YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OPTICAL POWER DISTRIBUTION AND OFDM/OFDMA MODULATION FOR VISIBLE LIGHT COMMUNICATION

M.Sc. Thesis by

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ANKARA

OPTICAL POWER DISTRIBUTION AND OFDM/OFDMA MODULATION FOR VISIBLE LIGHT COMMUNICATION

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"Optical Power Distribution and OFDM/OFDMA Modulation for Visible Light Communication"** completed by **Metin ÖZTÜRK** under supervision of **Assoc. Prof. Remzi YILDIRIM** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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OPTICAL POWER DISTRIBUTION AND OFDM/OFDMA MODULATION FOR VISIBLE LIGHT COMMUNICATION

ABSTRACT

High speed data transmission has become very important in recent years due to increasing data rates. To achieve this high rate data transmission, wireless communication has been a vital solution. Visible light communication (VLC) not only offers high data rates but also reduces the health problems resulted from electromagnetic radiations. In VLC systems, white LEDs are used because of their double-purpose usage; data transmission and illumination.

The focus of this study is two-fold; optical power distribution and OFDM/OFDMA modulation and these studies are performed for visible light communication. First of all, optical power distribution is considered. In order to examine the effects of the optical power distribution, four different layouts, which are designed by locating LEDs on the ceiling, are constructed. Performances of these four layouts are investigated by considering some important parameters such as received minimum and maximum optical powers, number of dead zones, and degree of uniformity. Layout 2 gives the best results among them. Then, half-angle illumination and distance between receiver and transmitter are changed for Layout 2 in order to see the effects of those parameters.

For the second part of the study, 64-QAM OFDM and 64-QAM OFDMA systems are constructed using simulation software. Bit-error rate (BER) performance of these two systems are examined for different optical signal-to-noise ratio (OSNR) values. Results show that these systems can be used for visible light communication. Apart from BER performance, eye diagrams and constellation diagrams also support that these systems are suitable for visible light communication.

Finally, BER performance of four layouts are investigated by setting received optical power to their received minimum optical powers. Layout 2 gives again best results among four layouts.

Keywords: visible light communication, optical power distribution, orthogonal frequency division multiplexing, orthogonal frequency division multiple access, optical communication, laser

GÖRÜNÜR IŞIK HABERLEŞMESİ İÇİN OPTİK GÜÇ DAĞILIMI VE OFDM/OFDMA MODÜLASYONU

ÖZET

Günümüzde, artmakta olan veri oranları dolayısıyla yüksek hızlı data transferi oldukça önemli bir hale gelmiştir. Yüksek orandaki bu data oranlarını karşılayabilmek için, kablosuz haberleşme ciddi bir çözüm olarak karşımıza çıkmaktadır. Görünür ışık haberleşmesi (VLC) yüksek data oranlarını karşılamanın yanında ayrıca elektromanyetik radyasyondan kaynaklanan sağlık problemlerini de azaltaktadır. VLC’de hem aydınlanma hem de data transferi gibi çift amaçlı kullanılabilmesinden dolayı beyaz LED’ler kullanılmaktadır.

Bu çalışmanın odak noktası optic güç dağılımı ve OFDM/OFDMA modülasyon teknikleri olmak üzere iki böümden oluşmaktadır ve bu çalışmalar görünür ışık haberleşme sistemleri için gerçekleştirilmiştir. İlk olarak optic güç dağılımı incelenmiş ve optic güç dağılımının etkilerini gözlemleyebilmek amacıyla LED’lerin tavana yerleşimini gösteren dört farlı dizilim tasarlanmıştır. Bu dört dizilimin performansları elde edilen minimum va maksimum güç, ölü alan sayısı ve homojenlik derecesi gibi önemli parametreler göz önüne alarak değerlendirilmiştir. Bu dört dizilim arasında, Dizilim 2 en iyi sonuçları vermiştir. Daha sonra, Dizilim 2’de yarı-ışıma derecesi ve alıcı-verici arasındaki uzaklık değiştirilerek, bu parametrelerin etkileri gözlemlenmiştir.

Çalışmanın ikinci bölümünde, 64-QAM OFDM ve 64-QAM OFDMA sistemleri benzetim yazılımları kullanılarak oluşturulmuştur. Sistemlerin değişik optic güç-hata oranlarına (OSNR) göre bit-hata oranı (BER) performansları incelenmiştir. Sonuçlar bu sistemlerin görünür ışık haberleşmesi için kullanılabileceğini göstermektedir. BER performansının dışında, göz şekilleri ve konstelasyon diyagramlarıda bu sistemlerin görünür ışık haberleşmesi için uygun olduğunu desteklemektedir.

Son olarak, optic gücü elde edilen minimum optic güçlerine ayarlayarak dört dizilimin BER performansları araştırılmış ve bu test sonucunda da Dizilim 2 en iyi sonucu vermiştir.

Anahtar Kelimeler: görünür ışık haberleşmesi, optic güç dağılımı, dikgen frekans bölmeli çoğullama, dikgen frekans bölmeli çoklu erişim, optic haberleşme, lazer

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2016, 12 May **Metin ÖZTÜRK**

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF GRAPHS

CHAPTER ONE

INTRODUCTION

Communication systems are very important in daily life. People call each other, send massages, surf on the internet, download music or video, etc. using communication systems. Almost everyone has started to use such systems in their daily life so need for these kinds of technologies have been increasing in time. In the past, rate of data transmission was small because people only search the information that they require or send text e-mails to each other using internet. Due to this reason, existing communication systems were able to meet the requirement. However, high data rates have been required in recent years because people have started to download videos and music and to use video call to communicate each other. Hence, existing systems cannot meet the requirements after all these developments.

Mobile wireless communication technologies play an important role to solve this problem. Global mobile data traffic has sharply increased between years 2009 and 2011, but it has decreased after year 2012 because of using mobile wireless communications [1]. For this reason, using wireless communication can cope with some problems that classical wired systems face such as bandwidth. This is because bandwidth is the main problem to meet high data rates. Using wired systems may be enough for voice transmission which has data rate of 20 Kbps with high bit-error-rates (BERs), but high data rate transmissions such as video call require wireless communications with less BERs [2].

In recent years, optical wireless communication systems have developed because wireless communication systems using radio frequency (RF) cannot also meet growing data rates. Same reasons and results are valid for this case; optical wireless communication systems have more bandwidth than classical wireless systems with less BER value. Because of this, the new trend in communication area is the optical wireless communications. Classical wired systems are not able to meet the demand for video conference systems, high-speed internet usage, and high-definition TVs as well as RF-based wireless systems [3]. However, optical wireless systems can be used for these applications besides not having limitations which others have. It has also advantage on using spectrum without a license and this provides unlimited bandwidth usage to optical wireless systems.

1.1. Visible Light Communication

Visible light communication (VLC) is one of the applications of optical wireless communications. Basically, optical wireless communication is divided in two about the electromagnetic spectrum usage: Infrared (IR) and VLC. Both IR and VLC can be used for indoor and outdoor applications.

Visible light uses the wavelength range between 380 nm and 700 nm which is visible to human eye while IR uses 800 nm and 1500 nm wavelength range which is not visible. Figure 1 shows the electromagnetic spectrum and allocations.

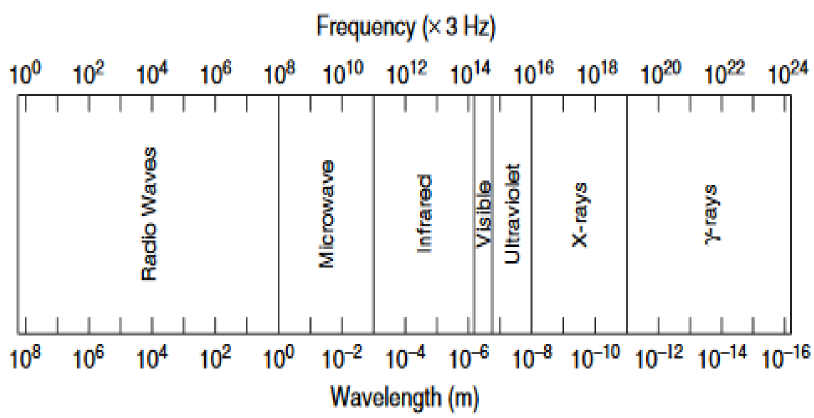


Figure 1: Electromagnetic spectrum [4].

Visible light communication systems were started to be used in communication area because of its some advantages and superiorities on RF and IR systems [5]. For example, it does not require external installations over existing illumination system, it is healthier to human eye, it is safer because light cannot pass through walls, and it has larger SNR values. Visible light communication which uses this spectrum is provided with white LEDs. White LEDs provide another advantage, which is double-purpose usage, to visible light communication systems since they are also used for illumination [6]. Studies on VLC systems have gained momentum because of all these and other advantages of VLC. Visible light communication systems are widely used for indoor applications and it does not give acceptable results for outdoor applications. It has not only indoor applications such as airplane usage and video conference but also outdoor applications such as car to car communication [7].

Visible light communication has very old history. For instance, US military used heliograph, which can be defined as wireless solar telegraph, in 1880s. The main principle of heliograph was based on sunlight; signals obtained with flashes of sunlight which were reflected by a mirror. Generally Morse code was used for those signals.

After that, Alexander Graham Bell achieved transmitting speech using modulated sunlight and this invention was called as a photophone in 1880. This was the main corner stone for visible light communication because it was understood that visible light can be used for data transmission after this invention. Bell obtained a patent regarding this invention which was entitled “Apparatus for Signaling and Communicating, called Photophone” in 1880 [8].

However, studies gained momentum in 2003 in Keio University by transmitting data using LEDs. For this purpose Nakagawa Laboratory was established. After that, numerous studies have performed regarding visible light communication in Nakagawa Laboratory and all over the world. Also, Visible Light Communication Consortium was established same year.

In 2010, 500 Mbit/s transmission was demonstrated using white LED by research group from Siemens and Fraunhofer Institute for Telecommunications, and this transmission was performed for 5 meters.

In 2012, VLC was standardized by conducting IEEE 802.15 which is called as IEEE 802.15.7. Its modulation schemes and dimming supports are given in the study [9].

In 2015, Philips and Carrefour supermarkets were collaborated to use visible light communication for shoppers'. This is very important development for visible light communication because it became an industrial application with this project.

In the literature, there are numerous important studies regarding visible light communication [10-19].

1.2. Organization of Thesis

The thesis starts with Introduction and continues with five different chapters.

Chapter 2 is Optical Power Distribution that includes light sources such as light emitting diode (LED) and laser diode. LED's general structure and its mathematical model about optical power are given in this chapter. Also, structure of laser diode and its transmitted optical power calculations are mentioned. Finally, calculations regarding optical power at the receiver part are given in this chapter.

Chapter 3 is Modulation Methods that consists of optical modulators such as electro-optic modulators, electro-absorption modulators, and interferometric modulators which are Mach-Zender and Fabry-Pérot. In addition to this, digital modulation techniques such as amplitude shift keying (ASK), phase shift keying (PSK), pulse position modulation (PPM), pulse code modulation (PCM), and quadrature amplitude modulation (QAM).

Chapter 4 is Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA). In this chapter, OFDM and OFDMA models and regarding mathematical backgrounds are given.

Chapter 5 is Simulation Studies that includes optical power distribution, 64-QAM OFDM system, and 64-QAM OFDMA system. Global parameters, components and their system parameters are introduced in this chapter. Also, there is Results and Discussions part which consists of results about the studies performed and discussions about the results. Chapter 6 is Conclusion which has brief conclusion about studies and results.

CHAPTER TWO

OPTICAL POWER DISTRIBUTION

Optical power distribution is very important parameter while designing optical wireless communication system, especially visible light communications because data transmission is provided by light. If there is no enough optical power on the surface where communication system is constructed, data cannot be transmitted. For example, when a room is used to communicate using visible light, almost every point has to achieve at least required minimum optical power so distribution of optical power plays important role. Also, this power should be distributed uniformly to obtain better communication system. There will be dead zones which have no required minimum optical power and minimizing such kind of dead zones is another vital factor. To achieve better communication systems, uniformity of optical power must be grater while amount of dead zones must be lower.

In this chapter, properties of light will be covered firstly for background information. Then, light sources which are LED and laser will be introduced briefly with their properties. After defining some important laws such as Lambert's emission law, mathematical model for both transmitted and received optical power will be covered. These mathematical models will be used in simulation system for optical power distribution in the last chapter.

2.1. Light Sources

When the state of an electron is changed from higher energy level to lower energy level, there will be excess of energy, which means that energy is generated. This excess of energy is generally emitted in the form of light, and there are two types of light emission which are spontaneous emission and stimulated emission [10].

In the spontaneous emission case, the energy level of an electron increased to the higher energy level, then the electron spontaneously come back to the lower energy level because lower energy levels are more stable than higher energy levels. Hence, light is emitted spontaneously after this process. According to [10], the wavelength of this emitted light can be known, but direction and phase cannot.

On the other hand, in the case of stimulated emission, after increasing the energy level of the electron to the higher level, it can stay there for a while. When a photon occurs to stimulate this electron, it emits its energy as another photon. All these processes happen before the electron come back to more stable energy level spontaneously. In the case of stimulated emission, the direction, phase, and wavelength of emitted photon are equal to the stimulating photon.

There are two kinds of light sources which are light emitting diode (LED) and light amplification by the stimulated emission of radiation (LASER). However, laser diodes instead of laser is covered in this chapter.

1.2.1. Light-Emitting Diode (LED)

LEDs produce an output light using the principle of spontaneous emission which is based on radiative recombination. In this process, a diode is forward biased and electrons and holes are in the active region of the diode. Hence, LEDs generate incoherent light and they do not have any threshold current to produce light [11]. In the process of spontaneous emission in LED, spontaneous photon generation rate must be equal to the spontaneous electron recombination rate because of the structure of LED [12]. In Figure 2, general structure of an LED is shown.

Because LEDs are made from semiconductor materials which are used in all light sources, they satisfy the properties of semiconductor diodes. The wavelength of the output light of LED is dependent to the band-gap energy, but they have an inverse proportionality. The equation of the wavelength of emitted light from LED is given in [10].

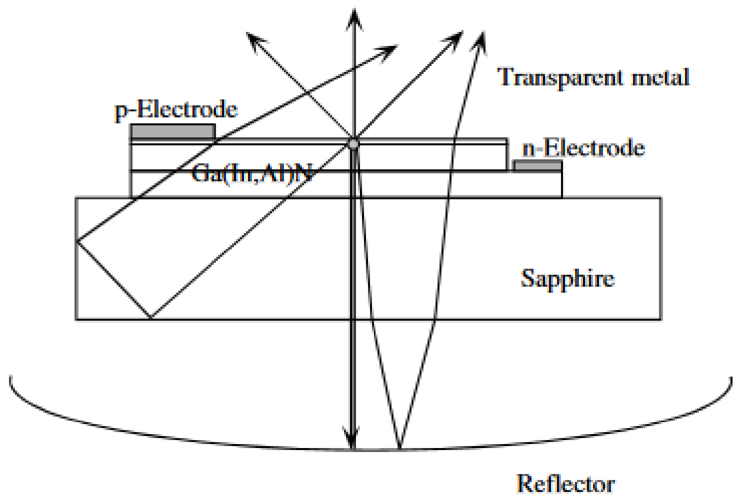


Figure 2: Light emitting diode [11].

$$\frac{hv}{\varepsilon_{ph}} = \frac{1.24}{\varepsilon_{ph}} = \lambda \qquad \textbf{(2.1)}$$

In this equation, λ represents the wavelength of emitted light, h is Planks constant, c is speed of light, and ε_{ph} is the photon energy. As understood from this equation, wavelength decreases when energy increases. According to [12], when a photon is emitted, the equation is obtained under steady-state conditions. This equation is as follows.

$$\frac{\eta_i I}{qV} = R_{sp} + R_{nr} + R_l \qquad \textbf{(2.2)}$$

In this equation, η_i, I, q, V, R_{sp}, R_{nr}, R_l are fraction, injected current, electric charge, volume of the active region, spontaneous recombination rate, nonradiative recombination rate, and carrier leakage rate, respectively. As seen from this equation, the rate of injected electrons consists of the spontaneous recombination, non-radiative recombination, and carrier leakage. There is no parameter for stimulated recombination in this equation because the working principle of an LED is directly based on a spontaneous emission.

After defining radiative efficiency, η_r, an optical power, P_{sp}, which is generated after spontaneous emission process can be calculated as follows and all these calculations are given in [12].

$$\eta_r = \frac{R_{sp}}{R_{sp} + R_{nr} + R_l} \quad \textbf{(2.3)}$$

$$P_{sp} = hvVR_{sp} = \eta_i \eta_r \frac{hv}{q} I \quad \textbf{(2.4)}$$

LEDs are commonly used in communication systems as well as other areas due to the fact that it has various advantages. For instance, they are very cost effective because LEDs are cheap components when compared to other light sources, such as laser, in communication area.

In the perspective of characteristics of LED, it has less output power than laser. Moreover, it produces wide spectrum because it does not produce a single wavelength. It also produces incoherent light, hence it needs lens to focus and this brings a disadvantage to LED. LED can be used with both analog and digital modulations, but it cannot reach gigabit speed in digital modulation [10]. In Figure 3, commercially available LEDs in different colors are shown.

LEDs have wide range of application area after the usage of blue color in LED. RGB (Red Green Blue) LEDs are used commonly in illumination systems, signalization systems, and architectures because of their life are very long. With the combination of this RGB LEDs, every color can be produced such as white light. This is one of the most important techniques of the production of white light.

Figure 3: LEDs in different colors [13].

1.2.2. Laser Diodes

Laser is the abbreviation of "*light amplification by stimulated emission of radiation*" and it is developed to provide single-color coherent light. It was firstly constructed by Theodore H. Maiman at Hughes Laboratories after the theoretical studies of Charles Hard Townes and Arthur Leonard Schawlow. There are various laser types in the literature such as gas laser, solid-state laser, fiber laser, photonic crystal laser, semiconductor laser, dye laser, and doped fiber laser [14]. In this thesis, semiconductor lasers which are also known as laser diodes are considered because their commonly usage in the communication field.

The general structure of the semiconductor diode is given in Figure 4. As seen from this figure, the semiconductor diode basically consists of p-type and n-type semiconductor materials and there is a thin active layer, where lasing actions happen, between these two semiconductor materials.

When the current is injected over the diode, laser light is emitted from cleaved facets of the semiconductor diode. The semiconductor diode in the figure is broad area laser due to the fact that the current is injected over the broad area. This kind of semiconductor diodes are not widely used in communication area because they have some disadvantages such as high threshold current [15].

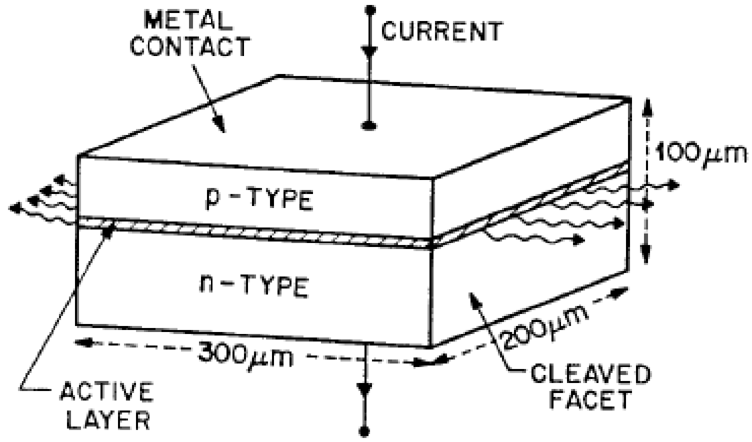


Figure 4: General structure of broad-area semiconductor laser [16].

Semiconductor lasers are also based on stimulated emission process which is valid for other types of lasers. There are important advantages of stimulated emission as providing high output power because of the nature of coherent light. Furthermore, semiconductor lasers have the property of direct modulation at high frequencies such as a few tens of GHz degrees. In addition to these advantages, they have also high coupling efficiency due to the narrow angular spread of the output beam [15]. All these structural properties provide extra advantages to laser when compared to LED, hence they are widely used in communication area.

According to [15], stimulated emission occurs when a population inversion is satisfied which is defined as having more members in the exited state than the lower state. There are some fundamental calculations for semiconductor lasers given in [15].

The first one is the optical gain; the peak gain can be calculated as follows.

$$g_p(N) = \sigma_g(N - N_T) \qquad \textbf{(2.5)}$$

In this equation, g_p represents the peak value of gain, N represents the injected carrier density, σ_g represents the differential gain, and N_T represents the transparency value of the carrier density. As understood from this equation, the carrier density and optical gain have direct proportionality. As seen from Figure 5, maximum gain increases while the carrier density increases after population inversion is occurred.

