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Using One-Bit Sigma-Delta Modulator for DCO-OFDM and ACO-OFDM Visible Light Communication System

by

Kobid Karkee

A THESIS

SUBMITTED TO DEPARTMENT OF ELECTRONICS AND COMPUTER ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN INFORMATION AND COMMUNICATION ENGINEERING

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A thesis submitted in partial fulfilment of the requirements for the degree
of Master of Science in Information and Communication Engineering
under the supervision of

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The undersigned certify that they have read and recommended to the Institute of Engineering for acceptance, a midterm thesis entitled “**Using One-Bit Sigma-Delta Modulator for DCO-OFDM and ACO-OFDM Visible Light Communication Systems "** submitted by **Kobid Karkee** in partial fulfilment of the requirements for the degree of “**Master of Science in Information and Communication Engineering”**.

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DEPARTMENTAL ACCEPTANCE

The thesis entitled “Using One-Bit Sigma-Delta Modulator for DCO-OFDM and ACO-OFDM Visible Light Communication Systems” submitted by Kobid Karkee in partial fulfilment of the requirement for the award of the degree of “Master of Science in Information and Communication Engineering” has been accepted as a bonafide record of work independently carried out by him in the department.

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ABSTRACT

Visible light communication based on white light emitting diodes provides optical wireless communication from 400 nm to 700 nm. Simple two-level on-off keying and pulse-position modulation are supported in IEEE standard 802.15.7 due to their compatibility with existing constant current light emitting diode drivers, but their low spectral efficiency have limited the achievable data rates in visible light communication. Orthogonal frequency division multiplexing has been applied to visible light communication due to its high spectral efficiency and ability to combat inter-symbol-interference. Direct current biased and asymmetrically-clipped are modified optical orthogonal frequency division multiplexing for visible light communication. The continuous magnitude of orthogonal frequency division multiplexed signals requires complicated mixed-signal digital-to-analog converter and modification of light emitting diode drivers. In this thesis, a one-bit sigma-delta modulator is introduced to the transmit signal generated by orthogonal frequency division multiplexing which produces two level output to drive the light emitting diodes. Such modification is compatible with the current light emitting diode lighting systems and drivers as the output of the one-bit sigma-delta modulator is equivalent to on-off keying signal, thus is immune to system nonlinearities. The use of sigma-delta modulator retains high spectral efficiency as the original input signal and improves the bit-error performance with respect to signal to noise ratio of the system as well.

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ABBREVIATIONS

ACO	Asymmetrically Clipped Optical
AWGN	Additive White Gaussian Noise
DAC	Digital to Analog Converter
DD	Direct Detection
DCO	DC biased Optical
IM	Intensity Modulation
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter-Symbol Interference
LED	Light Emitting Diode
OFDM	Orthogonal Frequency Division Multiplexing
OOK	ON-OFF Keying
PAM	Pulse Amplitude Modulation
PAPR	Peak-to-Average Power Ratio
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SDM	Sigma-Delta Modulation
VLC	Visible Light Communication

CHAPTER ONE: INTRODUCTION

1.1 Background

Visible light communication (VLC) is a subset of optical wireless communication technologies in which visible light between nearly 400nm to 700nm is used. The problem of congestion in RF spectrum and the development of fast growing solid-state lighting technology are the factors which have led to the development of VLC. VLC has provided a new direction of research for its potential to complement conventional RF communication. VLC uses white light emitting diodes (LEDs) for communication and illumination simultaneously with data rates up to 1Gbps [1]. The benefits of VLC includes, but not limited to, “piggyback” on existing illumination infrastructure, utilization of license-free spectrum, low cost front-ends, more security (visible light cannot penetrate wall), no electromagnetic interference, and being safe for human.

In visible light communication systems, white LED is utilized to simultaneously transmit information and illuminate. By definition of VLC humans can perceive the light through eyes but cannot see the data. Short-range wireless optical communication using visible light is defined by IEEE standard 802.15.7.

Intensity modulation (IM) is used at the transmitter side. The forward electric data signal drives the LED which converts the magnitude of the input electric signals into optical intensity. The human eye cannot perceive fast-changing variations of the light intensity, and only respond to the average light intensity. Direct detection (DD) is employed at the receiver. A photodiode transforms the received optical intensity into the amplitude of an electrical signal. Figure 1.1 shows the concept of intensity modulation and direct detection. Since the visible spectrum is of dispersive nature, orthogonal frequency division multiplexing (OFDM) has been applied to VLC due to its high spectral efficiency and ability to combat inter-symbol-interference (ISI) [2].

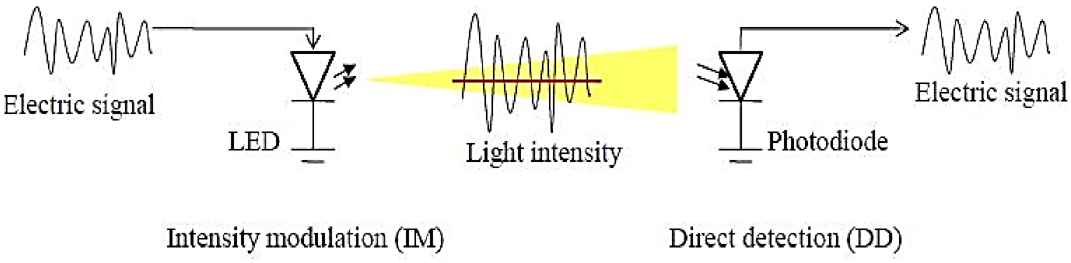

Figure 1.1: Intensity modulation and direct detection in VLC

1.2 Photodiodes

Photodiodes are solid-state devices that are used to perform the optical to electrical conversion. They produce an output electrical current, *y(t)*, proportional to the received intensity signal. The received current is then processed to extract the transmitted information.

The key parameter in photodiodes is the responsivity defined as,

$$R = \frac{I_p}{P_p} \qquad \text{…………………….(1.1)}$$

Where *Ip* is the average photocurrent generated and *Pp* is the incident optical power. The photodiode responsivity depends on the physical structure of the photodiode and has the units of ampere per watt (A/W). Two common photodiodes that are currently used in practice are p-i-n photodiodes and avalanche photodiodes. The first type has lower cost but lower modulation bandwidth.

The received power of the photodiode, *Pp*, is proportional to its effective light collection area. Thus, the photodiode effective area must be large enough to collect the transmitted signal. In general, photodiodes must be selected such that the cost, performance and safety requirements are satisfied.

1.3 Light Emitting Diodes

A light-emitting diode (LED) is a semiconductor light source. Two important lighting factors of LEDs are color rendering index and luminous efficacy. The color rendering index is a measure of the ability of the LED to produce color in comparison with an ideal light source. The luminous efficacy on the other hand, is the measure of the efficiency with which the source produces visible light from electricity. It is equal to the ratio of luminous flux to the total electric power consumed by the source. Therefore it has the units of lumen per watt (lm/W).

1.3.1 RGB LEDs

A simple way to form white light is to mix red, green and blue (RGB) colors with appropriate portions as shown in figure 1.2. The LEDs produced in this way are often referred to as RGB LEDs.

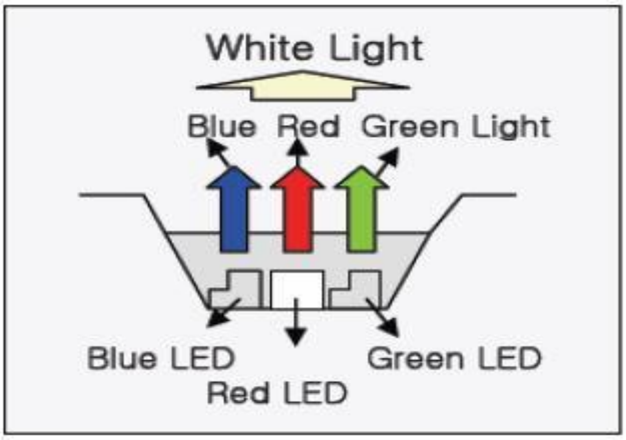

Figure 1.2: The structure of RGB white LEDs

Red-green-blue LEDs have the flexibility of mixing different colors and possess higher luminous efficacy (in excess of 90 lm/W [55]) compared to phosphor-based LEDs discussed in Sec. 1.3.2. However, they are seldom used in practice to produce white light. Other than requiring different color optical sources, RGB LEDs suffer from instability in the produced color. The RGB LED's performance degrades with rising temperature hence leads to a considerable change in the produced color.

1.3.2 Phosphor-based LEDs

This method involves coating a blue LED with a yellow emitting phosphor as shown in figure 1.3. The resulting LEDs are termed as phosphor-based white LEDs. Phosphor-based LEDs have a lower luminous efficacy compared to RGB LEDs (~80 lm/W) due to phosphor-related degradation issues. However, the majority of white LEDs that are currently in use on the market are manufactured using this technology. Apart from the advantage of requiring only a single color source, these types of LEDs are easier to design and are less expensive than complex RGB LEDs.

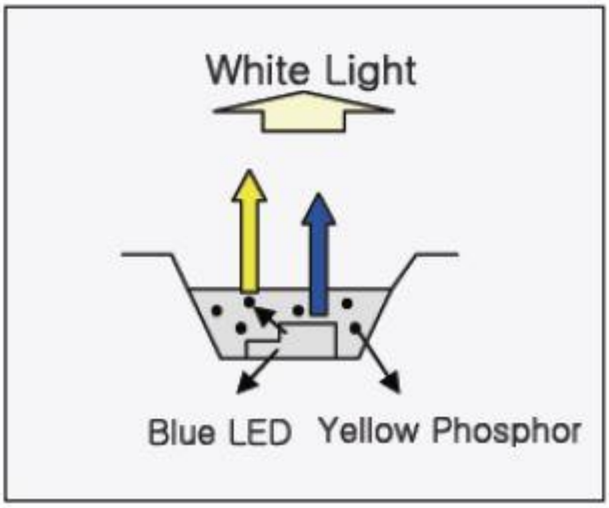

Figure 1.3: The structure of phosphor-based white LEDs

Furthermore, the available modulation bandwidth of such LEDs can be enhanced by at least an order of magnitude using blue filtering. Due to the long decaying time of the phosphor, the modulation bandwidth of the white emission is limited to ~2 MHz. However, the blue component has a larger modulation bandwidth ~20 MHz. As a result, to achieve a higher modulation bandwidth and therefore higher data rates, a common method is to only detect the blue part of the spectrum at the receiver termed as blue filtering.

