the negative part without losing any information as

$$x_{ACO,n} = \begin{cases} x_n, & x_n \geq 0, \\ 0, & x_n < 0. \end{cases} \tag{4.13}$$

It has been proved that the clipping noise only falls on the even subcarriers, which will not affect the demodulation of the transmitted data.

Channel modeling is a vital issue in VLC system design. LOS modeling scheme is simpler one and widely utilized in analysis of VLC system transmission characteristics. The optical pass loss is the most important quantity to characterize the channel. The received optical power in Watt at receiver plane in a LOS path (ignoring the reflection of walls) is given by equation 4.14

$$P_r = P_t H(0)_{LOS} \tag{4.14}$$

Where P_t is the transmitted optical power, P_r is the received optical power, and H (0) is the optical LOS path loss. The LOS channel path loss is defined as

$$H(0)_{LOS} = \frac{A}{D^{\,2}} R(\emptyset) Ts(\psi) g(\psi) \cos\psi \tag{4.15}$$

Where A is the active receiving area,D is the transmitter receiver distance, ϕ is the angle with respect to the transmitter ψ is the angle with respect to the receiver, $Ts(\psi)$ is the filter gain $g(\psi)$ is the concentrator gain, and $R(\emptyset)$ is the transmitter radiant intensity which is given by

$$R(\emptyset) = \frac{m}{2\pi} \cos^{\mathrm{m}}(\emptyset) \tag{4.16}$$

where, m is the order of Lambertian emission. The order of Lambertian emission m is related to the LED semi angle at half-power $\emptyset_{1/2}$ (also called the transmitter beam angle) by equation 4.17

$$m = \frac{ln2}{\ln(cos\,\emptyset_{1/2}\ )} \tag{4.17}$$

A photodiode is used in the receiver side to transform the received optical intensity into the amplitude of an electrical signal. After passing through the channel, the received signal is obtained as in equation 4.18

$$y(t) = h(t) \otimes F\big(r(t)\big) + n_{AWGN}(t) \tag{4.18}$$

where $y(t)$ represents the received distorted replica of the transmitted signal, $r(t)$, which is subjected to the non-linear distortion function, $F\big(r(t)\big)$, of the transmitter front-end. The nonlinearly distorted transmitted signal is convolved with the channel impulse response,$h(t)$, and it is distorted by additive white Gaussian noise (AWGN), $n_{AWGN}(t)$, at the receiver. Here, $\otimes$ stands for linear convolution. Since, OFDM is based on IFFT and FFT algorithms, the implementation on the DSP is straightforward, the following equivalent discrete model for a noisy communication link is employed in the system description

$$y = h * F(r) + n_{AWGN} \tag{4.19}$$

where * stands for discrete linear convolution.

4.2 PAPR

One of the main disadvantages of OFDM is the high PAPR though it has a number of advantages. PAPR is an important criterion to measure the performance of VLC system. Due to presence of High PAPR in VLC system will increase the hardware complexity and reduced the performance of system. High PAPR places pressure on the design of components such as the word length of the IFFT/FFT pair, mixer stages, and most importantly the HPA, which must be designed to handle irregularly occurring large peaks, decreases the Signal-to-Quantization Noise Ratio of ADC and DAC. The PAPR is defined as

$$PAPR = \frac{\max x_m^2}{E[x_m^2]} \tag{4.20}$$

Where $max\, x_m^2$ is maximum value of the OFDM signal power, *E [•]* the average of those values. Any reductions in PAPR are normally illustrated using a PAPR complementary cumulative distribution function (CCDF) diagram. The PAPR of OFDM signal is used to evaluate the PAPR reduction performance accurately from the statistical analysis. The CCDF of the PAPR is defined as the probability that the PAPR of an OFDM frame exceeds a given threshold value PAPR0 and it is the most frequently used measure for describing PAPR reduction and given by

$$CCDF\ (PAPR(x(n)))\ =\ Pr\ (PAPR(x\ (n))\ >\ PAPR0 \tag{4.21}$$

Therefore to lessen the difficulty of complex hardware design it has become imperative to employ efficient PAPR reduction techniques. There are number of techniques to minimize the PAPR of VLC. Some of the techniques such as clipping, Partial Transmit Sequence (PTS), Selected Mapping (SLM), Discrete Fourier Transform Spread, etc. techniques are widely used. Among them SLM and PTS methods to minimize PAPR are analyzed here.

4.2.1 PTS Technique Model

PTS method is a distortion less optimization technology which provides better PAPR reduction with good BER over clipping technique. PTS method is carried out the random signal phase weight to calculate the lowest signal PAPR. The block diagram is shown in Figure 12 for PTS method used in VLC OFDM system.

The input data symbols in X are partitioned into N disjoint sub blocks represented by vectors $\{X_n | n = 0, 1 \ldots\ N - 1\}$. So, X can be written as,

$$X = \sum_{n=0}^{N-1} X_n = [X_0, X_1, X_2 \ldots\ X_{N-1}]^T \tag{4.22}$$

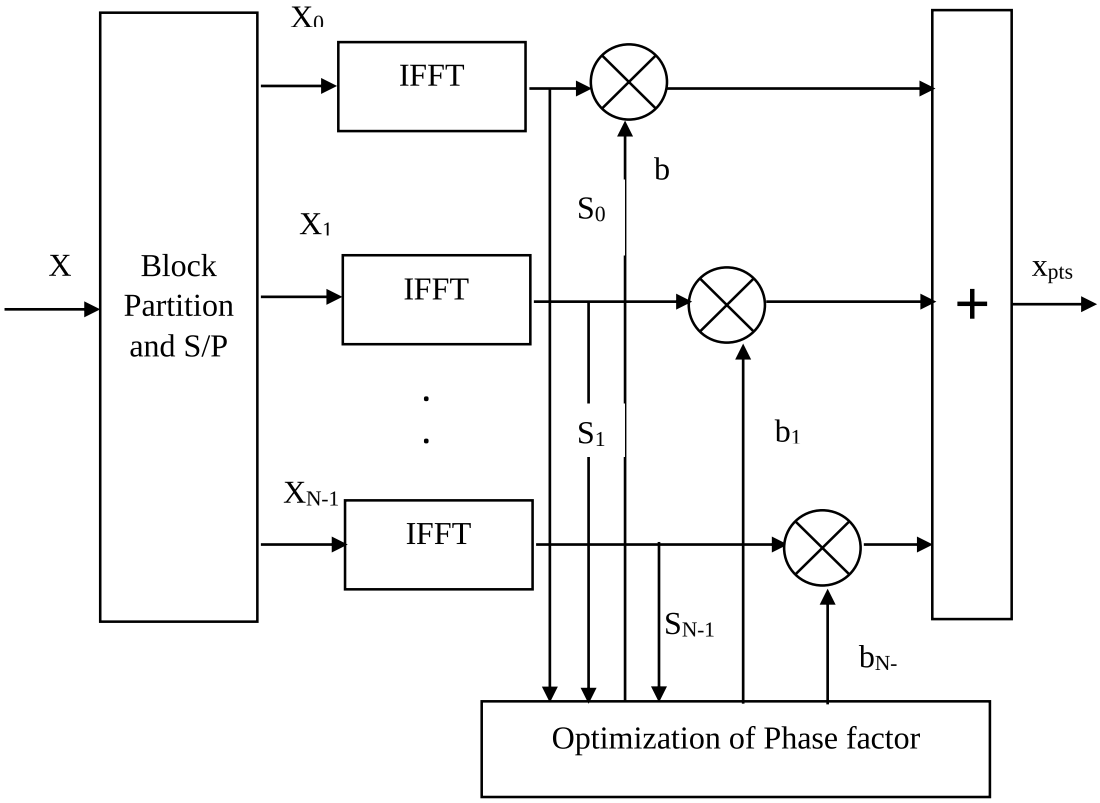

Figure 12: PTS technique for minimization of PAPR

These sub blocks X_n are transformed into N time-domain partial transmit sequences and the resulted signals are independently rotated with weighting phase factors b_n represented as $b_n = e^{j\theta n} | n = 0, 1 \dots N-1\}$ with phase factor $\emptyset_n = 0 \; or \; 2\pi.$ Taking its IFFT gives,

$$\hat{x} = IFFT\left\{\sum_{n=0}^{N-1} \hat{b}_n X_n\right\} \tag{4.23}$$

$$= \sum_{n=0}^{N-1} \hat{b}_n \hat{x}_n \tag{4.24}$$

The weighting coefficients b_n are selected that minimize the PAPR of the combined signal.

$$[b_1 \dots b_{N-1}] = \underset{[b_1 \dots b_{N-1}]}{\arg} \; min\left(\max_{n=0\dots N-1}\left|\sum_{n=0}^{N-1} \hat{b}_n \hat{x}_n[m]\right|\right) \tag{4.25}$$

These signals are then combined to further produce the time domain OFDM signal packet back. The lowest value of the corresponding transmit input sequence will be selected by PTS algorithm.

$$x_{pts} = \sum_{n=0}^{N-1} b_n \hat{x}_n \tag{4.26}$$

4.2.2 SLM Technique Model

PAPR performance of SLM-OFDM is improved as efficient phase rotation factors are chosen, which is the most popular PAPR reduction method used in VLC system.

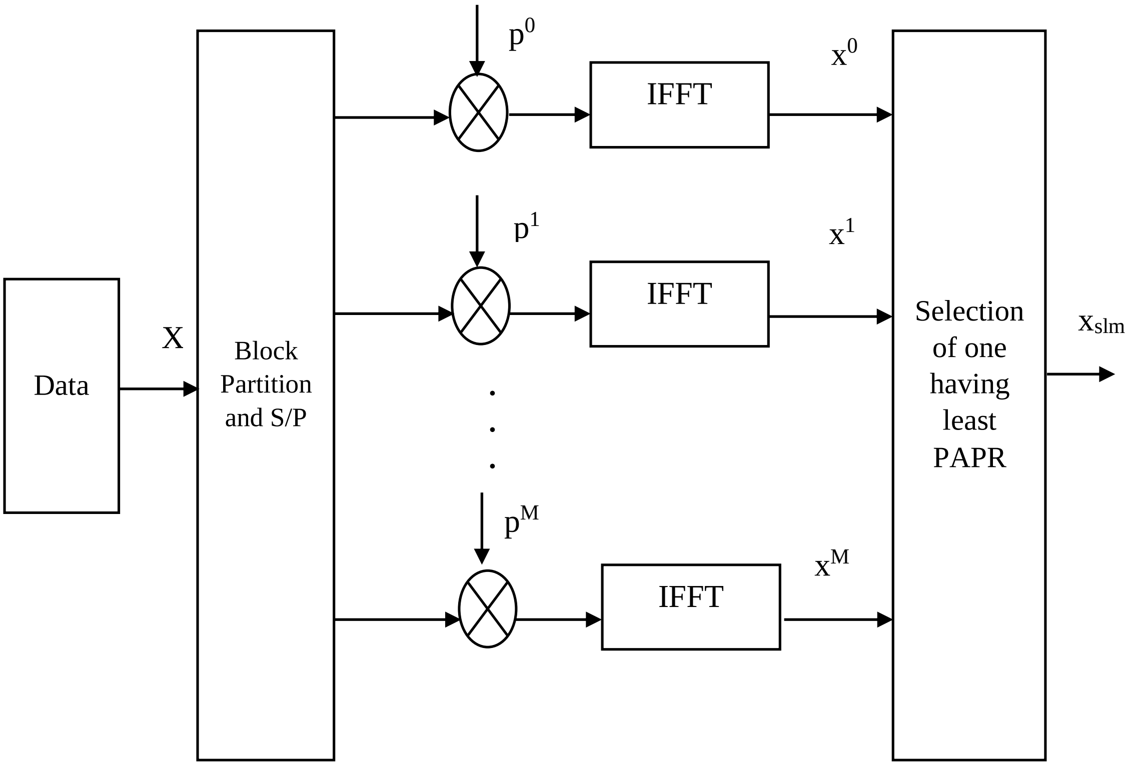

Figure 13: SLM technique for minimization of PAPR

In SLM, first of all, the input data signal is partitioned into the sub blocks *X* represented as $\{X_m | m = 0, 1 \ldots M - 1\}$ and parallel data sequences are multiplied with the independent phase rotation sequence $p^{(M)}$ given as,

$$p^m = [p_0, p_1, \ldots p_{M-1}]^T \tag{4.27}$$

After the application of SLM, the signal becomes,

$$x_{slm}(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_m p . e^{j2\pi n \Delta f t} \tag{4.28}$$

The resulted frequency domain signal is converted into the time domain with the help of IDFT operation. All data sequences x^m are combined and the one signal is selected having lowest PAPR value. The block diagram for SLM-OFDM VLC System is shown in Figure 13.