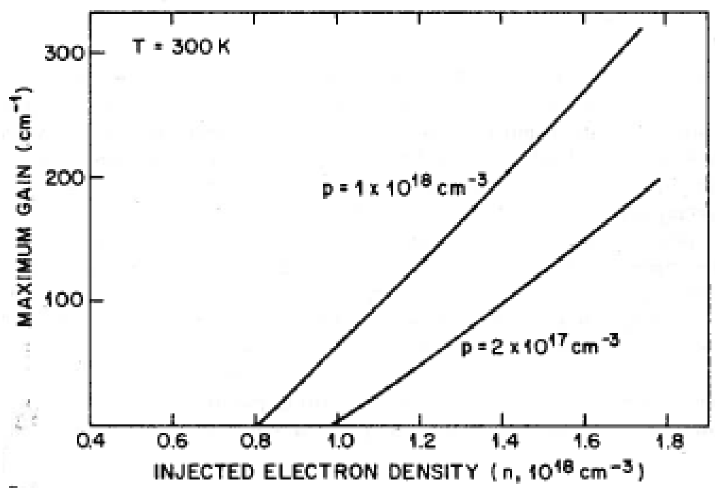


Figure 5: Carrier densities vs. maximum gain [16].

This graphic is obtained using two different hole concentrations for p-type InGaAsP laser.

Semiconductor lasers or laser diodes have numerous application areas apart from communication field. For example, they are widely used in computer technology such as CD players, CD-ROMs and DVD technologies. They are also used in barcode reading systems, medicine, optical data recording, laser printers, image scanning technology, and illuminators. There are also different types of semiconductor laser as quantum well lasers, double hetero-structure lasers, distributed feedback lasers, and so on.

1.1.2.1 Transmitted Optical Power

Semiconductor lasers are emitting light after stimulated emission process, and this emitted light is dependent to the device current. Due to this reason, light-current characteristics of laser diodes are generally taken into consideration [17]. In order to obtain output power which is emitted by laser diode, starting point should be the current. All these output power calculations are given in [16].

The current can be calculated as follows.

$$I = I_a + I_L \tag{2.6}$$

where I_a and I_L are the active region and leakage currents, respectively. Since the active region current is directly proportional to the carrier density, it can be written as;

$$I_a = wLJ \tag{2.7}$$

where w, L, and J are active region width, cavity length, and J is the carrier density, respectively. Another parameter in order to calculate output power of laser diode is intracavity photon density. It can be calculated using Equation 2.8.

$$N_{ph} = \eta_i \left(\frac{\tau_p}{qd}\right)(J - J_{th}) \tag{2.8}$$

where η_i, τ_p, q, d, and J_{th} are internal quantum efficiency, photon lifetime, electron charge, active layer thickness, and threshold current density, respectively. Expressions for τ_p and J_{th} are given as follows.

$$\tau_p^{-1} = \vartheta_g(\alpha_m + \alpha_{int}),$$
$$\vartheta_g = \frac{c}{\mu_g} \tag{2.9}$$

$$J_{th} = \frac{qdn_{th}}{\tau_e(n_{th})} \tag{2.10}$$

where ϑ_g, α_m, α_{int}, μ_g, n_{th}, and $\tau_e(n_{th})$ are group velocity, mirror loss, internal loss, group index, threshold carrier density, and carrier recombination time which is a function of n_{th}, respectively. Hence, the carrier density is calculated as;

$$n_{th} = n_0 + \frac{(\alpha_m + \alpha_{int})}{\alpha\Gamma} \quad \textbf{(2.11)}$$

where n_0 is the transparency value when population inversion occurs, α is the absorption coefficient, and Γ is the confinement factor.

After defining all required parameters, output power can now be written as follows.

$$P_{out} = \frac{1}{2} h\nu \vartheta_g \alpha_m V N_{ph} \quad \textbf{(2.12)}$$

where Vis active volume and is calculated as;

$$V = Lwd \quad \textbf{(2.13)}$$

When equations are combined in order to write the output power more clearly, the equation becomes;

$$P_{out} = \frac{h\nu}{2q} \frac{\eta_i \alpha_m}{\alpha_m + \alpha_{int}} (I - I_{th} - \Delta I_L) \quad \textbf{(2.14)}$$

where I_{th} is the threshold current.

2.2. Received Optical Power Supplied from LED

LEDs have some advantages over other light sources so they will be used in future application of communication area such as visible light communication. These advantages can be counted as low power consumption, fast switching, long life expectancy, and compact size. Another important advantage of LED is its dual purpose usage: illumination and communication [3]. This property of LEDs cannot be satisfied using lasers because the output of a laser is coherent and have higher power. Hence, this can be dangerous to human health. LEDs are the main candidate of visible light communication systems due to their dual purpose usage property as well as fast switching property. Fast switching is one of the most important features of light sources because data is obtaining by switching the light source. For example, data is 0 digitally when the light source is closed and data is 1 digitally when the light source is opened. By performing such kind of switching, overall digital information is obtained.

Output power of an LED is very important factor while designing the visible light communication system since data transferred through light. There must be enough optical power at the receiver side to obtain the transmitted information. If there is no enough received optical power on any area, this kind of areas are called as dead zones. In ideal visible light communication system inside a room, there must be no dead zones. However, dead zones are occurred in real systems and they must be minimized in term of their amount. Hence, the mathematical models are needed for both transmitted and received optical powers to minimize the dead zones by performing some simulations.

In these mathematical models, there are some parameters regarding LEDs properties such as half-angle illuminance. These parameters can be known using data sheets of LEDS which have all the features of any special LED. After deciding the LED type which will be used in communication system as a light source, its special features is used to simulate the overall system to see how the optical power is distributed on the receiver plane.

In [3], mathematical models for visible light communication are given. One of these models is the received optical power.

The luminous intensity which expresses the brightness of LED is as follows.

$$I = \frac{d\Phi}{d\Omega} \tag{2.15}$$

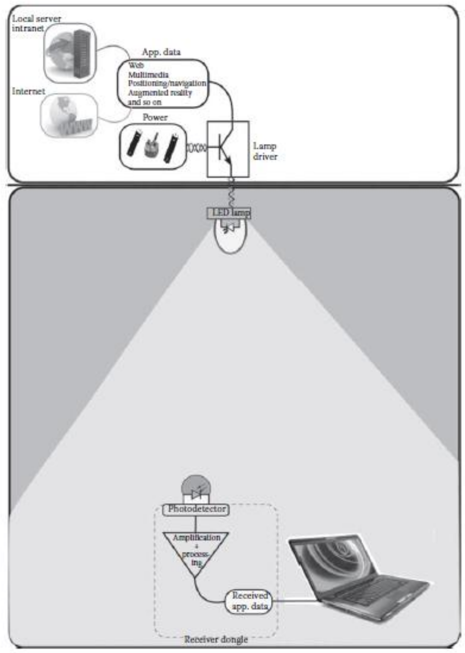


Figure 6: General structure of visible light communication [3].

Φ and Ω represent the luminous flux and spatial angle, respectively. Luminous intensity is defined as the wavelength-weighted emitted optical power from a source of visible light. As seen from this equation, the luminous intensity and spatial angle have inverse proportionality. Therefore, the luminous flux in Eq. 2.15 can be calculated as follows.

$$\Phi = K_m \int_{380}^{780} V(\lambda)\, \Phi_e(\lambda) d\lambda \quad \textbf{(2.16)}$$

In this equation, Φ_e is the energy flux, $V(\lambda)$ is the standard luminous curve, and K_m is the maximum visibility. The standard luminous curve is also called as the standard luminosity function which is described as "the measure of the effectiveness of lights of different wavelengths defined for specific matching tasks." according to [18]. The photopic and scotopic luminosity functions are shown in Figure 7. Photopic and scotopic luminosity functions are the responses of the human eye under normal conditions and under low light level conditions, respectively.

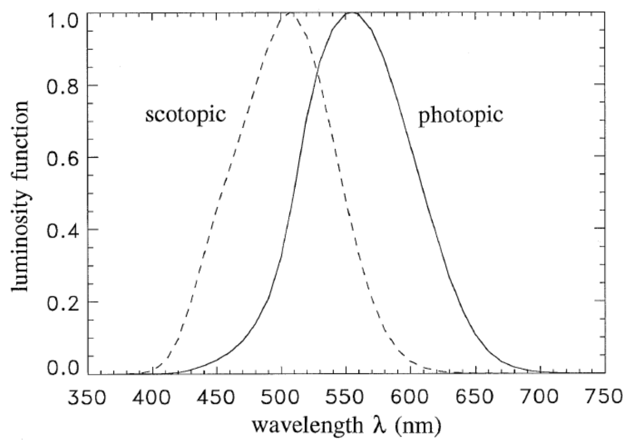


Figure 7: Photopic and scotopic luminosity functions.

As seen from Figure 7, the luminosity function is shifted to the left under low light level conditions. This function also gives different characteristics for different eye-based diseases.

After this point, transmitted optical power can be calculated as [3].

$$P_t = K_m \int_{\Lambda_{min}}^{\Lambda_{max}} \int_{0}^{2\pi} \Phi_e(\lambda) d\lambda \quad \textbf{(2.17)}$$

The output light of an LED satisfies the Lambert's emission law. According to the Lambert's emission law, the luminous intensity observed from a Lambertian surface, which is ideal diffusely reflecting, is proportional to the angle between the surface normal and the observer's line of sight.

$$I(\emptyset) = cos^m(\emptyset) I_0 \quad \textbf{(2.18)}$$

In this equation, $\emptyset$ is the angle between the surface normal and the observer's line of sight, I_0 is the intensity of the incident light, and m is the Lambertian order. This Lambertian order can be calculated as [19].

$$m = \frac{\ln 2}{\ln (\cos \Phi_{\frac{1}{2}})} \quad \textbf{(2.19)}$$

$\Phi_{\frac{1}{2}}$ represents the semi-angel at half power. Using all these equation, received power can be calculated as [3].

$$P_{Rx} = P_{Tx}.\frac{m+1}{2\pi d^2} cos^m(\emptyset) T_s(\varphi) g(\varphi) \cos(\varphi) \, , 0 \le \varphi \le \varphi_{con} \quad \textbf{(2.20)}$$

where

$\boldsymbol{P_{Rx}}$: Received power,

$\boldsymbol{P_{Tx}}$: Transmitted power,

$\boldsymbol{\varphi}$: Reflected angle of receiver surface with respect to normal,

$\boldsymbol{T_s(\varphi)}$: Filter transmission,

$\boldsymbol{g(\varphi)}$: Concentrator gain,

$\boldsymbol{\varphi_{con}}$**:** Concentrator field of view,

$\boldsymbol{d}$: Distance between transmitter and receiver.

The concentrator gain can also be calculated using the function below [16].

$$g(\varphi) = \begin{cases} \dfrac{n^2}{sin^2.\varphi_{con}}, & 0 \le \varphi \le \varphi_{con} \\ 0, & 0 \ge \varphi_{con} \end{cases} \quad \textbf{(2.21)}$$

Here, n represents refractive index. In the Figure 8, the sample room which is used for visible light communication system is shown.

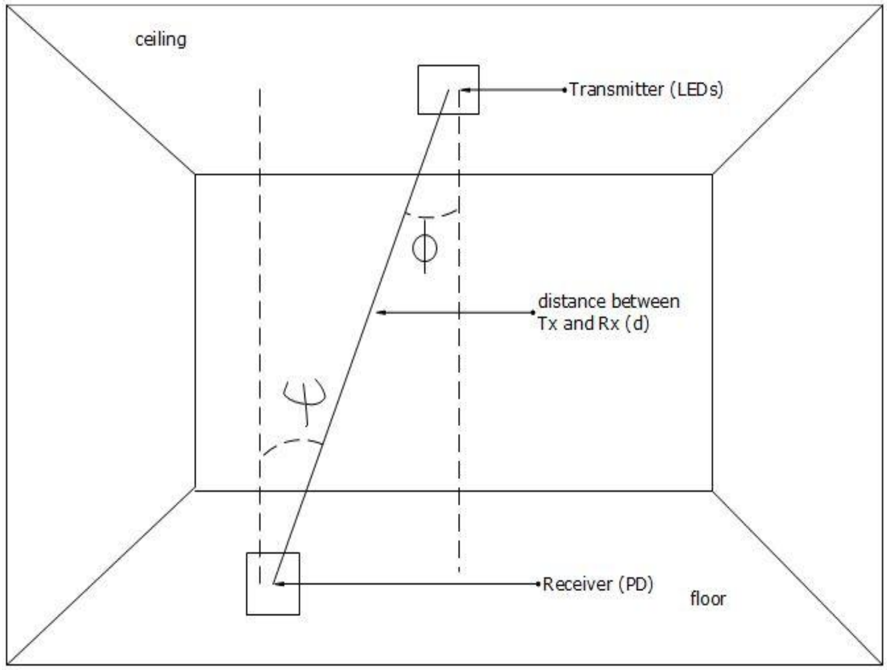


Figure 8: Symbolic room with LED illumination.

As seen from Figure 8, LEDs are used as a light source while photodiodes are used as a receiver in this communication system. In illumination systems, light sources are located on the ceiling of the room. From this point, LEDs are also located on the ceiling in visible light communication system because in such systems LEDs are used for both illumination and communication.

After obtaining the equations above, especially the received optical power, the overall system can be simulated. The results from these simulations define the performance of the system. Optical power distribution can be obtained after modeling the received optical power. By obtaining the optical power distribution, amount of dead zones are specified. Hence, according to this information, the performance of the system is tried to be improved such as minimizing the amount of dead zones.

CHAPTER THREE

MODULATION AND ACCESS METHODS

Communication between people almost involves whole daily life because people contact each other using communication technologies. The main objective of the communication systems is transmitting data from transmitter to receiver. Although data to be transmitted is mostly the baseband signal which has low frequencies, the channel that is used as a medium for transmission is needed high frequencies which are pass-band frequencies. Because of this reason, signal must be made suitable to the channel in order to perform the transmission between transmitter and receiver.

Modulation is used for this purpose which is making the data suitable to the transmission channel by shifting the frequency of the signal from baseband to pass-band frequencies. After this modulation process, data can be transmitted easily. To perform this frequency shift, high frequency carrier signals are used.

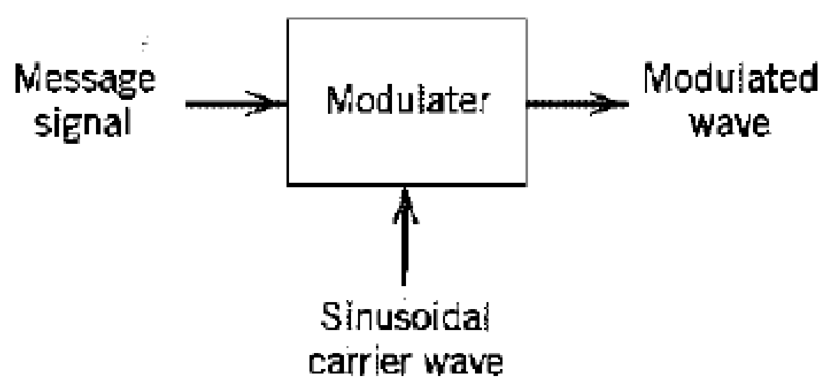


Figure 9: Modulation process [20].

As seen from Figure 9, the message signal come to modulator block with sinusoidal carrier wave and the combination of these two signals create the output signal which is modulated wave. The modulation process seen on the figure is the continuous wave modulation technique which uses continuous waves such as sinusoidal wave as a carrier.

Modulation can be classified into numerous subsets such as analog modulation, digital modulation, optical modulation, and multi-carrier modulation. All these modulation techniques have some advantages/disadvantages and properties in terms of their system performances. Each of these modulation techniques can be used according to certain application. For example, multi-carrier modulation techniques should be used if the channel efficiency is needed in the proposed system.

In this chapter, the classification of modulation techniques will be as follows: Optical modulation and digital modulation. After introducing all these techniques, multi-carrier access methods such as time division multiple access (TDMA) and frequency division multiple access (FDMA) will be introduced.

3.1. Optical Modulators

Optical modulators are devices to modulate light by controlling its properties such as intensity, polarization, and phase. For wired communication systems, the electrical signal is used to transmit the data from transmitter to receiver. The main conveying thing is electrical signal, and this electrical signal is passing through a transmission medium such as copper to accomplish the data transmission. Before transmission happens, the electrical signal is modulated in order to make it suitable for the channel. There are various modulation techniques regarding such kind of communication system such as amplitude modulation, phase modulation, frequency modulation, and so on.

For the optical communication systems, the transmission medium may be fiber for wired communication, and it may be air for wireless communication. Moreover, the data to be transmitted is conveyed by light for optical communication systems. There is also modulation process for optical communication systems as in the wired communications.

There are two main class for optical modulators; direct modulation and external modulation. However, direct modulation cannot meet the increasing speed requirements for some applications. Because of this reason, only external optical modulators will be introduced in this part.

Electro-optic modulators, electro-absorption modulators, acousto-optic modulators, and interferometric modulators are main modulator types for light-base communication systems.

3.1.1. Electro-Optic Modulators

Electro-optic modulators are devices that are working with the principle of electro-optic effect. There are some unique materials which are changing their optical properties when electric field is applied. When low frequency or dc electric field is applied to such kind of certain materials, their refractive indices are changed, and this change originates the fundamentals of electro-optic effect. Although the change on refractive index of the material is not large, there is an important effect on light which is travelling through the medium [21].

If electric field is applied to the electro-optic material while light is passing through it, there will be a change on effect of the material on light. This happens because the optical properties of the material are changed. If its properties change, its effects on light also change.

There are two main effect of the electric field application to the electro-optic material. One of them is known as a Pockels effect which is defined as a linear effect on refractive index of the material with respect to electric field. In other words, there is a direct proportionality between electric field and refractive index.

The second effect is known as a Kerr effect which defines the quadratic relationship between electric field and refractive index. In other words, refractive index is proportional to the square of the applied electric field [21].

Pockels cells are developed to be used in communication systems, and they work using Pockels effect. They are basically electro-optic crystals and light can easily travel through them. Their control can be provided with electric voltage; when electric voltage is applied on them, the electric field occurs. By this way, the modulation process can be performed. In Figure 10, IRX series CdTe Pockels cells belonging to Gooch&Housego Company is shown.

Figure 10: IRX series CdTe Pockels cells [22].

After constructing the background information about electro-optic effect and Pockels cells, electro-optic modulators that are used in communication systems can be introduced.

Electro-optic modulators are devices that are developed to modulate light by changing its some main properties such as phase, power, and polarization. To perform the modulation process, it needs some electrical signals such as electric voltage to generate the electric field. Because of this, these modulators are also called as signal-controlled modulators.

In order to perform phase modulation using electro-optic effect, phase of the light which enters to the material must be changed. Assume a laser beam, which has an amplitude of A_l and frequency of ω, propagating through the material. After a sinusoidal voltage, which has another frequency level of φ, is applied to the material. After combining these two, there will be one original signal and two different sidebands which are $\omega + \varphi$

and $\omega - \varphi$. Then, the phase delay occurs after application of electric field using electric voltage.

The typical phase modulators with the help of electro-optic effect are shown in Figure 11. In this figure, electro-optic material, electrodes, incident light, and modulated light are shown clearly.

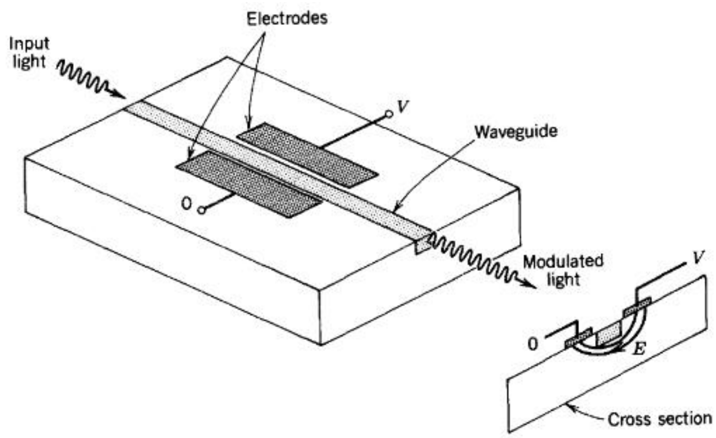


Figure 11: Phase modulator [21].