1.4 Problem Statement

With current LED technology, the modulation bandwidth of the LED, which acts as the transmitter in the VLC system, is limited to a few tens of MHz [1]. In addition, the LED nonlinearity introduces significant distortion to a signal with large PAPR. OOK modulation and variable pulse-position modulation (VPPM), which are two-level modulations, can be applied to avoid nonlinear effects. However, the spectral efficiency with such modulations is not satisfactory. Orthogonal Frequency Division Multiplexing (OFDM) and its variations have been extensively studied in the VLC system for their high spectral efficiency. However, nonlinear distortions of LED can be even more detrimental for such signals with large PAPR [3, 4].

1.5 Objective

- To analyse the performance of DCO-OFDM and ACO-OFDM with and without using a sigma-delta modulator.

CHAPTER TWO: LITERATURE REVIEW

A modulation that efficiently deals with selective fading channels is orthogonal frequency division multiplexing (OFDM). Specifically, it has inherent resistance to dispersion in the propagation channel. Visible channel is dispersive in nature and use of LEDs and photodiodes requires the transmit signals to positive and real valued, i.e. unipolar. In unipolar communication, intensity modulation with direct detection (IM/DD) technique is commonly used for data transmission. However, IM/DD communication is non-coherent and transmit signal must be real and positive. These additional constraints require some special care, if OFDM is to be used in unipolar communications, since the equivalent baseband time-domain OFDM signal is usually complex. Channel dispersion or multipath fading may cause the inter-symbol interference and degrade the performance of such unipolar communication systems. To compensate these effects, unipolar OFDM can be used.

DC-offset OFDM (DCO-OFDM), uses the Hermitian symmetry property with a DC-bias to generate a real and positive time domain signal [6]. However, the DC bias depends on the PAPR of the OFDM symbol. Since OFDM has a high PAPR, the amplitude of the DC bias is generally significant. It was shown by J. Armstrong et al. (2008)showed that the requirement of large DC bias makes DCO-OFDM optically power inefficient and conversely, the use of lower DC bias can lead to frequent clipping of the negative parts of the time-domain signal. This can cause inter-carrier interference and create out-of-band optical power [8].

Asymmetrically clipped optical OFDM (ACO-OFDM) was proposed by J. Armstrong and A.J. Lowery and does not require any DC bias [7]. ACO-OFDM uses odd subcarriers to transmit information symbols, and the negative part of the time-domain signal is clipped. It was shown that this clipping does not distort information symbols in odd subcarriers, although their amplitudes are scaled by half. J. Armstrong et al. compared the performance of ACO-OFDM to other modulation schemes such as on-off keying and DC offset OFDM (DCO-OFDM); and it was shown that ACO OFDM has better power efficiency over optical wireless channels[7, 8, 9].

Orthogonal frequency division multiplexing (OFDM) and its variations have been extensively used in the VLC system for their high spectral efficiency. One of the demerits of OFDM is that it has high PAPR. Current LED technology is inherent with non-linearity. Thus, nonlinear distortions of LED can be detrimental for OFDM signals with large PAPR [3]. To deal with nonlinear effects of the LED, one approach is to linearize the overall system response. H. Elgala et al. (2007) presented a pre-distortion linearization technology to compensate for the LED nonlinearity at the transmitter [4]; while Z. Yu et al. (2014) suggested a post-distortion method to compensate for the LED nonlinearity at the receiver. The later approach is to change the waveform of transmit signal and make it robust or less vulnerable to nonlinearities. OOK and VPPM modulations are such waveforms immune to nonlinear effects. Z. Yu et al. (2014) first proposed to avoid nonlinearities by modulating the input waveform with one-bit SDM. An SDM modulator was used to convert a continuous magnitude OFDM digital signal into a two level analog signal that can directly serve as the input of a LED. This scheme eased the design of the mixed signal DAC and driving circuits, as well as avoids nonlinear distortion due to a high PAPR.

CHAPTER THREE: OFDM IN VISIBLE LIGHT COMMUNICATION

Orthogonal frequency division multiplexing (OFDM) is a multiple subcarrier modulation scheme which has widely been employed in optical wireless system. The advantages of OFDM includes the ability to remove the inter-symbol interference (ISI), the ability to easily adapt to different channels and the ability to remove narrowband interference.

3.1 DCO-OFDM

Figure 3.1 displays the block diagram of an optical wireless communication system using DCO-OFDM. First a higher rate serial data is partitioned into N parallel data streams with lower rates. Each data stream is then mapped on a complex value using QAM or PSK modulation assigned with Hermitian symmetry for reality of the time signal. These complex values are then mapped onto a data vector X.

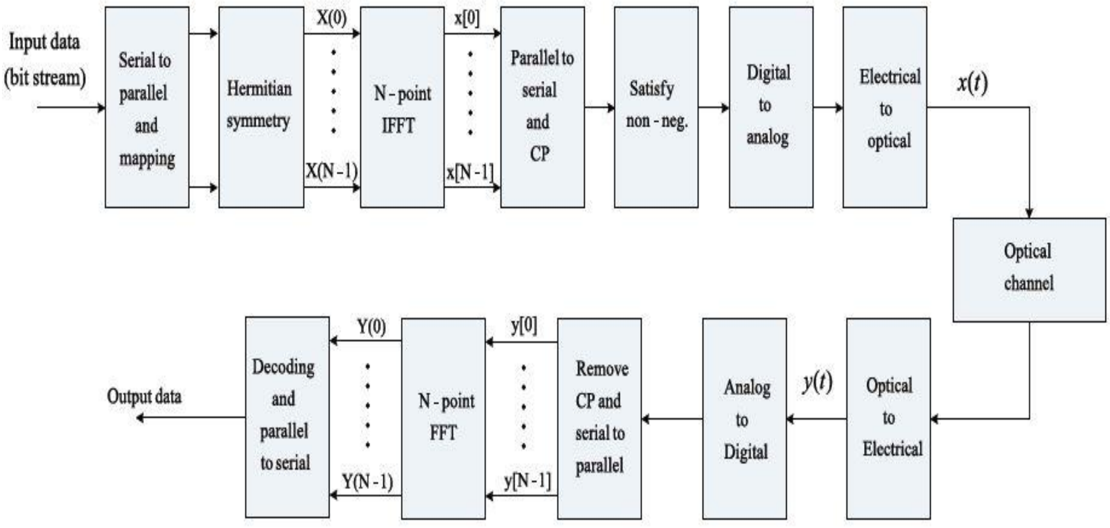

Figure 3.1: Block diagram of an optical wireless system using DCO-OFDM

Let $\{X_k\}_{k=-N/2}^{\frac{N}{2}-1}$ be the frequency domain sequence of an OFDM symbol, where N is the number of subcarriers and Δf is the subcarrier spacing. A Nyquist rate discrete time-domain block x={x_0, x_1,..., x_{n-1}} is generated by applying the inverse FFT (IFFT) operation to a frequency domain sequence as

x_n = IFFT of (X_k) = $\frac{1}{\sqrt{N}}\sum_{k=-N/2}^{\frac{N}{2}-1} X_k e^{j2\pi\frac{kn}{N}}$

n=0, 1..., N-1 ……………………………………..(3.1)

To generate real-valued and positive-baseband OFDM signal, DCO-OFDM was introduced for VLC [2]. From the property of Fourier transform, a real valued time domain signal x_n corresponds to a frequency-domain signal X_k that is Hermitian symmetric, i.e., $X_k = X_{-k}^*$ for $1 \leq k \leq N/2-1$, where * denotes complex conjugate.

The resulting time values are then converted back to serial. Moreover, a cyclic prefix (CP), which consists of the end of the OFDM signal, is transmitted during the guard interval to allow linear convolution of the channel be modeled as circular convolution. However, the time samples are not still appropriate for transmission through the channel and the non-negativity of them must be satisfied. This is done in the block referred to as "Satisfy non-negativity" in figure 3.1. Usually a DC bias is added to the time samples. Hence this technique is termed as DCO-OFDM.