4.2.3 DCT Transform

The Discrete Cosine Transform (DCT) is similar to Fourier transform. DCT transform reduces the autocorrelation of the input sequence, reducing the issue of peak to average power in OFDM signal. It does not require side information to be transmitted to the receiver. Applying the DCT matrix converts the time-domain signal into new transform-domain signal. It is an orthogonal linear transform that can be implemented similar to the IFFT. It is a real transform in which the data are multiplied by cosine function. The DCT of one-dimensional of length *N* is given as,

$$X_c(k) = \alpha(k) \sum_{n=0}^{N-1} x(n) \cos\left[\frac{\pi(2n+1)k}{2N}\right] \tag{4.29}$$

for $k = 0 \ldots N - 1$

The inverse transformation is,

$$X_c(k) = \alpha(k) \sum_{u=0}^{N-1} \alpha(k) X_c(k) \cos\left[\frac{\pi(2n+1)k}{2N}\right] \tag{4.30}$$

for $n = 0 \ldots N - 1$

For both Equation 4.29 and Equation 4.30 are defined as,

$$\alpha(u) = \begin{cases} \frac{1}{\sqrt{N}} & for\ k = 0 \\ \frac{2}{\sqrt{N}} & for\ k \neq 0 \end{cases} \tag{4.31}$$

This equation can be expressed in matrix form as,

$$X_c = C_N\, x \tag{4.32}$$

where X_c and x are both vectors with $N \times 1$ and C_N is a DCT transform matrix with $N \times N$. The rows/columns of the DCT transform matrix C_N are orthogonal matrix vectors. This property of DCT matrix is used to reduce the power of OFDM signals.

4.2.4 PTS with DCT Transform

To reduce the PAPR, the combination of PTS with DCT transform can be used. The subblock partitions of the data is first transformed by DCT transform matrix and the output signal from individual precoder is given as input for IDFT of PTS section.

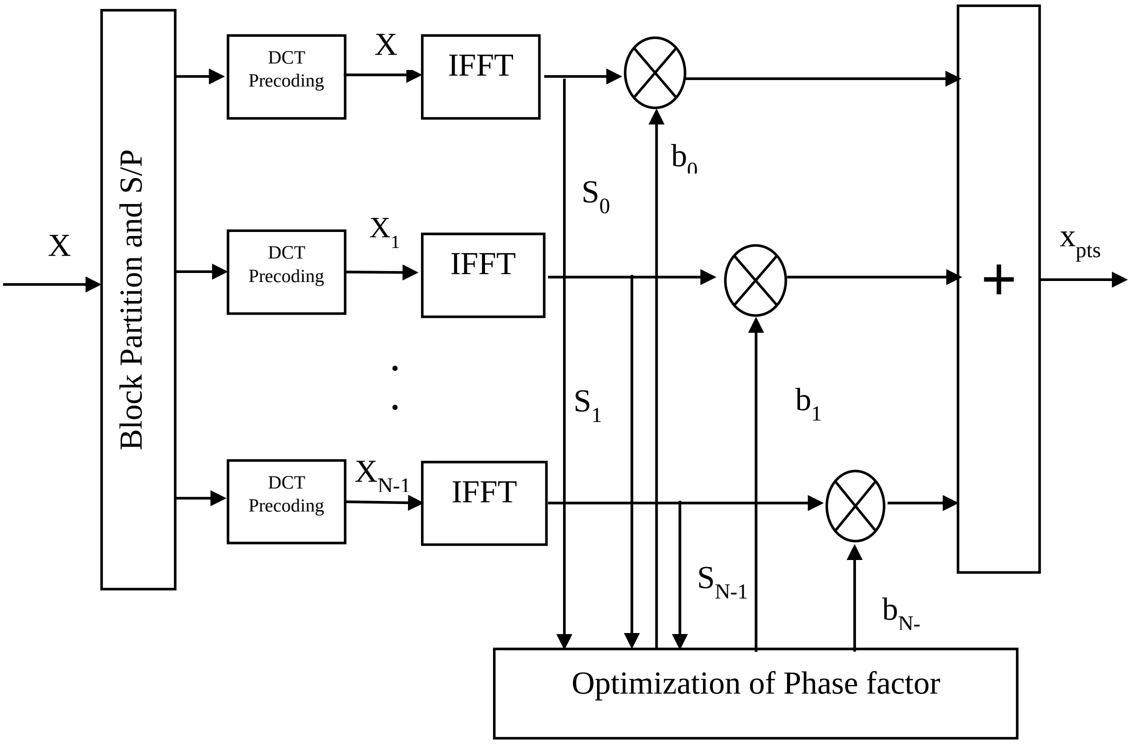

Figure 14: PTS with DCT Transform for PAPR minimization

The use of DCT transform initially reduces the PAPR of the OFDM signal which is further reduced by the PTS in the next step.

4.2.5 SLM with DCT Transform

Similarly, the combination of SLM with DCT transform can be used to reduce the PAPR of OFDM signal. The sub block partitions of the data is first transformed by DCT transform matrix and the output signal from individual pre-coder is processed by the SLM section.

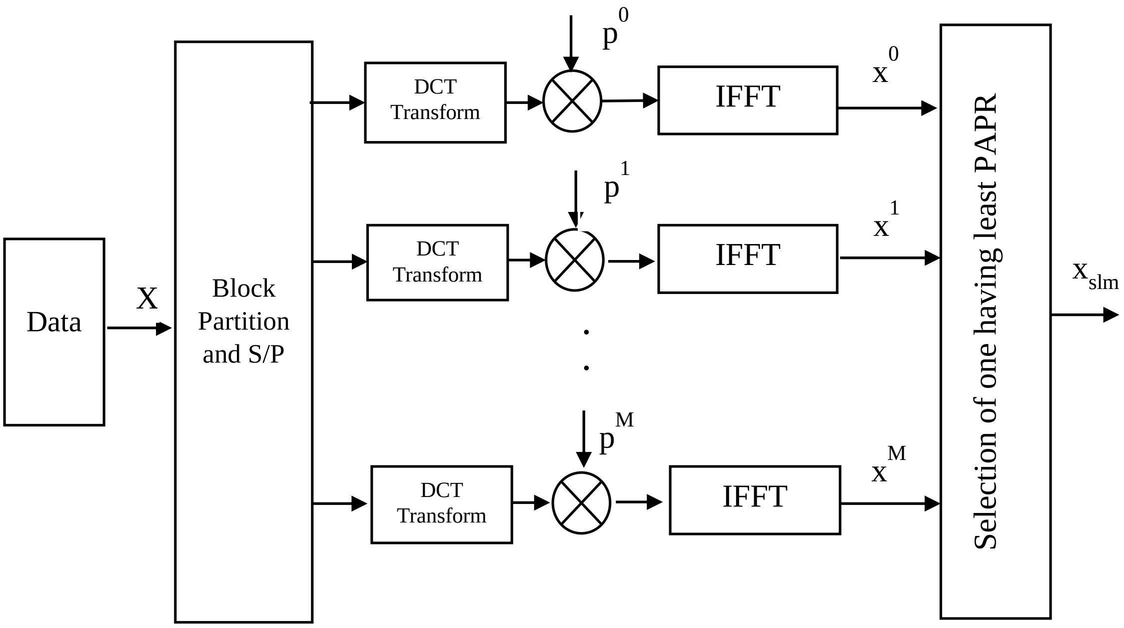

Figure 15: SLM with DCT Transform for PAPR minimization

4.3 Simulation Environment

To study the performance of VLC systems, for which the theory was described in the previous chapters, simulations are performed. For this research work, some considerations were made about the system properties. The channel is considered line of sight. The path loss and multipath dispersion are neglected. The interference due to artificial light is neglected.

In general a simulation is a simplified model of reality in which the focus is on what are believed to be the dominant phenomena and second order effects can be neglected. This model usually is translated into a computer algorithm that is able with a finite number of steps to calculate the parameters that one wants to evaluate.

The simulation is carried with MATLAB, the BER curve as a function of the SNR DCO-OFDM and ACO-OFDM multi carrier modulation schemes used in VLC system. The BER was calculated by comparing the original signal upstream of the transmitter, with the received signal after the receiver. This will not be equal to transmitted signal because it will be immersed in noise. The BER is the function that tells how many errors there are as a function of the SNR used in the transmission. In telecommunication, BER is very important because it is a good parameter to estimate the quality of the communication system. The Table 3 shows the system parameters used for the simulation of the VLC system.

Table 3: System Simulation Parameters for the VLC System

Simulation Parameters	**Values**
System	ACO and DCO-OFDM based VLC
IFFT size	64
Modulation	16 QAM
Channel	OWC with AWGN
Subblocks	4
Weighting phase factor	2
CP length	16
Room Size	5m * 5m * 3m
Reflection Coefficient	0.8
Location of four LEDs	(1.25, 1.25, 3), (1.25, 3.75, 3), (3.75, 1.25, 3), (3.75, 3.75, 3)
Location of the single LED	(2.5, 2.5, 3)
Semi Angle at half power	60
Transmitted power	20 mW
Number of LEDs per array	60 * 60
Center luminous Intensity	0.73
Receive Plane above the floor	0.85 m
Active area	1 cm^2
Half angle FOV	50
Elevation	90
Δt	0.5ns

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Simulation Results

Multicarrier modulation techniques such as OFDM can convert the frequency selective fading of the communication channel into a flat fading by employing the computationally efficient single tap equalizer. In addition, OFDM supports adaptive power and bit loading which can adapt the channel utilization to the frequency response of the channel. This can maximize the system performance. Supporting multiuser communication systems is an inherent advantage of OFDM, where each user could be allocated certain subcarriers.

The system performance in terms of BER and SNR is analyzed in this section. For different order of QAM, the BER performance of original VLC-OFDM signal is evaluated and shown in Figure 16. From the figure it can be clearly seen that as value of SNR is increased, the value of BER is decreased. It can be also concluded that higher SNR is required to achieve same BER when QAM is changed from lower order to higher order of QAM.

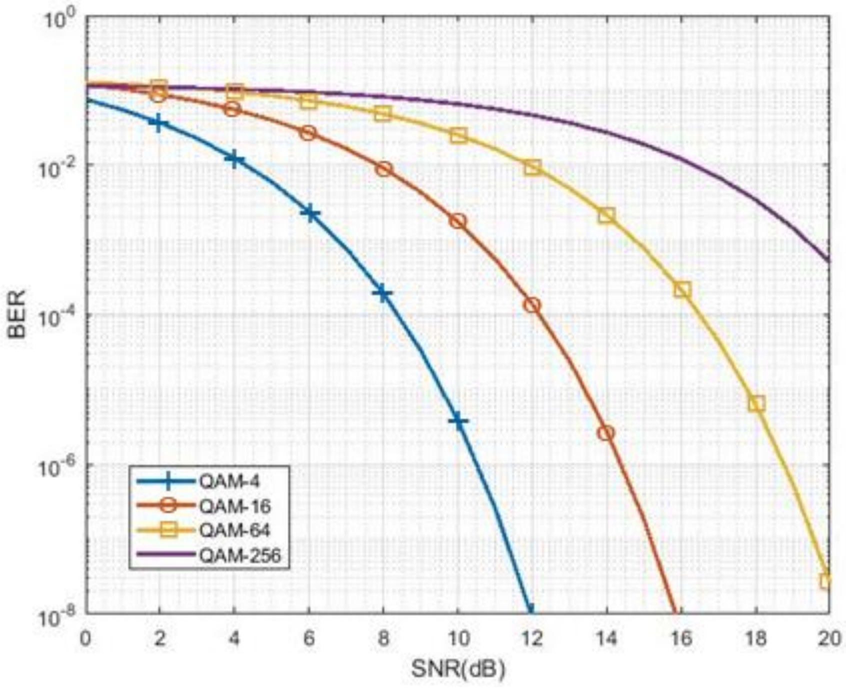

Figure 16: BER vs. SNR of different order of QAM

BER of a VLC system is defined as the ratio of number of error bits received and total number of bits transmitted during a specified period of time. It can be measured by comparing the transmitted signal bit with the received signal bit.