Polarization and amplitude of the incident light such as laser beam can also be modulated using electro-optic modulators; for example, polarization of the incident light can affect the phase delay which occurs after application of electric field.

3.1.2. Electro-Absorption Modulators

Electro-absorption modulators are devices which are using the Franz-Keldysh effect. Franz-Keldysh theory states that optical absorption of a semiconductor material can change when electric field is applied on it. This electric field is generated with the application of electric voltage. Moreover, the electric field application also changes the effective bandgap of a semiconductor material. When electric field applied to the material, effective bandgap gets smaller. There is an important concept that is behind the working principle of electro-absorption modulators; if the energy of the bandgap is greater than the energy of the incident light which is entering the semiconductor material, $E = hv$, the material becomes transparent. Hence, the incident light can easily pass through the material. However, when electric field is applied to the material, the material starts to absorb the incident light due to the fact that the bandgap energy gets smaller [23].

By using the Franz-Keldysh effect, semiconductor materials can be used as modulators for light-wave. For instance, they can modulate the intensity of the laser beam by applying the electric field. This kind of modulators are called as electro-absorption modulators because they use the electric field to control the intensity of the laser beam using electric, and this process is based on absorption change in semiconductor material.

There are various advantages belonging to electro-absorption modulators. For example, they need lower drive voltage, they can be used in applications that require high speed modulation, and they have also integrability property [24].

3.1.3. Interferometric Modulators

Interferometers are devices that are used in optical systems commonly. They are mostly used in optical measurements systems; in other words, they are used as optical sensors. Normally, the interference is unwanted situation that occurs in optical systems. It affects the system performance in a negative way. For example, it is a problem in communication systems because of its negative effects on data transmission.

However, the interference property can be also used in a positive way. Interferometers use the property of interference to modulate the light in order to measure some parameters. Assume there is an incident light, and it meets with beam splitter which is used for splitting light waves into more than one beams. After two separate light beams occur, they travel and recombine as a property of superposition, and the phase difference occurs. This recombination gives some information about external conditions.

There are some commonly known interferometric modulators such as Mach-Zender modulator, Fabry-Pérot modulator, and Michelson modulator. In the remaining part of this section, some of these modulators will be introduced.

3.1.3.1. Mach-Zender Modulators

Mach-Zender modulators consist of some materials which have important electro-optic property. These materials can be counted as $LiNbO_3, GaAs,$ and InP. Beam splitters are used to split the incident light into two separate beams which have same power.

As a main process of Mach-Zender interferometers, the electric field is applied on each path, hence the phase difference between these two paths occur. The Mahc-Zender interferometer structure is shown in Figure 12.

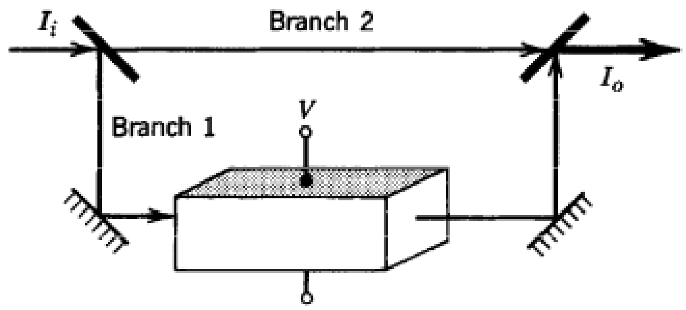


Figure 12: Mach-Zender interferometer [21].

As shown in Figure 12, the incident light is split by beam splitter, and then one branch is passed through a material. Then, two different beams are recombined another beam splitter. As shown, the mirrors are also used to change the direction of light.

The beam which is labeled as Branch 1 is propagating in the material, and the electric voltage is applied to the material to generate electric field. After this process, the phase of the Branch 1 is shifted. All these processes are shown mathematically as follows.

$$I_0 = \frac{1}{2}\mathrm{I_i} + \frac{1}{2}\mathrm{I_i}\cos\varphi \quad \textbf{(3.1)}$$

In this equation, φ represents the phase difference.

$$\varphi = \varphi_1 - \varphi_2 \tag{3.2}$$

As understood from all these processes, the Mach-Zender performs a phase modulation. However, this phase modulation can be turned out to be an intensity modulation by adjusting the optical path difference [21].

3.1.3.2. Fabry-Pérot Modulators

The Fabry-Pérot etalon plates form the Fabry-Pérot modulators. These plates are separated using an electro-optic material such as Potassium Dihydrogen Phosphate (KDP). Figure 13 shows the general structure of Fabry-Pérot modulator.

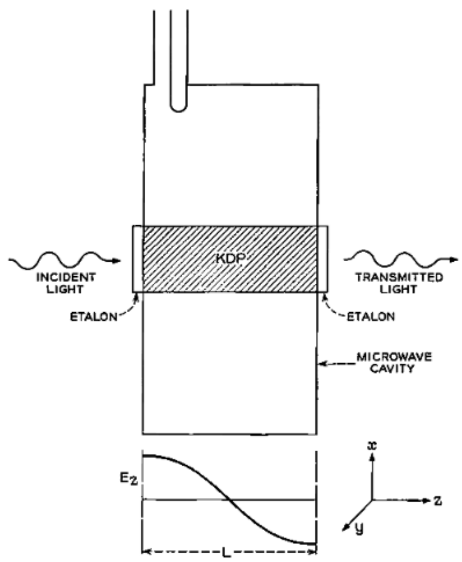


Figure 13: Fabry-Pérot modulator [25].

When Fabry-Pérot modulators are compared with the Mach-Zender modulators which need high driving voltages and large size, Fabry-Pérot modulators have lower driving voltage and more compact structure. The compact device can be obtained because they have less phase changes than Mach-Zender modulators.

3.2. Digital Modulation

Analog modulation techniques are old fashioned modulation techniques because they have some problems such as bandwidth information capacity and security. Digital modulation techniques can solve some of the problems that analog modulation has. For instance, there is more information capacity in the digital communication if it is compared with the analog communication. Furthermore, quality of the overall communication system can be improved while providing higher data security using digital modulations [26]. As mentioned earlier, the main discussion topics in communication technologies are bandwidth efficiency and power considerations. Digital modulation techniques are more suitable to overcome these problems than analog modulation techniques.

Another important issue in communication system is spectrum sharing. Number of user is increasing day by day and the spectrum must be shared among these users. Analog modulation is also not capable to perform such operations and digital modulation techniques are the main candidate to perform these objectives [23]. These means that analog modulation techniques are about to complete their lifetimes.

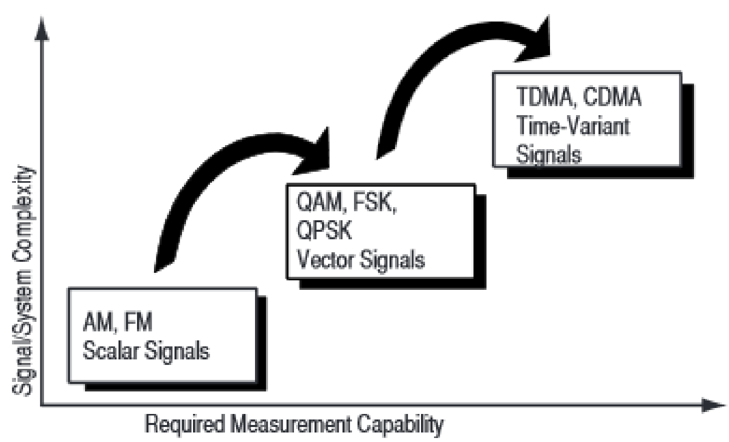


Figure 14: Modulation techniques trend in the industry [26].

As seen from the Figure 14, although the analog modulation techniques such as AM, FM, and PM have less system complexity, they have also less measurement capabilities.

Because of this kind of reasons, trend in the industry is going from analog modulation to digital modulation methods [26].

In this part of the chapter, commonly used digital communication techniques will be introduced with some mathematical backgrounds.

3.2.1. Amplitude-Shift Keying (ASK)

Amplitude shift keying is one of the most commonly used digital modulation techniques. In this modulation technique, there are two or more discrete amplitude levels to combine carrier signal which is generally sinusoids [27]. There are basically two types of amplitude shift keying modulation methods which are binary-ASK (BASK) and M-Ary ASK (M-ASK).

In the BASK, there are two levels which are 1 and 0. The BASK signal is represented as follows.

$$s(t) = A\, m(t)\cos(2\pi f_c t) \qquad 0 \leq t \leq T \tag{3.3}$$

In this equation, A_c is the amplitude which is constant, $m(t)$ is the message signal which has values of 1 and 0 only, f_c is the frequency of the carrier signal. Also, T can be defined as time duration. The power becomes:

$$P = \frac{A^2}{2} \tag{3.4}$$

then

$$A = \sqrt{2P} \tag{3.5}$$

While the energy can be calculated as

$$E = PT \tag{3.6}$$

which is the multiplication of the time and power, BASK signal can be written as follows.

$$s(t) = \sqrt{E}\sqrt{\frac{2}{T}}\cos(2\pi f_c t) \qquad 0 \leq t \leq T \tag{3.7}$$

Moreover, the Fourier transform of this BASK signal is as follows.

$$S(f) = \frac{A}{2}M(f - f_c) + \frac{A}{2}M(f + f_c) \tag{3.8}$$

Since BASK is the switching the amplitude of the carrier signal between *on* and *off* states, it is also called as *on-off keying* (OOK). As seen from Eq. 3.8, the frequency of the message signal is shifted on the spectrum to f_c by multiplying the carrier signal [28].

In Figure 15, there are the message signal which is shown on the top of the figure and ASK signal which is shown on the bottom of the figure. To generate such kind of ASK signals, sinusoidal carrier signals must be used.

To demodulate the ASK signal, amplitude detection is needed. To perform such amplitude detection, both tunable low pass filter and comparator components should be used.

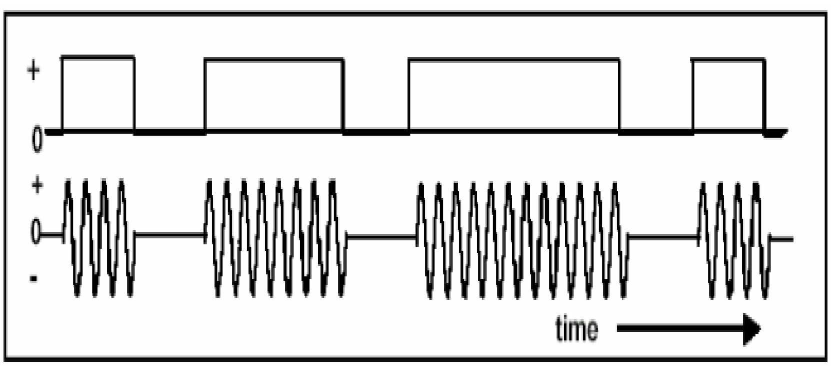


Figure 15: Binary amplitude shift keying [27].

M-ASK signal is represented by as follows.

$$s(t) = \begin{cases} A_i \cos(2\pi f_c t), & 0 \le t \le T \\ 0, & otherwise \end{cases} \qquad \textbf{(3.9)}$$

where

$$A_i = A[2i - (M-1)] \quad i = 0,1,2,3, \dots, M-1 \qquad \textbf{(3.10)}$$

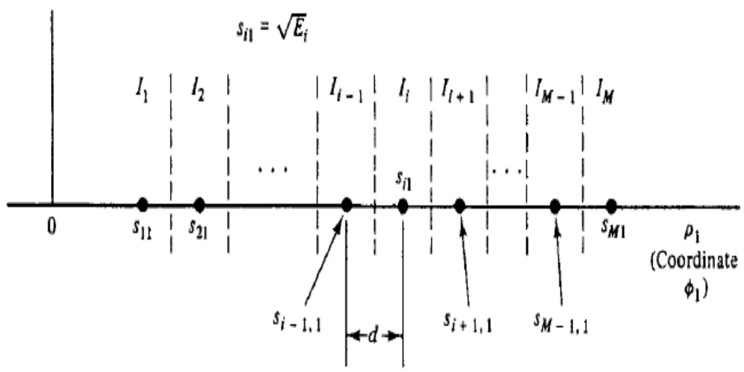


Figure 16: M-ASK constellation diagram [29].

3.2.2. Phase-Shift Keying (PSK)

Phase shift keying (PSK) is another commonly known digital modulation technique which transports data by altering the phase of the carrier signal. Before starting to give mathematical background of PSK, the baseband pulse shape filter $g(t)$ must be defined. This pulse shape function must satisfy the following properties [2].

1) $\int_0^T g^2(t) \, cos^2(2\pi f_c t) dt = 1$

2) $\int_0^T g^2(t) \, cos^2(2\pi f_c t) \sin(2\pi f_c t) dt = 0$

(3.11)

According to [2], the most basic pulse that satisfies these two properties is the rectangular pulse shape whose mathematical representation is given below.

$$g(t) = \sqrt{\frac{2}{T}} \tag{3.12}$$

where

$$0 \leq t < T$$

After defining the pulse shaper, the mathematical background of PSK can be given. The transmitted signal can be calculated as

$$s(t) = A\ g(t) cos\left[\frac{2\pi(i-1)}{M}\right]\cos(2\pi f_c t) - A\ g(t) sin\left[\frac{2\pi(i-1)}{M}\right]\sin(2\pi f_c t) \tag{3.13}$$

Modulation type of PSK is changing regarding M value which is calculated as

$$M = 2^k \tag{3.14}$$

where

$$k = 2, 4, 8, \ldots$$

k value in the Eq. 3.14 represents the number of bits to be transmitted. According to this k and M values, MPSK is determined. For example, MPSK becomes 2PSK which is also called as Binary PSK (BPSK) when $k = 1$ and $M = 2$. Analogically, MPSK become 4PSK when $M = 4$ and this modulation type is also known as quadrature phase shift keying (QPSK) [2].

In Figure 17, gray encodings for 4PSK and 8PSK are shown. To demodulate the PSK signal, the first step is multiplying PSK signal with the carrier signal. The second step is applying low pass filter to this multiplied overall signal. Decision making process is used to obtain the signal which is desired to transmit. All these processes which are called as demodulation of PSK are performed at the receiver side of the communication system.

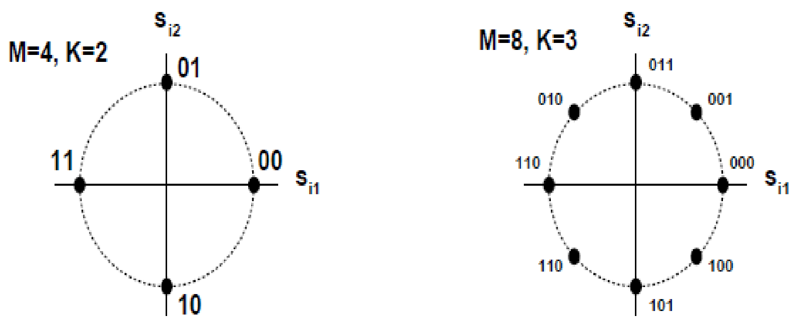


Figure 17: 4PSK (QPSK) and 8PSK constellation diagrams [2].

3.2.3. Pulse-Position Modulation (PPM)

Pulse position modulation (PPM) is one of the pulse modulation techniques. In this category, there are some other methods such as pulse amplitude modulation (PAM) and pulse code modulation (PCM). Furthermore, it is one of the orthogonal modulation schemes which use orthogonal signals while transmitting data. As well as on-off keying (OOK) method, PPM can also be used for optical communication systems.

Basically, there are two intensity levels in PPM which is same in the OOK. These intensity levels are as follows.

$$I_0 = 0, \quad I_1 = MI \tag{3.15}$$

BER performance of PPM is given in the equation below.

$$BER \geq \frac{M}{2} Q(\sqrt{\frac{ME}{2N_0}}) \tag{3.16}$$

where E and N_0 are received electrical energy and the noise power spectral density, respectively. Also, Q represents the Q-function which is defined as the tail probability of the standard normal distribution and is calculated by [30].

$$Q(x) = \frac{1}{2\pi} \int_{x}^{\infty} e^{\frac{-t^2}{2}} dt \tag{3.17}$$

In PPM, the symbol interval is divided into some subintervals and the number of these subintervals is determined by M. The message to be sent coded to the one of the subintervals for each symbol, and then the intensity level becomes 0 for the other subintervals [1].

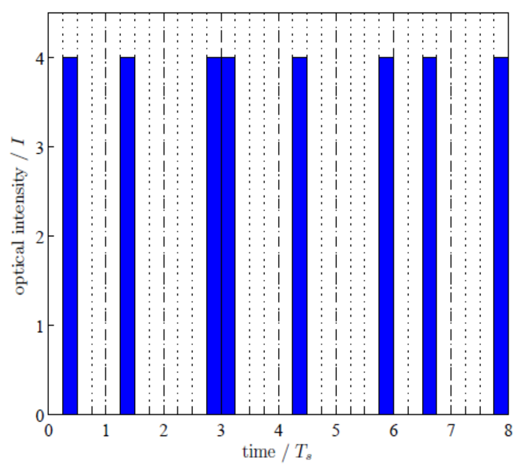


Figure 18: An example of pulse position modulation [1].

Although PPM has more complexity than OOK, higher bandwidth and power efficiency can be provided in PPM when compared to OOK [3].

3.2.4. Pulse-Code Modulation (PCM)

Pulse code modulation is another digital modulation technique which is also in the family of pulse modulation schemes. It is one of the encoding techniques to represent the analog signals such as audio signals into digital form. To achieve this purpose, there are mainly three steps: Sampling, quantization, and coding. In the sampling step, the samples of the amplitude of the analog signal are taken with some time interval. As a second step, every sample must be quantized.

Quantization process mainly stands for mapping. At the sampling process, there are some samples taken from the original analog signal. Then, these samples may take some values. In the quantization process, some definite values are determined, and then the values of the samples are mapped to these definite values according to the relation of the values of sample and quantization level.

In the Figure 19, quantization levels are determined after sampling step. After that, values of the samples are mapped the quantization levels.

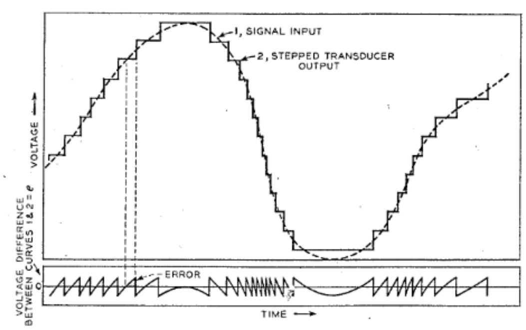


Figure 19: Quantization process [31].

The noise calculation for the quantization process is as follows.

$$e(n) = x(nT_s) - x_q(nT_s) \quad \textbf{(3.18)}$$

where $x(t)$ is the original signal whose sampled one is $x(nT_s)$ and $x_q(nT_s)$ is the quantized signal of the sampled signal. By using the Eq. 3.18, the quality of the quantization process can be determined.

All these steps and generating PCM signal is shown in Figure 20.

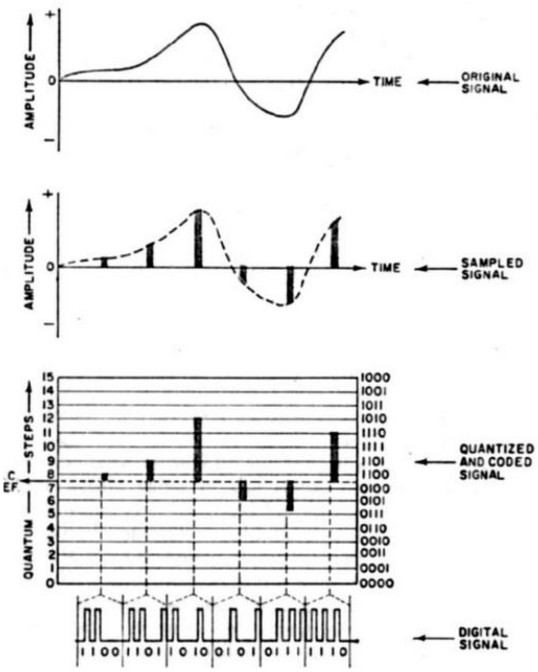


Figure 20: Generating PCM signal with all steps.

3.2.5. Quadrature Amplitude Modulation (QAM)

Quadrature Amplitude Modulation (QAM) is a modulation technique which is used for both analog and digital communications. It is applied by altering the phase and amplitude values of the carrier signal. In contrast to Quadrature Phase Shift Keying (QPSK) modulation technique, amplitudes are also modulated in QAM which is expanded version of QPSK. Therefore, QAM modulation technique which uses more phase and amplitude may be preferred while transmitting data instead of QPSK which has four phase possibilities [32]. 16, 64, 128, or more phase and amplitude locations for different bits can be obtained using QAM. In QAM modulation, for example, for 2-QAM, two carriers (generally sinusoidal signals) are separated each other by 90^0 phase shift. For this reason, QAM includes two different components: in-phase (I) and quadrature (Q).