3.2 ACO-OFDM

An alternative to DCO-OFDM is asymmetrically clipped optical OFDM (ACO-OFDM). Figure 3.2 shows the block diagram of ACO-OFDM based optical wireless system:

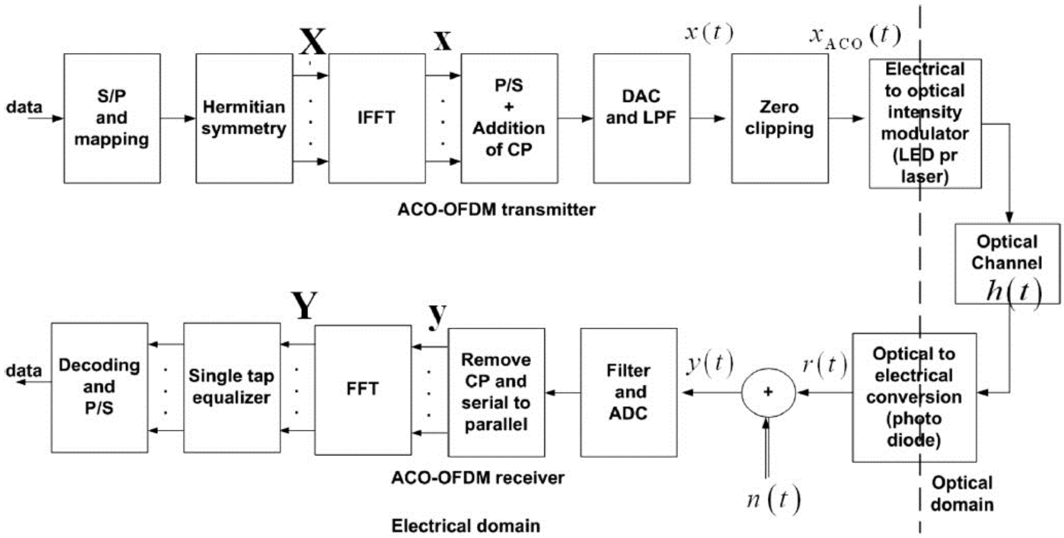

Figure 3.2: ACO-OFDM based optical wireless system

ACO-OFDM uses the properties of the Fourier Transform and asymmetrical clipping to create unipolar signals in time domain. The data are mapped only to the odd subcarriers and then the negative parts are clipped without loss of information [6,7,8].

Assume N to be the number of total subcarriers and $X(k)$ be the complex value of the k^{th} subcarrier assigned with Hermitian symmetry. Consider the case where only odd subcarriers are modulated and the even subcarriers are set to zero:

$X(k) = 0; k\colon even$ ……………………………………………………………….(3.2)

From equation (3.1), the n^{th} time domain sample, $x[n]$, can be found by performing IFFT on the subcarriers. Let the portion of $x[n]$ due to the k^{th} subcarrier be denoted by $x(k, n)$ as,

$x[k,n] = \frac{1}{N} X(k) \exp\left(\frac{j2\pi kn}{N}\right)$…………………………………..……………………..(3.3)

Thus,

$x[n] = \sum_{k=0}^{N-1} x[k,n]$ …………………………………………..……………………..(3.4)

Forming $x[k, n+N/2]$,

$$x[k, n+N/2] = \frac{1}{N} X(k) \exp\left(\frac{j2\pi k(n+\frac{N}{2})}{N}\right)$$

$$= \frac{1}{N} X(k) \exp\left(\frac{j2\pi kn}{N}\right) \exp(j2\pi k)$$

$$= x[k,n](-1)^k \text{………………………………………………(3.5)}$$

It can be seen in equation (3.5) that for k odd, $x[k, n+N/2\,] = -x[k, n]$ which results in,

$x\left[n + \frac{N}{2}\right] = -x[n]$ ……………………………………………………………..(3.6)

This anti-symmetry in time domain leads to the conclusion that clipping the resulting amplitudes at zero level guarantees no loss of information as the data can be recovered from the corresponding positive samples.

However one of the demerits of both ACO-OFDM and DCO-OFDM is the high peak-to-average power ratio (PAPR) i.e.,

$$PAPR\{x_n\} = \frac{\max x_n^2}{\sum_{n=0}^{N-1} x_n^2} \quad \text{……………………………..……………………….......(3.7)}$$

High peak signal values in OFDM result from the superposition of a large number of usually statistically independent sub-channels that can constructively sum up to high signal peaks in the time domain. Therefore, the OFDM signal suffers from significant in-band and out-of-band distortions due to nonlinearities introduced at the transmitter. The in-band component determines the system bit-error ratio (BER) degradation [12], whereas the out-of-band component affects adjacent frequency bands [13].

Owing to the high PAPR, non-linear distortions in the transmission chain can significantly compromise the performance of OFDM as they incur inter-channel interference. The light emitting diode (LED) is the main source for such distortions due to its nonlinear behavior [13]. The non-linear characteristics of LEDs can limit the data transmission performance of the system especially in the case of multiple subcarrier modulation schemes like OFDM [14].

CHAPTER FOUR: METHODOLGY

4.1 System Model

In a visible light communication (VLC) system, the modulation bandwidth of light emitting diode (LED) is limited with current technology. In addition, the nonlinearity inherited in the LED prevents the application of spectral efficient modulation schemes with high peak-to-average power ratio (PAPR). These characteristics limit the overall throughput of the VLC system. In this proposal, a one-bit sigma-delta modulator (SDM) is introduced to the transmit signal. Such modification is compatible with the current LED lighting systems and LED drivers as the output of the one-bit SDM is equivalent to on-off keying (OOK) signal, thus is immune to system nonlinearities [5]. In addition, the output of the one-bit SDM enjoys high spectral efficiency as the original input signal does. The out-of-band quantization noise can be taken care of at the receiver with analog filtering and digital signal processing. Figure 4.1 shows the block diagram of a DCO-OFDM VLC system with sigma-delta modulator.

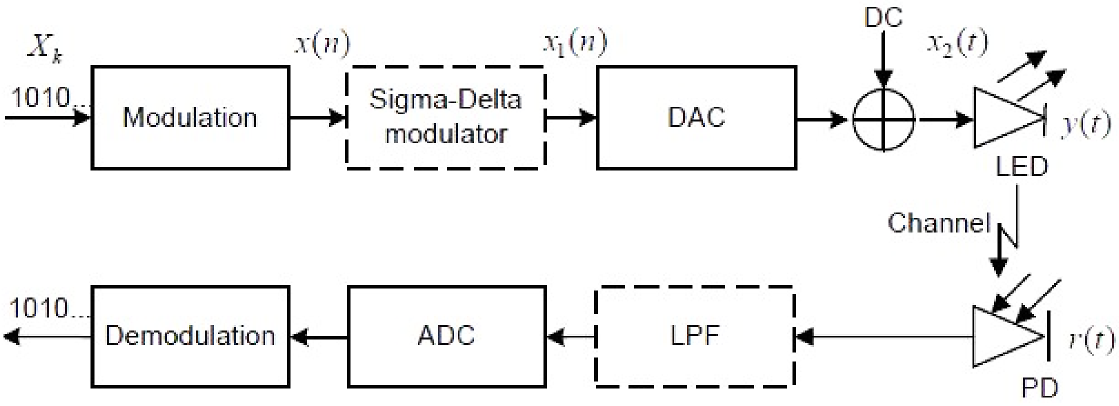

Figure 4.1: Block diagram of DCO-OFDM VLC system with sigma-delta modulator

In the transmit path, information bits are modulated to time-domain signals by the modulation block, which supports OOK, VPPM, pulse amplitude modulation (PAM), OFDM, etc. Then, the modulated signal is converted to analog domain signal by a digital-to-analog converter (DAC). A direct current (DC) bias is necessary to ensure that the LED’s input signal works in the operational region. In the receive path, a photodiode (PD) is utilized to detect the light intensity. The analog signal is sampled by the analog-to-digital converter (ADC) and processed by the demodulation block. In the VLC system, the LED is a nonlinear device. In addition, the modulation bandwidth of the LED is limited. The LED may be modelled as a bandpass filter. The VLC channel is usually considered to be a typical line-of-sight channel with additive white Gaussian noise (AWGN). The baseband equivalent model of the transceiver system can be written as [5]:

$$r(n) = LTI\left(f\big(x(n)\big)\right) + v(n)$$

$$= \sum_{d=0}^{D} \sum_{k=1}^{K} \alpha_d \beta_k x^k (n-d) + v(n) \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.1)}$$

where*r(n)* is the received baseband signal and *v(n)* is the AWGN. In equation (4.1), *K* denotes the highest order of nonlinear terms, *D* denotes the maximum length of delay taps of the LTI system, β_k is the coefficient of nonlinear characteristics, and α_d is the coefficient of the LTI system. The DC bias is dropped out in above representation as it contains no information.

From equation (4.1), for the OOK or VPPM modulation, the input *x(n)* only takes values of -1 and 1. The nonlinear distortion does not show up in the expression. It can be concluded that the OOK or VPPM modulations are immune to the nonlinear distortion. On the other hand, the spectral efficiency of the OOK or VPPM modulation is 1 bit per symbol, which limits the overall throughput of the VLC system [5]. To improve the spectral efficiency, high-order modulations, such as PAM, OFDM signals can be applied.

OFDM signals are in general bipolar signals and have both negative and positive amplitudes. One common method that can be used to guarantee non-negativity of the transmitted signal, is to add a DC bias to the bipolar OFDM signal. The required DC bias to satisfy non-negativity is equal to the maximum negative amplitude of the OFDM signal. Another method that has been employed suggests adding a DC bias equal to twice the standard deviation of the bipolar OFDM signal and clipping the resulting amplitudes at the zero level. This method requires less DC bias, however, it suffers from the distortion caused from the clipping noise.

ACO-OFDM uses the properties of the Fourier Transform and asymmetrical clipping to create unipolar signals in time domain. The data are mapped only to the odd subcarriers and then the negative parts are clipped without loss of information. Figure 4.2 shows the block diagram of ACO-OFDM VLC system using SDM.