5.1.1 DCT Transform Method

The BER performance of DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying DCT Transform to the OFDM signal. The results are obtained as shown in the Figure 17.

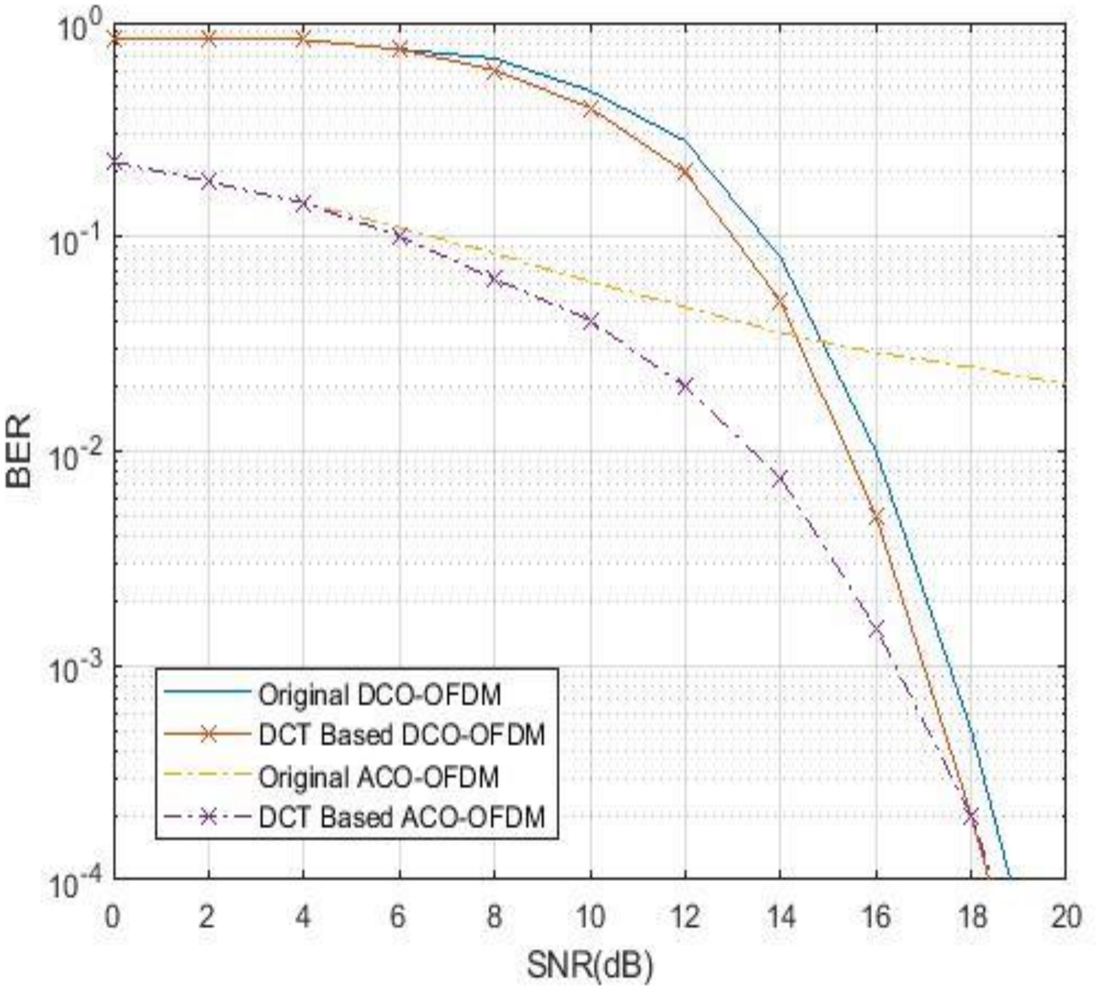

Figure 17: BER vs. SNR of ACO and DCO-OFDM with DCT Transform

It can be observed that for ACO-OFDM it requires more than 20dB of SNR to achieve BER of 10^{-3} and the same BER can be achieved by expensing 17.8 dB of SNR in case of DCO-OFDM. But, the same BER can be achieved by utilizing 16.1dB of SNR in case of ACO-OFDM and 16.9dB of SNR in case of DCO-OFDM with DCT Transform method.

Similarly the CCDF vs. PAPR graph for DCO-OFDM and ACO-OFDM of a VLC system was analyzed by applying DCT Transform to the OFDM signal. The results are obtained as shown in the Figure 18.

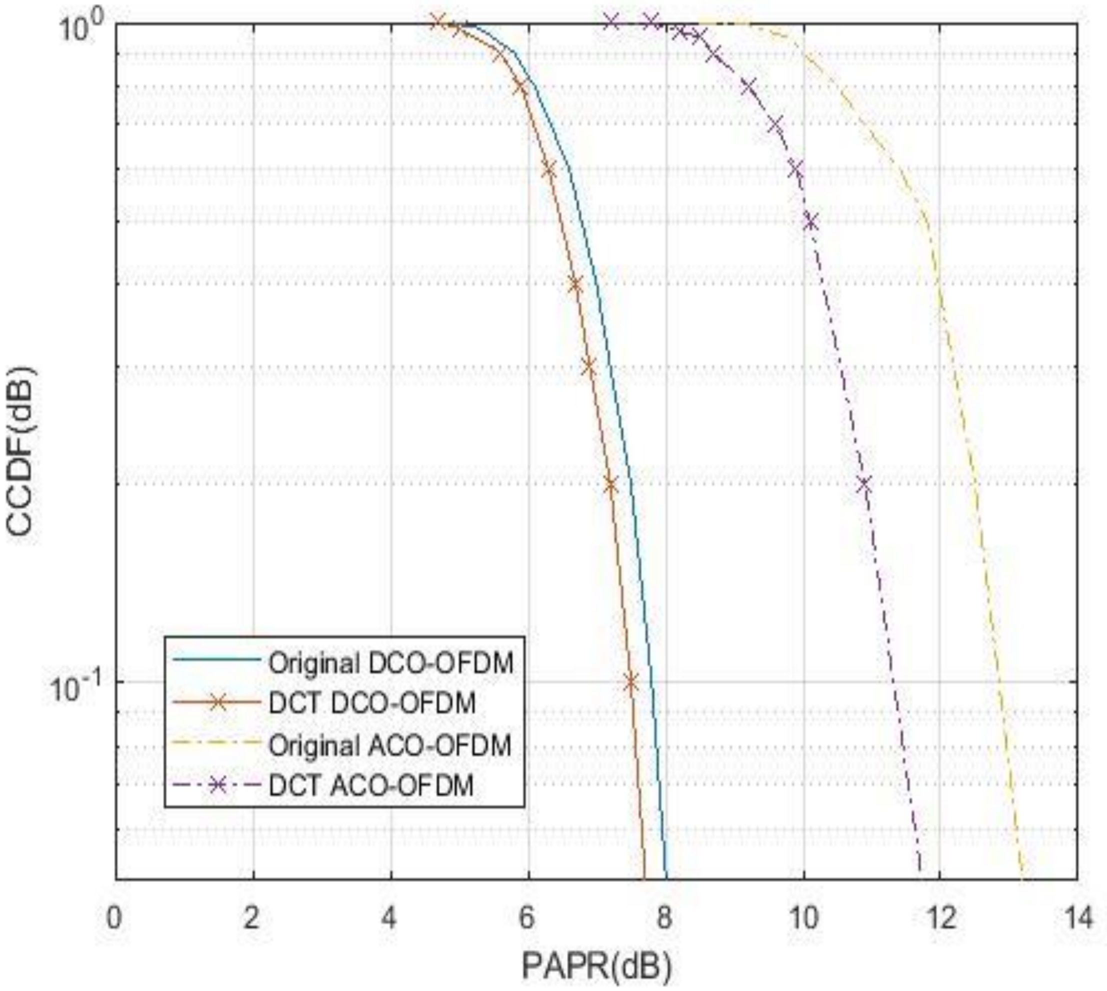

Figure 18: CCDF performance of ACO and DCO-OFDM with DCT Transform

It can be observed from PAPR vs. CCDF plot that DCT Transform DCO-OFDM performs better than original DCO-OFDM for CCDF of 10^{-1} and similarly DCT Transform ACO-OFDM performs better than original ACO-OFDM PAPR reduction gain than ACO-OFDM in terms of PAPR reduction gain same CCDF.

5.1.2 PTS Method

The BER performance of DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying PTS method to the OFDM signal. The results are obtained as shown in the Figure 19.

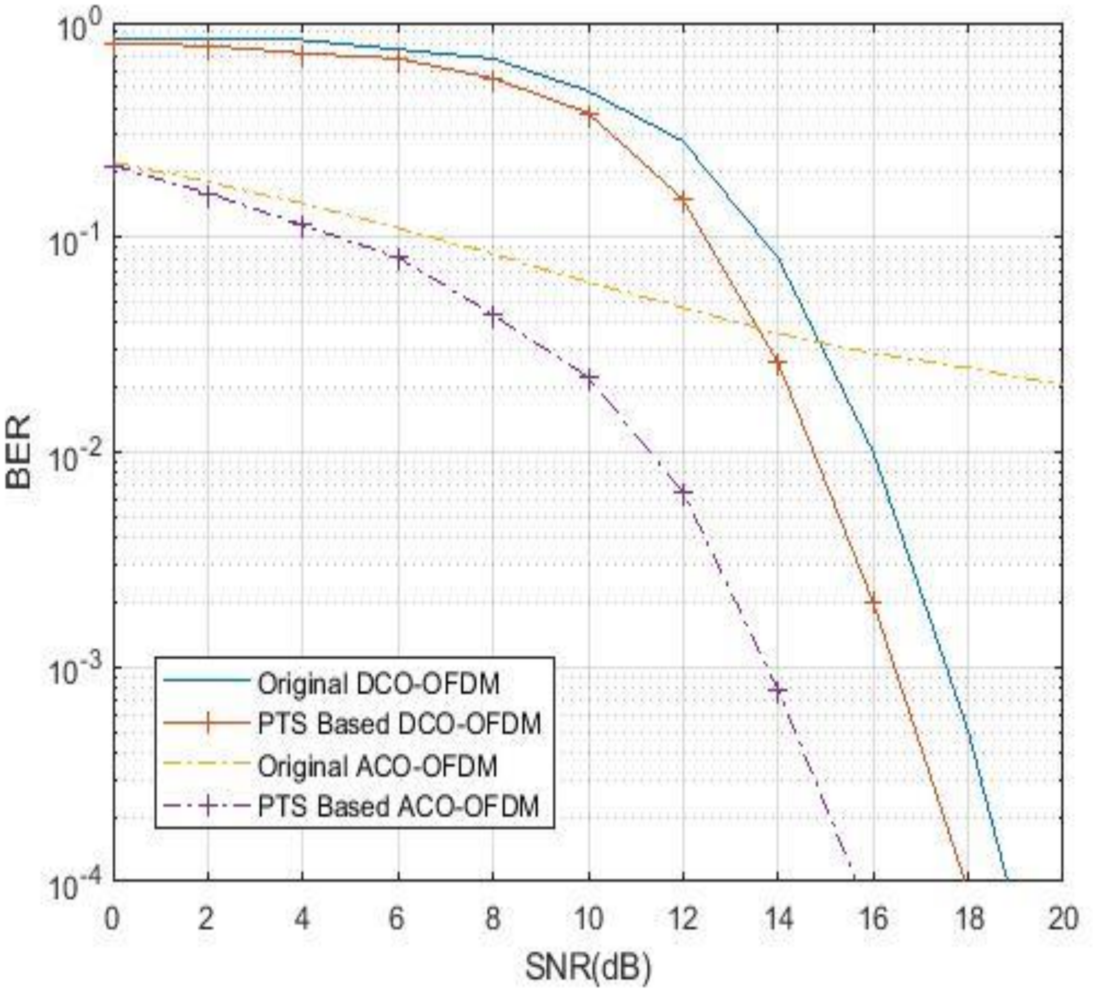

Figure 19: BER vs. SNR of ACO and DCO-OFDM with PTS Technique

It can be observed that as discussed in DCT Transform technique section for original ACO-OFDM greater value of SNR is required to achieve BER of 10^{-3} and the same BER can be achieved by expensing 17.8 dB of SNR in case of DCO-OFDM. But, for ACO-OFDM 13.9 dB of SNR is required to achieve BER of 10^{-3} and the same BER can be achieved by expensing 16.2 dB of SNR in case of DCO-OFDM with PTS method.