The mathematical calculations regarding QAM are given in [2].

$$s_i(t) = Ag(t)\cos(\theta_i)\cos(2\pi f_c t) - A\, g(t)\sin(\theta_i)\sin(2\pi f_c t), \quad 0 \leq t \leq T \qquad \textbf{(3.19)}$$

$s_i(t)$ is the transmitted signal and $g(t)$ is the pulse shaper. The energy is regarding the transmitted signal is as follows.

$$E = \int_0^T s_i^2 (t) dt = A^2 \tag{3.20}$$

The distance between two symbols is given below.

$$d_{ij} = \sqrt{(s_{i1} - s_{j1})^2 - (s_{i2} - s_{j2})^2} \tag{3.21}$$

Figure 21 shows the constellation diagrams for 4-QAM and 16-QAM.

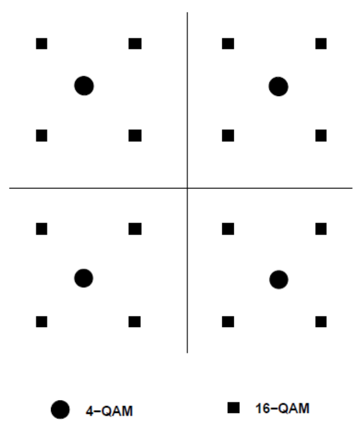


Figure 21: Constellation diagrams 4QAM and 16QAM [2].

Figure 21 shows the probability of errors versus the energy per bit to noise power spectral density ratio for 16-QAM, 64-QAM, and 256-QAM. As understood from the figure, system performance decreases while M value increases.

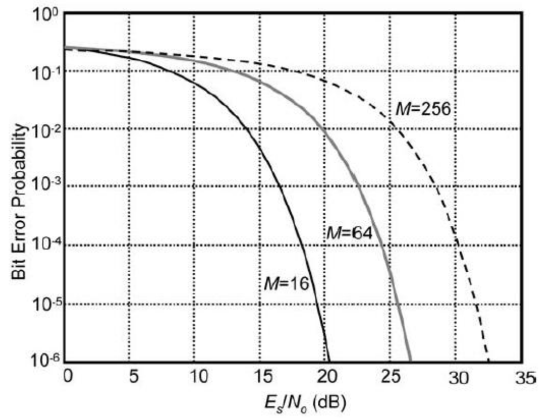


Figure 22: Performances of different MQAMs [32].

3.3. Multiple Access Methods

When there are more than one user which use the same medium for the transmission, generally multiple access methods are used. This can be achieved with various methods such as time-division multiple access (TDMA), frequency-division multiple access (FDMA), and code-division multiple access (CDMA).

3.3.1. Time-Division Multiple Access (TDMA)

One of the multiple-access techniques is time-division multiple access (TDMA). As mentioned earlier, this method is common for OFDM and OFDMA systems.

In TDMA, every user has the same frequency to perform the data transmission, but their time slots are different. Time is divided into different slots and each user is assigned to a certain time slot, then one-after-one transmission is used. It means that simultaneous transmission is not possible for TDMA.

3.3.2. Frequency-Division Multiple Access (FDMA)

Frequency-division multiple access (FDMA) is another access method and it used in OFDMA system, but it cannot be used in OFDM systems. In contrast to TDMA, simultaneous transmission is possible because different users use same time slot but different frequencies in FDMA.

In other words, different users can share the medium for transmission at the same time, and this is achieved by frequency division. Because OFDMA is based on both TDMA and FDMA while OFMD is based on only TDMA, the main difference between these techniques is simultaneous transmission.

3.3.3. Code-Division Multiple Access (CDMA)

Code-division multiple access method is can be classified as a spread spectrum method. Similarly, more than one user can use the spectrum simultaneously, but there is a distinct signature sequence for all users in CDMA. Pseudo-random code is used in order to spread the bandwidth of the data, and each transmission is coded with their own pseudo-random codes. Furthermore, receiver can distinguish the individual user from these special codes. In CDMA, different users overlap both frequency and time domains [33].

CHAPTER FOUR

OFDM and OFDMA

4.1. Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) transmission system which is one of the multi-channel systems provides transmission using multi-carriers. In contrast to classical frequency division systems, sub-carriers are overlapped on the spectrum to provide efficiency from bandwidth [34], [35].

4.1.1. Orthogonality

Orthogonality gains much importance in OFDM systems. Due to this reason, orthogonality of signals must be investigated mathematically and systems should be performed using such mathematical model. The starting point of these mathematical modeling is how two signal becomes orthogonal. These calculations are given below.

Inner product of two signals must be zero to become orthogonal. For instance, assume there are two exponential f and g functions which are defined between 0 and x, and their inner product can be represent with the expression above [36].

$$(f, g) = \int_0^x f(t)\, \overline{g(t)}\, dt \tag{4.1}$$

If there are time-limited complex exponential signals;

$$\left\{e^{j2\pi f_k t}\right\} \begin{matrix} N-1 \\ k=1 \end{matrix} \tag{4.2}$$

Then, the frequencies belonging to different sub-carries are as follows.

$$f_k = {}^{k}/_{T},\quad 0 \leq t \leq T \tag{4.3}$$

The orthogonality;

$$\frac{1}{T}\int_0^T e^{j2\pi f_k t} e^{-j2\pi f_i t}\, dt = \frac{1}{T}\int_0^T e^{j2\pi \frac{k}{T} t} e^{-j2\pi \frac{i}{T} t}\, dt$$
$$= \frac{1}{T}\int_0^T e^{j2\pi \frac{k-i}{T} t}\, dt = \begin{cases} 1, \forall\ integer\ k = i \\ 0, \qquad otherwise \end{cases} \tag{4.4}$$

Orthogonality function could be represented by Equation 4.4. After orthogonality is guaranteed, bandwidth efficiency is ensured by overlapping the sub-carriers with each other.

4.1.2. System Model

Block diagram to show the working principle of OFDM based system is shown in Figure below.

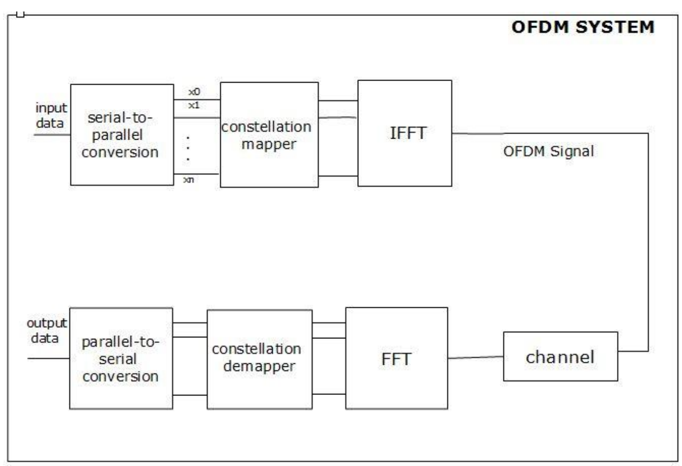


Figure 23: OFDM system.

In transmitter part of OFDM systems, input symbols are firstly converted from series form to parallel form. Then, their domain is also converted from time to frequency by applying inverse fast Fourier transform (IFFT). The next step is putting data in the digital-to-analog converter (DAC) to make data digital. On the receiver side, data is first met the analog-to-digital converter (ADC) to make it analog. Then, it is converted to the frequency domain again by using fast Fourier transform (FFT). Finally, transmitted data is obtained after parallel to series conversion process.

The OFDM signal can be expressed as follows [37].

$$v(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T}, \quad 0 \le t < T \tag{4.5}$$

In Equation 4.5, N is the number of sub-carriers, X_k is the data symbol, T is the symbol time.

One of the important properties of OFDM is cyclic prefix usage. With this cyclic prefix usage, OFDM obtain some advantage which will be mentioned later in this chapter. If cyclic prefix is added to OFDM signal, the equation becomes;

$$v(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T}, \quad -T_g \le t < T \tag{4.6}$$

In this equation, T_g represents the guard interval length. Cyclic prefix is transmitted in the duration of T_g.

As understood from Equations 4.5 and 4.6, the signals are low-pass signals. The transmitted signal is generally written as follows.

$$s(t) = Re\left\{v(t)e^{j2\pi kt/T}\right\} = \sum_{k=0}^{N-1} |X_k| \cos\,(2\pi \left[f_c + \frac{k}{T}\right] t + arg[X_k] \tag{4.7}$$

In the Equation 4.7, general transmitted signal for OFDM is shown. f_c is the carrier frequency.

Due to the fact that all sub-carriers are overlapped on the frequency spectrum, there is important efficiency is provided in terms of spectrum. This efficiency difference is shown in Figure 23.

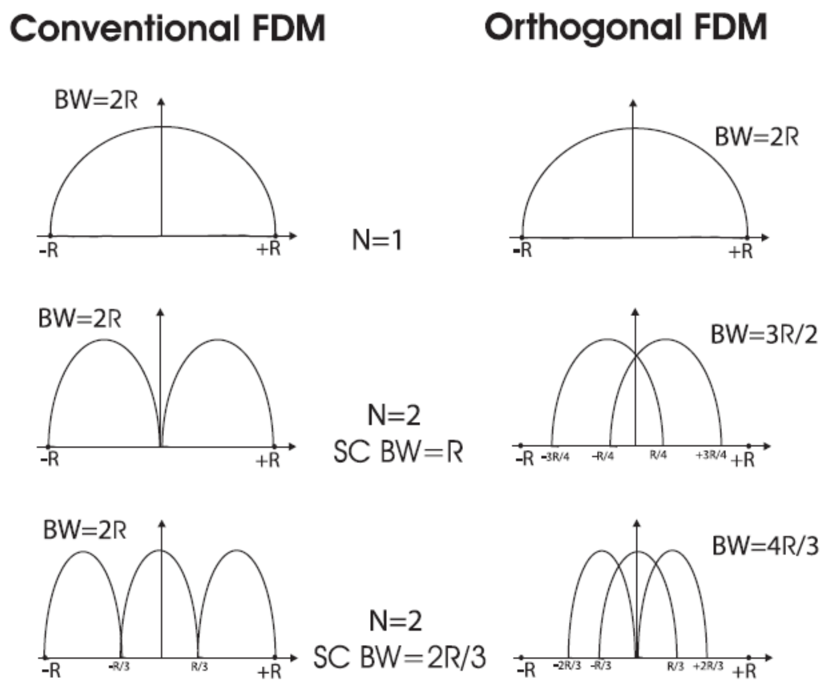


Figure 24: FDM versus OFDM for different number of subcarriers [38].

In the figure above, conventional frequency division multiplexing (FDM) method and orthogonal FDM method are compared with respect to their spectrum efficiencies. It is clearly shown that OFDM system provides much more spectral efficiency than classical FDM systems because of overlapping the sub-carriers.

Figure 23 shows another block diagram belonging to OFDM system, but this figure also shows the adding and removing cyclic prefix which is one of the most important properties of OFDM system.

As mentioned earlier in this chapter, cyclic prefix is used to prevent the system from inter-symbol interference (ISI) kinds of undesired situations. Cyclic prefix (CP) can be added by copying the end of the symbol to the start.

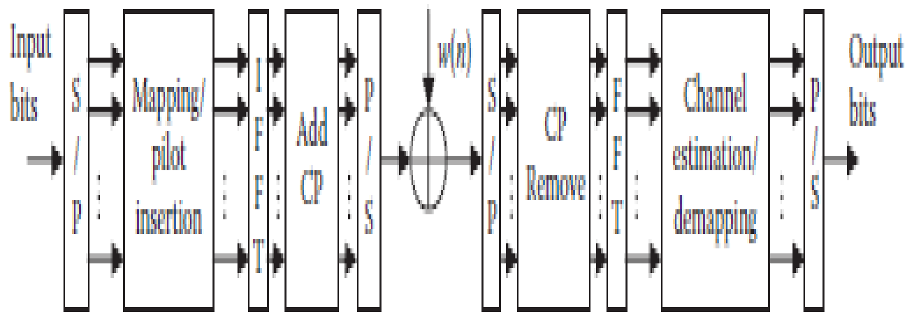


Figure 25: OFDM system with CP [3].

There are several advantages and disadvantages of OFDM system. They can be counted as follows.

Apart from the spectral efficiency, some advantages of OFDM system can be counted as follows. It gives better results about the frequency selective fading than single carrier methods due to its multi-carrier structure. Moreover, the system can be protected well by using OFDM against impulsive parasitic noise and co-channel interference.

As well as it has a lot of advantages, there are also some disadvantages that OFDM system has. Some of these disadvantages can be counted as follows. OFDM system needs RF power amplifiers because it has some noise whose dynamic ranges are large. Furthermore, single carrier techniques are more resistant to carrier frequency offset and drift.

However, when advantages and disadvantages of OFDM system is compared, advantages always more than disadvantages. Because of this, it is very commonly used in communication area.

There are numerous application areas belonging to OFDM system such as digital radio broadcasting, future mobile communication technologies; for instance 4G, WiMAX, and ADSL.

4.1.3. Bit-Error Rate (BER) and Signal-to-Noise Ratio (SNR)

Bit-Error-Rate (BER) is very important concept for communication systems to specify the system performance. It gives really important information about the quality of the communication systems. Basically, BER is the ratio between the number of bit errors and total number of bits that are transmitted within a certain time interval. This bit errors occur because of some undesired parameters such as noise and interference.

As understood its definition, when the value of BER increases, system quality decreases. In other words, higher BER value means lower system performance. Because of this reason, the main focus for almost every communication systems is decreasing BER value.

If Additional White Gaussian Noise (AWGN) is assumed for MQAM modulation technique, BER can be calculated as follows.

$$P(e|MQAM) = 2\left[1 - \frac{1}{\sqrt{M}}\right] erfc\left(k\sqrt{\frac{E_s}{N_0}}\right) - \left(1 - \frac{2}{\sqrt{M}} + \frac{1}{M}\right) erfc^2\left(k\frac{E_s}{N_0}\right) \qquad \textbf{(4.8)}$$

where E_s represents the energy per symbol. Then, $\frac{E_s}{N_0}$ ratio can be written in terms of $\frac{E_b}{N_0}$ ratio as follows.

$$\frac{E_s}{N_0} = \frac{E_b}{N_0} log_2 M \qquad \textbf{(4.9)}$$

where $\frac{E_b}{N_0}$ represents energy per bit to noise power spectral density ratio.

Signal-to-Noise Ratio (SNR) is another important evaluation factor for communication systems. It gives some information about the system performance. It is basically the ratio between the signal power and noise power. It means that, higher level SNR means better system quality. It can be calculated as follows.

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{4.10}$$

If SNR value is desired to be calculated in dB, the equation regarding this calculation is as follows.

$$SNR_{dB} = 10log_{10}\frac{P_{signal}}{P_{noise}} \tag{4.11}$$

$\frac{E_b}{N_0}$ value is known as normalized SNR, and also SNR per bit. For OFDM system, it can be calculated as follows.

$$\frac{E_b}{N_0} = \frac{E\left\{\left|x_{k,m}\right|^2\right\}}{log_2 M}\frac{P_0}{\sigma_N^2} \tag{4.12}$$

where $\{x_{k,m}\}$ is the symbol set with $m = 1, 2, \ldots, M$. In this equation, M represents the order of the modulation, P_0 represents the average power, and σ_N represents the noise variance.

BER is the probability of an error, which occurs during transmission, theoretically, and this error occurs when $x_{k,m} \neq x_{k,i}$ where $x_{k,i}$ is the transmitted signal. Furthermore, the probability of the error can be calculated as follows [39].

.

$$P_e = P\{M_d(x_{k,n}) < M_d(x_{k,i})\} \tag{4.13}$$

where $x_{k,n}$ is the chosen symbol by the optimum detector at the receiver side, and M_d is the metric distance. This probability defined the BER theoretically.

By using these BER calculations, BER performance for 64-QAM OFDM is plotted under AWGN channel. This graph is theoretical because only above equations are used to calculate BER with different SNR levels.

As understood from this figure, BER performance is increased while SNR level is increasing. In other words, BER performance of the system is directly proportional to SNR level.

For this figure, 10^{-5} BER is achieved when E_b/N_0 is equal to about 14. As mentioned earlier, this figure is plotted using mathematical model of BER and this BER performance can change for different systems. However, the difference between theoretical and practical BER performances must not be so high in order to provide good communication systems.

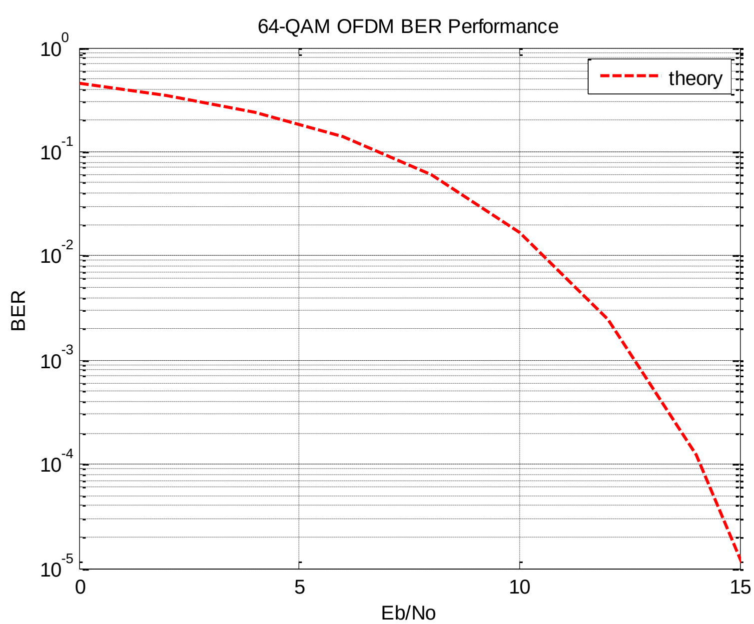


Figure 26: 64-QAM OFDM BER performance.

4.1.4. Channel Coding

Channel coding, which is also called Forward Error Correction (FEC), is very important for all digital communication systems because it allows to obtain less errors while data transmission. There are lots of different coding techniques and they are based on Shannon's limit which states that the probability of error is small if channel capacity is greater than the transmitted information. Otherwise, probability of error at the receiver is not small [40].

Main advanced coding techniques are convolutional coding, Reed Solomon coding, and turbo coding. In this part, these different advanced coding techniques are introduced briefly.

4.1.4.1 Convolutional Coding

In convolutional coding, parity bits are generated using bits to be transmitted. Then, only parity bits are transmitted over a communication channel instead of message bits. In order to perform this process, window is sliding firstly to compute parity bits. In addition to this, number of parity bits is greater than 1.

There are important parameters to specify the coding type which are number of input bits (k), number of output bits (n), and number of memory register (m). There is another parameter in convolutional coding which is constraint length which represents the size of window. Constraint length is calculated as follows.

$$Constraint\ Length\ (K) = k(m-1) \tag{4.14}$$

Furthermore, the code rate can be calculated as $1/r$ where r represents the number of parity bits. There is also polynomial generator which is represented by g. By using message signal and polynomial generator, parity bits can be calculated as follows [38].

$$p_i[n] = mod\ 2\left(\sum_{j=0}^{k-1} g_i[j]x[n-j]\right) \quad \textbf{(4.15)}$$

where $x[n]$ is the message signal. Polynomial generator defines the bits to be added in order to produce parity bits. Hence, selection of polynomial generator is very important. There are some examples regarding polynomial generators found by J. Busgang for $1/2$ code rate. These examples are shown in Figure 26.

Constraint length	G_1	G_2
3	110	111
4	1101	1110
5	11010	11101
6	110101	111011
7	110101	110101
8	110111	1110011
9	110111	111001101
10	110111001	1110011001

Figure 27: Polynomial generators for different constraint lengths [41].

4.1.4.2 Reed-Solomon Coding

Reed-Solomon codes are one of the important error correcting codes. In the process of applying Reed-Solomon codes, extra bits are added to the main message signal in order to detect and recover the data which has errors after transmission.

Reed-Solomon codes are linear and non-binary cyclic codes and defined as (n, k) where n is the total length of code symbols and k is the length of original message signal. Basically, Reed-Solomon codes are the block codes and their structures are shown in Figure 27. As seen from this figure, overall coded signal consists of original message and parity.