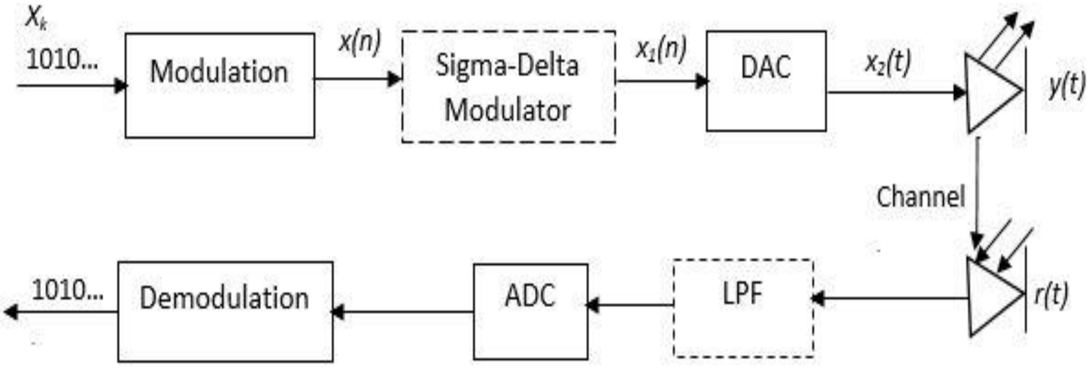

Figure 4.2: Block diagram of ACO-OFDM VLC system with sigma-delta modulator

In this thesis, the signals generated from DCO-OFDM and ACO-OFDM are subjected to sigma-delta modulation which converts the signals into two level signal. The two level signal after proper biasing condition drives the led which converts into optical energy through intensity modulation. At the receiver side direct detection is employed which results in optic-electric conversion. The demodulation for SDM modulated signals is simply by passing through a low-pass filter which is easy to implement.

4.2 Sigma-Delta Modulator

A block diagram of sigma-delta modulator is shown in the figure 4.3. The SDM along with a DAC and interpolator is sigma-delta DAC.

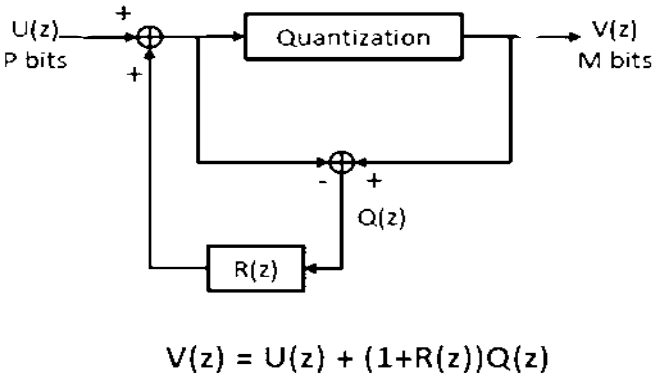

Figure 4.3: Block Diagram of sigma-delta modulator

The block of sigma-delta DAC is shown in figure 4.4:

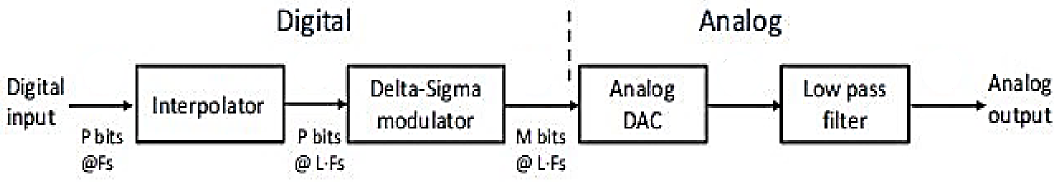

Figure 4.4: Block diagram of sigma-delta DAC

The interpolator in sigma-delta DAC oversamples the signal at the input having sampling rate F_s with an oversampling factor of L. Then the delta-sigma modulator converts the digital signal with 2^P levels into digital signal with 2^M levels, M<P. But the high signal to noise ratio is still maintained [5]. The operation of delta-sigma modulator can be expressed in z domain as

$$V(z) = U(z) + (1+R(z))Q(z) \quad \text{……………………………………………}(4.2)$$

where U(z), V(z) and Q(z) are the z-transform of the input, output and the quantisation error respectively. (1+R(z)) is the noise transfer function (NTF) . A mixed signal DAC at the output two level analog output which is passed through the low-pass filter that removes most of the out of band noise power.

CHAPTER FIVE: RESULTS, COMPARISON AND ANALYSIS

For the simulation purposes the modulation bandwidth of the white LED is 1.875 MHz which is that of phosphor-based LEDs [7].

5.1 Simulation of DCO-OFDM

DCO-OFDM is simulated for 4-QAM, 16-QAM, 64-QAM and 256-QAM schemes. Figure 5.1 shows the BER vs SNR comparison for various QAM modulation schemes of DCO-OFDM.

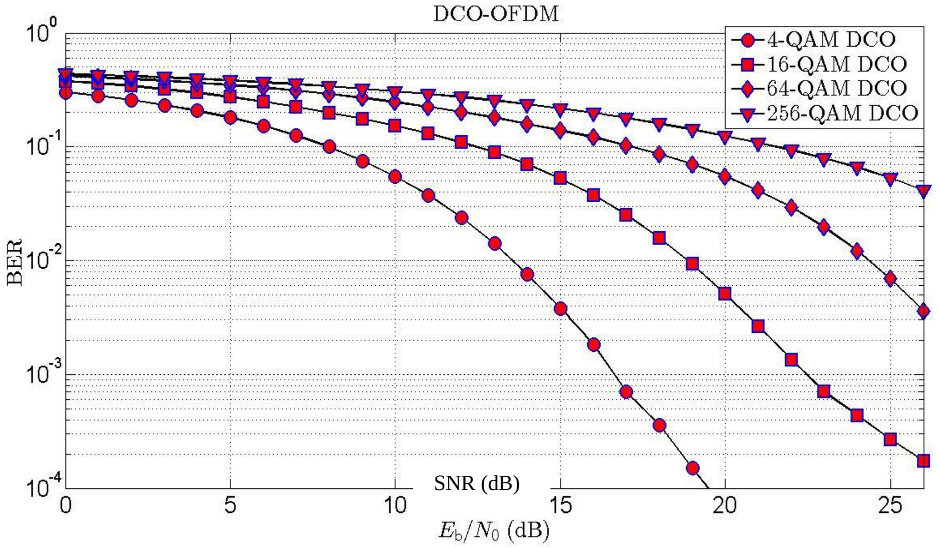

Figure 5.1: BER vs SNR for DCO-OFDM

5.2 Simulation of ACO-OFDM

ACO-OFDM is also simulated for 4-QAM, 16-QAM, 64-QAM and 256-QAM modulation schemes. Figure 5.2 shows the BER vs SNR comparison for various modulation schemes of ACO-OFDM.

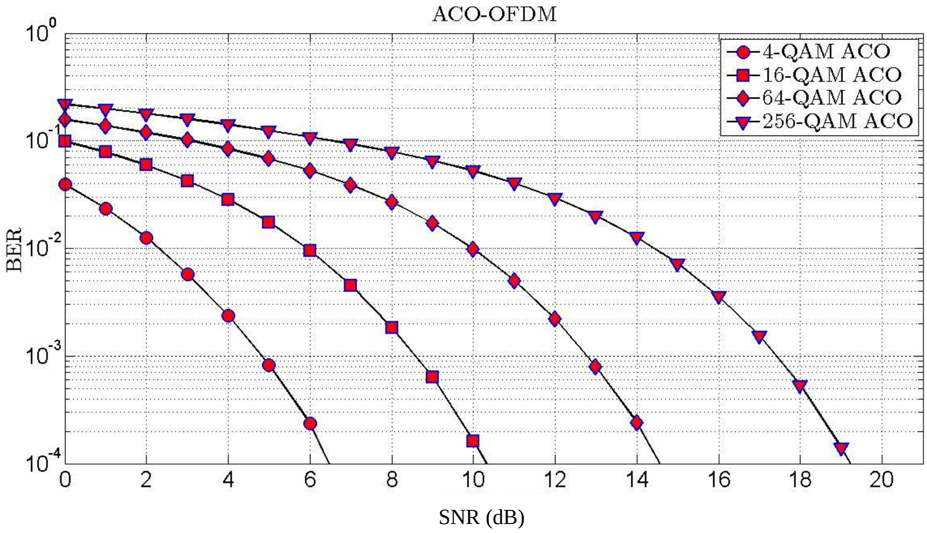

Figure 5.2: BER vs SNR for ACO-OFDM

5.3 Use of Sigma-Delta Modulator for DCO-OFDM

One-bit sigma-delta modulator is applied to the transmit signals for each modulation resulting in two level or 1-bit representation. The two level signal can be then converted into two analog voltages using ADC or simply be used as on-off signal. Figure 5.3 shows the OFDM signal and corresponding sigma-delta modulator output for 4-QAM DCO-OFDM.

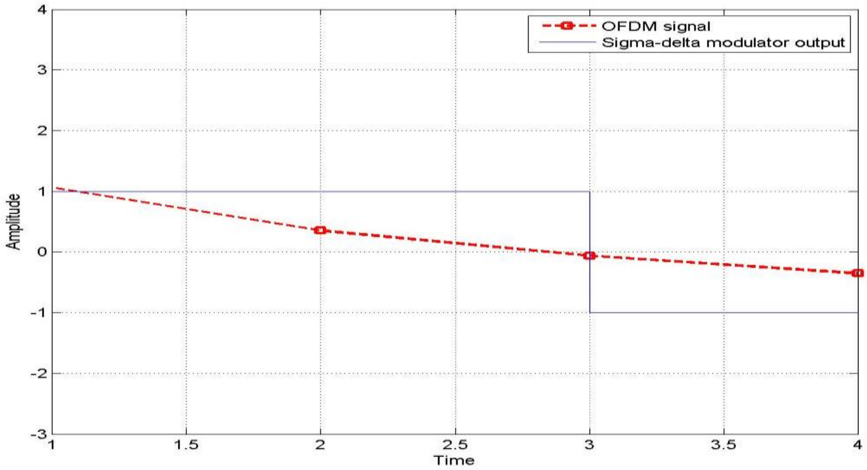

Figure 5.3: Input and output sequence of sigma-delta modulator for 4-QAM DCO-OFDM

Figure 5.4 represents the OFDM signal and corresponding sigma-delta modulator output for 16-QAM DCO-OFDM.