Similarly the CCDF vs. PAPR graph for DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying PTS method to the OFDM signal. The results are obtained as shown in the Figure 20.

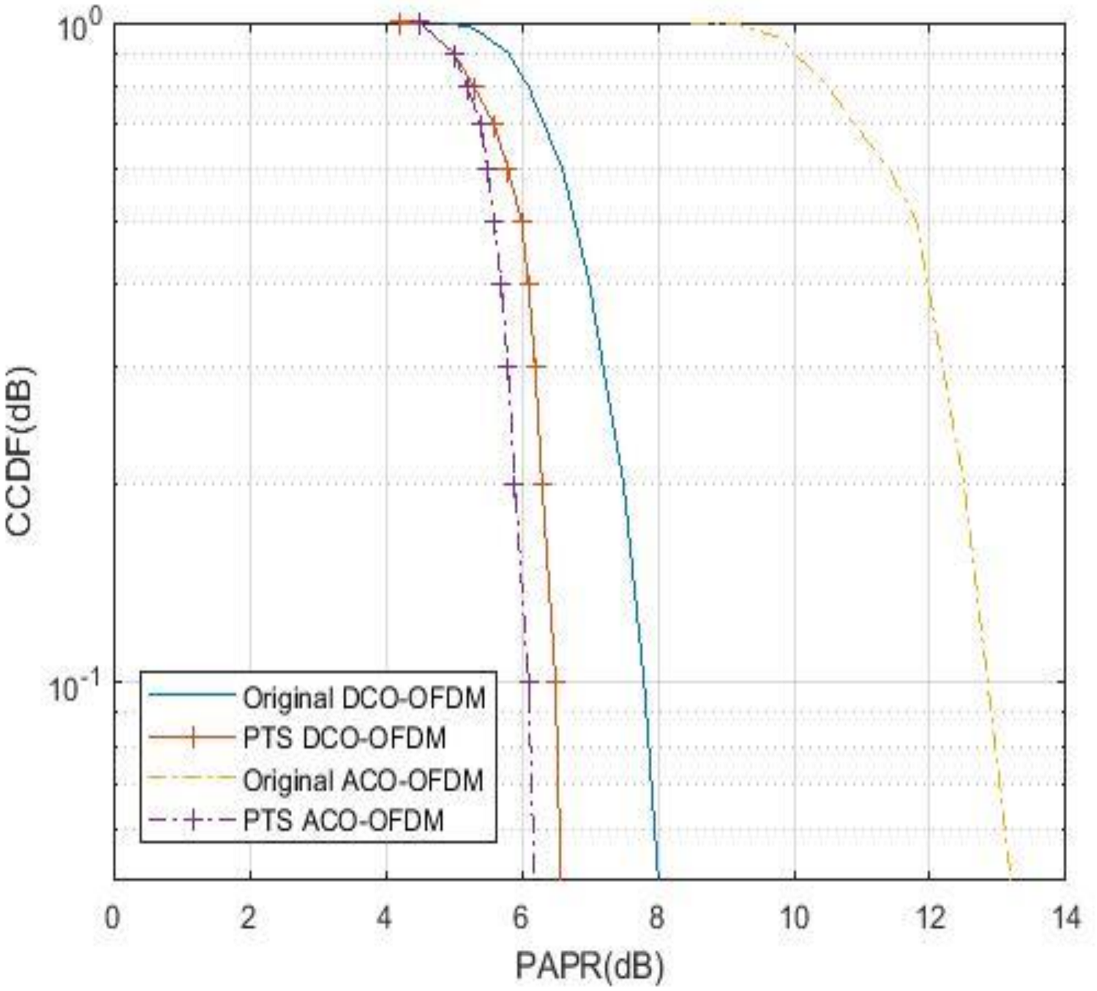

Figure 20: CCDF performance of ACO and DCO-OFDM with PTS Technique

It can be observed from PAPR vs. CCDF plot that for DCO-OFDM 1.4 dB of PAPR reduction gain for CCDF of 10^{-1} by PTS method and for the ACO-OFDM 6.8 dB of better PAPR performance than original ACO-OFDM with PTS method for same CCDF value.

5.1.3 SLM Method

The BER performance of DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying SLM method to the OFDM signal. The results are obtained as shown in the Figure 21.

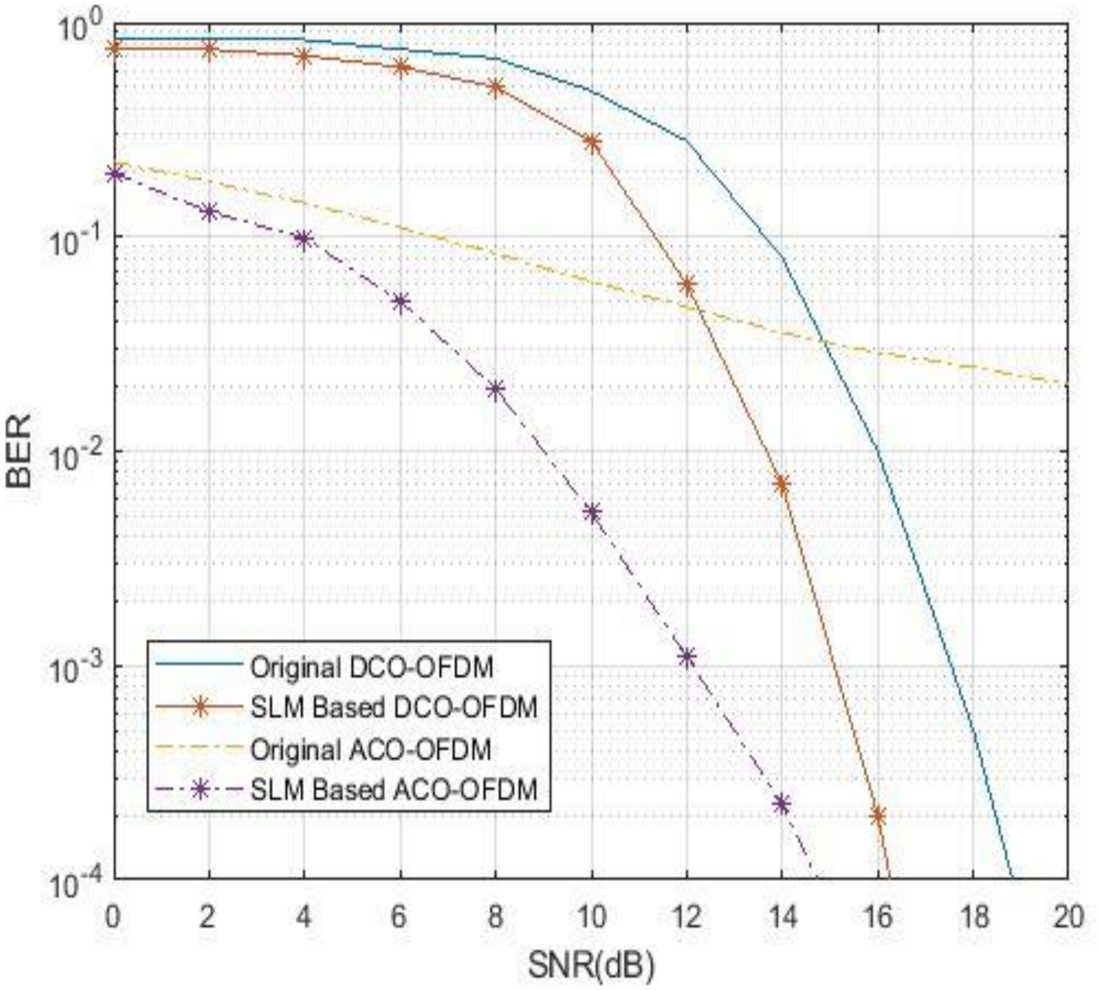

Figure 21: BER vs. SNR of ACO and DCO-OFDM with SLM Technique

It can be observed that for ACO-OFDM it requires 12.1dB of SNR to achieve BER of 10^{-3} and the same BER can be achieved by utilizing only 15.2dB of SNR in case of DCO-OFDM with SLM method.

Similarly the CCDF vs. PAPR graph for DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying SLM method to the OFDM signal. The results are obtained as shown in the Figure 22.

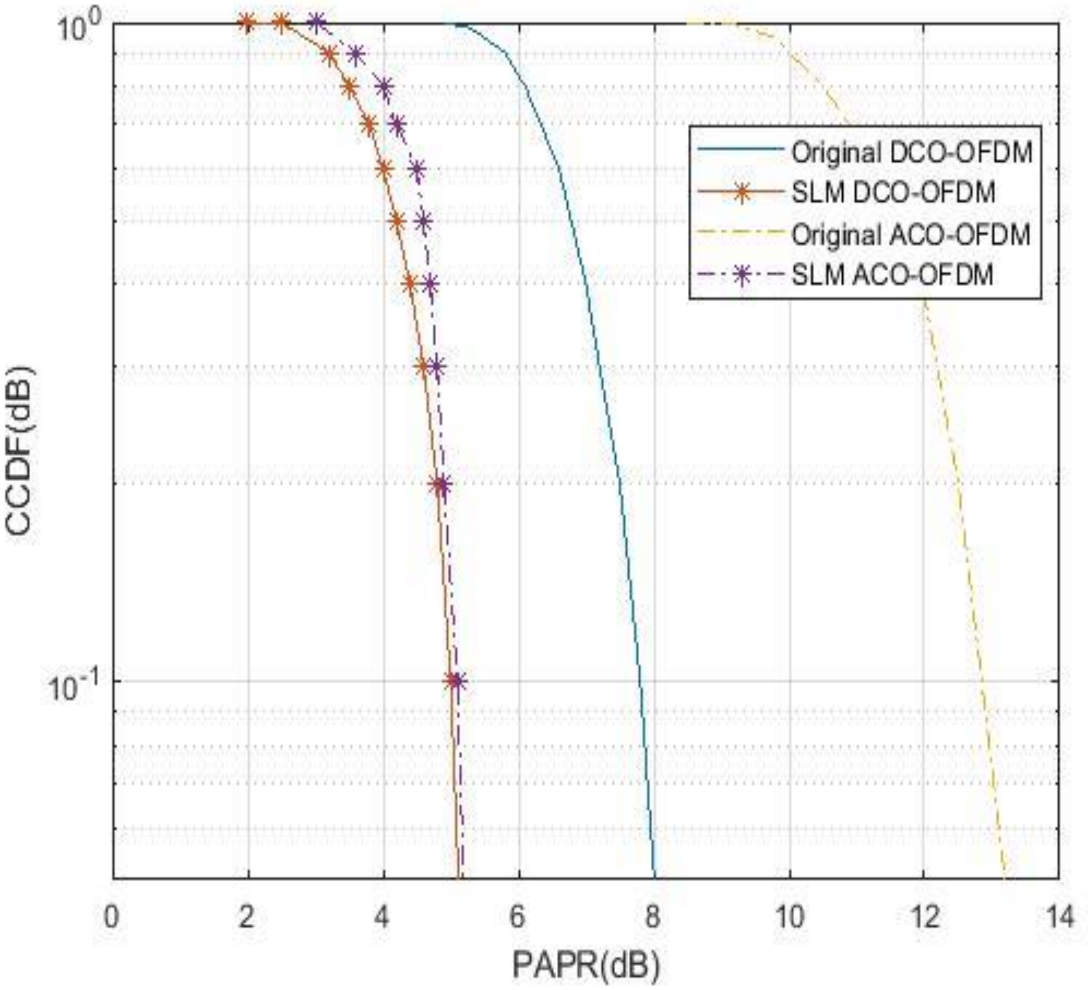

Figure 22: CCDF performance of ACO and DCO-OFDM with SLM Technique

It can be observed from PAPR vs. CCDF plot that for DCO-OFDM performs 2.9dB better PAPR performance than original DCO-OFDM. Similarly, for ACO-OFDM 7.6dB of better PAPR performance than original ACO-OFDM with SLM technique for CCDF of 10^{-1}.