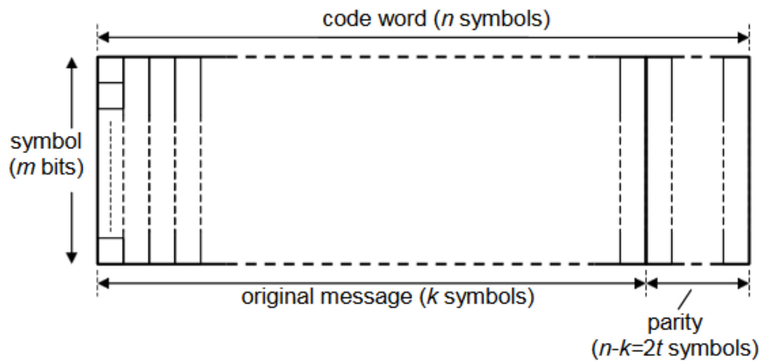


Figure 28: Structure of Reed-Solomon codes [42].

As seen from the figure, there is another parameter in Reed-Solomon coding; number of bits in each symbol (m). Then, there is an important relationship between n and m:

$$n \leq 2^m - 1 \qquad \textbf{(4.16)}$$

The parity length is $2t$ and it can be calculated as $2t = n - k$. For Reed-Solomon coding, t symbols can be corrected.

4.1.4.3 Turbo Coding

There is an important limitation which is power requirement for convolutional and block coding systems. In order to provide Shannon's limit for those systems, long constraint lengths or long blocks are needed. However, decoding such large codes is not practical due to required power.

Turbo coding is one of the solutions for this problem. It can solve the problem by using both recursive coding and iterative soft decoding. Basically, turbo codes are specific version of convolutional coding. At the transmitter side, recursive coding is applied to shorten the constraint length. At the receiver side, estimation of message signal is developed by using iterative decoding [43].

4.2. Orthogonal Frequency Division Multiple Access (OFDMA)

In OFDM systems, broadband channel is divided into narrow band sub-channels to provide to provide spectral efficiency. Orthogonal frequency division multiple access (OFDMA) is basically the multiple access version of OFDM system. As mentioned earlier in this chapter, there is a FFT and IFFT process in OFDM system; hence OFDM system can be applied to multiple access method because of this reason. This multiple access can be done by mapping subset of subcarriers to individual users. Using this principle, more than one data transmission can be achieved simultaneously using same physical medium [44].

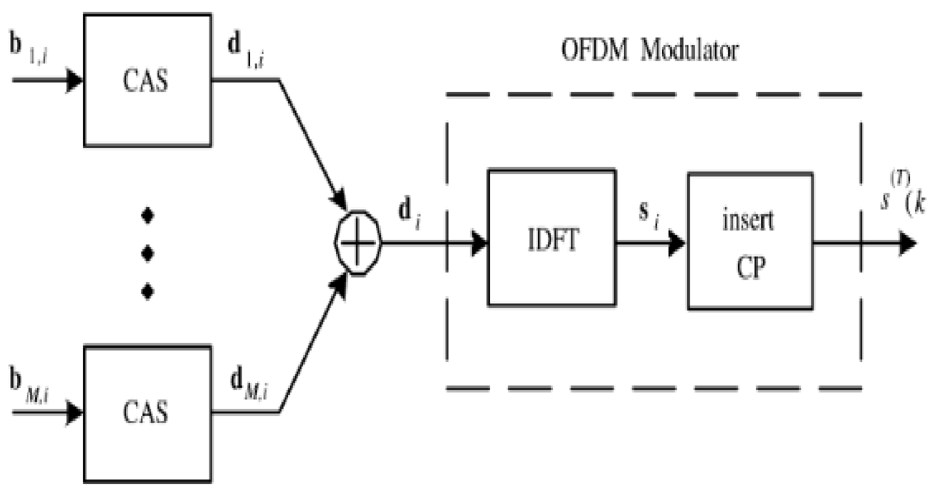
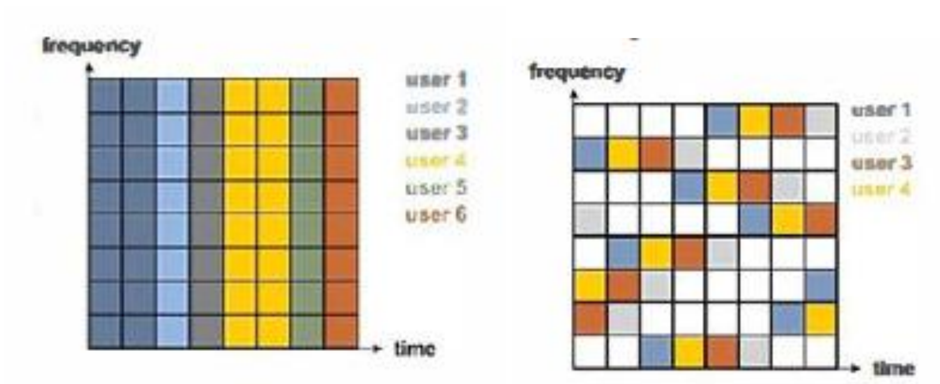


Figure 29: OFDMA downlink transmitter [45].

Figure 28 shows the OFDMA downlink transmitter after channel coding and symbol mapping processes. CAS block shown in the figure stands for carrier assignment scheme. This CAS block assigns the sub-carriers onto different individual users. Then, after combining these signals, the system becomes a classical OFDM system which includes IDFT (Inverse Digital Fourier Transform) and cyclic prefix insertion [45].

Channel estimation is another important step for OFDMA systems. At the transmitter side of the OFDMA system, the reference symbols are added to the data streams to be transmitted. This process is performed to overcome some problems. In OFDMA systems, there are numerous sub-carriers which have amplitudes and phase. All of them are reached to the receiver side. When they received at the receiver side, their phase and amplitudes are arbitrary. Hence, the reference symbols are used to solve this problem. At the receiver side, the reference symbols are compared in order to remove phase and amplitude shifts.

In Figure 29, the main difference between OFDM and OFDMA is shown clearly. As understood from the figure, the main difference between OFDM and OFDMA schemes is mapping sub-carriers to different users. Without this process, the system of OFDMA becomes an OFDM system.



(a) (b)

Figure 30: Difference between OFDM (a) and OFDMA (b) [46].

For multi-user system, OFDM uses Time-Division Multiple Access (TDMA) while OFDMA uses both TDMA and Frequency-Division Multiple Access (FDMA). This means that only one user can transmit data simultaneously in OFDM because of TDMA, however different users can transmit data at the same time in OFDMA due to FDMA.

In OFDM system, data stream is divided into sub-carriers, but only one data transmission can be achieved at the same time. On the other hand, more than one transmission can be achieved using OFDMA based systems.

For the receiver side of OFDMA system, reverse processes of transmitter side are performed respectively such as removing cyclic prefix. This process is shown in Figure 30.

There are some advantages and disadvantages regarding OFDMA system. For example, it offers better coverage using single frequency network coverage. However, it has more sensitiveness to phase noise and frequency offsets.

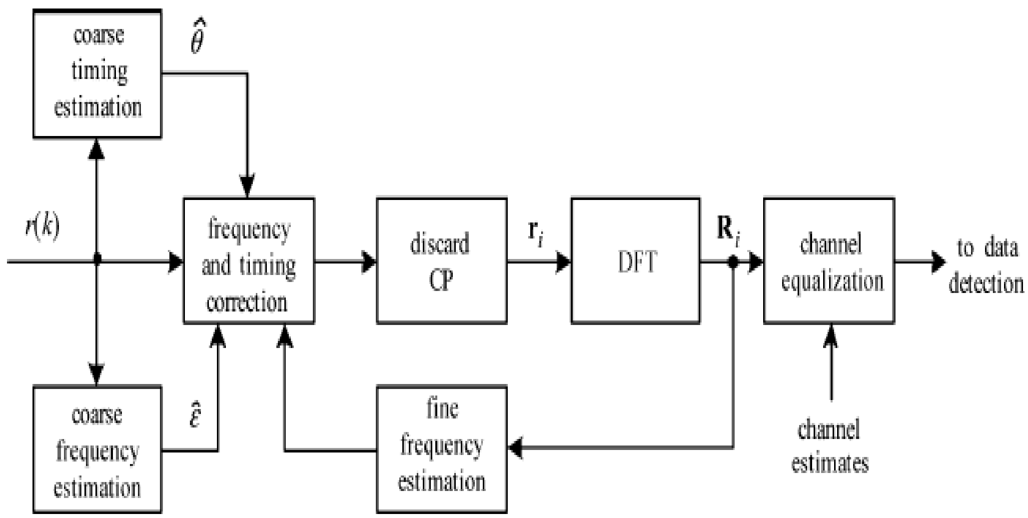


Figure 31: OFDMA downlink receiver [45].

CHAPTER FIVE

VLC SYSTEM DESIGN AND RESULTS

In this chapter, there are simulations studies regarding optical power distribution and OFDM/OFDMA systems. These simulation studies are performed under various conditions.

In optical power distribution part, the main focus is decreasing the dead zones which occur in the receiver plane of communication area. Although the main purpose of the optical power distribution study is dead zone minimization, there are some other studies belonging to optical power. For instance, different conditions that affect the system performances such as LED illumination angle, the distance between the transmitter and receiver, and LED placements are also examined in this part.

Apart from these, other function is defined, which is called as uniformity function, to see the uniformity of the optical power distribution under various conditions. Furthermore, received minimum optical power and received maximum optical power are also investigated. All these parameters will define the quality of the system performance.

Second study area is about the modulation technique. Orthogonal frequency division multiplexing (OFDM) modulation technique, which is the most commonly used multi-carrier modulation scheme, is studied, and this technique is applied to visible light communication (VLC) systems. While applying OFDM system to visible light communication system, quadrature amplitude modulation (QAM) technique is used, and this system is called as M-QAM-OFDM visible light communication system. M value defines the type of QAM method such as 4-QAM and 64-QAM. System performances are examined for 64-QAM OFDM VLC.

In this part, orthogonal frequency division multiple access (OFDMA) which is one of the multi-carrier access method is also examined. This study is performed for 64-QAM OFDMA with multi-user.

5.1. Optical Power Distribution Studies

Optical power distribution is one of the important design parameter for visible light communication systems. It deeply affects system performance because if the receiver plane cannot be covered well, data transmission becomes more difficult, and sometimes it will be impossible. Due to this reason, room ceiling design becomes the vital parameter for communication system. Data transmission cannot be achieved although other parts of communication system are designed well in terms of efficiency and speed. If there is no enough power on the receiver plane, remaining parts of the system do not make any sense.

A car example can be given to make this concept clear. Assume there is a car which is well designed; for example, its engine is very powerful, its fuel efficiency is very good, and its aerodynamic structure is designed using high level engineering. However, fuel is needed essentially to work this well designed car. This is similar with optical communication systems. If there is no optical power, the communication system does not work without considering how its remaining parts designed.

Because of such kind of reasons, optical power distribution is the fundamental study for all optical communication techniques. In addition to this, there are various parameters that define optical power distribution level. Degree of uniformity, received minimum optical power, received maximum optical power, amount of dead zones are some examples of these parameters.

As a brief introduction, degree of uniformity specifies how well optical power distributed to the receiver plane. After obtaining this value, optical power distribution quality is decided. Then, optical power varies on each point of the receiver plane. Some point gets smaller or greater powers than other points. Hence, a certain point receives the maximum power and another certain point receives the minimum power. Received minimum and received maximum optical power values are about this concept. Finally, there occurs not enough power at some points on the receiver plane, and these points are called as dead zones. Less amount of dead zone means better performance.

5.1.1. Uniformity Function

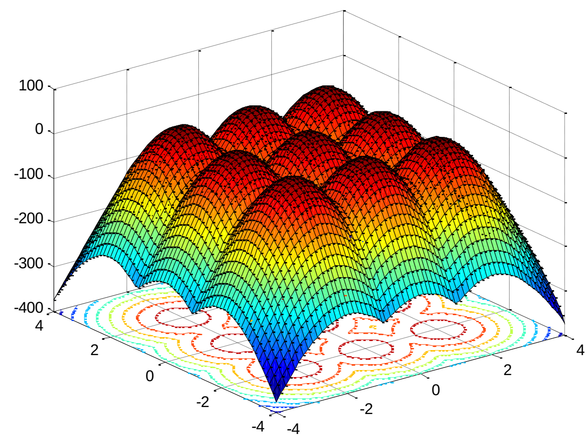
Uniformity function is one of the important parameters for optical power distribution studies. This function specifies how well the optical power distributed on the receiver plane. Uniformity of this distribution gives vital information about the system performance. If this uniformity study is not examined, there may occur huge differences between the point where takes maximum optical power and the point where takes minimum optical power. If the received optical power difference between those points increases, uniformity of the distribution decreases so system performance is affected in a negative way. This affects the system performance deeply because one can reach information easily while other person cannot reach.

This function is a unitless and it gives information about the uniformity of optical power distribution value. The higher value of this function means the better optical power distribution. This function will be denoted as u.

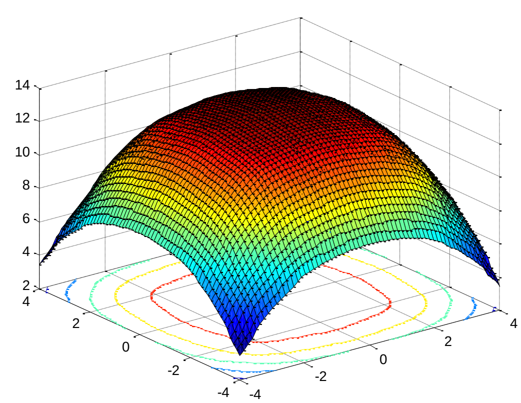
$$u = 10\log\left(\frac{P_{min_{dBm}}}{P_{max_{dBm}}}\right) \quad \textbf{(5.1)}$$

As understood from the Equation 5.1, uniformity function is directly proportional to received minimum optical power and received maximum optical power. As mentioned earlier in this section, if received maximum power is much greater than received minimum optical power; in other words, if the difference between those values is huge, u value becomes smaller. Small u value means bad system performance and bad coverage.

In Figure 31, optical power distributions for two different conditions are shown. Assume Figure 31 (a) is for Condition 1 and Figure 31 (b) is for Condition 2. As shown clearly from those figures, Condition 2 gives much better results because its uniformity is much better than Condition 1. In Condition 1, there are enough powers for most points, but some points cannot take any power. Also, optical power is varying for different points. However, there is almost no point which does not take enough power, and optical power for the receiver plane is almost constant for each point.



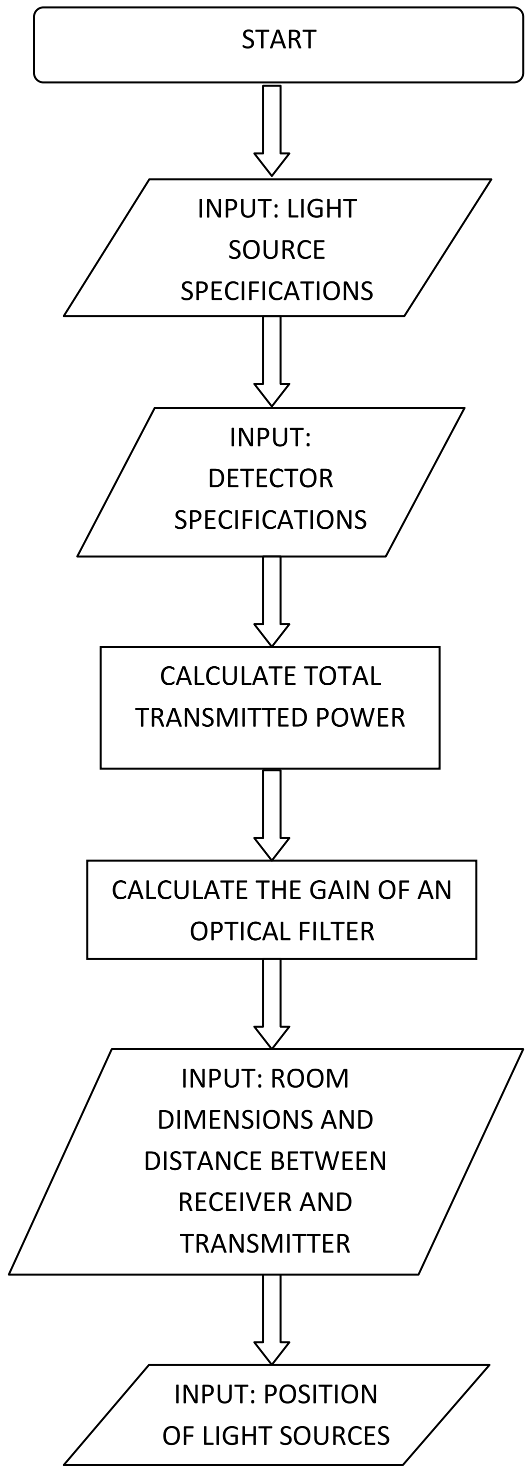
(a)



(b)

Figure 32: Optical power distributions for (a) Condition 1 and (b) Condition 2.

5.1.2. Calculation Algorithm for Received Optical Power



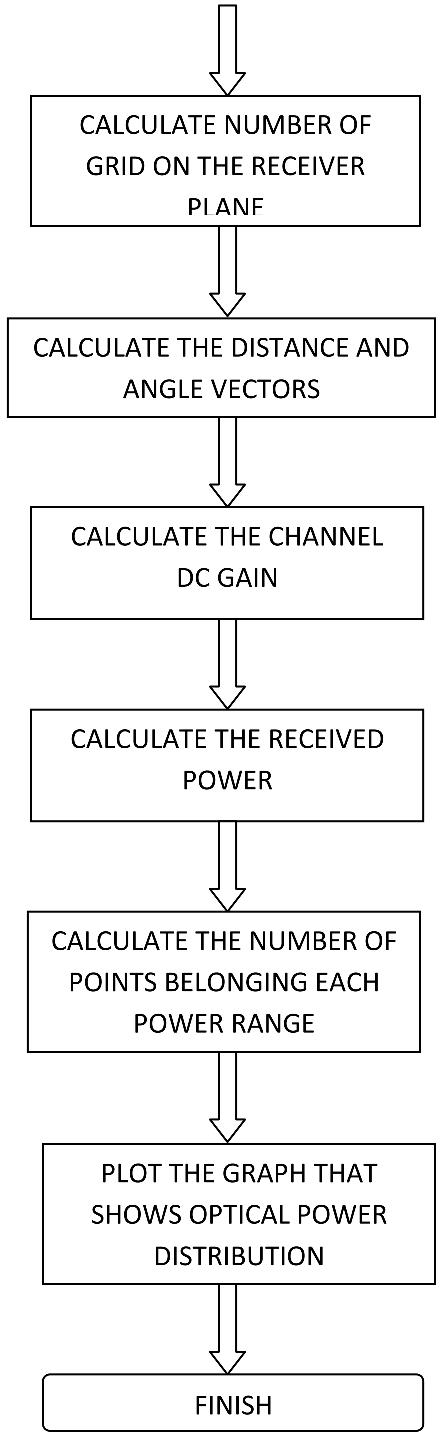


Figure 33: Flowchart of the simulation.

5.1.3. Transmitter and Receiver Specifications

Cree Company's CP41B-WES series LEDs are used in this study. Specifications regarding these LEDs are given in Table 1.

Table 1: Specifications of CP41B-WES.

Parameter	Value
Forward Current	35 mA
Peak Forward Current	100 mA
Reverse Voltage	5 V
Power Dissipation	154 mW
Luminous Flux	7000 mlm @ 30 mA forward current
Luminous Intensity	5200 mcd @ 30 mA forward current
50% Power Angle	60 degree @ 30 mA forward current

Photo-detector specifications which are given in [3] are used in this study. These specifications are given in the table below.

Table 2: Photo-detector specifications.

Parameter	Value
Active Area	1 cm^2
Half Angle FOV	60 degree
Elevation	90
Azimuth	0
Δt	0.5 ns

All these LED and photo-detector specifications are used in the simulation model. These parameters are the inputs that are written on the flow chart which is given in the previous section. After deciding which light source and which detector is used, received optical power can be calculated easily.