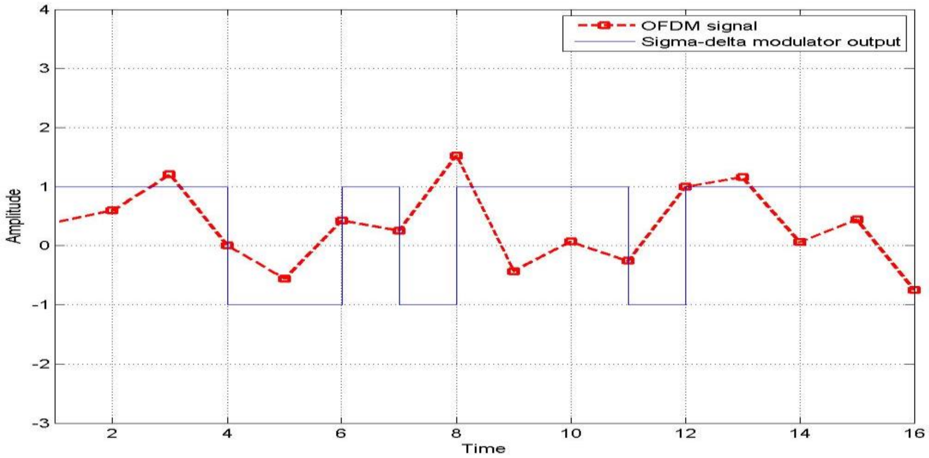

Figure 5.4: Input and output sequence of sigma-delta modulator for 16-QAM DCO-OFDM

Figure 5.5 shows the OFDM signal and corresponding sigma-delta modulator output for 64-QAM DCO-OFDM.

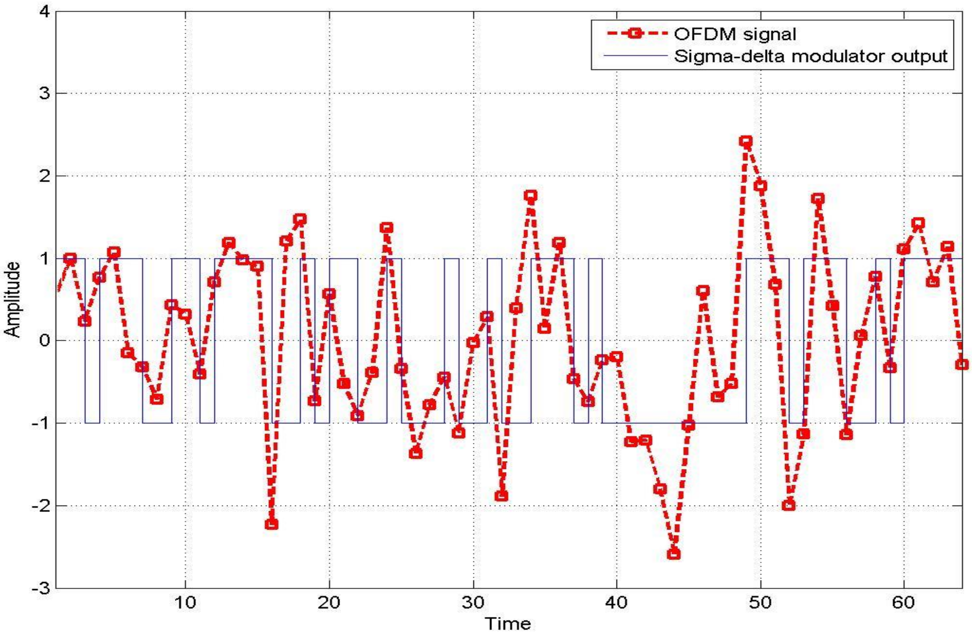

Figure 5.5: Input and output sequence of sigma-delta modulator for 64-QAM DCO-OFDM

Figure 5.6 shows the OFDM signal and corresponding sigma-delta modulator output for 256-QAM DCO-OFDM.

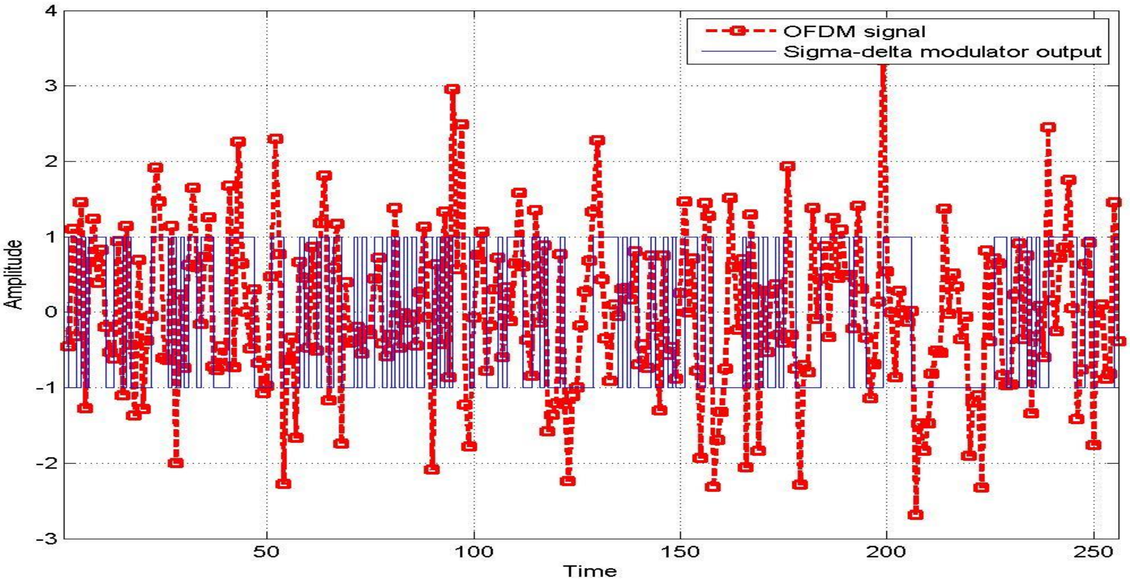

Figure 5.6: Input and output sequence of sigma-delta modulator for 256-QAM DCO-OFDM

5.4 Comparison of DCO-OFDM with and without SDM

Figure 5.7 shows the BER vs SNR for 4-QAM DCO-OFDM with and without using SDM. It is seen from the curve there is noise suppression with the system using SDM.

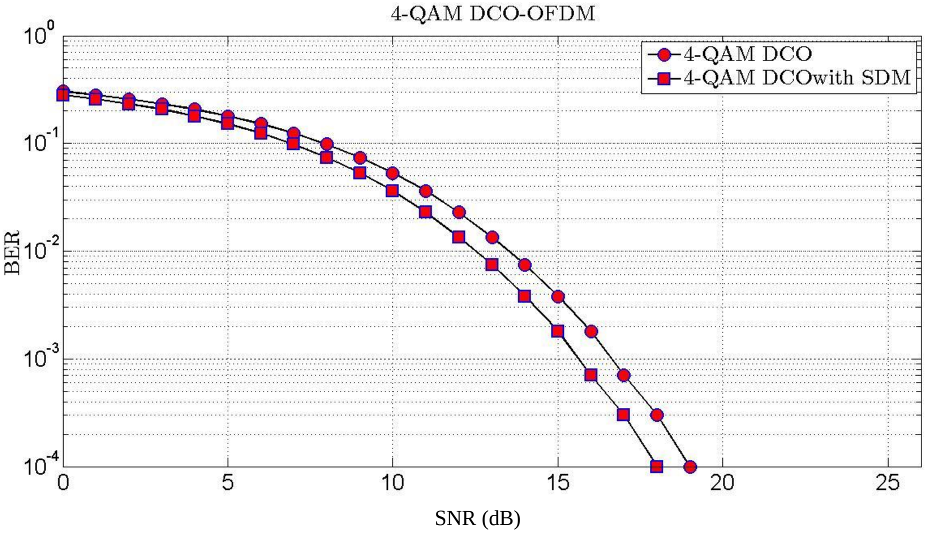

Figure 5.7: BER vs SNR for 4-QAM DCO

Figure 5.8 shows the BER vs SNR for 16-QAM DCO-OFDM with and without using SDM. It is seen that the performance of system without using the SDM is lower than the system using SDM.

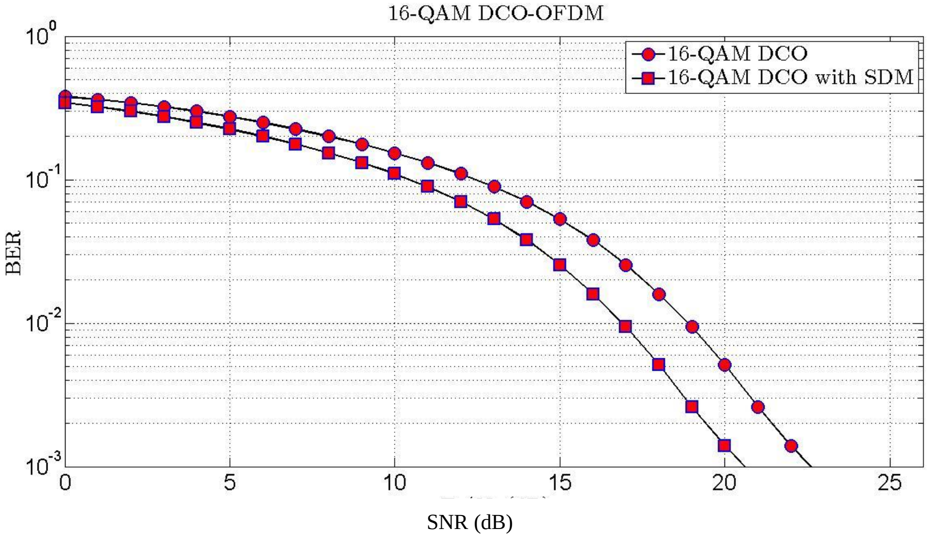

Figure 5.8: BER vs SNR for 16-QAM DCO

Figure 5.9 shows the BER vs SNR for 64-QAM DCO-OFDM with and without using SDM and improvement in the system using SDM is seen.