5.1.4 Hybrid SLM + PTS Method

The BER performance of DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying SLM + PTS Method to the OFDM signal. The results are obtained as shown in the Figure 23.

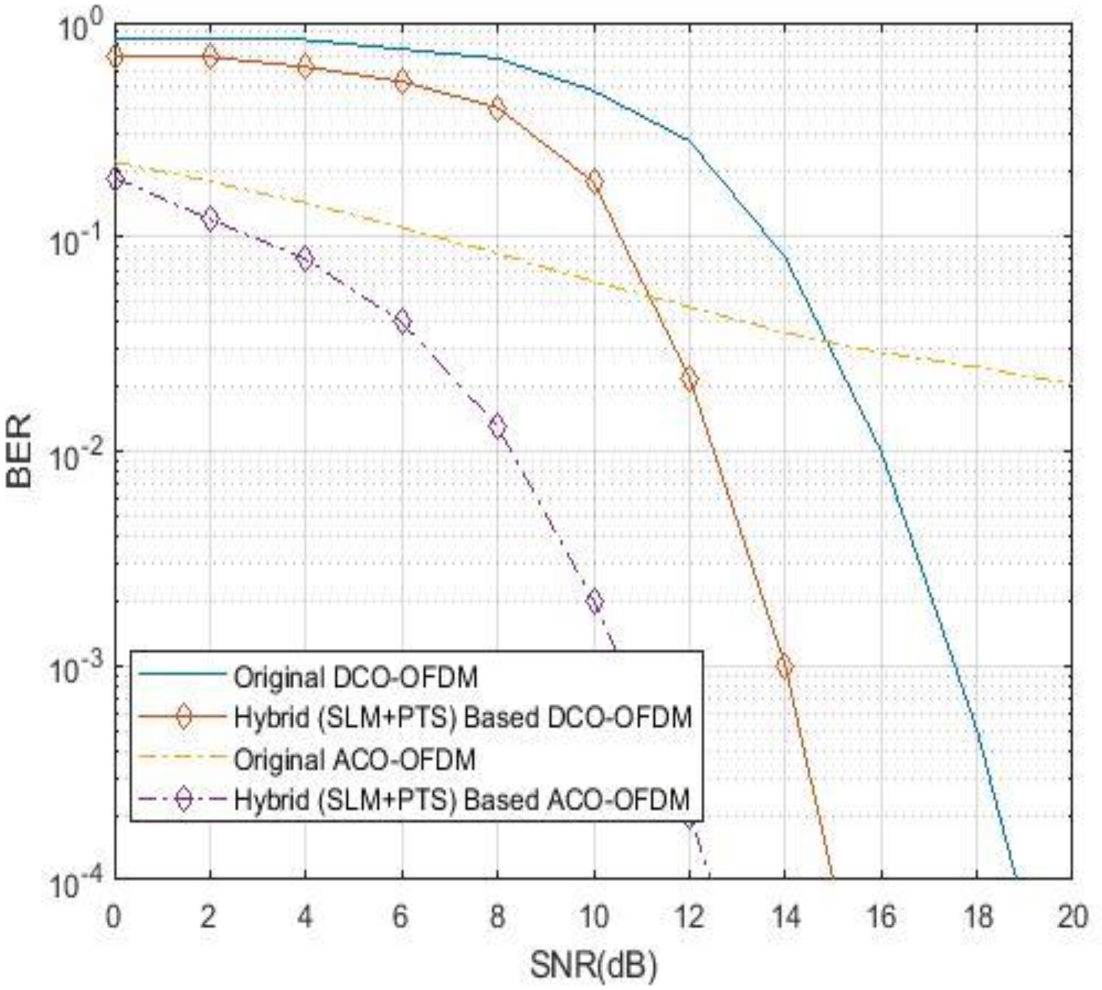

Figure 23: BER vs. SNR of ACO and DCO-OFDM with
Hybrid SLM+PTS Technique

It can be observed that for ACO-OFDM it requires 10.3 dB of SNR to achieve BER of 10^{-3} and the same BER can be achieved by expensing 14.1 dB of SNR in case of DCO-OFDM with SLM+PTS method

Similarly the CCDF vs. PAPR graph for DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying SLM+PTS method to the OFDM signal. The results are obtained as shown in the Figure 24.

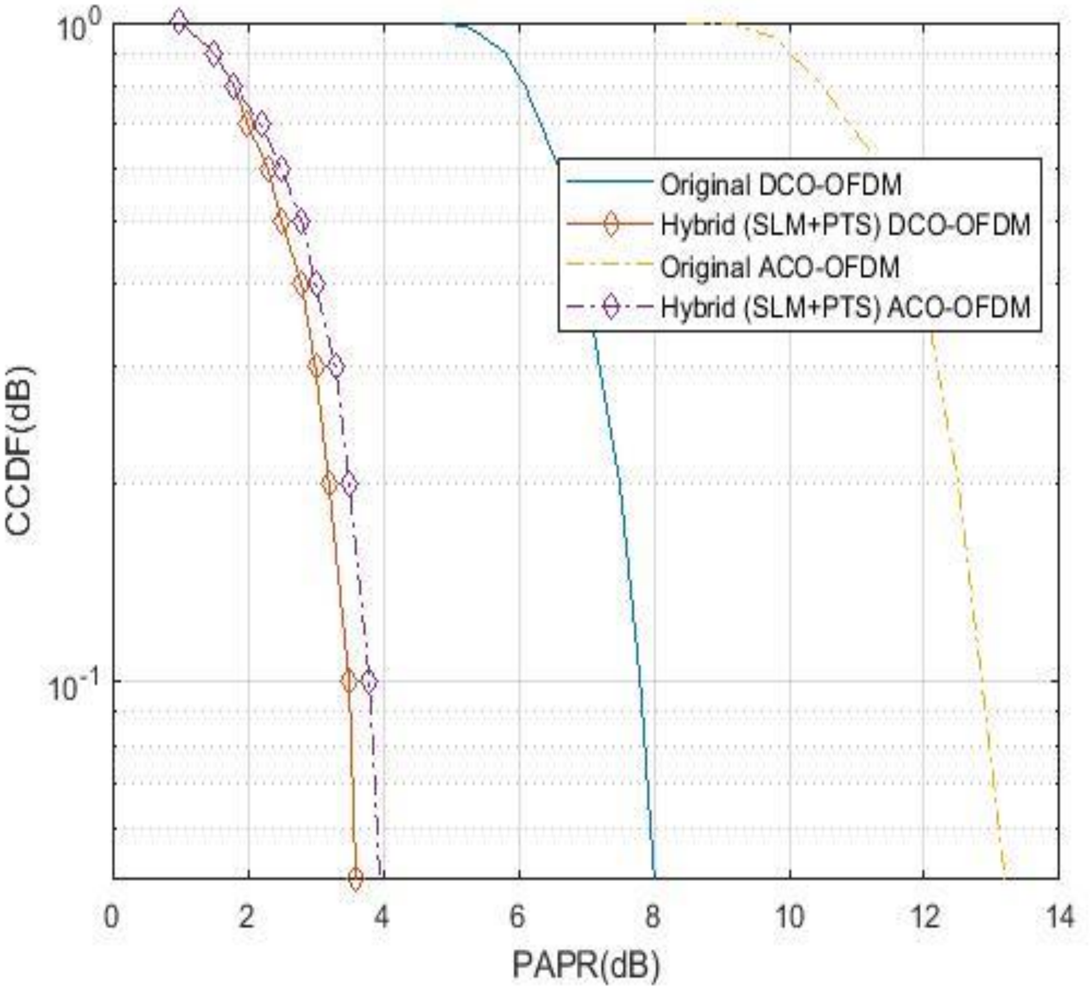

Figure 24: CCDF performance of ACO and DCO-OFDM with
Hybrid SLM+PTS Technique

It can be observed from PAPR vs. CCDF plot that for DCO-OFDM performs 4.6 dB better PAPR performance than original D CO-OFDM. Similarly, for ACO-OFDM 8.8 dB of better PAPR performance than original ACO-OFDM with SLM technique for CCDF of 10^{-1}

5.1.5 DCT Transform with PTS Method

The BER performance of DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying DCT Transform with PTS method to the OFDM signal. The results are obtained as shown in the Figure 25.

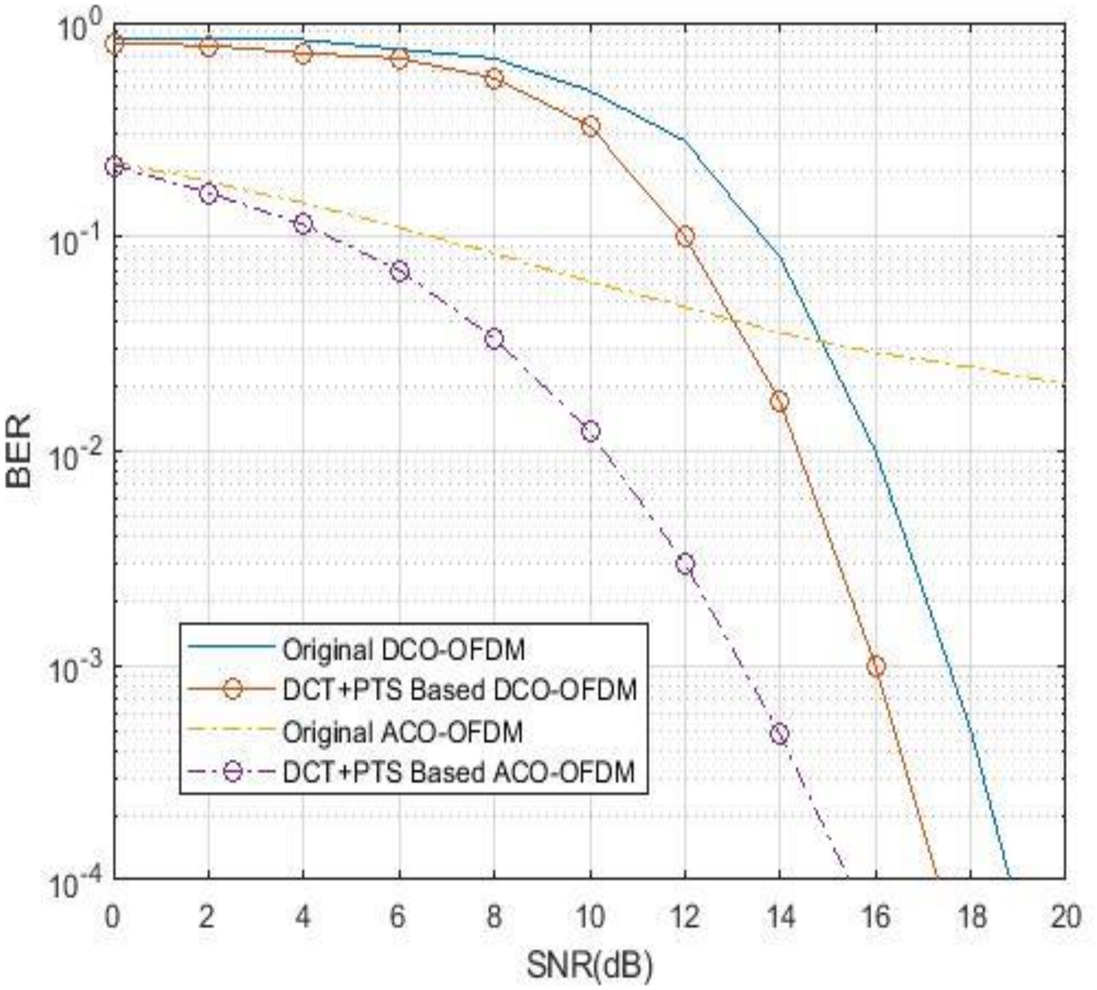

Figure 25: BER vs. SNR of ACO and DCO-OFDM with
DCT Transform with PTS Method

It can be observed that for ACO-OFDM it requires 13.1dB of SNR to achieve BER of 10^{-3} and the same BER can be achieved by expensing 15.9dB of SNR in case of DCO-OFDM with DCT Transform along with PTS method

Similarly the CCDF vs. PAPR graph for DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying DCT Transform to the OFDM signal. The results are obtained as shown in the Figure 26.