5.1.4. Different LED Placements on the Room Ceiling

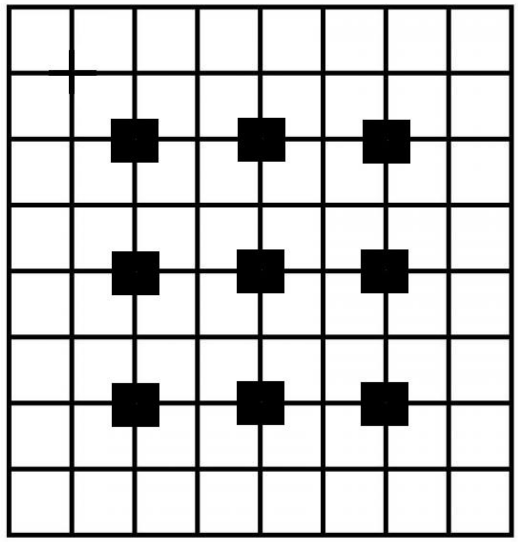


Figure 34: Layout 1

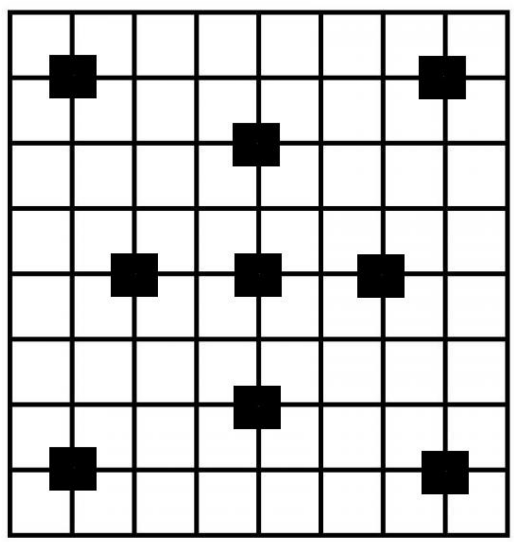


Figure 34: Layout 2

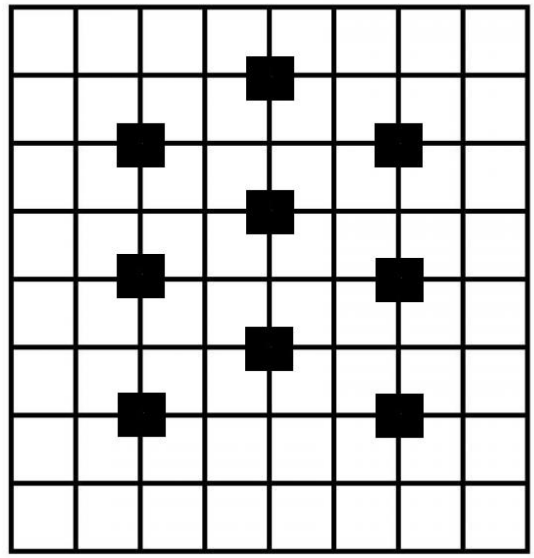


Figure 35: Layout 3

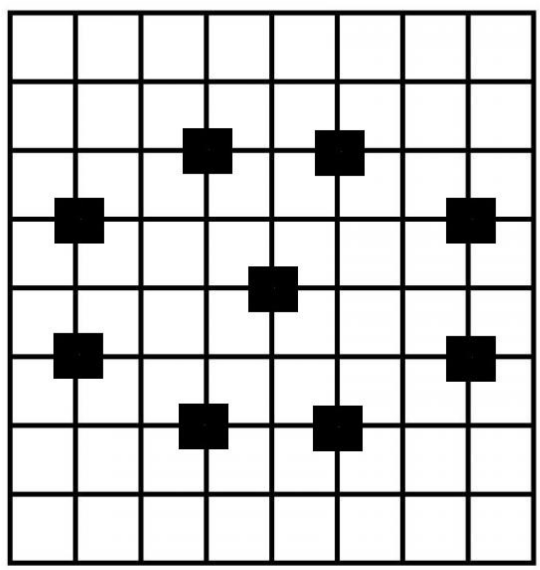


Figure 36: Layout 4

Figure 33, 34, 35, and 36 show four different LED layouts. Firstly, a room, where visible light communication happens, is assumed, and LEDs are installed on the ceiling of the room using these four layouts. Values regarding room dimensions and number of LEDs are given in the table below.

Table 3: Room dimensions and number of LEDs.

Parameter	Value
Width of the Room	$8\ m$
Length of the Room	$8\ m$
Height of the Room	$3\ m$
Number of LED Arrays	9
Number of LEDs per Array	$60\ \times 60 = 3600$

Parameters given in Table 3 are used in simulation study. These and other parameters are kept constant during simulating four different layouts in order to observe the effects of layouts alterations.

Four different factors are tried to observe to decide which layout gives the best results. The evaluation points are as follows.

1) Number of dead zones
2) Value of the uniformity function
3) Received minimum optical power
4) Received maximum optical power

Layout 1, Layout 2, Layout 3, and Layout 4 are compared with respect to evaluation factors mentioned above. These simulations are performed using MATLAB software.

The main purpose of this study is minimizing the number of dead zones, however other three evaluation points are considered because they also specify the quality of the system performance.

5.2. 64-QAM OFDM/OFDMA VLC Studies

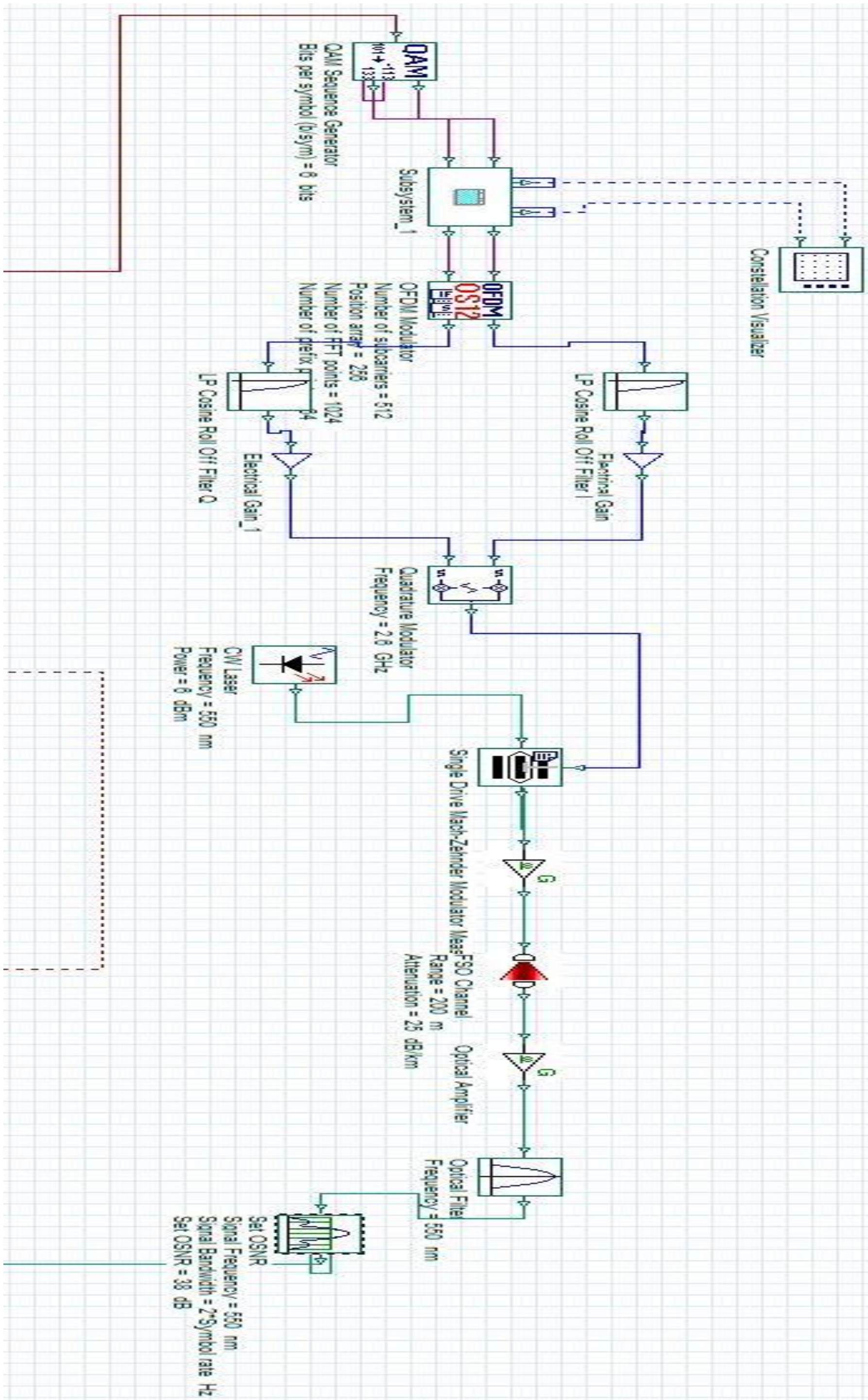


Figure 37: 64-QAM OFDM system - Transmitter

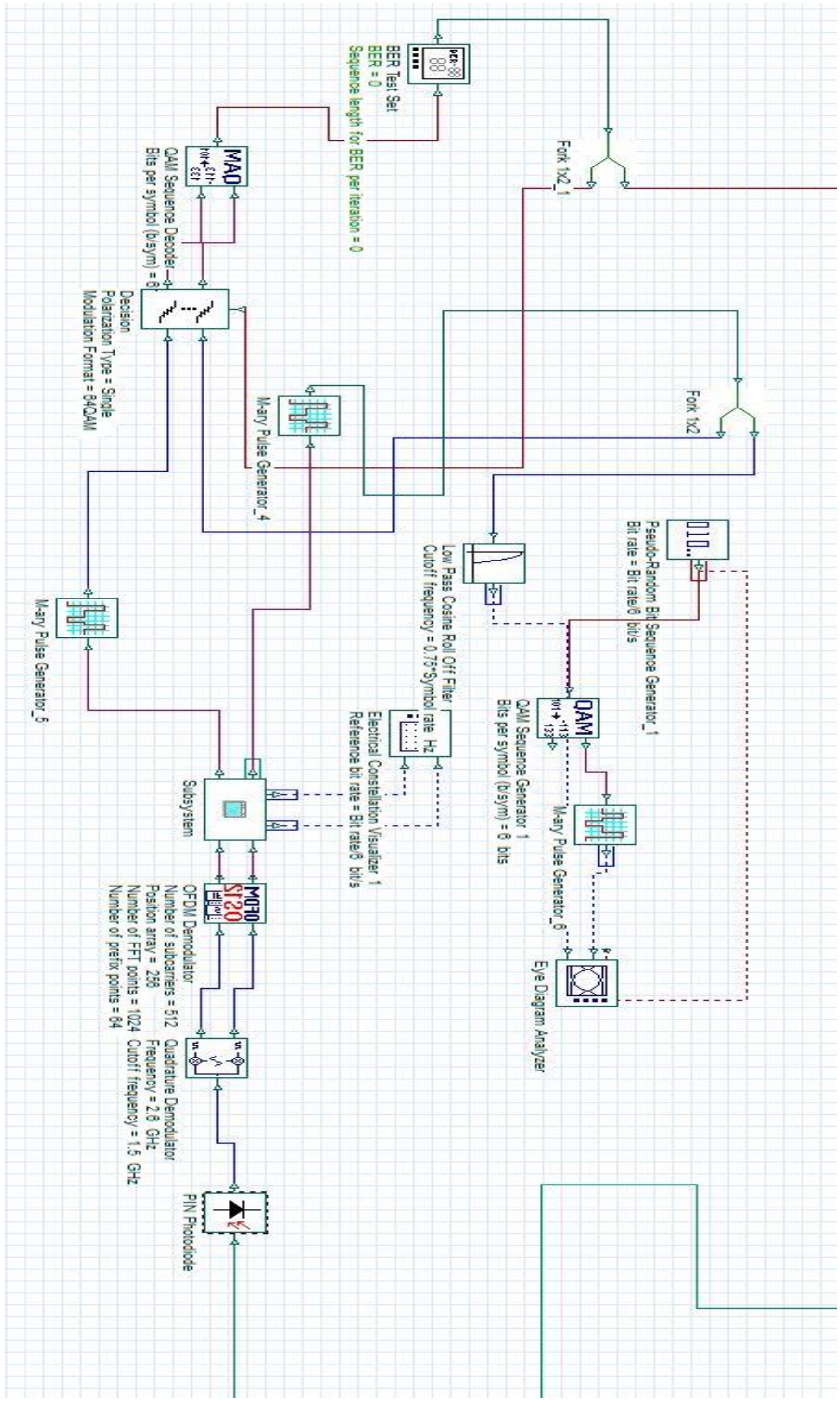


Figure 38: 64-QAM OFDM system - Receiver

The second study which is performed in this thesis is 64-QAM OFDM system for visible light communication. To construct this system, OptiSystem simulation software which is produced by Optiwave Company is used.

Simulation study is performed using one transmitter and one receiver. All detailed parts of this system will be introduced as follows.

5.2.1. Transmitter Side

In this part, all of the components which are used in transmitter side of MQAM OFDM system will be defined.

5.2.1.1 Pseudo Random Bit Generator (PRBG)

Bit sequences that will be transmitted are generated using Pseudo Random Bit Generator (PRBG) block. This block generates bits randomly, but user cannot select the mark probability according to a certain study. In other words, this software sets the probability of 1s and 0s as 0.5. It means that, number of 1s is equal to number of 0s after completing the simulation. In Figure 37, PRBG block is shown.

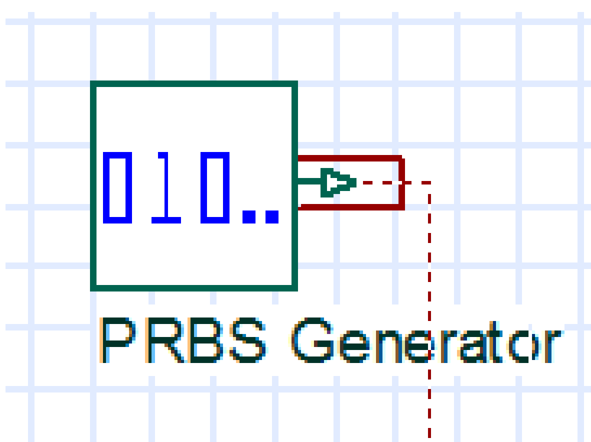


Figure 39: PRBG block.

.

To choose the bit sequence, there is another bit generator in this software. It is named as User Defined Bit Generator (UDBG). By using this bit generator, user can select the specific bits to be transmitted. For example, user can choose the sequence as ‘1100101011’, and each time UDBG generates these bits.

5.2.1.2 QAM Sequence Generator

In OFDM system, M-ary symbol sequences are needed instead of binary bit sequences. In order to achieve this, QAM Sequence Generator block is used. It converts binary signals to M-ary symbols. There is one input and two outputs belonging to this block. Input takes binary bits and the outputs give in-phase (I) and quadrature (Q) components of M-ary symbol. To perform this conversion, quadrature amplitude modulation (QAM) is used.

In order to specify M value of MQAM, bit per symbol (b/sym) can be entered by user. For instance, if b/sym is 2, it becomes 2QAM.

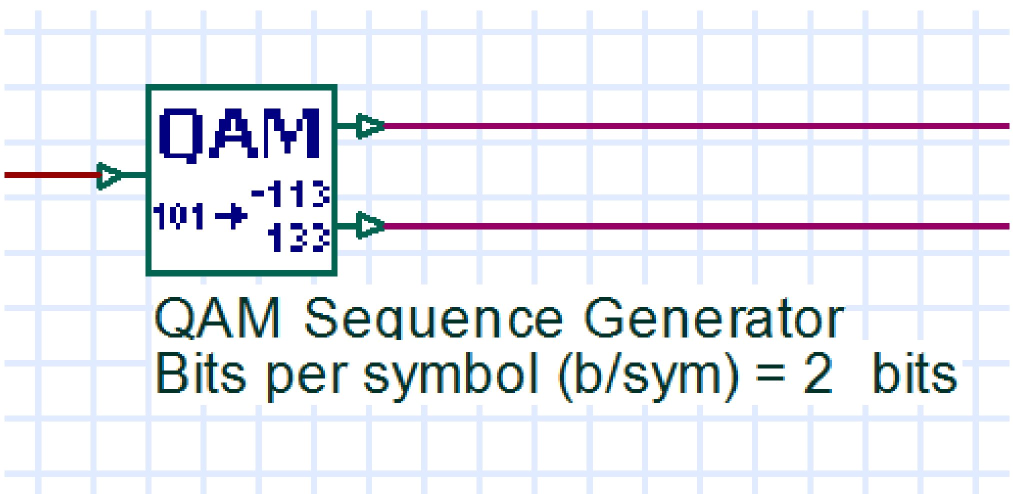


Figure 40: QAM sequence generator.

5.2.1.3 OFDM Modulator

This block is one of the most important blocks in this simulation system because OFDM modulation is performed in this block. M-ary symbols which are generated by QAM Sequence generator block become input for OFDM Modulator. This block takes those M-ary signals and converts them into orthogonal sub-carriers. It has two inputs and two outputs. While input signals are M-ary, output signals are electrical signals. Similarly, the output signal consists of in-phase (I) and quadrature (Q) components.

Table 4: OFDM Modulator parameters.

Parameter	Value
Number of Sub-Carriers	128
Position Array	400
Number of FFT points	1024
Cyclic Prefix	Symbol Extension

Parameters which are used in OFDM Modulator is given in Table 4.

5.2.1.4 Low-Pass Cosine Roll Off Filter

There is a filter used in transmitter part of the overall system. This filter is known as Low-Pass (LP) Cosine Roll Off Filter. This filter applies the cosine roll off frequency transfer function to incoming electrical signal, and then gives filtered electrical output.

The frequencies between the certain frequencies, which are f_1 and f_2, can pass from this filter. This frequencies are calculated as follows.

$$f_1 = 1 - r_p f_c \,, \quad f_2 = 1 + r_p f_c \qquad (5.2)$$

In Equation 4.2, r_p is the roll off factor and f_c is the cutoff frequency. Both these parameters can be specified by user. Cutoff frequency is adjusted to 25 GHz while roll of factor is 0.2.

Outputs of OFDM Modulator (I and Q components) are passed through this filter.

5.2.1.5 Quadrature Modulator

As mentioned earlier, the signal to be transmitted must modulated by multiplying with high frequency carrier signal. This is done because signals are mostly in the baseband, but they must be transformed to the passband. This is performed by multiplying baseband signal with sinusoidal carriers.

Quadrature Modulator block is responsible for this process. Output of the filter comes to this block, then I component is multiplied with cosine signal while Q component is multiplied with sine signal. Frequency of this modulator is selected as 30 GHz.

The block has two input and one output ports. Frequency, phase, and gain can be selected by user.

5.2.1.6 LiNb MZ Modulator

Lithium Niobate Mach-Zehnder Modulator performs optical modulation process. This modulator has three input port and one output port. One of these input ports is optical and other two inputs are electrical. The output is also optical signal. The optical input is supplied by the light source which is laser for this study. This incoming light is modulated using OFDM based electrical signal.

Detailed information regarding Mach-Zehnder optical modulator is given in Chapter3.

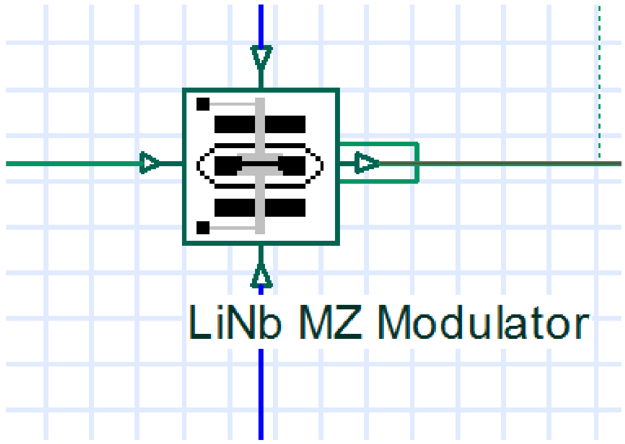


Figure 41: LiNb MZ modulator.

5.2.1.7 CW Laser

Continuous Wave Laser (CW Laser) is one of the light sources used in OptiSystem software. This component produces a continuous wave laser light, and then this light goes to the MZ modulator. There is only one output and no input for this component.

The software allows choosing frequency, power, linewidth, and other parameters. Parameters belonging to CW Laser are given in Table 5.

Table 5: CW Laser parameters.

Parameter	**Value**
Frequency	$550\ nm$
Power	$-4\ dBm$
Linewidth	$300\ THz$

Frequency and linewidth parameters are adjusted to cover whole visible light region.

5.2.2. Channel

Table 6: FSO Channel parameters.