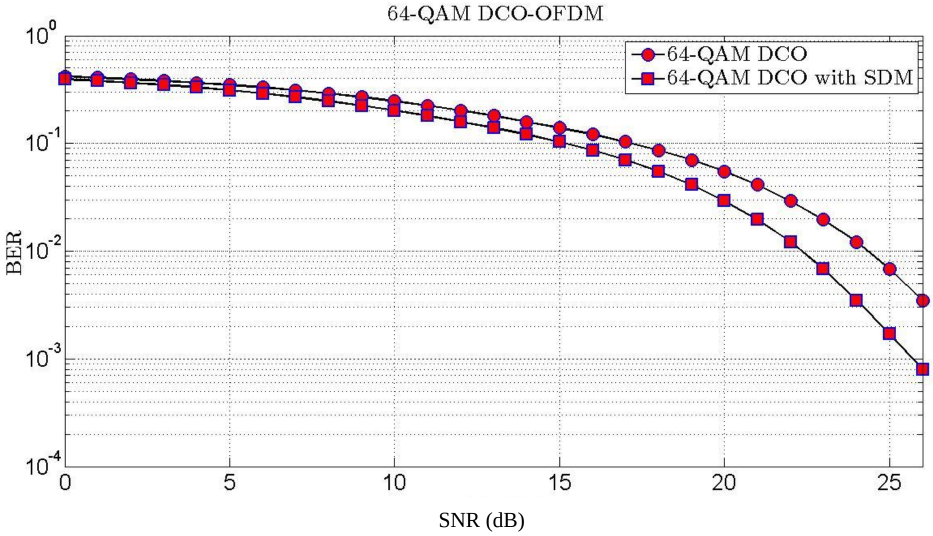

Figure 5.9: BER vs SNR for 64-QAM DCO

Figure 5.10 shows the BER vs SNR for 256-QAM DCO-OFDM with and without using SDM and similar results as in previous cases is obtained.

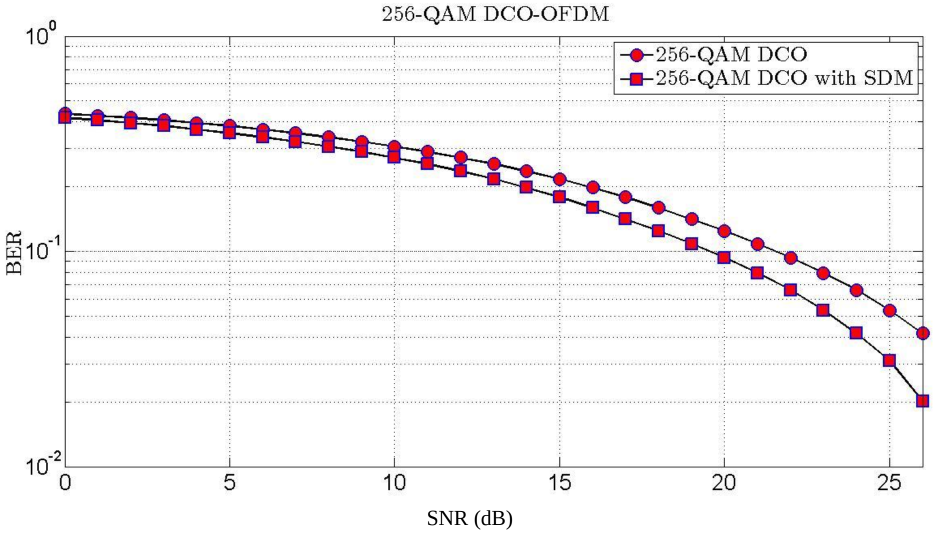

Figure 5.10: BER vs SNR for 256-QAM DCO

5.5 Use of Sigma-Delta Modulator for ACO-OFDM

Figure 5.11 shows the OFDM signal and corresponding sigma-delta modulator output for 4-QAM ACO-OFDM.

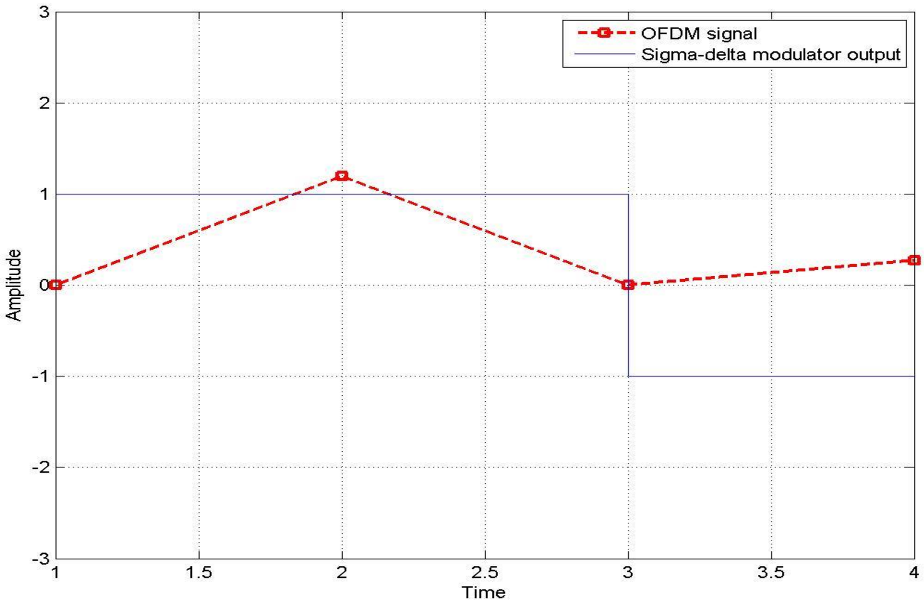

Figure 5.11: Input and output sequence of sigma-delta modulator for 4-QAM ACO-OFDM

Figure 5.12 shows the OFDM signal and corresponding sigma-delta modulator output for 16-QAM ACO-OFDM.

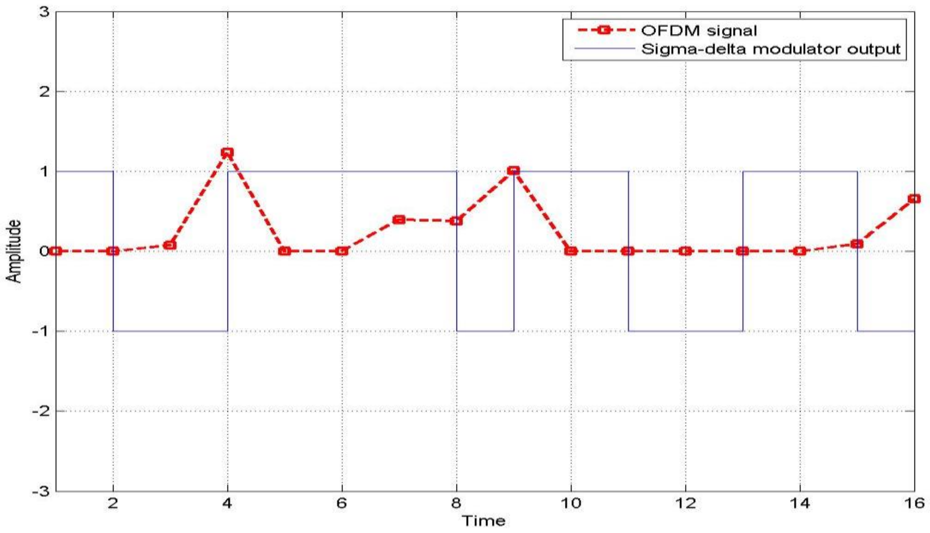

Figure 5.12: Input and output sequence of sigma-delta modulator for 16-QAM ACO-OFDM

Figure 5.13 shows the OFDM signal and corresponding sigma-delta modulator output for 64-QAM ACO-OFDM.

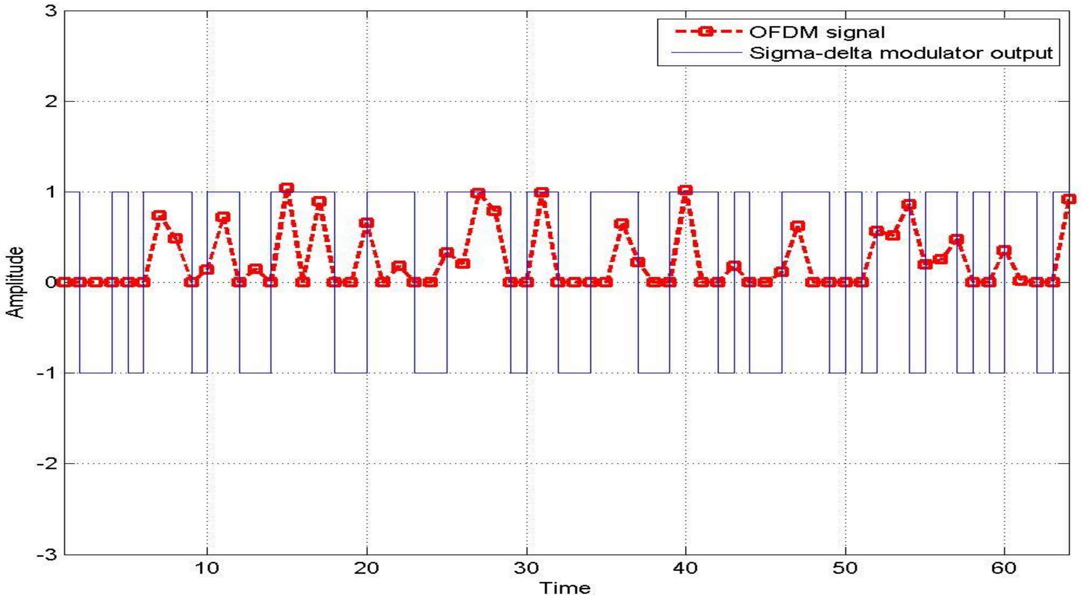

Figure 5.13: Input and output sequence of sigma-delta modulator for 64-QAM ACO-OFDM

Figure 5.14 shows the OFDM signal and corresponding sigma-delta modulator output for 256-QAM ACO-OFDM.