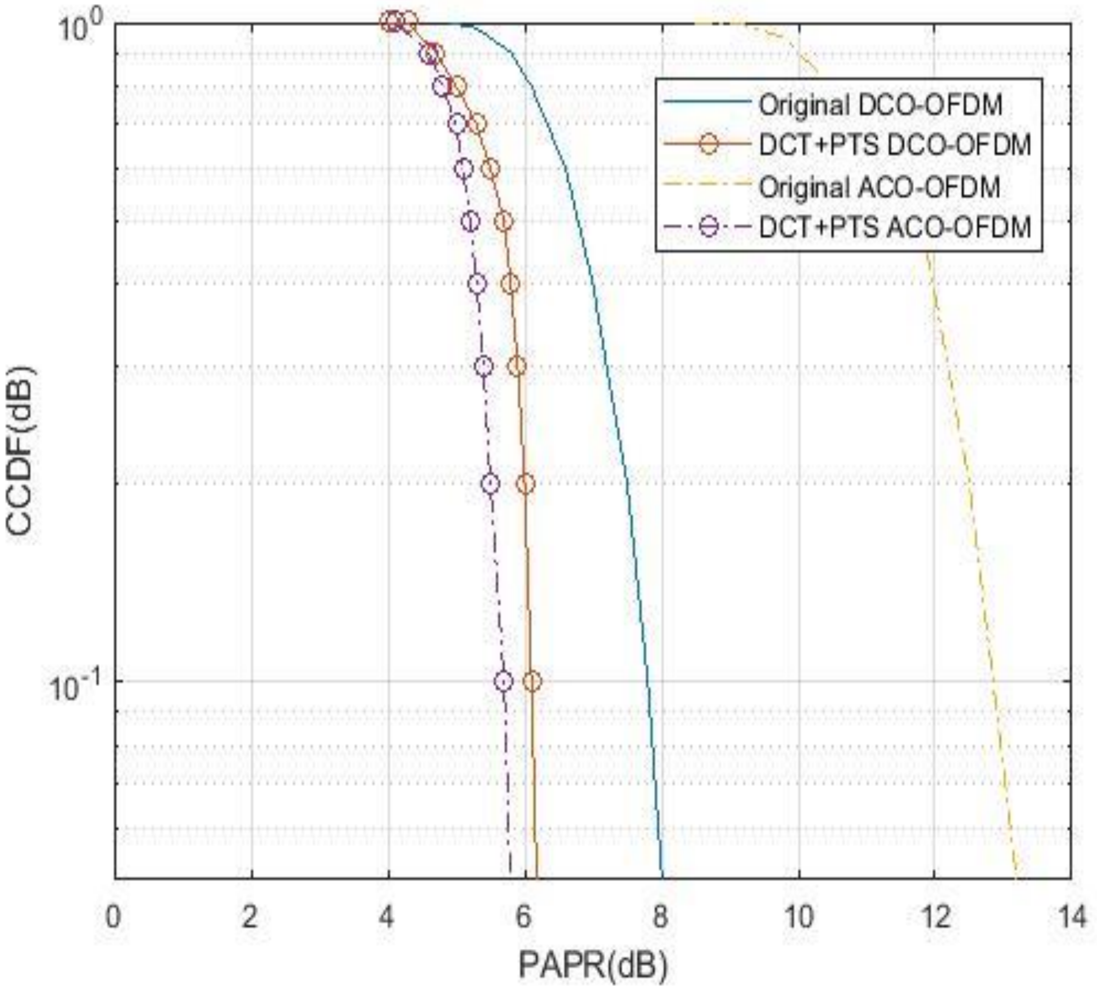

Figure 26: CCDF performance of ACO and DCO-OFDM with
DCT Transform with PTS Method

It can be observed from PAPR vs. CCDF plot that for DCO-OFDM 2.2 dB of PAPR reduction gain than original DCO-OFDM for CCDF of 10^{-1} with DCT Transform along with PTS method and for the ACO-OFDM 6.8 dB of better PAPR performance than original ACO-OFDM with PTS method for same CCDF value.

5.1.6 DCT Transform with SLM Method

The BER performance of DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying DCT Transform with SLM method to the OFDM signal. The results are obtained as shown in the Figure 27.

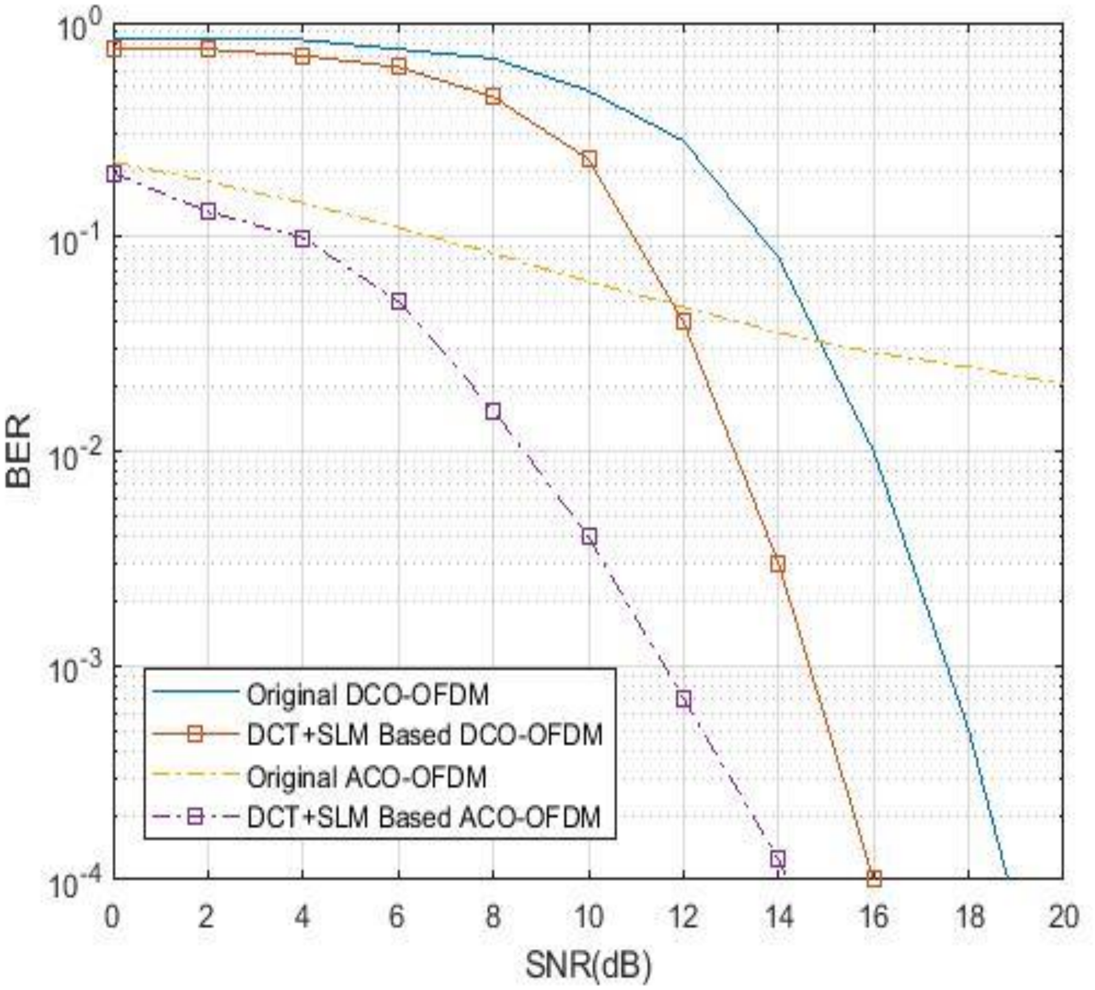

Figure 27: BER vs. SNR of ACO and DCO-OFDM with
DCT Transform with SLM Method

It can be observed that for ACO-OFDM it require 11.7dB of SNR to achieve BER of 10^{-3} and the same BER can be achieved by expensing 14.5 dB of SNR in case of DCO-OFDM with DCT Transform along with SLM method.

Similarly the CCDF vs. PAPR graph for DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying DCT Transform to the OFDM signal. The results are obtained as shown in the Figure 28.

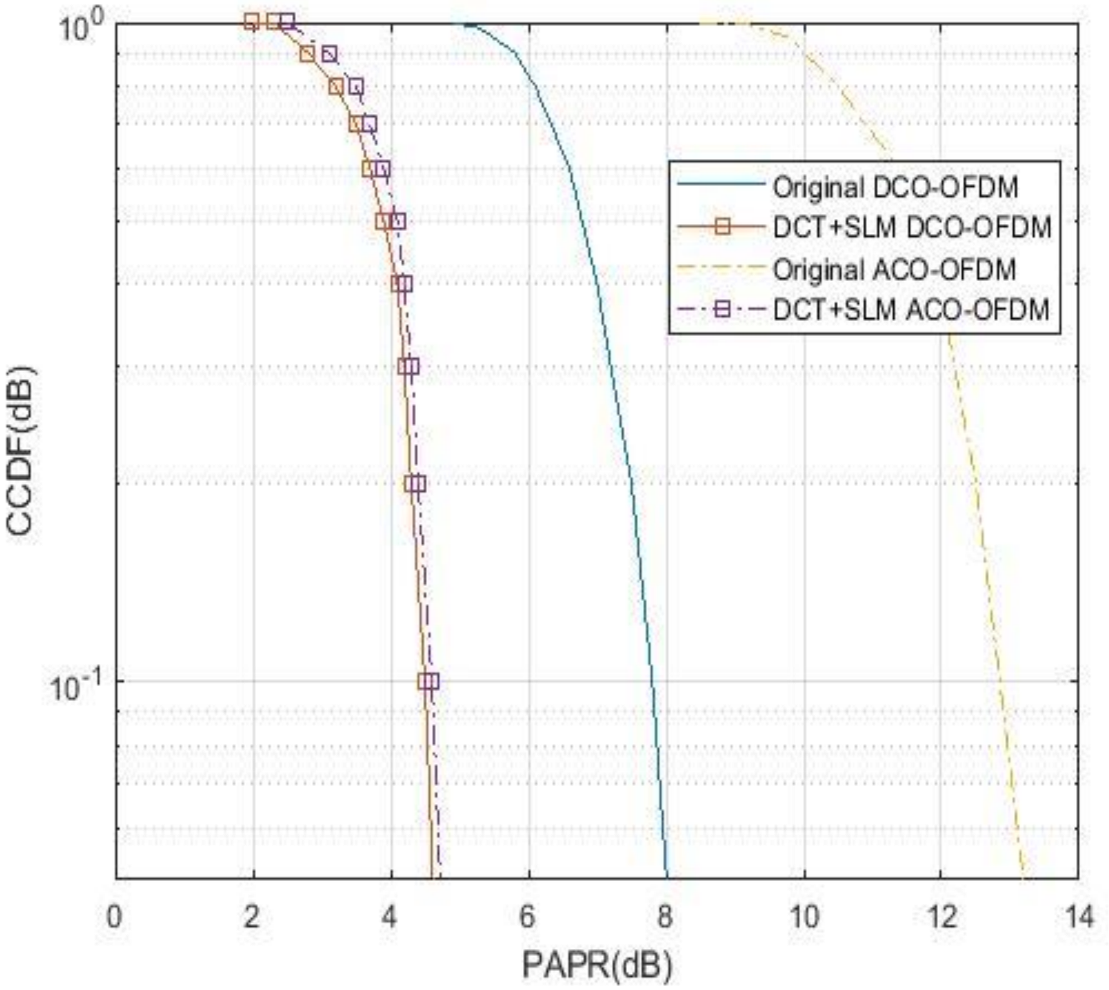

Figure 28: CCDF performance of ACO and DCO-OFDM with
DCT Transform with SLM Method

It can be observed from PAPR vs. CCDF plot that DCO-OFDM performs better PAPR reduction than ACO-OFDM with DCT Transform with PTS method.