Parameter	**Value**
Range	$200\ m$
Attenuation	$25\ dB/km$
Transmitter Aperture Diameter	$5\ cm$
Receiver Aperture Diameter	$20\ cm$

There are various channel types in OptiSystem software such as optical wireless communication (OWC) channel, free space optics (FSO) channel, and diffuse channel. In this study, free space optics channel is used, and parameters belonging to this channel are given in Table 6.

5.2.3. Receiver Side

In receiver side of the communication system, reverse processes of transmitter part are performed. The components belonging to receiver side are given as follows.

5.2.3.1 Avalanche Photodiode (APD)

Avalanche photodiode (APD) converts the optical signal to electrical signal. Optical signal which is generated by light source is taken by APD after passing through the FSO channel. APD has one input and one output. Parameters are as follows.

Table 7: APD parameters.

Parameter	Value
Gain	10
Responsivity	1 A/W
Ionization Ratio	0.9

5.2.3.2 Quadrature Demodulator

Quadrature Demodulator block demodulates the electrical signal obtained from APD. It has one input and two outputs which are in-phase (I) and quadrature (Q) components. Frequency of the demodulator must be equal to frequency of Quadrature Modulator. This frequency is selected as 30 GHz in both modulator and demodulator.

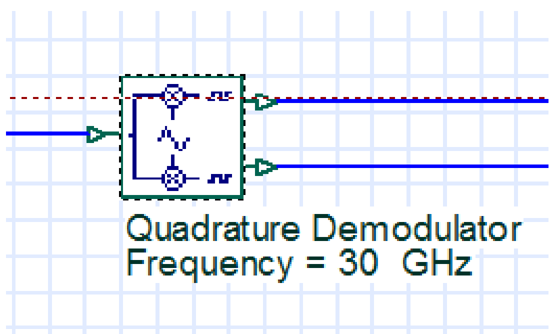


Figure 42: Quadrature demodulator.

5.2.3.3 OFDM Demodulator

This OFDM Demodulator component is used to demodulate the OFDM signal into digital signal. Its parameters are same with OFDM Modulator.

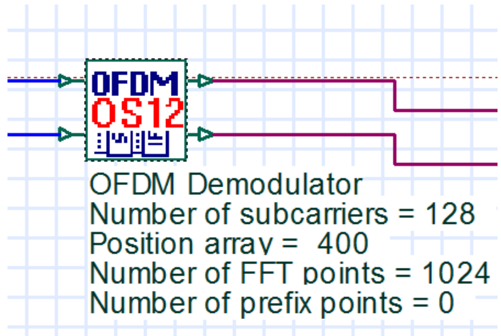


Figure 43: OFDM demodulator.

5.2.3.4 QAM Sequence Decoder

QAM Sequence Decoder component converts two M-ary signals into binary signal. Similarly, its parameters must be equal to parameters entered in QAM Sequence Generator.

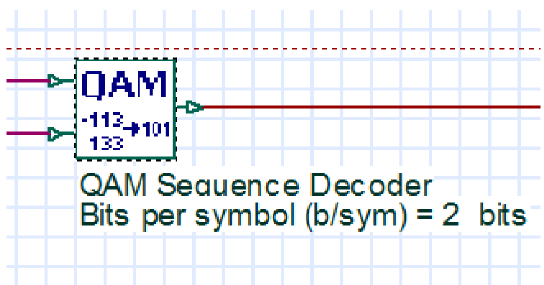


Figure 44: QAM sequence decoder.

5.2.4. Global Parameters

Global parameters used in this study are given in Table 8.

Table 8: Global parameters.

Parameter	Value
Bit Rate	10 Gbit/s
Time Window	$1.6384 \times 10^{-6}\ s$
Sample Rate	$160\ GHz$
Sequence Length	16384 bits
Samples per Bit	16
Symbol Rate	$2.5 \times 10^{9}\ symbols/s$

5.2.5. System Configuration

After introducing all parts of the system, Figure 43 shows the combination of all these components.

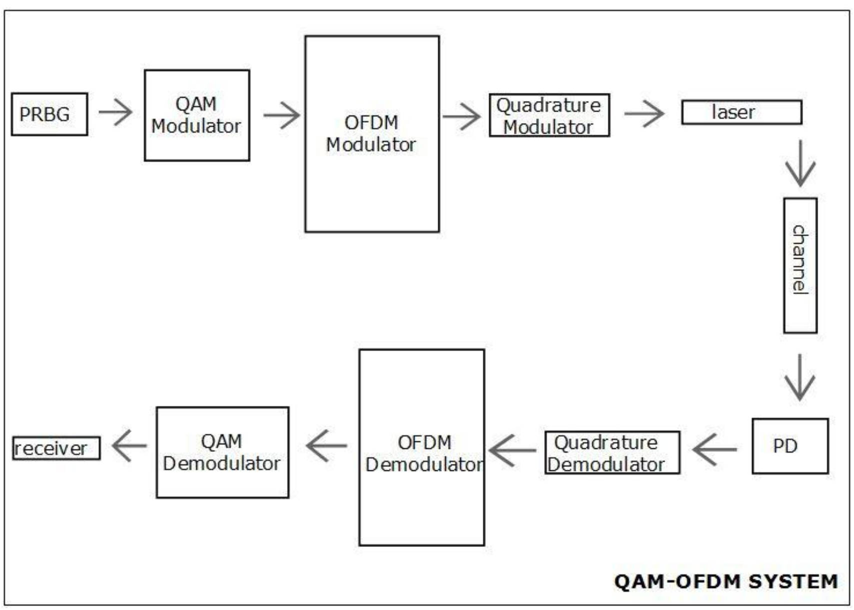


Figure 45: MQAM OFDM VLC system.

5.2.6. Proposed System

The following studies are performed in this thesis, respectively.

- 64-QAM OFDM system is constructed.
- 64-QAM OFDM systems are simulated.
- Results are analyzed and compared.
- 64-QAM OFDMA system is constructed.
- System is simulated for different number of users.
- Results belonging to 64-QAM OFDMA system are obtained.
- These results are compared in terms of the system performances.

5.3. Results and Discussions

In this chapter, obtained results including optical power distribution, MQAM OFDM VLC system, and MQAM OFDMA VLC system are given, respectively.

First study is about optical power distribution. In this study, four different LED placements are simulated in terms of their distribution performances. These four different LED placements are named as Layout 1, Layout 2, Layout 3, and Layout 4.

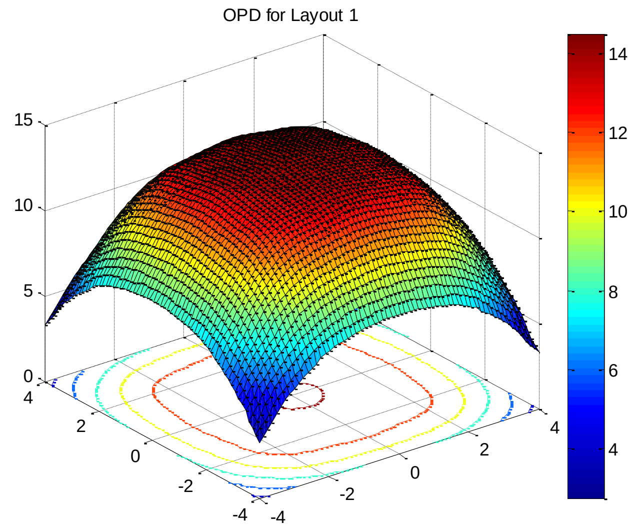
The evaluation parameters are given in Chapter 4; received minimum optical power, received maximum optical power, degree of uniformity, and number of dead zones. In this part, there are results about these parameters.

Second study is about the MQAM OFDM visible light communication system. Different MQAM OFDM VLC systems are constructed by changing M value. After constructing 4QAM OFDM, 16QAM OFDM, and 64QAM OFDM systems for visible light communication systems, their system performances are investigated. After that, comparisons regarding their performances are done in order to observe the effect of M value.

The third study is about MQAM OFDMA visible light communication systems. As mentioned earlier, OFDMA is the multi-user version of OFDM. For this study, different number of users is assumed, and effects of number of users are investigated.

For optical power distribution study, MATLAB software is used to perform the simulations. For MQAM OFDM VLC and MQAM OFDMA VLC systems, OptiSystem simulation platform is used.

In Graphs 1, 2, 3, and 4, optical power distribution performances of all layouts are shown clearly. 5 dB is selected as a threshold value, and the points that are received powers under 5 dB is named as dead zone.

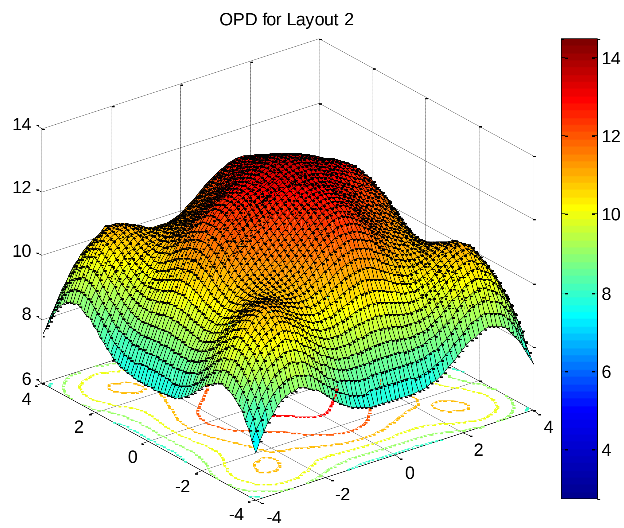


Graph 1: Optical power distribution for Layout 1.

Table 9: Results for Layout 1.

Parameter	**Value**
Uniformity	-24.9903
Minimum Received Power	3.3148 dBm
Maximum Received Power	14.1679 dBm
Mean of the Received Power	14.0788 dBm
Number of Dead Zones	60

Graph 1 and Table 9 give the results for Layout 1. As understood from Graph 1, some dead zones, which are represented by dark blue, occur on the receiver plane. This is because its received minimum optical power is under the upper limit of dead zone. Although this layout looks geometrically proper, its degree of uniformity is low which is -24.9903.

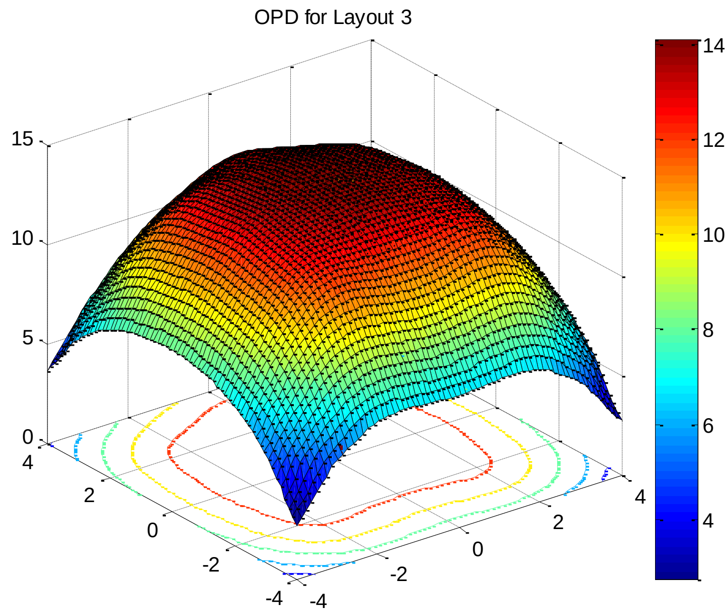


Graph 2: Optical power distribution for Layout 2.

Table 10: Results for Layout 2.

Parameter	**Value**
Uniformity	-13.9482
Minimum Received Power	7.4663 dBm
Maximum Received Power	13.5240 dBm
Mean of the Received Power	12.4109 dBm
Number of Dead Zones	0

Graph 2 and Table 10 show results for Layout 2. From Graph 2, there is no dark blue points on the receiver place. This means that no dead zones occurs. In other words, dead zones of Layout 1 are minimized by changing the LED placements. Also, degree of uniformity is improved from -24.9903 to -13.9482; it almost doubles. There is another good improvement in Layout 2 when it is compared to Layout 1: received minimum optical power. However, Layout 1's received maximum optical power and mean of the received power values are better than Layout 2, but they are very close to each other.

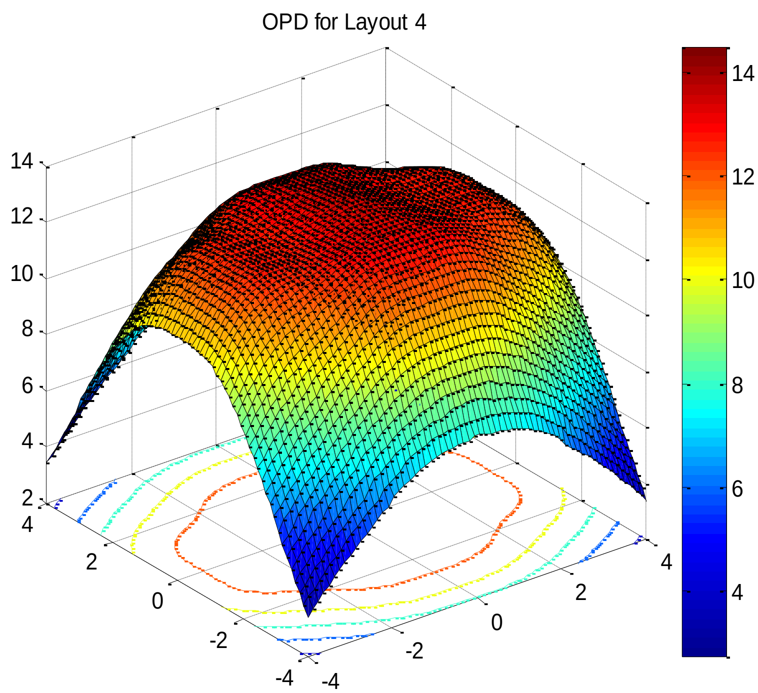


Graph 3: Optical power distribution for Layout 3.

Table 11: Results for Layout 3

Parameter	**Value**
Uniformity	−26.1362
Minimum Received Power	2.7515 dBm
Maximum Received Power	14.1023 dBm
Mean of the Received Power	13.9133 dBm
Number of Dead Zones	74

Graph 3 and Table 11 gives the results for Layout 3. By considering Graph 3, it is very similar to Layout 1, but their parameters are different. Similarly, there are some dark blue points on the receiver plane and dark red points which means high optical power. Degree of uniformity value of Layout 1 and Layout 3 are almost same. Their maximum received power and mean of the received power values are also close to each other. On the other hand, received minimum optical value of Layout 3 is lower than Layout 1. This causes greater number of dead zones on the receiver plane. It is already increased from 60 to 74.



Graph 4: Optical power distribution for Layout 4.

Table 12: Results for Layout 4.

Parameter	Value
Uniformity	-23.2749
Minimum Received Power	3.4280 dBm
Maximum Received Power	13.5362 dBm
Mean of the Received Power	13.3985 dBm
Number of Dead Zones	88

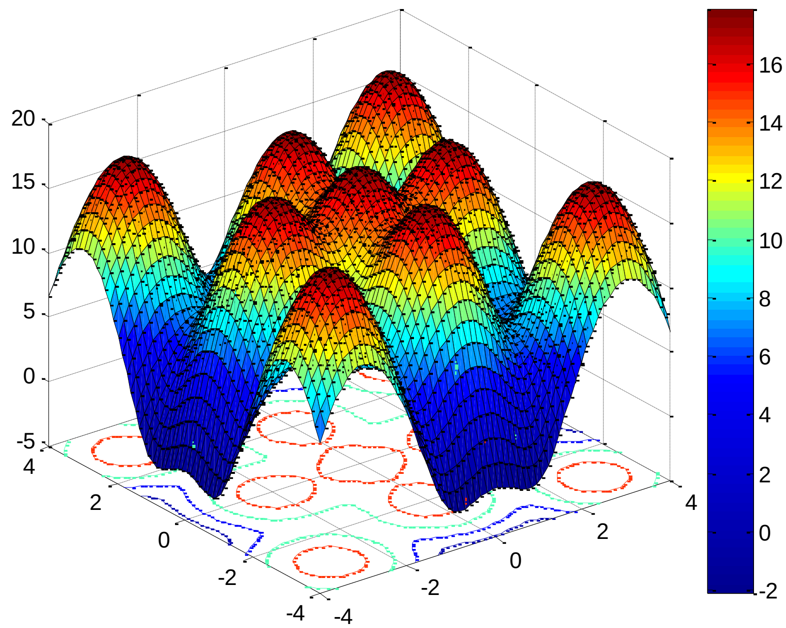
Graph 4 and Table 12 demonstrate the results belonging to Layout 4. Results are very close to ones in Layout 1 and Layout 3. Degree of uniformity, received maximum optical power, mean of the received optical power parameters are almost same for Layout 1, Layout 3, and Layout 4. However, received minimum optical power value of Layout 4 is different than others. In addition to this, number of dead zones for Layout 4 is 88 which is the worst result among four layouts.

This results show that, number of dead zones can be decreased by changing the LED placement on the ceiling, even it can be canceled. By arranging the LED positions, dead zone minimization can be performed.

If received minimum optical power and degree of uniformity is considered, Layout 2 gives much better results than other layouts. For the maximum received power, each layouts give close results which is about 13.5 dBm.

As a result, Layout 2 can be chosen as a best layout between these four layouts. Received minimum power and degree of uniformity parameters are improved crucially. Furthermore, number of dead zones is minimized.

After this study, Layout 2 will be the base of further researches such as effects of LED's illumination angle and distance between receiver and transmitter. Firstly, LED's illumination angle for Layout 2 is decreased to 20^0. Results are as follows.



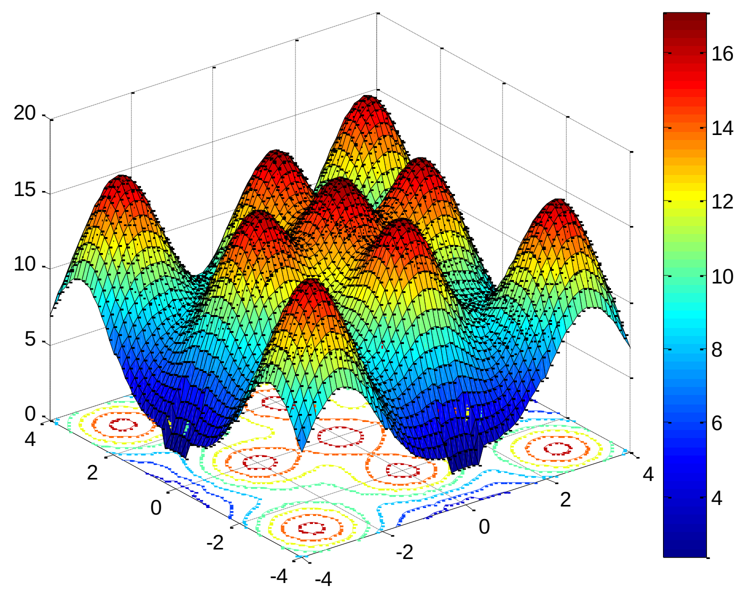
Graph 5: Optical power distribution for Layout 2 at 20^0.

Table 13: Results for Layout 2 at 20^0.

Parameter	**Value**
Uniformity	-45.9134
Minimum Received Power	-2.0674 dBm
Maximum Received Power	17.8725 dBm
Mean of the Received Power	18.3242 dBm
Number of Dead Zones	544

As understood from the results, almost all parameters are gotten worse. For example, number of dead zones increased sharply from 0 to 544. Only, received maximum power is increased, but this does not make any sense for lots of application. To sum up, if LED's illumination angle decreases, system performance also decreases.

Secondly, distance between transmitter and receiver (h) is changed by keeping the LED's illumination angle constant. It is decreased from 2.25 m to 1 m. Results are as follows.



Graph 6: Optical power distribution for Layout 2 for h=1 m.

Table 14: Results for Layout 2 for h=1 m.

Parameter	Value
Uniformity	-33.9401
Minimum Received Power	2.3761 dBm
Maximum Received Power	17.1161 dBm
Mean of the Received Power	15.5265 dBm
Number of Dead Zones	216

As understood from the figures, decreasing the distance between receiver and transmitter affect the system performance in a negative way because number of dead zones is increased deeply while degree pf uniformity decreases.