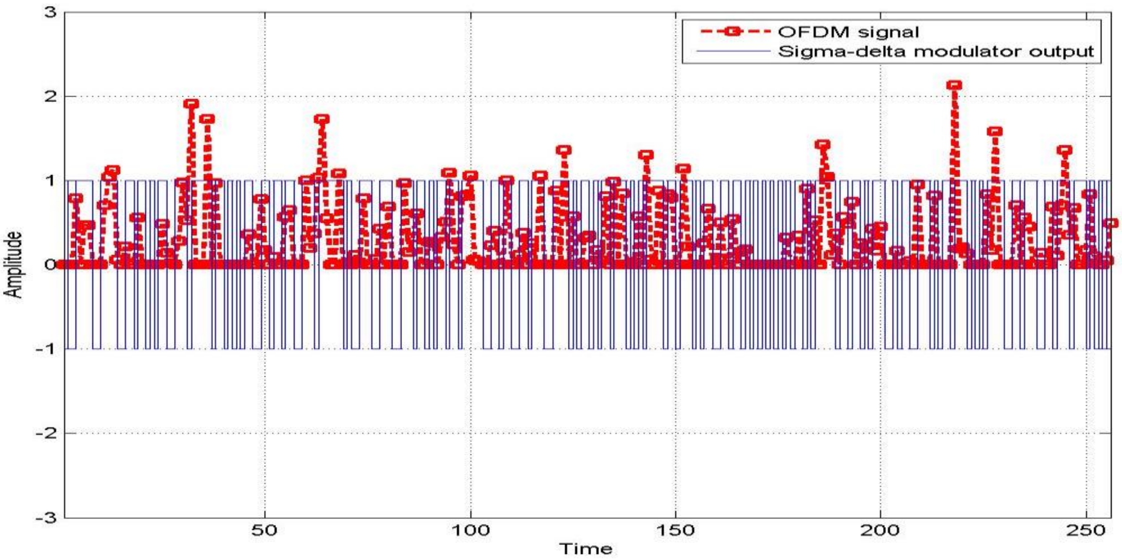

Figure 5.14: Input and output sequence of sigma-delta modulator for 256-QAM ACO-OFDM

The BER performance with respect to SNR is improved by using the SDM at the transmitter side similar to the case of DCO-OFDM.

5.6 Comparison of ACO-OFDM with and without Using SDM

Figure 5.15 shows the BER vs SNR for 4-QAM ACO-OFDM with and without using SDM.

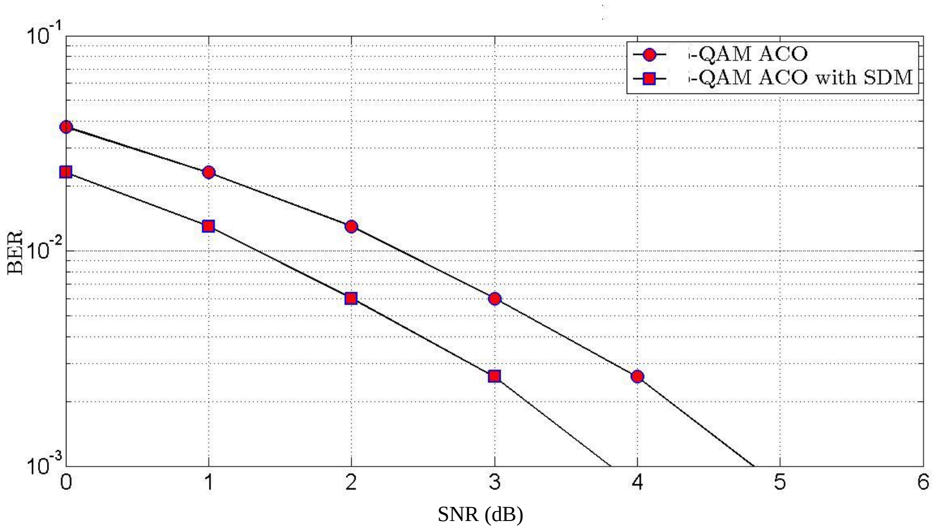

Figure 5.15: BER vs SNR for 4-QAM ACO

Figure 5.16 shows the BER vs SNR for 16-QAM ACO-OFDM with and without using SDM.

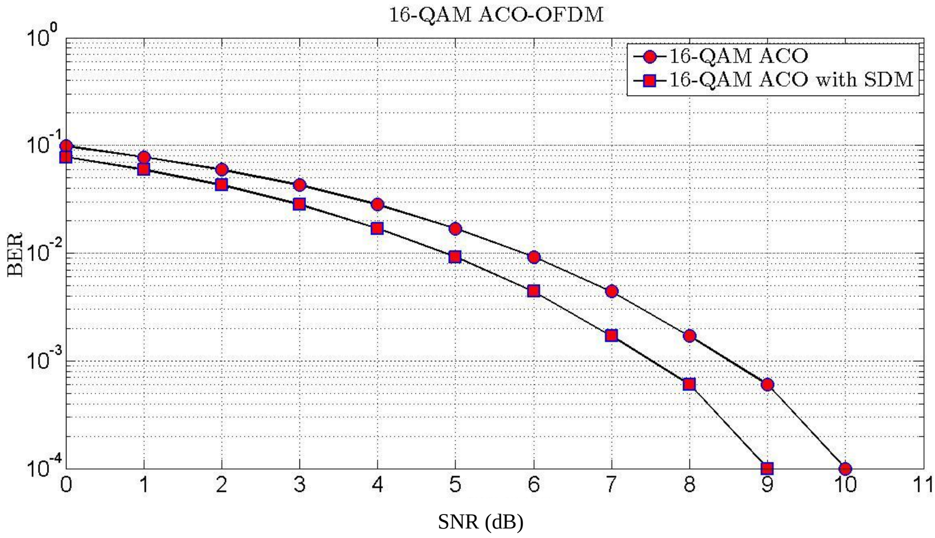

Figure 4.16: BER vs SNR for 16-QAM ACO

Figure 5.17 shows the BER vs SNR for 64-QAM ACO-OFDM with and without using SDM.

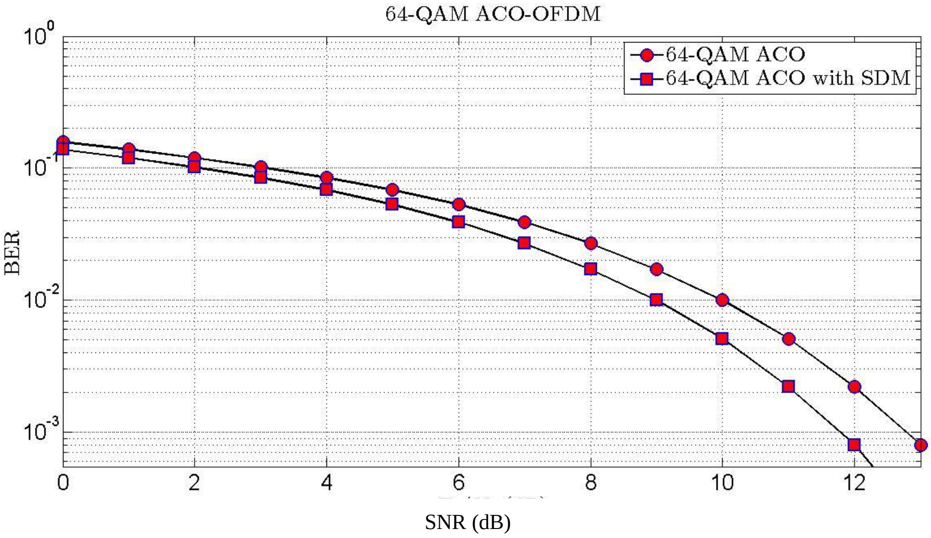

Figure 5.17: BER vs SNR for 64-QAM ACO

Figure 5.18 shows the BER vs SNR for 256-QAM ACO-OFDM with and without using SDM.

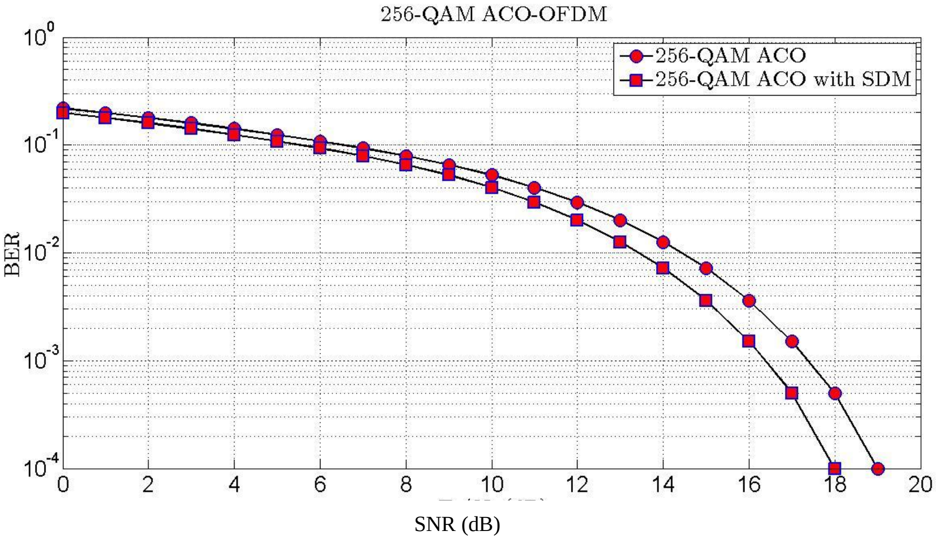

Figure 4.18: BER vs SNR for 256-QAM ACO

From figures 5.15, 5.16, 5.17 and 5.18 it is seen that the use of SDM at the transmitter side improves the performance of the ACO-OFDM system.