5.1.7 DCT Transform with Hybrid SLM + PTS Method

The BER performance of DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying DCT Transform with SLM+PTS method to the OFDM signal. The results are obtained as shown in the Figure 29.

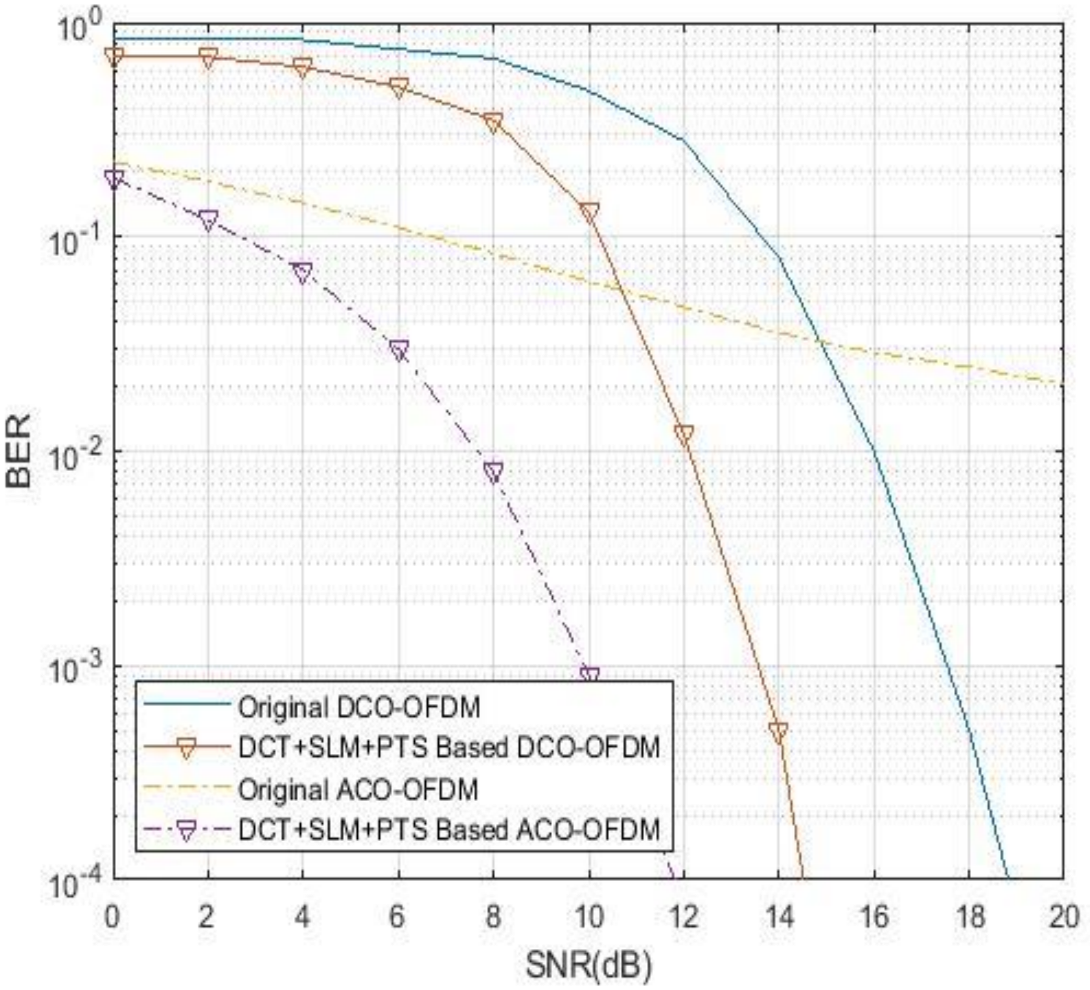

Figure 29: BER vs. SNR of ACO and DCO-OFDM with
DCT Transform with Hybrid SLM+PTS Method

It can be observed that for ACO-OFDM it requires 9.9dB of SNR to achieve BER of 10^{-3} and the same BER can be achieved by expensing 13.8dB of SNR in case of DCO-OFDM with DCT Transform along with SLM+PTS method.

Similarly the CCDF vs. PAPR graph for DCO-OFDM and ACO-OFDM of a VLC system is analyzed by applying DCT Transform with SLM+PTS method to the OFDM signal. The results are obtained as shown in the Figure 30.

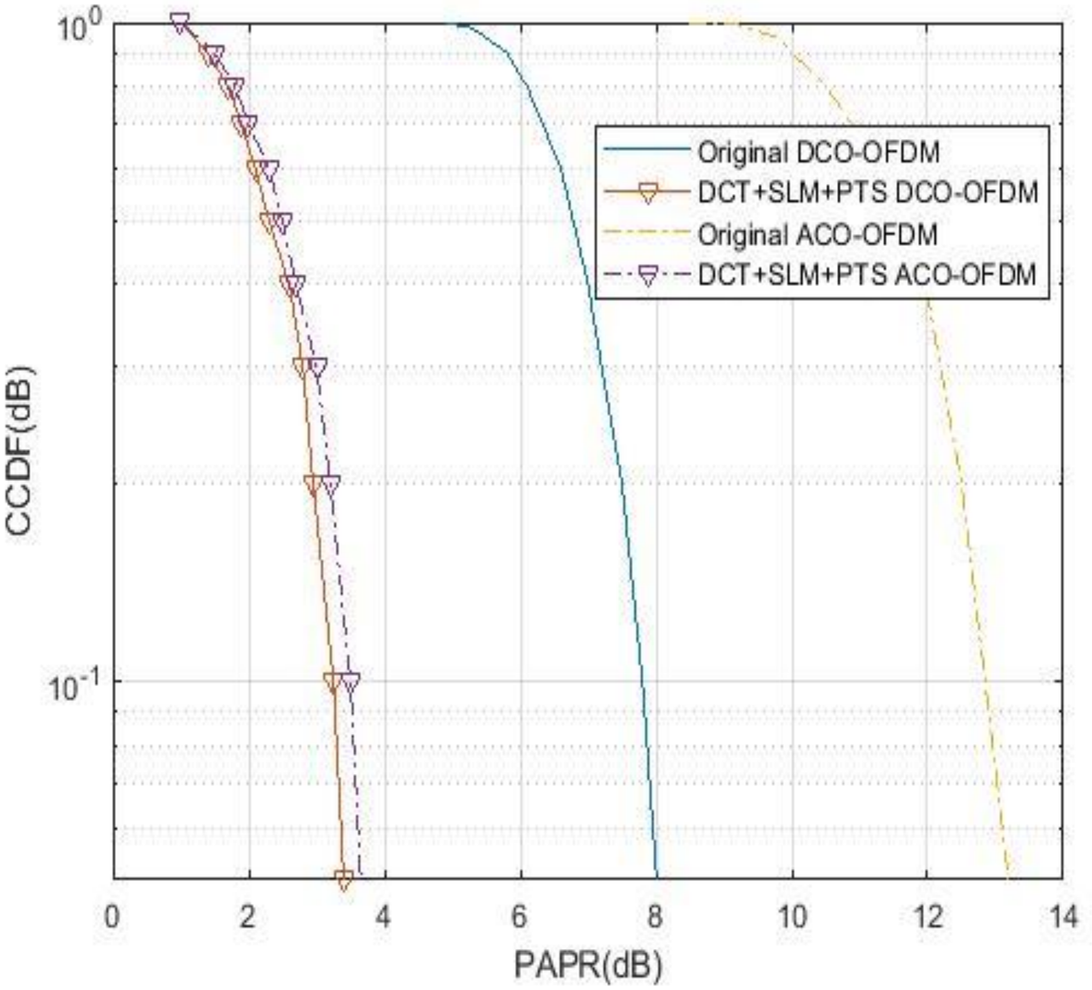

Figure 30: CCDF performance of ACO and DCO-OFDM with
DCT Transform with Hybrid SLM+PTS Method

It can be observed from PAPR vs. CCDF plot that for DCO-OFDM 4.5 dB of PAPR reduction gain than original DCO-OFDM for CCDF of 10^{-1} with DCT Transform along with PTS method and for the ACO-OFDM 9.1 dB of better PAPR performance than original ACO-OFDM with DCT Transform along with SLM+PTS method for same CCDF value.

5.2 Discussion

The BER performance of DCO-OFDM and ACO-OFDM is analyzed for individual method in previous section. From the above results, from the BER versus SNR plot of ACO-OFDM and DCO-OFDM, it can be observed that there is a clear difference between two OFDMs in terms of BER and SNR. It can be seen that the original ACO-OFDM signal has a better BER performance in compare with the original DCO-OFDM signal at lower SNR values due to its power efficiency. For example, to achieve BER of 10^{-3} the ACO-OFDM requires more than 20 dB of SNR but the same BER can be achieved at lesser than 20 dB of SNR for DCO-OFDM. This shows that at higher values SNR, DCO-OFDM outperforms ACO-OFDM. This is because of spectral efficiency of the OFDM signals. But for larger value of SNR, the value of BER for DCO-OFDM decreases. Because a larger DC-bias is used in DCO-OFDM, the nonlinear distortion is reduced, but more power is required. As there is no DC-bias for ACO-OFDM, it has significant advantages in terms of power efficiency. In other words, DCO-OFDM is less efficient in terms of average optical power in lower SNR values but for larger values it is power efficient. It is because the DC bias used in DCO-OFDM is inefficient in terms of optical power. On other hand the use of only half of the subcarriers to carry data in ACO-OFDM, it is inefficient in terms of bandwidth. It can be shown that the PAPR of DCO-OFDM signal can be reduced by using PTS and SLM individually, and PTS and SLM combined as shown in the results in the previous section. It is seen that the PTS technique provides a significant reduction of PAPR and SLM provides much better result than PTS technique. By analyzing PAPR performance graph of ACO-OFDM, it can be concluded that PTS and SLM combined technique of PAPR minimization offer better result than PTS and SLM individually as in case of DCO-OFDM. After combing these two i.e. PTS and SLM it provides excellent reduction of PAPR, making VLC system much more efficient. Though these techniques of PAPR minimization are little bit complex in nature, but they offer better minimization of PAPR in comparison to other techniques like clipping and enhances the PAPR performance of the VLC system in which PAPR can be reduced significantly with acceptable BER performance.

BER and PAPR both can be decreased by applying different techniques such as DCT, SLM and PTS. They are further decreased by applying the hybrid (PTS and SLM) technique. Better results can be obtained both in terms of BER and PAPR performance by combining these two techniques i.e. PTS and SLM along with DCT transform to design efficient VLC system.

PTS and SLM technique with DCT transform for PAPR minimization offer significant reduction of PAPR in both DCO-OFDM as well as in ACO-OFDM. The CCDF performance for these techniques for ACO-OFDM is shown in the results in previous section.

The comparison of BER performance of ACO and DCO-OFDM with different approaches is shown in Figure 31.