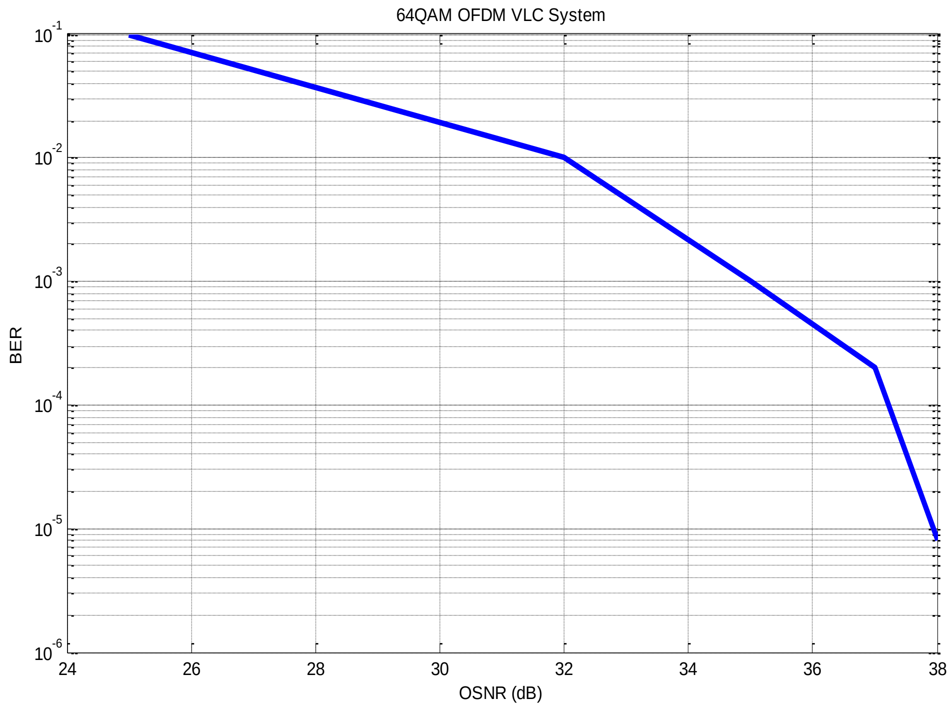
In the second part of the study, 64QAM OFDM system is constructed for visible light communication. System is constructed using OptiSystem 13.0 version.

Different Optical Signal-to-Noise Ratio (OSNR) values are used in order to obtain bit-error-rate (BER) of the system. BER vs OSNR graph is plotted to observe the required OSNR value for acceptable BER values.

There is an important limitation of the system on BER values. While the sequence length of the system is 131072, in other words 131072 bits are transmitted, minimum BER in the 10^{-5} level. The sequence length is in the 10^{5} level and assume that there is a mistake for only one bit which is the best case for transmission with error. Hence, BER value becomes:

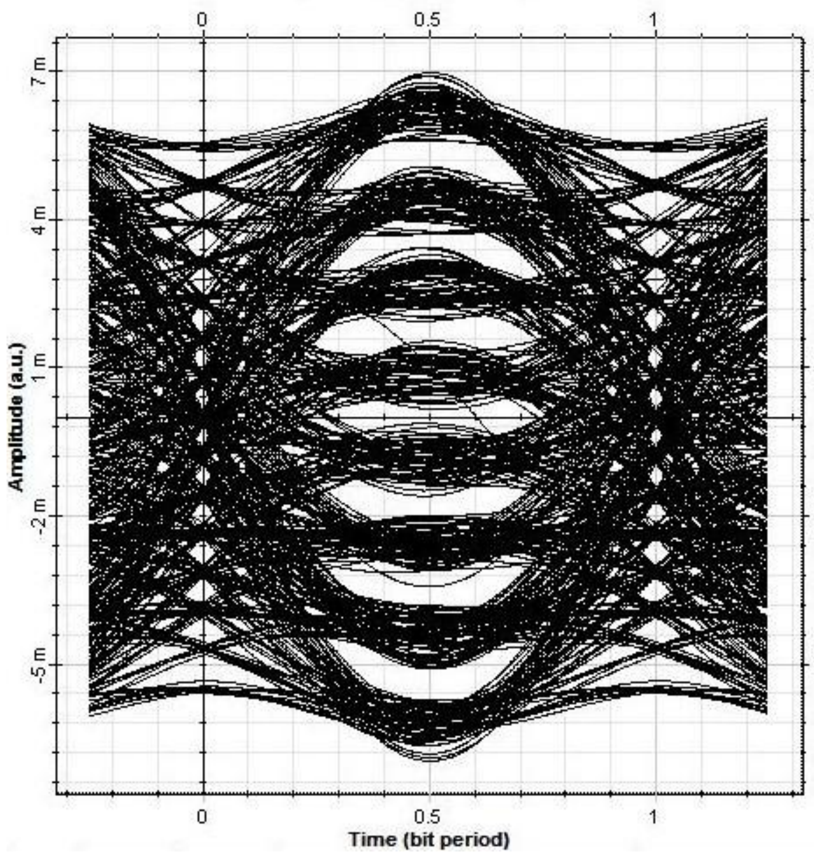
$$BER = \frac{Number\ of\ bit\ errors}{Number\ of\ total\ bits} = \frac{1}{10^5} = 10^{-5} \qquad \textbf{(6.1)}$$

If number of bit errors is decreased from this point, it becomes zero bit errors. If there is no error for the transmission, BER will be equal to 0 according to Equation 5.1. Because of this reason, after 10^{-5} level, BER value drops to 0.



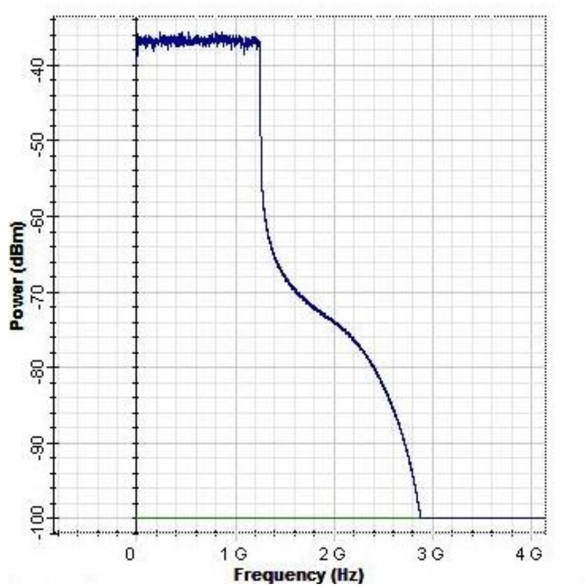
Graph 7: BER vs. OSNR for 64QAM OFDM VLC system.

In Graph 7, BER vs OSNR graph is shown. As seen from the figure, when OSNR=38 dB, BER is 10^{-5}. While OSNR value increases from 24 dB to 38 dB, BER value decreases from 10^{-1} to 10^{-5}. This shows that higher OSNR values give lower BER values, in other words better system performances.



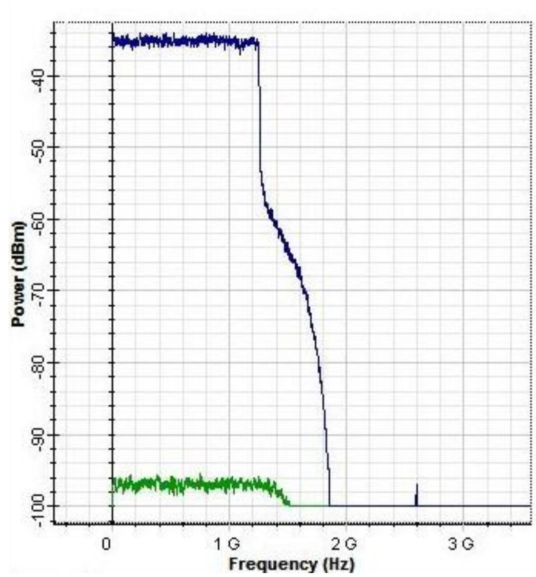
Graph 8: Eye diagram for 64QAM OFDM VLC system.

Graph 8 shows the eye diagram for the system. Ideally, height of eye openings must be equal to eye amplitude. As seen from the figure, eye diagram is obtained clearly. It means that data transmission is performed and data can be detected at the receiver. Half of the eye openings represents the SNR at the sampling point and the best SNR value can achieved at the eye openings. Dark black curves demonstrate the distortion which is set by SNR. In this graph, there are some distortions. Furthermore, slope of the curves gives the sensitivity to timing error. Smaller slope means better results. In this graph, the slope is almost 1.



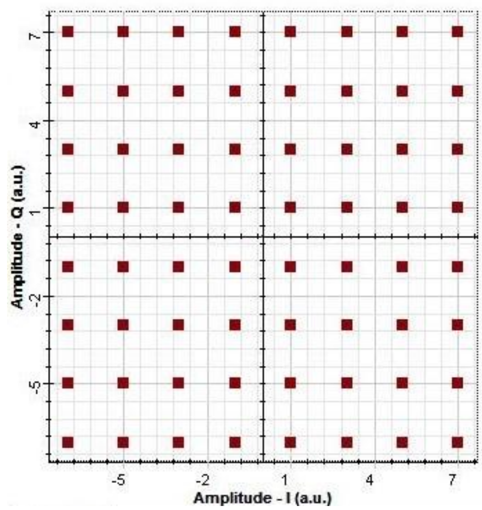
Graph 9: Transmitter RF spectrum.

Graph 9 shows the RF spectrum at the transmitter part of the communication system. Blue one indicates the message signal while green one indicates the noise. As seen from the graph, bandwidth of the signal is almost 3 GHz. Moreover, there is no noise on this graph because the signal has not yet meet the noisy medium.



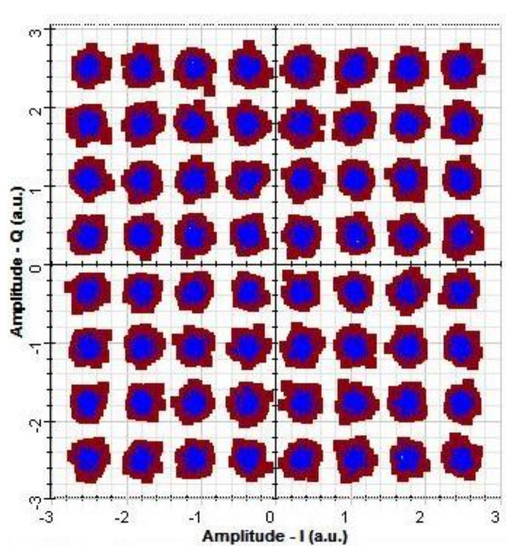
Graph 10: Receiver RF spectrum.

Graph 10 shows the RF spectrum at the receiver side of the communication system. Contrary to Graph 9, there is some noise seen on the graph. This noise affects the performance of the system. This effects can be also seen on the eye diagram.



Graph 11: Constellations from transmitter.

Graph 11 demonstrates the constellation diagram at the transmitter side. Similarly, there is no noise at the receiver so there is no distortion on the constellations of the carriers. Because 64-QAM is used, there are 8x8=64 locations and they are located in ia square shape.



Graph 12: Constellations from receiver.

Graph 12 shows the constellation diagram at the receiver part. If it is compared with Graph 11, there are some distortion caused by noise. After the signal complete the transmission, it includes some and because of this noise signal is distorted. If points does not touch the each other on the constellation diagram, data transmission and detecton is achieved successfully.

In order to support this thesis, eye diagram can be considered. Eye openings can be clearly seen so data transmission is achieved successfully. To make more quantitative analysis, BER values can be taken into consideration. At 38 dB OSNR level, BER is in the range of 10^{-5} which is good value for most communication systems.

64-QAM OFDM system for visible light communication is constructed and results are obtained. Results monitor that the transmission can be performed in acceptable range.

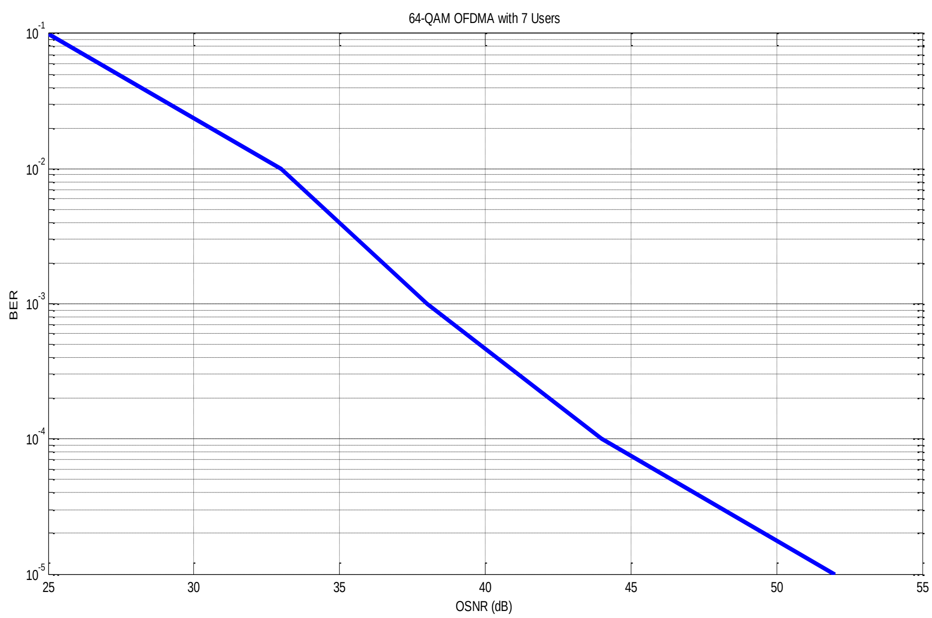
In order to combine first and second part of the study, BER performance of the points where take minimum received power will be discussed. To observe the effects of optical power distribution on performance of communication system, Layout 1 and Layout 2 are compared in terms of their received minimum optical power. Results are shown in Table 15.

Table 15: Comparison of Layout 1 and Layout 2.

Parameter	**Layout 1**	**Layout 2**
Received Minimum Optical Power	3.3148 dBm	7.4663 dBm
Number of Bit Errors	539	40
BER Performance	4×10^{-3}	3×10^{-4}

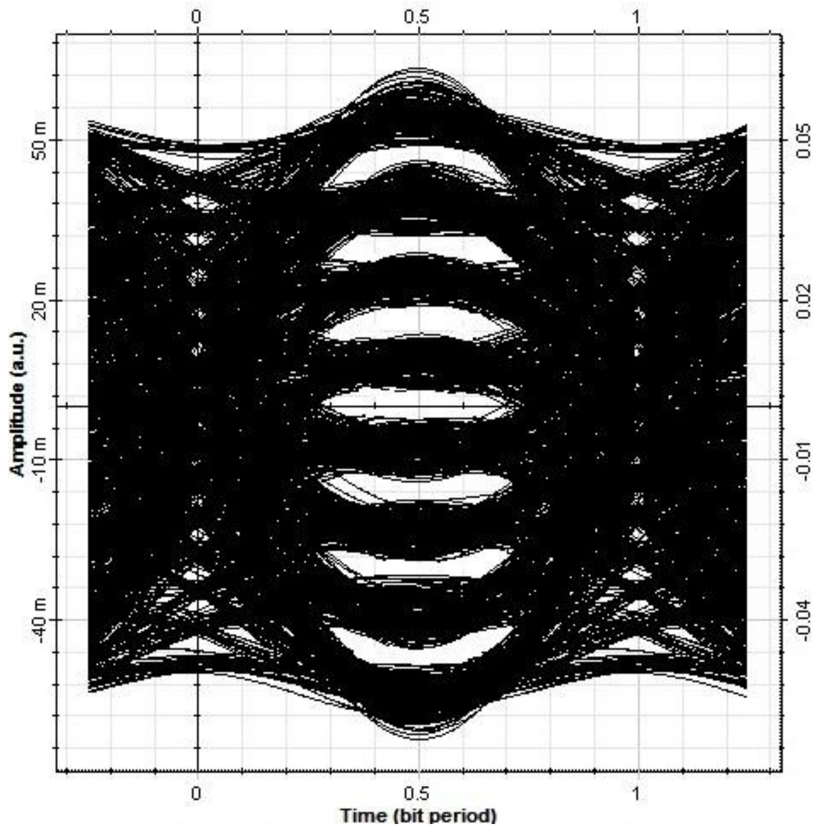
Layout 1 has 539 bit errors while Layout 2 has 40 bit errors. Furthermore, Layout 2 gives almost 13 times better BER performance than Layout 1. By using these values, one can conclude that altering LED placements has important effect on system performance because Layout 2 gives much better results in terms of both number of dead zones and BER performance.

In the third part of this study OFDMA system is constructed for visible light communication. This study is not related to the optical power distribution study. 64-QAM OFDMA system is constructed for seven different users. In Figures 5.12, 5.13, and 5.14, BER performance, eye diagram, and output constellation diagrams are shown respectively.



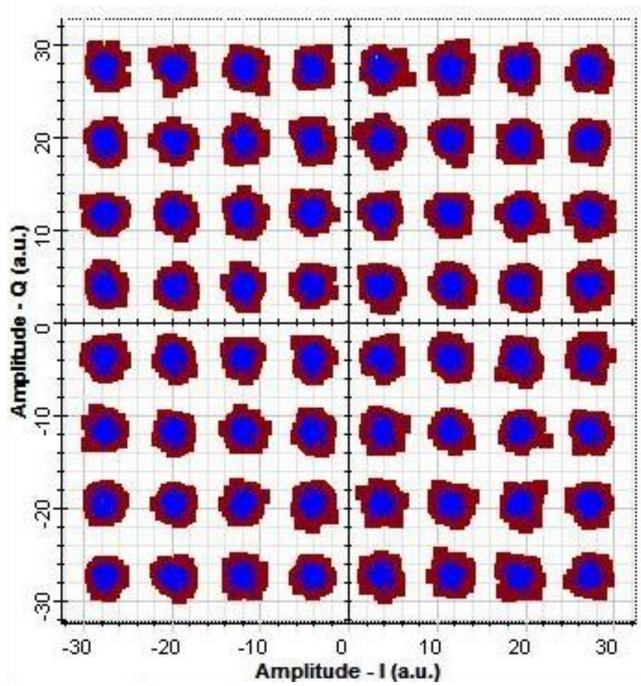
Graph 13: BER performance of 64-QAM OFDMA.

Graph 13 shows the graph OSNR in dB versus BER. As understood from the figure, almost 53 dB OSNR is required in order to obtain 10^{-5} BER value. This value was 38 dB for 64-QAM OFDM system. It can be concluded that more OSNR value is needed in OFDMA to obtain same BER performance with OFDM. This is because more than one user use the same time slot in OFDMA, and power is divided into several sub-channels, in other words, individual channel has less power. Because of this reason, more OSNR value is required in order to have same BER performance.



Graph 14: Eye diagram of 64-QAM OFDMA.

In Graph 14, eye diagram at the receiver is shown and eye openings can be seen clearly. Hence, performance of the system is in acceptable level. However, it this eye diagram is compared with eye diagram for OFDM system, there are more distortion on the signal. This can be understood from the width of the dark black curves. It can be concluded that 64-QAM OFDM system gives better results than 64-QAM OFDMA system.



Graph 15: Constellation diagram of 64-QAM OFDMA.

In Graph 15, constellation diagram taken from the receiver side is shown. Because no individual sub-carriers touch to each other, there is no certain problem for the transmission.

As a results, it is difficult to transmit data for 64-QAM OFDMA system than 64-QAM OFDM system. When number of user increased, more OSNR is needed. At the same OSNR value, OFDM gives better results than OFDMA system.

CHAPTER SIX

CONCLUSION

Visible light communication is developing area with is superiors. It can solve the health problems resulted from electromagnetic radiation, it provides much more bandwidth, and it is securer because visible light cannot pass through walls. With all these advantages of VLC, it is the main candidate to become an alternative of RF technology.

In this thesis, some fundamental studies belonging to VLC are performed. These studies are optical power distribution, 64-QAM OFDM system, and 64-QAM OFDMA system, respectively.

At the optical power distribution study, four different layouts for LED placement on the ceiling are tested. After simulations of those layouts, it can be concluded that changing LED placement minimize the number of dead zones. In addition to this, distance between transmitter and receiver and illumination angle of LED are other important parameters for the optical power distribution. After this study, dead zones are minimized and also degree of uniformity is improved importantly.

64-QAM OFDM system is performed and results show that this system is suitable for visible light communication. Furthermore, 64-QAM OFDMA system is constructed and similarly it can be used for visible light communication. However, 64-QAM OFDM system gives better results than 64-QAM OFDMA system.

Finally, BER performance of the layouts are investigated for 64-QAM OFDM system. Layout which has no dead zone has the best BER performance. From this result, it can be easily concluded that optical power distribution affects overall system because it has an effect on BER performance.

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