5.7 Comparison of Systems in Tabular Form

Table 5.1: Comparison of 4-QAM DCO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.3025	0.2775	8.26
1	0.2815	0.2436	13.46
2	0.2567	0.2302	10.32
3	0.2326	0.2007	13.71
4	0.2064	0.1744	15.50
5	0.1794	0.1498	16.50
6	0.1516	0.1196	21.11
7	0.1242	0.0998	19.65
8	0.0981	0.0724	26.20
9	0.074	0.0514	30.54
10	0.0532	0.0364	31.58
11	0.0363	0.0223	38.57
12	0.0228	0.0136	40.35
13	0.0134	0.0081	39.55
14	0.0075	0.0033	56.00
15	0.0038	0.0014	63.16
16	0.0018	0.0007	61.11
17	0.0007	0.0003	57.14
18	0.0003	0.0001	66.67
19	0.0001	0	-
20	0	0	-

Table 5.2: Comparison of 16-QAM DCO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.3785	0.3637	3.91
1	0.3615	0.3346	7.44
2	0.3423	0.3265	4.62
3	0.3211	0.3013	6.17
4	0.2986	0.2768	7.30
5	0.2747	0.2513	8.52
6	0.2497	0.2253	9.77
7	0.2247	0.2031	9.61
8	0.1999	0.1794	10.26
9	0.1762	0.1566	11.12
10	0.1534	0.134	12.65
11	0.1308	0.1129	13.69
12	0.1097	0.0925	15.68

13	0.0893	0.0733	17.92
14	0.0701	0.0561	19.97
15	0.0529	0.0411	22.31
16	0.0379	0.0286	24.54
17	0.0254	0.0191	24.80
18	0.0159	0.0126	20.75
19	0.0094	0.0083	11.70
20	0.0051	0.0029	43.14
21	0.0026	0.0017	34.62
22	0.0014	0.0007	50.00
23	0.0008	0.0004	50.00
24	0.0004	0.0003	25.00
25	0.0003	0.0002	33.33
26	0.0002	0.0001	50.00

Table 5.3: Comparison of 64-QAM DCO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.418	0.4113	1.60
1	0.4065	0.3985	1.97
2	0.3937	0.3844	2.36
3	0.3796	0.369	2.79
4	0.3642	0.3524	3.24
5	0.3476	0.3345	3.77
6	0.3297	0.3155	4.31
7	0.3107	0.2952	4.99
8	0.2904	0.2739	5.68
9	0.2691	0.2516	6.50
10	0.2468	0.229	7.21
11	0.2242	0.2065	7.89
12	0.2017	0.1845	8.53
13	0.1797	0.1636	8.96
14	0.1588	0.1441	9.26
15	0.1393	0.1255	9.91
16	0.1207	0.1079	10.60
17	0.1031	0.0911	11.64
18	0.0863	0.075	13.09
19	0.0702	0.0599	14.67
20	0.0551	0.0461	16.33
21	0.0413	0.034	17.68
22	0.0292	0.0243	16.78
23	0.0195	0.0169	13.33
24	0.0121	0.0084	30.58

25	0.0068	0.0035	48.53
26	0.0035	0.0002	94.29

Table 5.4: Comparison of 256-QAM DCO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.436	0.4283	1.77
1	0.4272	0.4185	2.04
2	0.4174	0.4076	2.35
3	0.4065	0.3959	2.61
4	0.3948	0.3833	2.91
5	0.3822	0.3697	3.27
6	0.3686	0.3552	3.64
7	0.3541	0.34	3.98
8	0.3389	0.3241	4.37
9	0.323	0.3076	4.77
10	0.3065	0.2907	5.15
11	0.2896	0.2734	5.59
12	0.2723	0.2555	6.17
13	0.2544	0.237	6.84
14	0.2359	0.218	7.59
15	0.2169	0.1987	8.39
16	0.1976	0.1794	9.21
17	0.1783	0.1605	9.98
18	0.1594	0.1424	10.66
19	0.1413	0.1254	11.25
20	0.1243	0.1094	11.99
21	0.1083	0.0945	12.74
22	0.0934	0.0805	13.81
23	0.0794	0.0671	15.49
24	0.066	0.0544	17.58
25	0.0533	0.0426	20.08
26	0.0415	0.03	27.71

Table 5.5: Comparison of 4-QAM ACO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.0377	0.0236	37.40
1	0.0231	0.0135	41.56
2	0.013	0.0059	54.62
3	0.006	0.0024	60.00

4	0.0026	0.0008	69.23
5	0.0008	0.0002	75.00
6	0.0002	0	-
7	0.0001	0	-
8	0	0	-

Table 5.6: Comparison of 16-QAM ACO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.0985	0.0791	19.70
1	0.078	0.0654	16.15
2	0.0593	0.0422	28.84
3	0.0426	0.0281	34.04
4	0.0281	0.0173	38.43
5	0.0169	0.0094	44.38
6	0.0092	0.0046	50.00
7	0.0044	0.0012	72.73
8	0.0017	0.0005	70.59
9	0.0006	0.0001	83.33
10	0.0001	0	-
11	0	0	-

Table 5.7: Comparison of 64-QAM ACO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.1579	0.1372	13.11
1	0.1383	0.1184	14.39
2	0.1195	0.1007	15.73
3	0.1018	0.0837	17.78
4	0.0848	0.0675	20.40
5	0.0686	0.0521	24.05
6	0.0532	0.0379	28.76
7	0.039	0.0258	33.85
8	0.0269	0.016	40.52
9	0.0171	0.0089	47.95
10	0.01	0.004	60.00
11	0.0051	0.0016	68.63
12	0.0022	0.0006	72.73
13	0.0008	0.0001	87.50
14	0.0002	0	-
15	0	0	-

Table 5.8: Comparison of 256-QAM ACO-OFDM without using SDM and using SDM

SNR	BER Values		Improvement (Percentage)
	Without SDM	With SDM	
0	0.2179	0.1991	8.63
1	0.1985	0.1797	9.47
2	0.1791	0.1608	10.22
3	0.1602	0.1425	11.05
4	0.1419	0.1253	11.70
5	0.1247	0.1091	12.51
6	0.1085	0.094	13.36
7	0.0934	0.0797	14.67
8	0.0791	0.0662	16.31
9	0.0656	0.0531	19.05
10	0.0525	0.041	21.90
11	0.0404	0.0301	25.50
12	0.0295	0.0207	29.83
13	0.0201	0.0132	34.33
14	0.0126	0.0078	38.10
15	0.0072	0.0042	41.67
16	0.0036	0.0021	41.67
17	0.0015	0.0001	93.33
18	0.0005	0	-
19	0.0001	0	-
20	0	0	-

5.8 Analysis

A sigma-delta modulator is used to convert continuous magnitude OFDM signal into one-bit or two level analog signal which can directly serve as the input of a LED. The OFDM schemes used are DCO-OFDM and ACO-OFDM. The transmit signals are modified using the SDM. The performance of the systems using the SDM are compared with the performance of the system without using the SDM in terms of BER. 4, 16, 64 and 256-QAM modulations are chosen.

DCO-OFDM uses dc-bias to ensure the input to the LED is always positive. However, the biasing value determined the system performance as high bias required more transmitter power and low bias may result in the clipping noise. ACO-OFDM only uses odd subcarriers and even subcarriers are clipped. This results in half the data rate than DCO-OFDM for same modulation. But ACO-OFDM has better BER performance than the ACO-OFDM.

The results and comparisons in the sections 5.1 through 5.7 show that the BER performance improves by using SDM at the transmit side while utilizing the high spectral efficiency of OFDM systems. The BER vs SNR curves are used to compare the performance of the systems using and not using the SDM. The results are represented in tabular form in section 5.7.

CHAPTER FIVE: CONCLUSION AND FUTURE WORKS

5.1 Conclusion

One-bit SDM can be used at the transmitter side of the VLC OFDM systems in order to modify the input signals to the LED. The continuous magnitude input OFDM signal is converted into one-bit or two level signals using SDM. The two level signals can be mapped into two different voltages and applied to LED. Such type of signaling is similar to OOK and free from high PAPR of OFDM signals. The BER performance of the system also improves by the use of SDM. ACO-OFDM has better optical efficiency than DCO-OFDM in both the systems with and without SDM.

Thus, using one-bit sigma-delta modulator simplifies the input signal to the LED, removes PAPR distortion while still maintaining high spectral efficiency and ability to combat ISI provided by the OFDM systems.

5.2 Future Works

DCO-OFDM has lower optical efficiency than ACO-OFDM but ACO-OFDM has half the data rate than DCO-OFDM for same modulation schemes. There is compromise in each OFDM scheme and use of SDM does not provide improvement. ACO-OFDM only transmit data using odd subcarriers and even subcarriers are clipped to zero. However, further enhancement can be done by using DCO-OFDM to transmit the data in the empty even subcarriers of ACO-OFDM and applying the resulting signal to SDM.

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