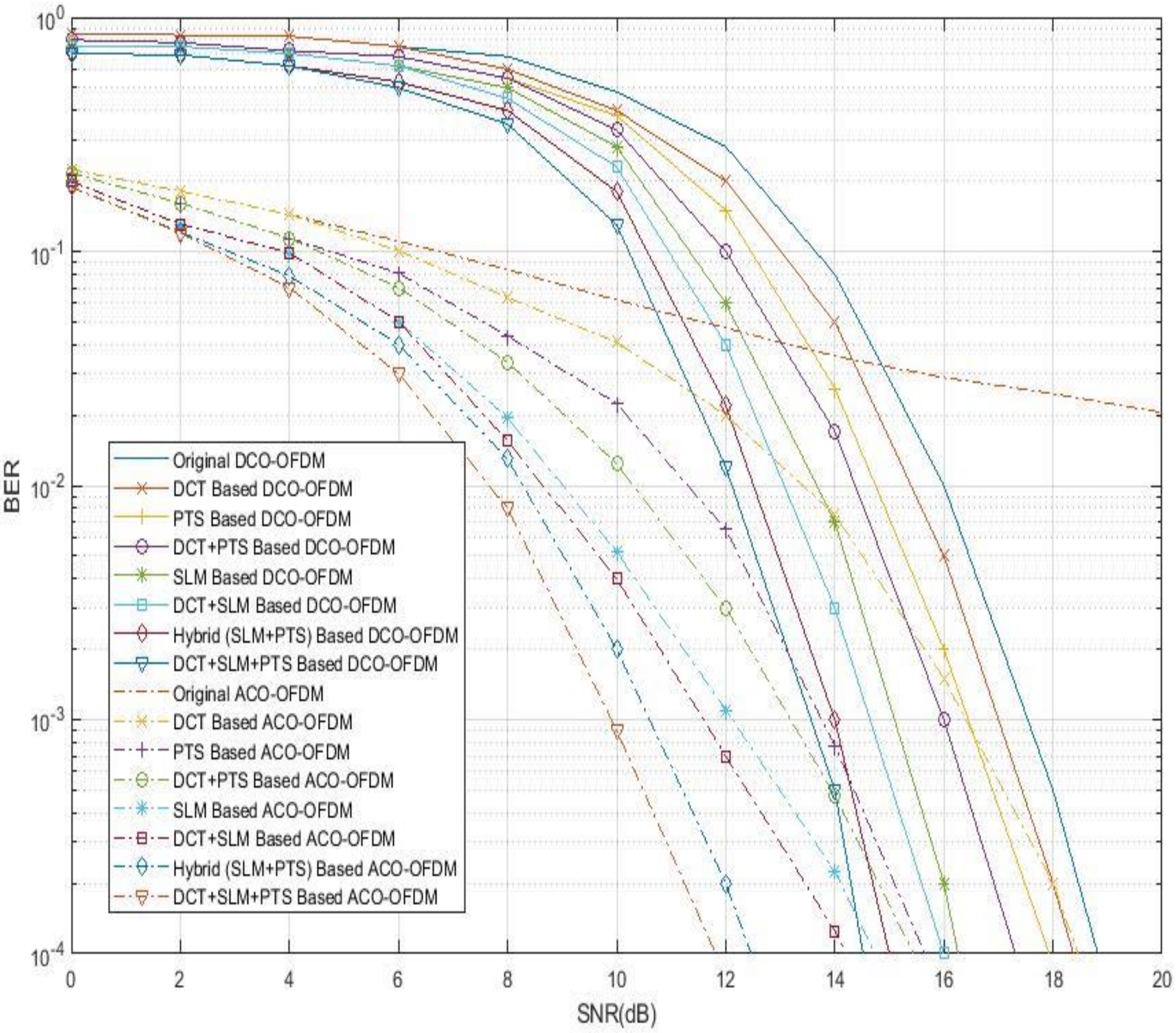

Figure 31: BER performance of ACO and DCO-OFDM with different approaches

The CCDF comparison of ACO and DCO-OFDM with different approaches is shown in Figure 32. It can be seen that DCO-OFDM performs better than ACO-OFDM in terms of PAPR reduction.

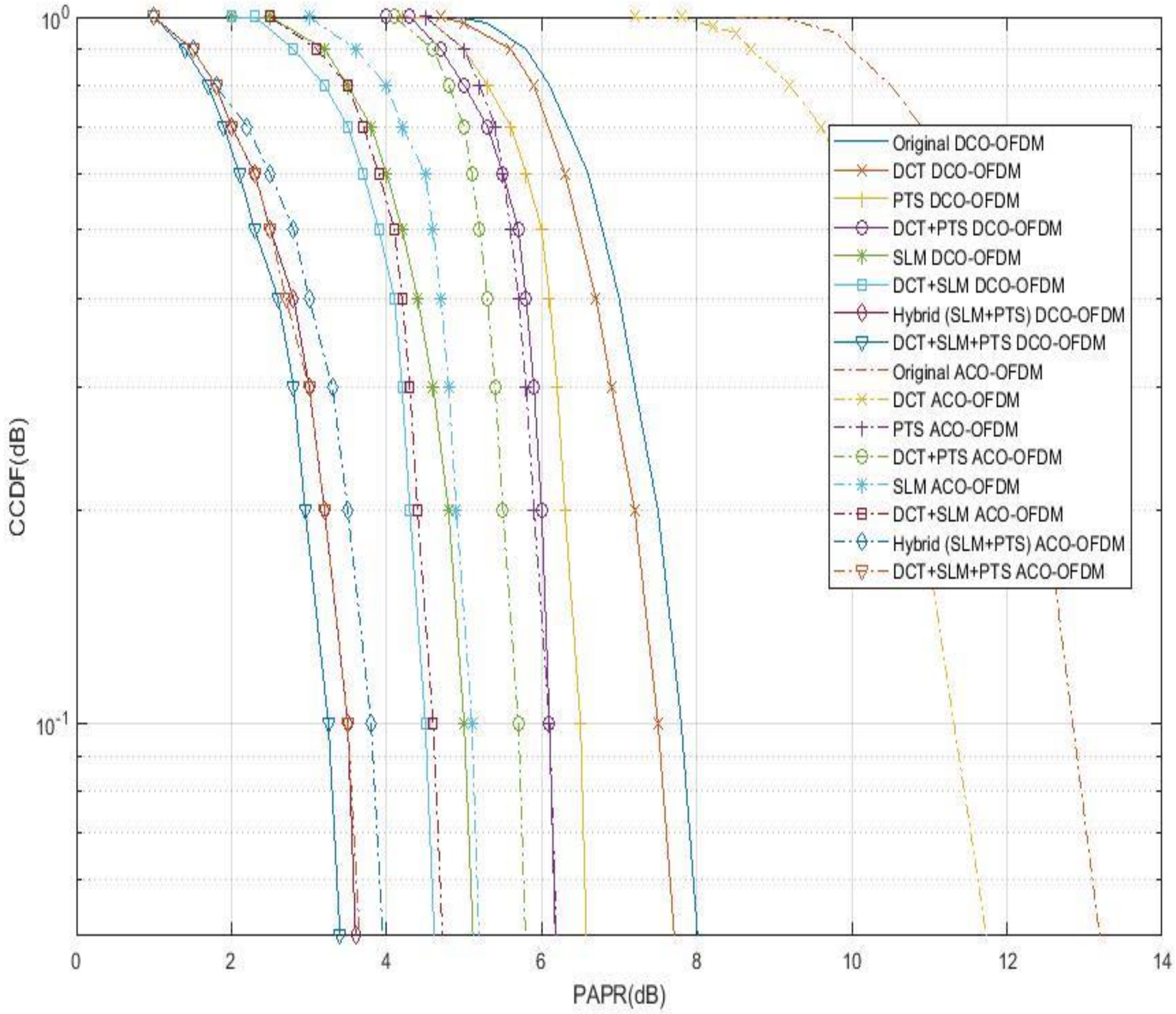

Figure 32: CCDF comparison of ACO and DCO-OFDM with different approaches

The above results shows that though ACO-OFDM performs better in terms of BER performance for each of corresponding method when it is compared with DCO-OFDM; DCO-OFDM has lower PAPR as compared to ACO-OFDM when using PTS and SLM method along with DCT transform.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusions

The performance of PTS and SLM along with DCT transform for PAPR reduction for an optical OFDM-based VLC system is analyzed in this research work. Different methods of reducing the PAPR have been considered here, namely, DCT, PTS, SLM, DCT with PTS, DCT with SLM, PTS and SLM, PTS and SLM with DCT transform. These methods have been applied with DCO-OFDM and ACO-OFDM and compared. PTS and SLM along with DCT transform provides better BER performance for ACO-OFDM than DCO-OFDM. However the PTS and SLM along with DCT transform provide better PAPR reduction gain for DCO-OFDM than ACO-FDM.

The employed technique of SLM and PTS technique along with DCT transform provided a significant reduction in PAPR and better BER performance. However, the complexity offered by combining these techniques is a little bit high, which effects the overall system complexity. This research is only simulated and may provide some degree of deviations when implemented in hardware, which could add some other kinds of hardware limitations.

The techniques employed consist of numbers of complex mathematical calculations resulting in hardware complexity. PTS and SLM techniques also require to transmit side information to the receiver for correct OFDM symbol recovery. However, this also adds to the system complexity and unnecessary overheads. The future work will include the minimization of this system complexity.

REFERENCES

[1] J. S. Lee, Y. W. Su and C. C. Shen, "A Comparative Study of Wireless Protocols:Bluetooth, UWB, ZigBee, and Wi-Fi," in *33rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, 2007.

[2] M. E.-K. ,. M. U. Parvanesh Shams, "MAC layer performance of the IEEE 802.15.7 Visible light communication standard," in *Transactions on Emerging Telcommunications Technologies*.

[3] C. W. ,. C. F.M.Wu, "Performance Comaprision of OFDM Signal CAP Over high Capacity RGB-LED based WDM Visible LIght Communication," in *IEEE Photonics Journal*.

[4] S. Shao, A. Khreishah, M. Ayyash, M. B. Rahaim, H. Elgala, V. Jungnickel, D. Schulz, T. D. C. Little, J. Hilt and R. Freund, "Design and Analysis of a Visible-Light Communication Enhanced Wi-Fi System," *J. opt. communication network,* vol. 7, 2015.

[5] Z. Wang, T. Mao and Q. Wang, "Optical OFDM for Visible Light Communications," *IEEE,* 2017.

[6] G. D. Campo-Jimenez, F. Jose, R. Perez-Jimenez and L. P. d. G. Canaria, "Modulation Schemes Effect on the Driver Efficiency and the Global VLC Transmitter Energy Consumption," *10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP),* 2016.

[7] A. A. Abdulkafi, M. Y. Alias and Y. S. Hussein, "A Novel Approach for PAPR Reduction in OFDM-Based Visible Light Communications," *International Conference on Platform Technology and Service (PlatCon),* 2017.

[8] M. FALL, G. YAN and Z. Zhong, "An integrated Single mode fiber communication and visible light communication system based on OFDM with Hadamard Transform," *15th International Conference on Optical Communications and Networks (ICOCN),* 2016.

[9] B. Yu, H. Zhang, L. Wei and J. Song, "Subcarrier Grouping OFDM for Visible-Light Communication Systems," *IEEE Photonics Journal,* 2015.

[10] Y. Yang, Z. Zeng, J. Cheng and C. Guo, "An Enhanced DCO-OFDM Scheme for Dimming Control in Visible Light Communication Systems," *IEEE Photonics Journal,* 2016.

[11] J. Xu, W. Xu, H. Zhang and X. You, "Asymmetrically Reconstructed Optical OFDM for Visible Light Communications," *IEEE Photonics Journal,* 2016.

[12] Q. Wang, Z. Wang, L. Dai and J. Quan, "Dimmable Visible Light Communications Based on Multi-Layer ACO-OFDM," *IEEE Photonics Journal,* 2016.

[13] T. Zhang, Z. Ghassemlooy, S. Rajbhandari, W. O. Popoola and S. Guo, "OFDM-PWM scheme for visible light communications," *Optics Communications,* 2017.

[14] T. Mao, R. Jiang and R. Bai, "Optical dual-mode index modulation aided OFDM for visible light communications," *Optics Communications,* 2017.

[15] M. Y. A. ,. Y. S. H. Ayad Atiyah Abdulkafi, "Performance Analysis of DCO-OFDM in VLC System," in *IEEE 12th Malasiya International Confrence on Communications(MICC),* Kuching,Malaysia, 2015.

[16] J. Wang, Y. Xu, X. Ling and R. Zhang, "PAPR analysis for OFDM visible light," *Optics Express 27457,* vol. 24, 2016.

[17] Z. Lu, P. Liu and S. Liu, "Experiment of Beneficial Clipping DCO-OFDM Based Visible Light," in *IEEE International Conference on Communication Software and Networks*, 2017.